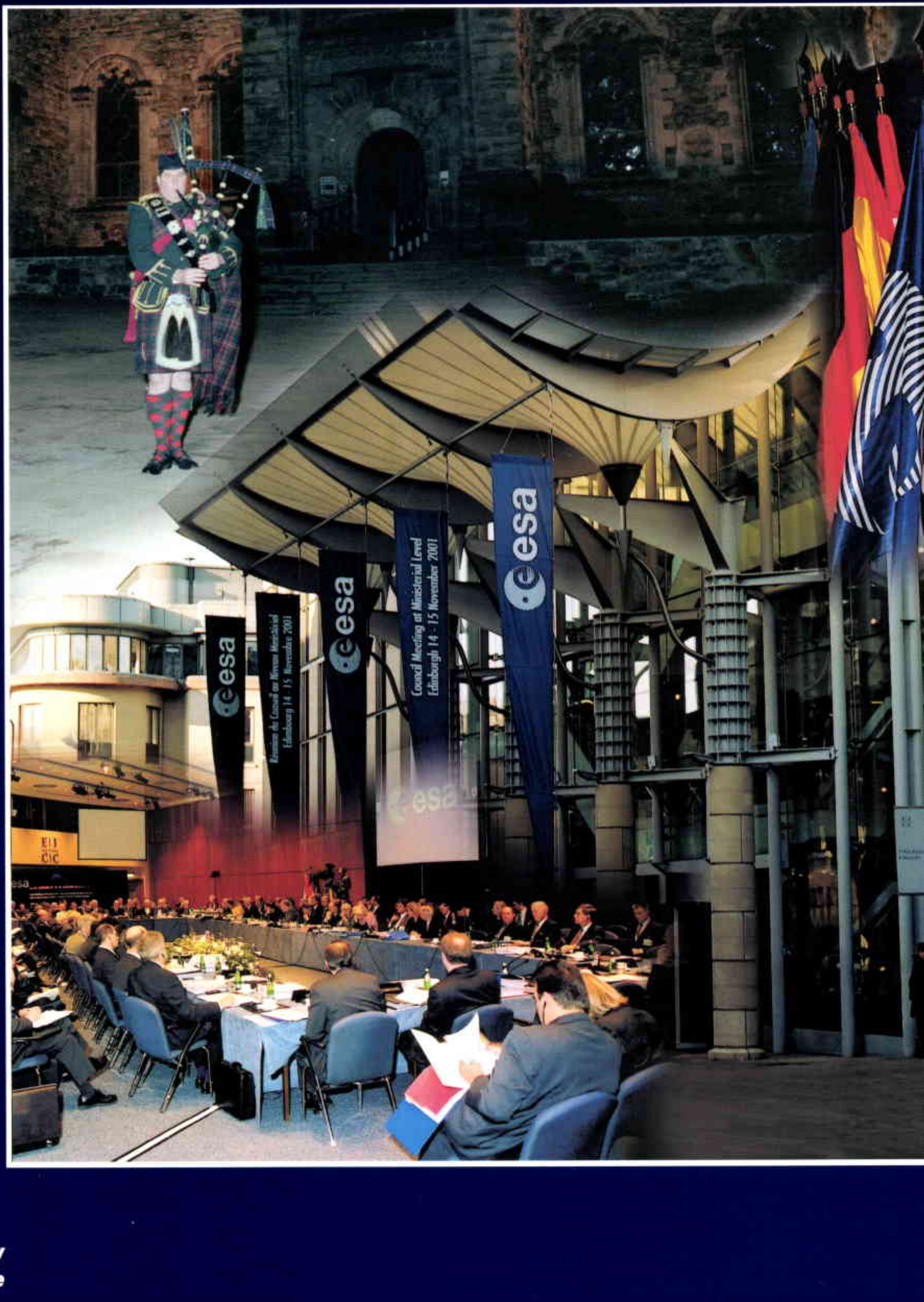
esa

bulletin

number 108 - november 2001



European Space Agency
Agence spatiale européenne

european space agency

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

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

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

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

The ESA HEADQUARTERS are in Paris.

The major establishments of ESA are:

THE EUROPEAN SPACE RESEARCH AND TECHNOLOGY CENTRE (ESTEC), Noordwijk, Netherlands.

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

ESRIN, Frascati, Italy.

Chairman of the Council: A. Bensoussan

Director General: A. Rodotà

agence spatiale européenne

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

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

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

L'Agence est dirigée par un Conseil, composé de représentants des Etats membres. Le Directeur général est le fonctionnaire exécutif supérieur de l'Agence et la représente dans tous ses actes.

Le SIEGE de l'Agence est à Paris.

Les principaux Etablissements de l'Agence sont:

LE CENTRE EUROPEEN DE RECHERCHE ET DE TECHNOLOGIE SPATIALES (ESTEC), Noordwijk, Pays-Bas.

LE CENTRE EUROPEEN D'OPERATIONS SPATIALES (ESOC), Darmstadt, Allemagne.

ESRIN, Frascati, Italy

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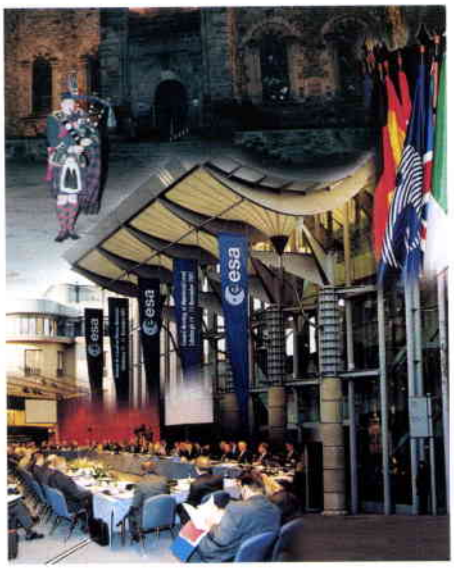

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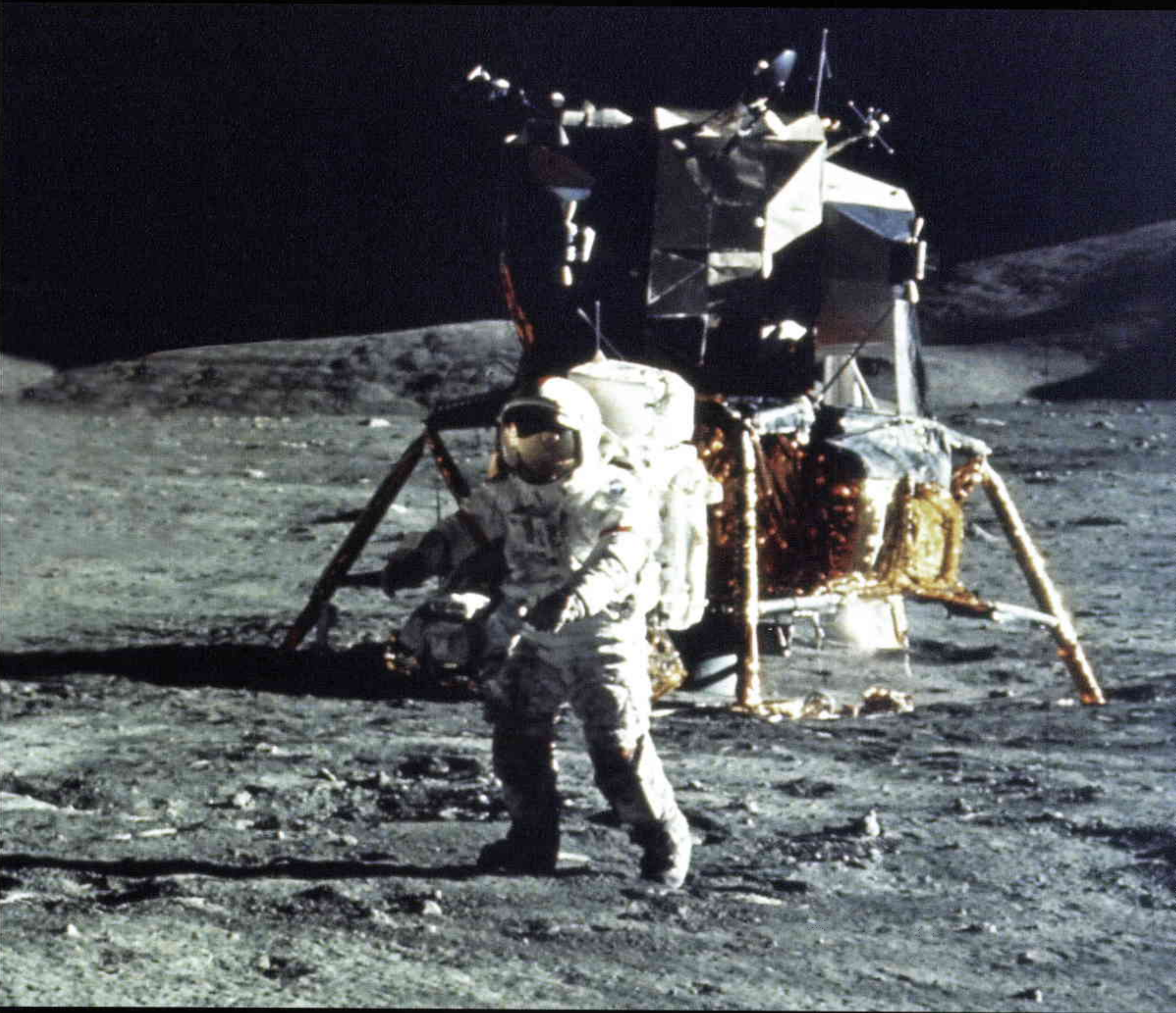
European Space Agency
Agence spatiale européenne

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The ESA Council at Ministerial Level

Edinburgh, 14-15 November 2001

The Director General's Proposal for ESA's Policy and Programmes

A. Rodotà

Space services are part of everyday life. TV broadcasting, weather forecasting, protection of the environment, financial services, and car-navigation all rely on globally operated satellite systems. At the same time, space is a vital tool for scientific research, serving the advancement of our understanding of the origins of life, the development of the Universe, and the complexity of the terrestrial ecosystem.

The resources offered by space also contribute significantly to meeting many of the challenges facing the Europe of today. I am thinking here of:
- safeguarding and further improving the well-being, security and prosperity of every citizen,
- protecting the environment and ensuring sustainable development, and
- preserving Europe's cultural identity, diversity and value systems,

in short, becoming 'the most competitive and dynamic knowledge-based economy in the World'.

To meet these challenges, Europe must do more than continue to exploit space effectively, drawing wherever possible on the results already achieved. It must also strive to improve the overall efficiency of the entire European space sector, which includes the efforts of scientists, industrialists, public agencies (national as well as ESA), and service companies.

Within this challenging environment, the European space community is already producing value for Europe. I am thinking in particular of:
- first-class science
- a large share in the World market for space infrastructure and services
- major contributions to public-service provision for citizens.

First-class science
Even with a continuing decline in the budget for science programmes, the European science missions have achieved significant results in the last six years:
- Soho has explored the Sun's internal structure, providing insights into the workings of the solar nuclear fusion reactor and the solar dynamo.
- Cluster is giving us a comprehensive vision of space weather.
- ISO has discovered the ubiquitous presence of water molecules in the Universe.
- XMM-Newton has greatly expanded our understanding of the composition of the enormous high-speed jets emitted by young stars.

A large share in the World market
Worldwide expenditure on space is estimated at around 70 billion Euros in 2001. The public sector still accounts for a very significant proportion of that spending, though the commercial sector is moving rapidly towards a share of about 50%.

Out of total public expenditure of about 38 billion Euros, the United States' share stands at 76%, the figure for Europe being just 14%, equally divided between ESA and the national programmes. The rest of the World spends 10% of the total.

Although in interpreting these figures account has to be taken of variations in purchasing power from one country to another, the fact is that Europe's investment is about one fifth of that of the United States. Even so, Europe has been able to secure a steady increase in its companies' share of the World commercial market – although the USA had a start of almost ten years.

In the early eighties, Europe launched no commercial payloads at all and was completely out of the market for commercial satellites, a market that had come into being some seven years before. Today, twenty years on, thanks to

substantial public investment in developing Ariane and building the first European communications satellites (ECS and Marecs), European companies have gone on to take:
- 56% of the global commercial launcher market, and
- 27% of the global commercial satellite market.

European companies have been equally successful in the telecommunications-services marketplace. They currently account for about 28% of the overall market and are increasingly globalising their business with the acquisition of large overseas international operators.

Public-service provision for citizens
There are at least three areas in which the contribution of space to the everyday life of citizens is both evident and, increasingly, vital.

The first is meteorology. Even though Eumetsat, the Agency that operates meteorological services, is currently a non-profit organisation, studies point to an indirect return on investment in excess of 8. Through the Meteosat and MetOp satellites, which ESA and Eumetsat have been jointly developing for a number of years, Europe is also contributing, together with the USA, Russia, China, India and Japan, to a global network disseminating meteorological information all around the World.

The second example is the use of Earth-observation data for disaster monitoring. The International Charter on Space and Major Disasters, initially signed by ESA and CNES, and later by ISRO, CSA and NOAA, seeks to provide a unified system for acquiring space data and delivering it to people dealing with natural or man-made disasters.

The third example is the contribution being made by space to the information-society infrastructure, providing a complementary but nonetheless important means of access to the Internet, and its enabling role for new services such as telemedicine and distance learning.

These enormously valuable results were achieved through the combined efforts, at European level, of the scientific community, industry and the space agencies.

What specific contribution has the European Space Agency made to the emergence of such first-class capabilities and the achievement of such outstanding results? I would like to focus on what I see as the three main strands of this specific ESA input:
- Programme management
- Technical management
- Internal efficiency.

Programme management
The evolution of mission cost per tonne is a good indicator of ESA's increasingly effective management of space – and in particular satellite – programmes. Mission cost per tonne has been in steady decline since the early eighties, falling by about 40%, with a roughly stable level of risk and innovation in the various programmes.

This in turn means that ESA has, over the last fifteen years, demonstrated its ability to put progressively larger payload masses into space per year, a clear pointer to the growing through-put of the entire European space sector. No such positive trend is to be found in the NASA programmes.

Technical management
It is important to underline that better performance in programme management has been obtained by ESA maintaining product quality. The following are just a few indicators demonstrating the technical quality of the Agency:
- ESA has never had any catastrophic satellite mission failures (compared with a 30% failure rate in NASA programmes).
- ESA has negotiated insurance premiums at about 50% of market rates.
- ESA satellites usually exceed their estimated and planned lifetimes (for instance, ERS-1).

Last but not least, I want to underline the recent recovery of our Artemis satellite, which, together with the earlier recovery of Soho, testifies to the excellence of our technical teams.

Internal efficiency
A lot of effort has been devoted to improving the Agency's internal efficiency. Two indicators confirm the gains in efficiency that have been made.

The first is the amount of budget managed per staff member. For programmes directly managed by ESA, the chart shows a steady yearly increase of 8.2% in recent years, compared to a 2.2% increase obtained by NASA. This has been accompanied by very tight cost control applied to ESA programmes.

The second indicator is the deviation of programme costs at completion from the costs initially estimated. Comparing the status of overruns on major ESA programmes in 1997 and in 2001 clearly demonstrates the effectiveness of the efforts devoted by managers at the Agency to proper control of all programmes, while at the same time organising industrial competition and an acceptable geographical distribution of contracts. Here again, if we compare our results with the data coming from NASA, we can be more than proud of our achievements.

I have perhaps taken too long over showing the results of the European space sector and the Agency in recent years. But I find it important, when you are about to decide on the future of the European space sector and on new investments for Europe, for you to feel convinced of the absolute necessity of these investments and of ESA's dedication to efficient, responsible use of taxpayers' money.

I would like to stress that all the reported achievements have been made possible by the continuous efforts of each and every Agency staff member and the intelligent support received from our Member States.

The Agency is now at a crossroads: it has to operate in a rapidly evolving space and industrial sector. European citizens have new requirements, and users have new demands with regard to space. Moreover, the context in which space activities are conducted is likely to be dramatically changed by the events of 11 September.

A few years ago, ESA initiated a comprehensive assessment of how it should evolve to meet the challenging demands of the future. This has already led to important results – first of all in the new relationship with the European Union. We are very proud that space has become firmly established on the European agenda and delighted that the President of the Commission will be addressing the ESA Council today.

Additional effort is now required to make space one of the pillars of tomorrow's Europe and to make ESA the Space Agency of Europe. This will translate into additional tasks for ESA. In order to maintain the quality of its work in response to these new demands, it will be necessary to slightly increase the general budget. This Council will hopefully give a clear indication in that direction, together with full support to the programmatic lines aimed at providing services to all European citizens.

I would like to come back to the events of 11 September, tragically echoed on Monday, since they have potential implications for the Agency. We have to consider whether those events put the very basis of our policies in question, or whether they simply mean that those policies have to be pursued in a number of additional directions? The Agency has already started deliberations on the matter, but it is too early to present conclusions, just a few preliminary observations.

This crisis is, indeed, a great test for Europe and does require a political response. The increasingly close links between the European Union and ESA will enable Europe to use space as a means to achieve its common foreign and security policy objectives. Technology is not an objective per se, but space technology, integrated with other technologies, will prove essential and even critical in the context of these policies. International peace and security are essential values to be preserved and space can make significant contributions to this crucial objective.

Within the complex situation emerging from the September events, it is furthermore evident that worldwide inequalities will have to be addressed in greater depth. Space systems have contributions to make in reducing inequalities: providing means of conveying education and information, supporting sustainable development, improving water and natural-resource management, enabling prevention, forecasting and management of natural and man-made hazards.

Most of the programmes proposed today for your attention address these issues. They are essential to the future of Europe. Decisions need to be taken now to ensure that Europe can use space to implement its policies in an independent manner. You,Ministers, are today called upon to take those decisions, supporting the programmes and giving the Agency the means to execute them successfully.

The Programmes and Budgets

The Programmes tabled for decision in Edinburgh covered the Level of Resources (Science and General Budget), Earth Observation, Telecommunications and Satellite Navigation, the International Space Station, Launchers and the start of a new European long-term initiative for the robotic and human exploration of the Solar System.

LEVEL OF RESOURCES

The Level of Resources determines the funding available for the basic activities of the General Budget and for the Science Programme.

General Budget

The General Budget covers corporate and administrative costs, technical activities such as the basic General Studies and Technological Research Programmes, plus Earthnet and Education (funding of fellowships, etc.).

The total of Member State contributions to the General Budget for the period 2002–2006 amounts to 775 MEuro.

Science Programme

The funding for the next five years should cover:

- the maintenance of scientific missions already launched (Hubble Space Telescope, Ulysses, Cluster-II, SOHO, Huygens/Cassini, XMM-Newton)
- approved scientific missions in the development phase (Integral, Rosetta, Mars Express, Smart-1, Herschel-Planck), and
- new missions under study or to be chosen and initiated within this period (i.e. the Cornerstones BepiColombo, GAIA and LISA
- with Smart-2, and the Solar Orbiter flexi-mission)

The total contribution received for the Science Programme for 2002–2006 amounts to 1869 MEuro.

EARTH OBSERVATION

Earth-Observation Envelope Programme, EOEP-2

The EOEP implements Earth Explorer Core and Opportunity missions and also funds mission exploitation, instrument redevelopment and support for market development. Earth Explorer missions such as Cryosat, the Gravity-field and steady-state Ocean Circulation Explorer (GOCE), the Soil Moisture Ocean Salinity (SMOS) mission and the initiation of full implementation of the Atmospheric Dynamics Mission (ADM-Aeolus) are major achievements of the first phase of this programme. The second phase, EOEP-2, will give the Earth Science community and industry a stable outlook whereby one new mission will be launched each year. It will also cover the preparation of Earth Watch missions.

The financial commitments received from Member States for EOEP-2 amount to 926.44 MEuro for the period 2003–2007.

Earth Watch Programme

The Earth Watch initiative will include a number of Earth-observation missions supporting public and private-sector applications such as mapping, natural-resource management, major risks and security, geology, etc. Earth Watch will also cover the requirements of the Global Monitoring for Environment and Security (GMES) initiative, currently being drawn up with the European Commission, addressing in particular global change, natural and man-made hazards, environmental stress and monitoring of treaty commitments.

The following financial commitments received from Member States for Earth Watch Slice-1 cover the period 2002–2006:

- GMES service elements: 83 MEuro.
- Thematic L/X-band SAR element based on the joint proposal from the British and German space agencies (BNSC/DLR) for Infoterra/TerraSAR: 25 MEuro.

- Consolidation of the infrared element based on the Spanish CDTI Fuegosat proposal: 9 MEuro.

TELECOMMUNICATIONS

Advanced Research in Telecommunication Systems (ARTES) Programme
Several actions/projects have been identified to further increase the competitiveness of European industry in satellite telecommunications, many of which are continuations and amplifications of ongoing activities within ESA's ARTES Programme:

ARTES 1: Preliminary Studies and Investigations
Funding for 2002–2006: 27.22 MEuro

ARTES 3: Satellite Multimedia (also covering mobility and inter-satellite links)
Funding for 2002–2006: 213.3 MEuro

ARTES 4: ESA/Industry Telecommunications Partnership (dealing with part of the technology and user-segment activities)
Funding for 2002–2006: 165.3 MEuro

ARTES 5: Advanced Systems and Telecommunications Equipment (consisting of technology, user segment and in-orbit demonstration)
Funding for 2002–2006: 53.85 MEuro

ARTES 8: Large Platform Programme
Funding for 2002–2006: 133.85 MEuro

Additional funding for the ARTES programme yet to be allocated to specific activities: 350 MEuro

Galileo Programme
Europe's global navigation system, Galileo, is a joint initiative of the European Commission and ESA and will deploy a full constellation of navigation satellites by the end of 2008, with superior technical and operational capabilities compared with the American GPS and Russian Glonass systems.

After a Definition Phase (end 1999 – end 2000) devoted to overall system design, Galileo is now entering its Development and Validation Phase (2001–2005). The in-orbit validation of the system is based on the deployment of a limited constellation of three to five satellites and a representative ground-control segment and test receivers.

ESA's contribution to the Galileo Development and Validation Phase is 527.87 MEuro. A similar contribution is expected from the European Union in December.

The full Galileo system will consist of some 30 satellites in medium Earth orbit at 24 000 km altitude, and the associated ground infrastructure. The cost of the overall Galileo project is estimated at some 3 BEuro. Financial schemes for the deployment and operational phase are currently being finalised.

HUMAN SPACEFLIGHT AND MICROGRAVITY

ISS Exploitation Programme Continuation
The objectives of the Programme are to develop European operational capabilities in the key areas required for long-term human space exploration, to build up the knowhow necessary to master the operation of a complex human outpost in space, and to support exploitation of the ISS by the European user community.

Exploitation Period 1 (2002–2006) covers activities such as partial funding of the first Ariane-5 and full procurement of the third Ariane-5 for the ATV, plus ATV procurement activities, including the first production unit. Period 1 of ISS exploitation is composed of fixed and variable cost activities.

The finances available for this programme amount to 846.69 MEuro.

Human Spaceflight Studies, Technology and Evolution Preparation (STEP)
The objectives are the improvement of existing ISS services, the reduction of operational costs and the preparation of future infrastructure capabilities. It is conceived as a framework programme structured in periods of three years, with contributions on a 'pay as you go' basis.

The first three-year period of activities (2002–2004) is funded with 12.4 MEuro.

ISS Commercialisation Utilisation Programme
This Programme is designed to lay the foundation for commercial utilisation of the ISS, to stimulate commercial utilisation to generate revenues and thus reduce the contributions payable by participants in the ISS exploitation programme, and to promote the image of the ISS in order to attract a larger community of users.

This Programme will be submitted for approval when the overall ISS situation is clarified.

ISS Additional Flight Opportunities Programme
This Programme's objectives are to maintain and develop an active and experienced

European Astronauts Corps, offering further flight opportunities. The Programme, which envisages the procurement from Russia of four Soyuz flights to and from the ISS in the period 2003–2006, will be submitted for approval in connection with the submission of the European astronaut policy in Spring next year.

ELIPS Programme
The Programme's objectives are to maximise the benefits to society of ISS utilisation, to promote European competence and competitiveness in the life and physical sciences, to pursue basic scientific research in the life and physical sciences and also industrial and commercial applications in space, and to set up a coherent framework for European activity in this area.

The financial envelope for Period 1 of the Programme (2002–2006) amounts to 166.52 MEuro at 2001 economic conditions.

LAUNCHERS

Ariane-5 Research and Technology Accompaniment (ARTA-5) Programme
The objectives of the ARTA-5 Programme are to maintain the reliability and level of qualification of the Ariane-5 launcher throughout its operational lifetime, to eliminate any design flaws and weaknesses that might appear during operational use, and to improve knowledge about the functional behaviour of the launcher in flight.

The four-year extension of the ARTA-5 Programme (2003-2006) is funded with 302.97 MEuro (2001 e.c).

Ariane-5 Infrastructure
This Programme, covering the fixed costs of the ELA-2 (Ensemble de lancement no. 2) and ELA-3 launch complex facilities, covers the period 2002–2004.

The three-year extension is funded with 131.45 MEuro (2001 e.c.).

Guiana Space Centre, CSG (Centre Spatial Guyanais)
The agreement on CSG management and funding has until now covered the upkeep and operating costs of the Centre's range facilities to ensure long-term stability of the strategic investment in Europe's assured access to space.

The new proposal covering CSG's fixed costs for the five-year period 2002–2006 has a budget of 423.2 MEuro (2001 e.c.).

Ariane-5 Plus
The objective of this Programme is to ensure that Ariane-5 evolves and remains competitive on the World market by increasing its performance and versatility, and bringing down the launch price.

The Ariane-5 Plus Programme has been broken down into three steps. The first step, decided at the Council Meeting in June 1998, covered the first year of activities. The second was decided at the Council Meeting at Ministerial Level in May 1999 and covered the initial development of the Vinci engine, initial ground segment upgrading and full development of the versatile version of the existing upper stage, together with completion of the Ariane-5 ESC-A version (first launch planned for mid-2002), raising its lift capacity to geostationary transfer orbit to 9 tonnes.

The third step will round off the Programme, and will see the completion of Vinci engine development, completion of the ground segment upgrade, and completion of the Ariane-5 ESC-B version and its first launch (planned from 2006), bringing the GTO lift capacity to 12 tonnes.

The completion of the Ariane-5 Plus Programme has a budget allocation of 699.14 MEuro (2001 e.c.).

AURORA PROGRAMME

Aimed at developing a European long-term plan for the robotic and human exploration of bodies in the Solar System, in particular those holding promise of traces of life, the Aurora Programme activities will be pursued in co-ordination with European and international partners. Relevant technologies and mission scenarios will be developed in the three-year preparatory period.

The overall financial commitment for the first three-year period is 14.1 MEuro (2001 e.c.)

ESA Press Release

15 November 2001

The Ministers responsible for space affairs in the countries that make up the European Space Agency – its Fifteen Member States and Canada – today concluded a two-day meeting in Edinburgh of the Agency's ruling Council by endorsing the next stages in a series of ongoing programmes and committing to new initiatives that will help keep Europe at the forefront of space science and technology, Earth monitoring from space, telecommunications, satellite navigation, launchers, human space flight and planetary exploration.

In particular, ESA and its Member States made significant progress in shaping a range of future-oriented programmes, with major decisions aimed at enhancing Europe's role in the space sector.

The Agency signalled its strong commitment to closer cooperation with the European Union. A first Resolution highlighting the importance of a balanced, ambitious space programme serving Europe's citizens was adopted unanimously.

The Members agreed on a Declaration embodying financial commitments for the development of Galileo, Europe's satellite-navigation system. ESA now looks forward with confidence to the European Union Transport Ministers' approval of their contribution to Galileo at their December meeting. Galileo is a major component of Europe's transport policy and will be deployed in partnership with the business sector. It will offer a wide range of independent navigation services for commercial and private users, and promises to generate new commercial services in areas such as road-vehicle navigation and air-traffic control.

Further collaboration with the European Union will focus on the Global Monitoring for Environment and Security (GMES) Programme, which will address such issues as global change, natural and man-made hazards, environmental trends and monitoring of treaty commitments. Earth observation is today an essential resource for surveillance of the environment and the management of natural resources. GMES and a number of other Earth-observation projects were approved as the first elements in a series of applications missions within the Agency's Earth Watch initiative.

The Delegations also decided to back a programme that will see the Ariane launcher, which for many years now has held more than half of the World market for commercial launches, evolve in terms of power and versatility. ESA is confident that Ariane will remain the World's number one choice for carrying commercial satellites into orbit. The European strategy for independent and affordable access to space is based on the provision of competitive European launch systems. The Ministers stressed that to make that strategy work the right balance has to be struck between the respective roles, responsibilities and financial commitments of the public and private sectors. Restructuring of the launcher sector in Europe would be another key factor.

Concerning the ongoing discussions in the United States on the future configuration of the International Space Station (ISS), the European Ministers sent a clear message to the ISS partners confirming that ESA will fulfil all of its obligations, and by the same token expects NASA to keep to the International Treaty. ESA's main focus of interest is an intensive scientific research programme calling for specific onboard resources, one being the presence of full-size crews. One of the Resolutions passed by the Ministers, concerning ISS utilisation, provides the financial resources required by ESA, but makes release of the final 60% conditional on NASA's confirmation of the original agreement.

The Science Programme is the backbone of ESA's activities – its highly successful missions have made Europe a World leader in space science. The outcome of the meeting ensures that science at ESA will remain a European flag carrier, contributing to our knowledge-based society.

Telecommunications satellites provide services that enhance many aspects of our lives, and Europe already provides more than a quarter of the World's commercial platforms. The ongoing ARTES Programme will lead to new services and offers the prospect of continuing commercial success in a rapidly evolving market.

Europe now needs to exploit the strategic potential of space systems more effectively to further its scientific, economic, social and political objectives. The Ministers acknowledged this in Edinburgh by renewing and expanding ESA's mandate to establish closer ties with the European Union.

The process of wedding the public policy objectives of the European Union and the capabilities of the European Space Agency got underway some years ago. ESA is increasingly committed to closer cooperation with the European Union to further its aim of putting space at the service of European citizens, and also to focus attention on space at the highest political level in Europe. Pursuing these goals, ESA and the EU are now engaged in the development and implementation of a truly European space policy. The foundations of that policy were laid in November last year, when the ESA and EU Councils endorsed a joint document on a European Strategy for Space.

As Europe grows, ESA is bound to grow too: the recent accession of Portugal, the interest expressed by Greece in becoming a Member State, and the intensifying cooperation with Central and Eastern European countries, all testify to the continuing vitality of the Agency and its programmes.

The cooperation extends beyond Europe, with last year's renewal by Canada of its long-standing Cooperation Agreement with ESA and an expansion in the Agency's joint work on facilities and programmes with the United States. Japan and ESA are also working together closely in Earth observation and science. The existing cooperation arrangements with Russia will be further developed in areas of benefit to Europe. Ventures involving emerging space-faring nations – notably in the Asia-Pacific region and in Latin America – are also on the ESA agenda.

Outstanding space programmes are only possible with a strong technology base, which is the key to the competitiveness of European industry in World markets. The Ministers sought therefore to underline the importance of deriving maximum benefit from technology, with measures to encourage technology transfer and spin-off.

The Ministers expressed appreciation for ESA's efforts in coordinating communication and education programmes and in encouraging young people to widen their career horizons. They urged the Agency to make European citizens more aware of the knowledge and benefits they can derive from European-led space research.

The closing Press Conference: from right to left, Minister Edelgard Bulmahn of Germany, who chaired the Edinburgh Ministerial Conference, Mr Antonio Rodotà, ESA Director General, and Mr Franco Bonacina, ESA Spokesman

Council in Session

Lord Sainsbury hands over the Chair to Mrs Edelgard Bulmahn

Welcome by the Lord Provost of Edinburgh, the Rt. Hon. Eric Milligan

The participating Ministers, together with EC President Romano Prodi


NORWAY


FINLAND


IRELAND


CANADA


PORTUGAL


AUSTRIA


SWITZERLAND

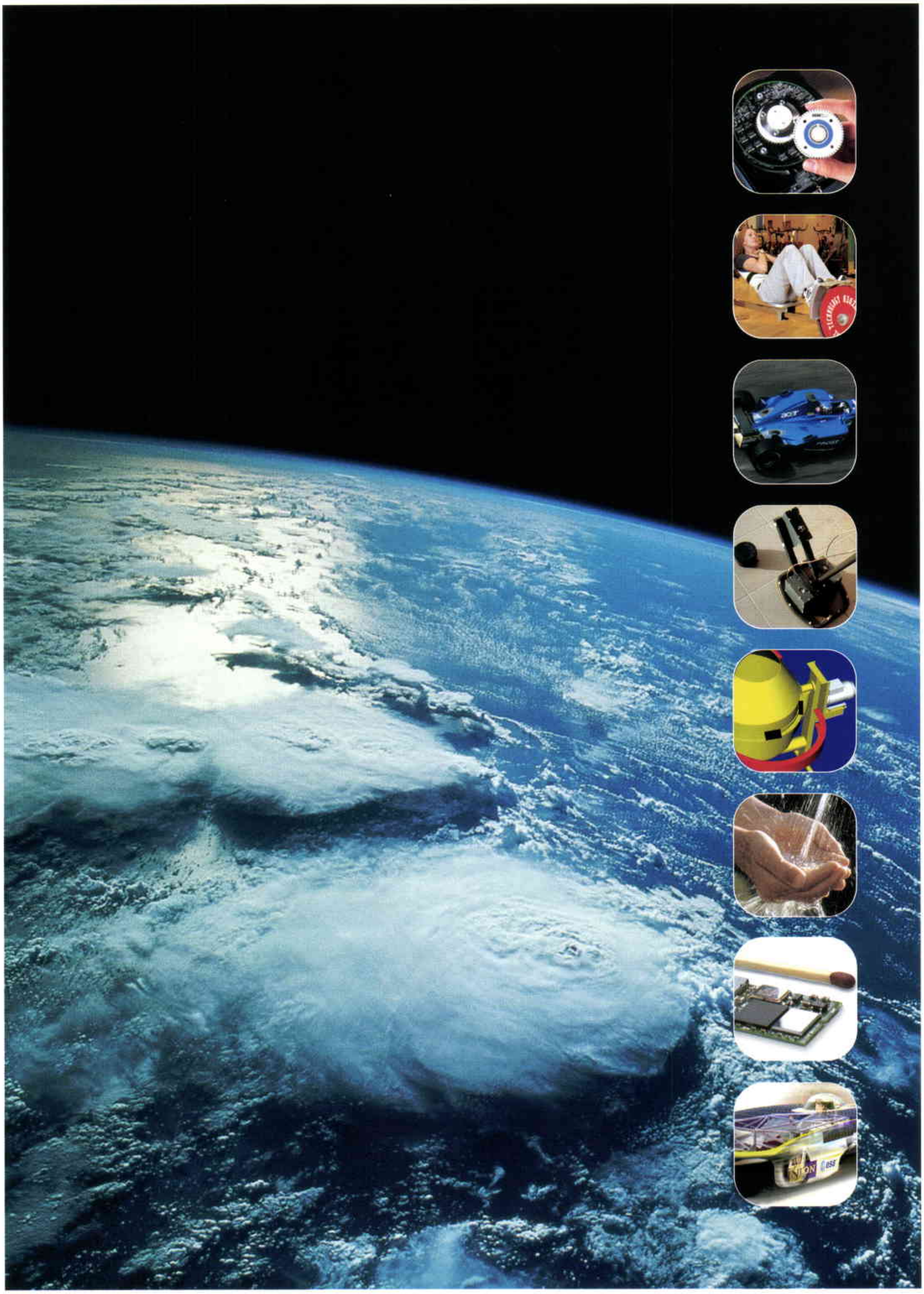

ITALY


FRANCE

OBSERVERS

Arrival of Mr Romano Prodi

The closing Press Conference



Down to Earth
– Everyday Uses for European Space Technology

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Every year billions of dollars are spent on research and development activities in virtually every technological sector. Sadly, although many such activities have a wide potential of application, the results of this research are still a long way from commercialisation. However, companies, research organisations and academic institutes are now waking up to the fact that it has become increasingly necessary to exchange, transfer and license the technologies (including software) and knowledge they have developed in order to access new markets and revenue streams. On the other hand, it also becomes ever apparent that companies need to acquire new technologies, particularly the leading-edge technologies being developed within the space industry, in order to exploit their ideas and create new products.

Introduction

Technology transfer is the process of using technology, expertise, know-how or facilities for a purpose they were not originally intended for by the developers. Technology transfer thus implies that a technology developed for one sector is then used as a spin-off in a totally different area. It often results in the commercialisation of products through licensing or the improvement of products and processes – though this usually takes a couple of years to happen.

Where space is concerned, it is worth bearing in mind that much of the technology that lies at the heart of spacecraft and their systems has its origins on the ground – the earliest space systems were based on established 'terrestrial' technologies. What space programmes have done over the past 40 years is to invest in raising these technologies to new levels of performance and capability – and this is the benefit that is 'spun off' to us here on Earth. The reason, as is made only too clear by the occasional costly failure on the launch pad, is that space exploration is a complex and risky business. It is also very difficult to get into space to fix equipment when it breaks down, and it used to be impossible before the advent of the Shuttle. From the outset then, reliability has been the primary requirement for spacecraft systems. Wherever possible, early designers sought out tried and trusted materials and components with which to make their spacecraft, and most of these were themselves spin-offs from the European and US defence and weapons industries developed after the Second World War.

What space research has done has been to develop and perfect these technologies to unprecedented levels such that the technologies can be transferred to new and often highly beneficial applications down on Earth. The range of these applications is enormous and organisations have established special programmes to facilitate technology transfer and commercialisation.

In the framework of its research and development (R&D) activities, ESA spends some 250 million Euros each year and, recognising the enormous potential of the know-how developed within its R&D activities, set up a Technology Transfer Programme over ten years ago. The Programme saves money by adapting space technologies, systems and know-how to other non-space users and applications. It maximises the return on investment in space research conducted by ESA for the benefit of its Member States and minimises the duplication of research between the space and non-space sectors. In addition, the Programme provides opportunities for researchers to collaborate with other organisations, thus allowing the possibility for two-way transfer – both through spin-off from space to non-space sectors and 'spin-in' of technologies developed in non-space sectors which might be relevant for space.

Over the past ten years, ESA's Technology Transfer Programme has achieved some remarkable results:

- more than 100 successful transfers of space technologies
- over 120 million Euros received by companies making the technologies available
- 15 new companies established as a direct result of exploiting space technologies
- nearly 2500 jobs created or saved in Europe
- a portfolio of over 450 space technologies available for transfer and licensing.

This article provides a few examples of successful transfers of space technologies that have been achieved in Europe and Canada over the past few years.

Applications for Health and Fitness

A healthy outlook

Using technology that enables astronomers to probe the distant reaches of the Universe – and with a little help from the glow worm – biomedical researchers can see deep inside a living cell. Like all modern optical instruments used by astronomers, the Hubble Space Telescope's Faint Object Camera (FOC), developed by ESA, exploits detectors called 'charge-coupled devices', or CCDs. These are silicon chips consisting of arrays of light-sensitive 'pixels', which convert impinging light into an electric charge that can then be used to generate an image. Today, CCDs are found everywhere – in digital and video cameras, for example, and in the office photocopier – but those employed in the Faint Object Camera are rather special in that they can detect single particles of light (photons).

These CCDs are controlled by special software, which ESA subsequently licensed to a British company specialising in making CCD cameras for biomedical applications. The company supported the work of medical researchers in the UK who were using some novel techniques for 'observing' the workings of living cells. Inserting a bio-luminescent protein extracted from glow worms into a living cell illuminates the cell's activity. The luminescent molecules attach themselves to calcium ions (thought to be the cell's 'messengers'), which can then be followed visually as they move around the cell. Using the CCD detector, cells can be seen responding in real time and, in an early experiment, the response of a seedling being touched by an ice cube was noted. This ability to observe the innermost workings of a cell is important in understanding and controlling disease, and is the focus of much of the current work.

The story does not stop, however, with CCDs. The technology is moving on and a new type of light detector called a superconducting tunnel junction (STJ) diode is being developed, which can also register the colour of the photons – information of great interest to astronomers and biomedical researchers alike. Researchers at the University of Wales College of Medicine are now developing a range of genetically engineered 'rainbow' proteins, programmed to change colour when they bind with a particular chemical in a living cell. This research has exciting implications for our future health. For example, a potentially cancerous cell will change from red to green, or from red to blue, and the next generation of cameras will be able to record this, providing scientists with more valuable information for the fight against the deadly disease.

How nosy can you get?

In a different application, technology that emulates our sense of smell is now being used to detect infections. The human nose is extremely sophisticated – it can detect and distinguish a huge range of odours and, as well as informing and enhancing the experience of eating, our noses also act as early-warning devices by helping to sense danger or decay. If you smell gas at home, it is usually easy enough to locate the source. This is not quite so easy to do in space, however, and this is why ESA supported the development of sensors to act as gas detectors on space stations such as Mir.

Scientists studying how smell works in humans have employed electronics to mimic the processes involved. Arrays of sensors can imitate the different types of olfactory receptors found in our noses. Processing electronics then convert the signals from the sensors into patterns and store them for future recognition. Typical 'electronic noses' employ many different types of sensors and sampling devices. The University of Manchester Institute of Science and Technology (UMIST) in the UK was contracted by ESA to produce a gas-sensing device for monitoring vital safety functions on Mir – the air quality, in particular any contamination resulting from leakages, and also signs of any fire break-outs.

In 1994 the technology was transferred from UMIST to a company called Aromascan (now Osmetech plc). Osmetech employs sensors made of conducting polymers arranged in arrays of up to 48 individual detectors. The way the polymers are arranged is unique to Osmetech and enables each element on the array to have a different conductive property. These multiple sensors can detect a range of distinctive smells and odours. Osmetech realised that there were many potential applications for the electronic-nose technology.

Figure 1. The Osmetech core sensor array

For example, when micro-organisms metabolise, they emit volatile components often possessing a characteristic smell, which the Osmetech sensor array technology can detect. The company recognised that the sensor arrays could therefore detect the presence of pathogenic bacteria, fungi and moulds such as those causing urinary tract infection (UTI), infections that result in women going into early labour, bacterial throat infections and pneumonia. These sensors can now be incorporated into automated multi-sample instruments for use in a hospital laboratory or at the doctor's surgery.

Keeping fit with a yoyo

Keeping fit in the weightless environment of space requires special kinds of exercise programmes and equipment. In space, everyone can manoeuvre objects they would not have a chance of lifting on Earth, but the downside of this is that the body does not get the exercise it needs to keep in top condition. Being in space is an extremely demanding activity, and a huge amount of attention is paid to astronauts' well-being and fitness, particularly as missions get longer and longer. Engineers and doctors are working together to design equipment and exercise programmes suited to the specific needs of space travel and weightlessness.

YoYo Technology based in Stockholm, Sweden has developed a machine designed to meet these unusual requirements. With support from the Karolinska Institute, the Swedish Space Corporation and the Swedish National Space Board, YoYo has developed equipment that uses the inertia of flywheels to provide resistance. The Fly-Wheel Resistance Exerciser differs from the normal equipment found in gyms because it provides 'two-way' resistance. The user is required to pull the cord from a flywheel and at the full stroke the flywheel begins to wind the cord back in. The user has then to resist this by pulling back on the cord. In effect, this is the same principle as that behind the familiar children's toy of the same name. The advantage of this system is that the load can be easily varied by changing the flywheel or altering its diameter. Users can also determine the amount of 'impact' in their training. Unusually, astronauts in space are encouraged to do high-impact exercise as it maximises body strength while minimising bone loss at the same time.

Having successfully designed equipment to meet the needs of the space industry, YoYo Technology is now turning its attention to terrestrial applications such as sports training and medical rehabilitation. The equipment is used by the Swedish Olympic athletics team, and also employed in orthopaedics to aid the recovery of stroke patients. It is proving particularly useful in re-establishing nerve connections in damaged muscles. A variant of the equipment is also being developed for use in home gyms, a market worth many millions of Euros worldwide.

Materials for Vehicle Security

Fabricating a defence against thieves

Vehicle manufacturers are continually looking for ways to improve reliability and safety. Technology originally designed for space applications can contribute to such developments. Belgian Spacelink partners (Spacelink is the ESA Technology Transfer Programme's network of technology brokers) introduced a French textile manufacturer to a consortium who needed to tackle road- and rail-transport theft across Europe. Theft from lorries and haulage containers is a growing problem, with those vehicles whose sides are

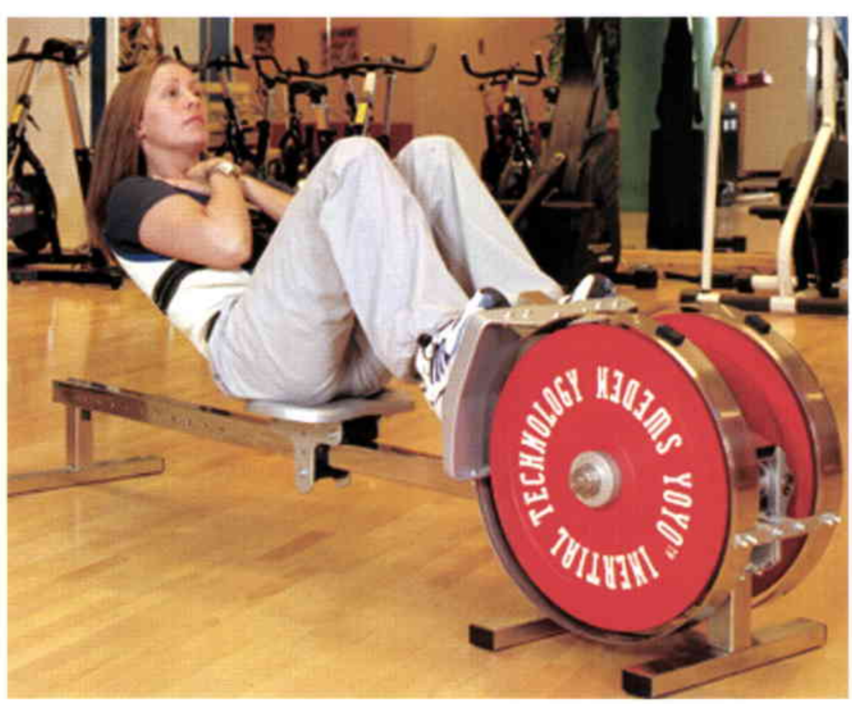

Figure 2. One of YoYo Technology's flywheel-based exercisers

made of fabric being particularly vulnerable to attack. Cargo containers spend a lot of time unattended in loading or storage depots and their tarpaulin covers, while light and convenient to use, offer little protection against the knives of vandals and thieves. By 1996, so serious had this problem become that three companies, a French manufacturer of haulage containers, a Belgian plastics and composites company and a large Belgian rail/road haulier, joined forces with CRIF – a Belgian collective industrial research centre – as the main focus of research to develop a new protection system for containers. The work was supported under the European Commission's CRAFT scheme.

The initial studies pointed towards the development of a better material for fabric screens, which would retain the advantages of lightness, flexibility and ease of cleaning, while offering great strength and resistance to attack. But where to find such a material? As part of its ESA-sponsored work, the Spacelink network surveys non-space companies throughout Europe to determine what kind of technology they might need. It was through this mechanism that the Belgian Spacelink partner Creaction circulated the requirement for a vandal-resistant textile and got a response from a French company Société Ariégeoise de Bonneterie which, following the success of its flame-proof textiles used on the Ariane rockets, had modified its knitting technique to create a flexible fabric from steel wire that was extremely difficult to cut and well-suited to the application.

By December 2000, research was completed and large-scale testing had begun. Parcouri, a consortium of eight European companies that includes a Dutch multinational producer of vehicle covers and a French SME specialising in coach building and kit fixing systems, is now developing a vandal-resistant alternative to the standard tarpaulins currently in use. Within an existing global market of 120 000 units a year, current predictions for the new material show a healthy potential market opening of 7000 units annually.

Hot brakes and airbags

Two French companies are also showing how vehicle safety is being improved with space technologies. Composite materials composed of a carbon matrix reinforced with long carbon fibres can withstand high temperatures, and are very resistant to wear. These materials were originally developed for use in the extreme conditions found in the nozzles of rocket motors. The developers realised that brakes made from such composites were more reliable, reduced vibration, and caused less pollution than traditional braking systems fitted on planes and road vehicles. Messier-Bugatti, based in France, produced a novel carbon braking system for use on aircraft such as the Airbus and now supplies one third of the world market for carbon composite brakes for commercial planes with more than 100 seats (over 230 planes were equipped in 2000 alone). Similar systems have also been employed on Formula-1 racing cars, heavy goods vehicles and passenger trains.

Another important safety feature – the airbag – has contributed a great deal to safe car travel in recent years, saving many lives and helping to prevent serious injury in collisions. Today, the device is considered to be one of the most important safety features since the seat belt was first introduced in the 1960s. When an impact above a certain force is sensed, the airbag inflates: an igniter activates compressed-gas capsules and these fill the bag with an inert gas. The whole inflation

Figure 3. A Formula-1 racing car with carbon brakes

process occurs within a split-second and the bag is completely deployed in less than one second – fast enough to save the driver. As most new cars use such safety devices, the market for the pyrotechnic charges is large. The French company SNPE Propulsion is using its knowledge in the field of solid propulsion for space launchers to design and develop the pyrotechnic charges used in airbag gas generators and seat-belt tighteners. SNPE Propulsion estimates that its products are used in one out of every four safety devices fitted into new cars each year.

Improvements for Seeing and Feeling

A cracking solution

Ginger, an ESA technology effort, set out to develop a ground-penetrating radar in support of a proposed programme to explore the Moon. Now, the same technology is showing great promise in two new life-saving roles – in preventing mining accidents and in detecting landmines. As computer processing power increases and becomes cheaper, ever more complex signal processing can be applied to radar signals and, by careful choice of frequencies, it is now possible to use portable radars to penetrate the ground and produce images of hidden structures and objects. In tunnels deep underground, liners and supports are often used to maintain their integrity. In some areas where the rock is hard, fine cracks can lead to tunnel collapse and a phenomenon known as 'rockburst'. Until now, all that miners could rely on was experience and intuition to tell them what is hidden beneath a rock surface, so a means of assessing the rock conditions and the integrity of underground supports would be of great benefit.

Based on the work of Ginger, RST Radar Systemtechnik of Switzerland and MIRARCO of Canada have developed CRIS, a dedicated ground-penetrating radar prototype, to detect cracks in the walls and roof of mine drifts. The radar can look through metal mesh and spray-on linings. It can identify cracks from a few millimetres to a depth of more than one metre. A hand-held CRIS prototype has been field-tested and has successfully met all design targets. Future work will concentrate on perfecting the device for use in the harsh underground environment.

Finding land mines

Ground-penetrating radars hold out great hope in another area. Anti-personnel land mines have become virtually undetectable and they carry a high toll in terms of injuries and lives each year. Now, four industrial partners, Vallon, RST, Spacebel and Bats, and four research organisations, DLR, RMA, ONERA and ISL, have joined with the Universities of Karlsruhe, Bochum and Milan to create 'HOPE', a hand-held multi-sensor land-mine detector. It consists of a metal detector, a radiometer and a ground-penetration radar. The aim is to reduce the number of false alarms when detecting mines, to speed up the process and to improve safety for operators. The 5 million Euro development is being partially funded by the Schweizer Nationalfond, the ESA Technology Transfer Programme, and the European Union, with a further 50% from industry.

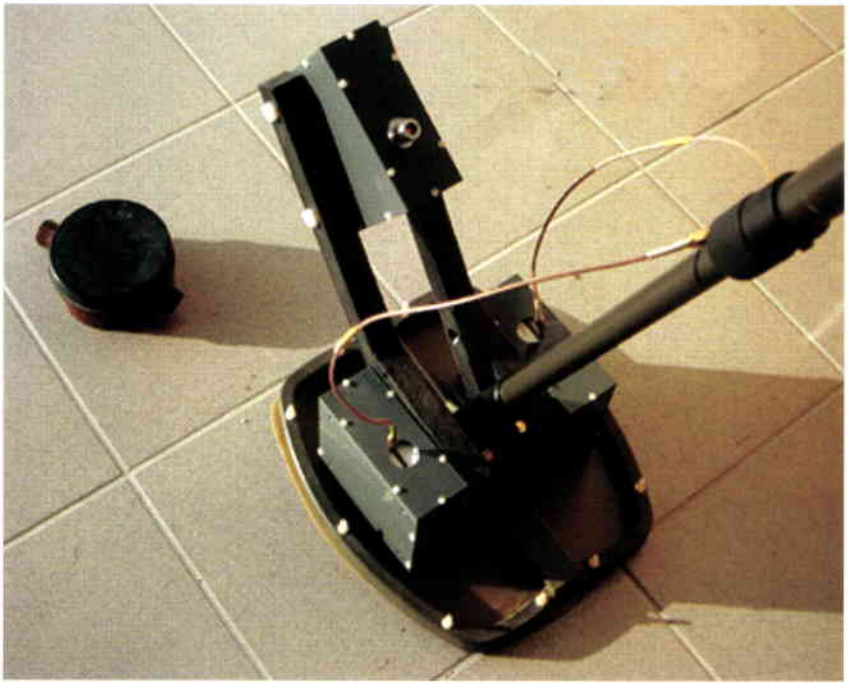

Figure 4. The Hope detector, and an anti-personnel mine

So far, the results are very promising. The three-sensor device detects foreign bodies, including plastic mines, by collecting radar data from the ground in horizontal slices; advanced off-line techniques can then be employed to generate a 3D image of the body to ascertain whether the object is a mine or some harmless piece of metal or rock. A prototype system in Bosnia has successfully detected small land mines to a depth of 40 cm.

A human touch

However, seeing is only one sense – feeling is another. To help in the construction and maintenance of the International Space Station, the Canadian Space Agency has been coordinating the development of the 'Special Purpose Dexterous Manipulator' (SPDM). This is a two-handed robot which is essentially an extension of the astronauts' own limbs. Until recently, these augmented limbs lacked one critical feature – a sense of touch! Without a sense of touch, machines can accidentally knock into other objects, which in space can have drastic consequences. Although automated vision systems have been under intensive development for several years, tactile sensing technologies are still rare and relatively primitive.

Recognising this challenge, Canadian company Canpolar East developed KINOTEX – a novel sensor that imitates human touch and can be applied like a skin or sleeve to cover entire robotic limbs. Described as a 'deformable integrating cavity', the sensor consists of a sheet or block of polymer foam with an opto-electronic transducer embedded in it. When the foam is deformed, its optical properties are altered, generating a signal in the transducer. Normally arranged in arrays, these sensors can detect and interpret contacts at many points over the surface of the machine. Because they use light to detect change, KINOTEX sensors can be very small and are immune to interference from such sources as electromagnetic radiation. They are also very responsive, sensing minute amounts of pressure and reacting extremely quickly to change.

Canpolar East is aware that KINOTEX could have many commercial uses and is adapting the technology in partnership with a number of other organisations. One of the first companies to market an application is Tactex Controls. Their KINOTEX touch pad measures the pressure and position of fingers placed on its surface, so a musician can 'play' it like an instrument. The touch pad can also be used to control mixers and other sound processors, and in 2001 it won an award for 'Most Innovative Product' from a leading music-industry publication. Tactex is also developing touch pads for the computer-games market. Many other industries are also implementing KINOTEX products. For example, car companies have acquired the rights to develop pressure-sensitive car seats that help increase safety. The KINOTEX sensors are also being considered for incorporation into energy-absorbing bumpers to determine the severity of crashes and detect collisions with pedestrians.

Getting Rid of Bad Vibes

Disturbing cables

Anti-vibration technology developed from space platforms is finding wide application in the building construction and instrumentation markets. In space, problems with very small vibrations are particularly acute and since satellite instruments usually focus their attention on small objects at very great distances, any local disturbances become greatly accentuated. These same instruments must often rely on motors and moving parts that excite the very vibrations that impede their performance.

Sensors are used to detect unwanted vibrations and, through a control loop, electromechanical actuators are used to cancel them out. The active damping of a truss structure using piezoelectric actuators was successfully demonstrated as early as 1989 and attracted ESA's interest. This early success led to several collaborations with European aerospace companies and research laboratories. A first in-orbit active-damping experiment was flown in 1995. A leader in the field, the Université Libre de Bruxelles, created a spin-off company in 1999 called Micromega Dynamics which specialises in active vibration control.

Micromega is also investigating active-damping technology to control long cable supports like those used in Space Station construction and suspension bridges. Cable-stayed bridges already span 750 metres and in future may exceed 1000 metres. These structures are very flexible and, as a result, they are sensitive to wind and traffic-induced vibration. To improve their structural damping, Micromega places an actuator at the end of each cable. The actuator, obeying signals from an associated sensor system, exerts a force that counteracts and cancels incoming vibrations. Cable structures are increasingly seen in large construction projects, including guyed towers and the roofs of large buildings, and their integrity is widely taken for granted. Active-vibration damping, based on space technology, offers a safe route to sustaining even larger and lighter structures with the same degree of confidence.

Stirred but not shaken

Another technology developed to protect satellites and space structures from vibrations during launch is making life a little quieter on building sites. The reason why concrete mixers are so noisy is because mechanical shocks occurring in the mixers due to the rough contact between the gears and the driving crown cause the tank to vibrate and act like a bell. Edil Lame, an Italian concrete-mixer manufacturer, has been investigating various possible technical solutions to reduce the noise. Unfortunately, these solutions have not proved to be reliable, mainly because of the poor conditions in which the systems have to operate (dust, water, weight of the mixed materials, etc).

D'Appolonia, the Italian representative of the Spacelink Group, found the answer in space technology. The French company Artec Aerospace had developed the SPADD (Smart

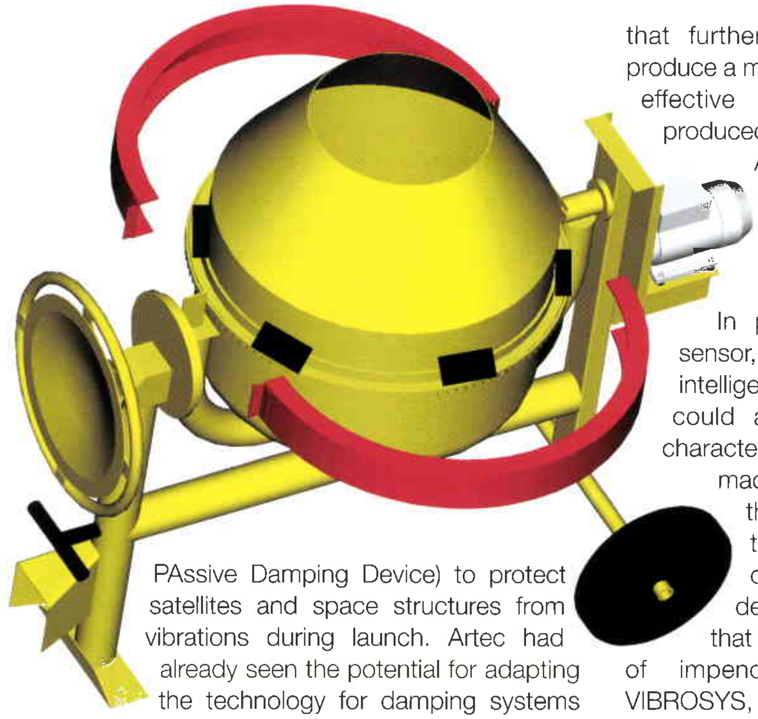

Figure 5. CAD image of a SPADD-equipped concrete mixer

PAssive Damping Device) to protect satellites and space structures from vibrations during launch. Artec had already seen the potential for adapting the technology for damping systems needed in a range of other applications, including electronic circuit boards and tennis racquets. D'Appolonia made the introduction and, based on the successful results of a feasibility study supported by the ESA Technology Transfer Programme, a contract has now been signed between Artec and Edil Lame for the manufacture and marketing of the first batch of 1000 SPADD devices. Edil Lame expects to introduce the SPADD device into between 3000 and 5000 concrete mixers per year.

Good vibrations

In yet another exploitation, tiny sensors from space are helping to warn of potentially catastrophic equipment failure caused by vibration. The German company Ops Automation recognised the need for a vibration detector that was robust and inexpensive and could be applied to a wide range of industrial machinery. At the Hannover Fair in 1998 the company noticed the tiny sensors exhibited by another German company called Mirow. These had been developed for the aerospace industry and were based on piezofoil technology – transparent plastic films that develop an electrical charge when a mechanical stress is applied. The effect depends on direction, so piezofilm sensors are excellent at detecting pressure fluctuations, vibrations or force changes.

The sensors were extremely sensitive and reacted quickly. They had been employed by Mirow and the Technical University of Berlin to sense, for example, pressure changes that indicate what is happening to spacecraft as they pass through the Earth's atmosphere. Ops Automation realised that piezofoil sensors had potential as industrial vibration detectors, but that further development was needed to produce a marketable product – a strong, cost-effective device that could be mass-produced. The work was carried out by Ops Automation with support from ESA and the project culminated in 2000 with the patent application on the design.

In parallel with the design of the sensor, the company also developed an intelligent signal-processing unit, which could analyse the frequencies of the characteristic vibrations that occur in a machine. If any defects occur, such as the machine's bearings breaking up, the noise changes. It is the combination of the vibration detector and the noise-analysis unit that gives operators advance warning of impending machine failure. Called VIBROSYS, the system is now being used in a variety of applications, such as monitoring the huge numbers of pumps employed in the petro-chemical industry, and in many other machines used by various processing companies. Based on its successes, Ops Automation, now a public company, has created 20 new jobs and is expected to have a turnover of some 20 million Euros by 2005.

Water Purification and Management

Purification by simulation

We take it for granted that the water flowing into our homes is clean and safe to drink. However, to maintain its quality, water-engineers are continually looking for better ways to remove impurities, and advanced software developed for space engineering is helping to keep harmful bacteria out of our water supplies.

One serious biological contaminant is the common parasite Cryptosporidium. It is found in water drawn from farmland where sheep and cattle graze and it causes serious illness in humans. Since the bacterium cannot be safely eradicated by chemical means, water companies have to rely on a multi-layer filtering system known as rapid gravity filtration – usually the final physical removal process in water treatment. The efficient management of the whole process, especially the filter beds through which the water passes, is therefore of paramount importance to the water industry.

In order to optimise the operation of their water treatment plants and so reduce the risk of Cryptosporidium contamination, the UK water utility Yorkshire Water decided to model the filtration process on a computer. They asked

Figure 6. Clean water, one of life's essentials!

the advanced control-software company Cogsys to develop a suitable simulation programme that would explore the ideal working conditions in different environmental scenarios. To develop the program, the company used an in-house computer tool ESL (European Simulation Language), which is well-suited to modelling highly complex systems. ESL is a robust simulation software package which was developed for ESA and has proved itself in many engineering applications over 20 years or more. Now, the same advanced software system that was originally used for space simulation is being used to help ensure that our drinking water is kept free from unwanted bugs!

Filtering out impurities

Also in the quest for purer water, a recycling system developed to supply astronauts with drinking water has helped a leading bottler of spring water to clarify a cloudy problem. Water is one of the heaviest consumable items on manned spacecraft, and on long-duration missions the crew will consume many litres. To help reduce the amount of water that needs to be launched from the ground, ESA engineers have developed an innovative automated filtration system to recycle waste water into drinking water. The waste water may include the condensation that forms on the inside surfaces of the spacecraft, effluent from washing clothes and dishes, and also water discharged from experiments and the life-support equipment.

One of the challenges of recycling waste water from a variety of sources is that it is difficult to anticipate what impurities will be present. It may contain, for instance, volatile organic compounds and pathogenic microbes, both of which are notoriously difficult to remove. The system developed by ESA has proved to be highly effective at removing all types of contamination. The system uses a series of membranes, which filter out the various impurities from the waste water as it is pumped through them. Although currently configured to meet only the astronauts' needs, the same concept can be used to treat several hundred litres of waste water per hour.

Such has been the success of this system that it attracted the interest of a major European bottler of spring water. The company concerned was looking for a filtration technology to help it overcome problems at several of the wells it was using as a water source. Water extracted from some natural springs can be discoloured as a result of high concentrations of minerals. This is a particular problem for water obtained from springs fed by hydrothermal wells. Trials carried out with the technology showed that the ESA filtration system was highly efficient at removing these minerals and other impurities. The same filtration technology is now being considered for recycling waste water on ocean cruise liners.

Space works to water works

When we turn on the kitchen tap we don't stop to think about how the clean water reaches our homes. Extracting, treating and distributing water across whole nations is a complex business. A single water utility company may have responsibility for literally dozens of reservoirs, pumping stations and treatment plants, all of which are required to operate as an integrated network in order to meet the public's demands for constant fresh water. With the privatisation and amalgamation of water utilities across Europe, individual companies have been forced to cut costs and devise new and ever-more labour-efficient ways of both monitoring and controlling their water-distribution networks. One of the problems they have had to address has been the wide geographical spread of the individual facilities.

The needs of water companies and utilities actually correspond quite closely to those of satellite operators who, ever since the start of space exploration, have needed to devise systems to enable them to remotely monitor and control spacecraft many miles from Earth. Now, these water companies are also tapping into satellite-tracking technology to operate their facilities remotely.

Science Systems is a UK company that first developed satellite-tracking systems in the early 1980s. Via telemetry links, data may be downloaded, system status monitored and routine commands enacted, allowing the day-to-day operation of the satellite to proceed largely free from the need for human intervention. Science System's desire to diversify into new markets, coupled with the privatisation of the water industry in the UK – and the consequent release of investment funds – led to the development of complementary computer-based systems which could be used by water companies. Supervisory Control and Data Acquisition (SCADA) systems, as they came to be known, have now been successfully adopted by several water companies, including Welsh Water, Thames Water and Lyonnaise des Eaux. Like the spacecraft orbiting the Earth, many water-company sites now operate highly effectively unmanned. Their status and serviceability are constantly monitored, and their routine operations controlled remotely from a central operations centre serving several sites.

Applications to Mobile Devices

Checking the waves

Mobile phones are just the latest contributors to the sea of electromagnetic radiation in which we are all immersed. The nature of the cellular system means that many base stations are needed to provide coverage of the areas served, and their effectiveness is strongly affected by local conditions. The need to offer users a good service must be offset against the need to limit stray radiation and protect the public against possible effects from prolonged exposure. From a practical point of view, effective management of this electromagnetic pollution requires tools to optimise the radio-frequency levels generated by base-station transmitters, and software designed to test the electromagnetic compatibility of satellite systems has been further developed to optimise cellular-phone networks.

For many years an Italian company, Space Engineering SpA, has been developing techniques to analyse and model electro-magnetic fields from spacecraft antennas and their effects on nearby equipment. These checks on antenna performance and electromagnetic compatibility, which are vital to avoid malfunctions in sensitive onboard electronic systems, have formed part of several space projects. On Earth, propagation of the very-short-wavelength signals used for telecom-munications can be badly affected by the presence of buildings, trees or even rainfall. In 1993, the company successfully turned its satellite expertise to modelling the complicated conditions experienced by mobile receivers in urban locations, and in 1998 Space Engineering spun-off TeS (Teleinformatica e Sistemi srl.) as a separate company. The aim of the new company was to exploit the know-how derived from the space work in the rapidly expanding commercial communications market.

The resulting system, Quickplan, has been developed to fulfil the needs of both radio system developers and environmental agencies. The system can calculate and display radio-frequency field levels across a highly complex urban environment, indicating both the optimum location of transmitters and the resulting electromagnetic pollution. Quickplan draws upon multiple maps and a powerful graphical interface to create a 3D image of the territory, with colour coding that clearly identifies regions where radio-frequency power levels are above or below the desired thresholds. This successful transfer of space-based expertise has provided a powerful aid for planners of radio systems to reduce their environmental impact and improve the servicing of our seemingly insatiable demand for new services.

Un-wired for sound........and text and pictures

The need for wireless equipment in manned spacecraft is further helping to drive the development of truly mobile technology on Earth. The mobile phone has revolutionised personal communications and wireless, handheld devices can combine many different features, including a connection to the Internet and text messaging. Now the frontiers of wireless technology are expanding even further with a new wireless communications standard called 'Bluetooth', which has been developed by a consortium of leading electronics companies, which includes 3Com, Ericsson, IBM, Intel, Lucent, Microsoft, Motorola, Nokia and Toshiba. Bluetooth is a tiny microchip which incorporates a radio transceiver that is built into a variety of digital devices such as mobile phones, personal digital assistants, printers, fax machines, personal computers, laptops, digital cameras, stereos and headsets, allowing them to be connected together without wires or cables. In the next few years Bluetooth will be built into hundreds of millions of electronic devices worldwide.

ESA quickly recognised the unique value of Bluetooth for space exploration, where wireless connections between spacecraft equipment and astronauts are the ideal solution. ESA sponsored Parthus Technologies, an Irish company, to develop a wireless technology based on Bluetooth that could easily be embedded into a variety of spacecraft equipment. Parthus is a world leader in the design and development of the integrated circuits and software that underpin mobile devices. The result was BlueStream, a chip design that can be used as a basis for a wide range of wireless applications – not just for spacecraft operations but

also for computing and global positioning systems. Parthus' approach of integrating BlueStream with other complementary technologies also helps to overcome one of the main challenges of wireless technology, namely power consumption. Today, Parthus' BlueStream chip design is the most widely licensed Bluetooth technology in the wireless industry, with four of the top ten wireless semiconductor companies integrating it into their products. Furthermore, BlueStream accounts for some 35% of Parthus' revenues.

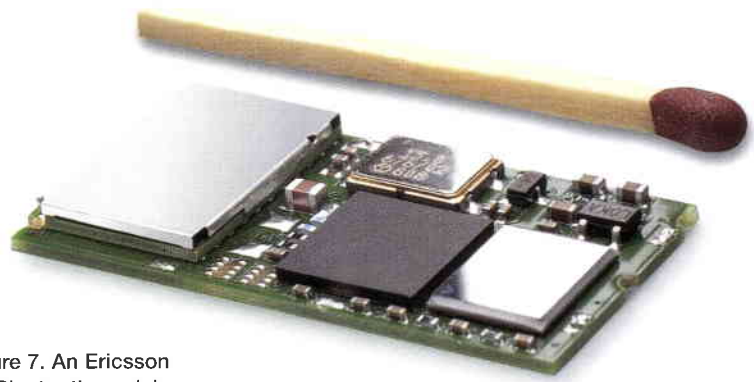

Figure 7. An Ericsson Bluetooth module

NUNA, powered by space technologies

The World Solar Challenge is the biggest race in the world for vehicles powered purely by solar energy. The race, held every two years, crosses the Australian continent north to south (Darwin to Adelaide) – a distance of over 3000 km. The first World Solar Challenge was held in 1987 in order to show the world the potential of solar power. The best solar cars perform extremely impressively, being capable of speeds in excess of 150 kph and travelling the 3000 km for a total sum of just over 6 Euros – about 50 times more efficient than an average family car!

Since the cars rely only on solar power, designers have to take into account factors such as weight, aerodynamics, robustness and safety. In addition, since solar cells do not function well at the high temperatures found in the desert, a system has to be developed to cool the cells (as well as the driver!). In order for the car not to be too heavy, the bodywork must contain a lot of plastics and composites – but the very low weight also requires a system to prevent the car being blown off the road by extreme gusts of wind.

The competition participants vary from multinational companies to high schools and universities. This November, a team from The Netherlands, consisting of students from the Delft University of Technology and the University of Amsterdam, entered the race and won in a new world record time! ESA expertise in spacecraft technology (particularly batteries and fuel cells) was provided to the team. In addition, one of the unique features of NUNA, the Dutch entry, was that their vehicle was partially powered by solar cells provided by ESA, which were actually flown on the Hubble Space Telescope. The Dutch team also used new cells designed by the people who produced the cells for Hubble, and they are among some of the best performing and most efficient solar arrays ever designed (see 'In Brief' for a full race account).

Prime Movers

Creepy crawlies

The fact that laboratory experiments on the International Space Station (ISS) have benefited from ESA research will come as no surprise. But would you have thought that the same applies for crawlers used in oil pipelines? As a Space Shuttle flight typically lasts less than two weeks, facilities designed for conducting experiments onboard are generally used only for short periods. By contrast, on the ISS the experiments are likely to be used for many years and consequently their design has to be fundamentally different. ESA has led

Figure 8. The solar car designed by the Alpha Centauri team

the development of new design concepts to improve safety and reduce the time required for the astronauts to carry out equipment maintenance and calibration.

One of the companies helping ESA was Norwegian-based Prototech. By studying the design of ESA's original Spacelab facility for the Shuttle, the company was able to significantly improve the reliability, accessibility and performance of experiment modules for the ISS. For example, the pressure tubing used for the Spacelab experiments has been replaced by a novel compact manifold system. Other operations such as the exchange of filters, calibration procedures and leak testing have also been improved.

Prototech's activities were not confined to space applications, however. The company also designs and manufactures equipment for the inspection of offshore pipelines. The repercussions of failures may be as critical in these operations as they are in space, so Prototech exploited its technology originally developed in collaboration with ESA to improve the reliability of tools for pipe inspection. One example is the redesign of a crawler (called a 'Pipecat') used to pull ultrasonic inspection tools through oil pipelines. The crawler uses two sets of pads – one is pressed to the tube wall while the other set moves forward. Using the same design techniques as for space systems, the number of failure points was significantly reduced, and the redesigned system was made more compact and reliable. This has resulted in significant savings for the oil companies in terms of equipment-maintenance and retrieval costs.

Gearing up for lower speeds

In a less-specialised environment, many everyday appliances rely upon small electric motors to operate them – video recorders, car window winders and seat adjusters, tape drives and CD players all have them. Often the required shaft speed of the motor is quite low but, to provide significant power, small machines work best at high speeds. To reduce the speed of rotation and so gain an increase in output torque, or twisting power, a gearbox is needed just as in a car. If the difference between the speed of the motor and its load is great, conventional gears may need several stages of speed reduction. This leads to power loss, noise and expense. Unfortunately, large increases in output torque also cause large forces on the teeth of conventional gears, so larger teeth and better materials are needed.

Drawing upon the apparent gearing effects of nutation, an Italian space company Stam srl has created a new form of gearbox that overcomes these disadvantages. The device called SPACEGEAR was developed for use in satellites and uses an arrangement in which one bevel gear 'nutates' with another instead of rotating. The gear ratio is determined by the difference in the number of teeth of the fixed and moving gears and not, as with conventional gears, on the ratio of their circumferences. By applying the principle of nutation twice, very high reduction ratios of up to 3000 can be achieved. The design, which combines two pairs of gears, makes any ratio possible with the same simple configuration. Because the design ensures that at least two teeth are in contact at any one time, loadings are reduced and materials of lower strength may be used.

The SPACEGEAR is particularly suited to electrically-driven automotive components where high reduction ratios are required but space is at a premium. Using nutator technology, smaller, faster electric motors can provide the same level of mechanical power as their conventional counterparts. At present, such mechanisms and their electric motors typically cost from 200 Euros for a small car to 2000 Euros for a luxury car. The European automotive industry produces about 15 million cars per year, offering a potential market of 4.5 billion Euros. Stam is exploring materials for mass manufacture – both metal and plastic – and is developing a computer program for designing nutating-gear systems.

Conclusion

The first 40 years of space spin-offs have given us smaller, faster computers, exotic materials and a host of advanced technologies to enhance our everyday lives. Spin-offs from the next 40 years are likely to reflect the increase in importance of prolonged, manned space missions and miniaturised satellite systems. As may be expected, the type of spin-off we get from space tends to reflect the types of space missions being mounted. In the past, ESA has concentrated on Earth observation, communications and space science missions, leaving manned spaceflight largely to the USA and Russia, and the high level of spin-off of imaging and communication technologies and analytical software from European programmes tends to reflect this. In the future, ESA's involvement in the International Space Station (ISS), the planned Mars missions, the increased emphasis on small satellite clusters and robotic exploration, together with the inexorable drive towards the goals of 'smaller, cheaper, more efficient' space systems, should lead to new and ever more exciting technology-transfer opportunities. esa

A New Generation of Space X-Ray Imagers that Could Help Fight Cancer

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A new generation of X-ray imagers for future space-science missions is being developed by ESA in cooperation with European industry. These devices were initially intended for X-ray astronomy and remote planetary sensing, but have now been found to have immediate applications in clinical radiology. In particular, the devices are ideally suited for the imaging of low-density, low-contrast media such as breast tissue, making them invaluable in the diagnosis and clinical support in the fight against cancer.

X-ray imaging is an essential tool for a wide range of disciplines, from astrophysics to material science. Whilst the majority of applications rely on film, phosphor storage screens or other analogue integrating formats, the future development of this field lies in the exploitation of spatially resolved spectroscopy. Commercially available systems generally utilise secondary detection media, such as phosphor plates or scintillator conversion layers.

However, these methods have a number of shortcomings related to resolution and light collection efficiency, and consequently they do not offer much improvement in imaging performance, in terms of 'detective quantum efficiency' (a figure of merit describing a system's ability to resolve imaging detail in weak signals) over more traditional film-screen systems. Additionally, such systems do not make use of 'colour' information and therefore do not lend themselves easily to advanced techniques employing differential absorbtiometry.

While astrophysics has pioneered the utilisation of semiconductor detectors based on silicon at soft X-ray energies (below 10 keV or longward of 1 Angstrom), the hard X-ray band (10 to 200 keV) has proved particularly difficult to develop and has remained relatively unexplored. This band is important because it bridges the transition between thermal and non-thermal emission processes predicted to occur throughout the galaxy. By coincidence, this band is also of crucial importance in medicine and encompasses all the main energies used in clinical radiology. However, while astrophysics can, at least for now, use data from lower X-ray energies to interpolate the underlying high-energy physics, medical applications are not so lucky, since the human body is essentially opaque below 10 keV. In fact, all clinical investigations are carried out in the hard X-ray region, for example at 20 keV for mammography, 60 keV for thoracic radiography, and 140 keV for nuclear medicine (Table 1).

Table 1 shows the key X-ray energies used in space sciences and medicine. Even though the two disciplines are literally worlds apart, they clearly share a lot of common characteristics and an X-ray imager designed for space

Table 1. The various space and clinical applications of X-ray imaging

Space-science radiology	X-ray energy (keV)	Clinical radiology	X-ray energy (keV)
Earth observing (Auroral)	1–20	Mammography	17–20
Planetary	0.2–7	Dental	60–70
X-ray astronomy	0.1–10	Thoracic	50–70
Hard X-ray astronomy	10–200	Nuclear medicine	30–300

science can also be used for medical applications. However, observationally the similarity ends. Astrophysicists, for example, need only to observe for a longer time to improve image quality – in other words the higher the dose the better. In medicine, the converse is true, in view of the risk to the patient. Therefore in clinical radiology other methods have to be found to enhance contrast whilst simultaneously reducing dose. The simplest solution, however, is also the most beneficial to astrophysics – simply detect each photon with 100% efficiency and record its energy, arrival time and position.

It has been clear for some time that the next major step forward in this region of the electromagnetic spectrum will be made through the development of an efficient imaging detector, operating at room temperature, which converts X-rays directly into electrical signals whose amplitudes are proportional to their energies or colour. Alternatively, one may think of this as an X-ray camcorder. The potential market is enormous, not only for space sciences, but also in all branches of medicine, particularly mammography, general radiography, fluoroscopy and nuclear medicine.

At soft X-ray energies, the power of such a system has already been dramatically demonstrated in astrophysics by ESA's XMM-Newton and NASA's Chandra X-ray observatories, which have produced some of the first very high resolution 'colour' images of the X-ray sky using silicon charge-coupled devices (CCDs). As an example, Figure 2 shows two images of the Crab Nebula, the remains of an exploded star known as a supernova remnant. An old star, at the end of its life, exploded in 1054 AD leaving behind the diffuse gaseous nebular we see today, together with the core of the star – known as a 'pulsar' or, more specifically, a neutron star. The event was memorable because Chinese astronomers and probably the ancestral Pueblo Indians recorded it. The left-hand image of Figure 2 is an optical photograph showing the expanding nebula with its characteristic filamentary structure. This is known as a synchrotron nebula. The light we see is simply the radiation from energetic electrons, spiralling in the remnant's magnetic field. The electrons, in turn, are accelerated by (and beamed out of) the central pulsar. Using the world's first superconducting camera, also developed by ESA,

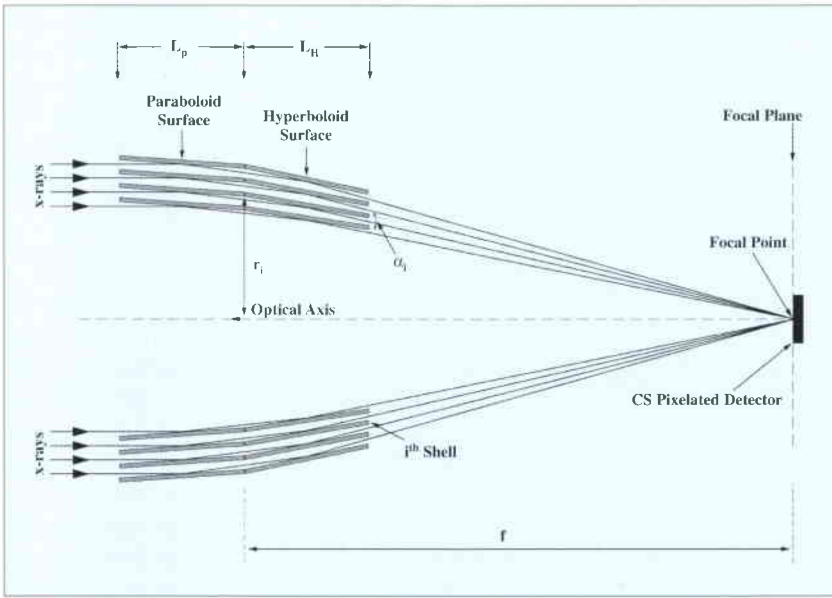


Figure 1. The astrophysicists' approach to soft X-ray imaging through the use of an X-ray telescope and imaging detector

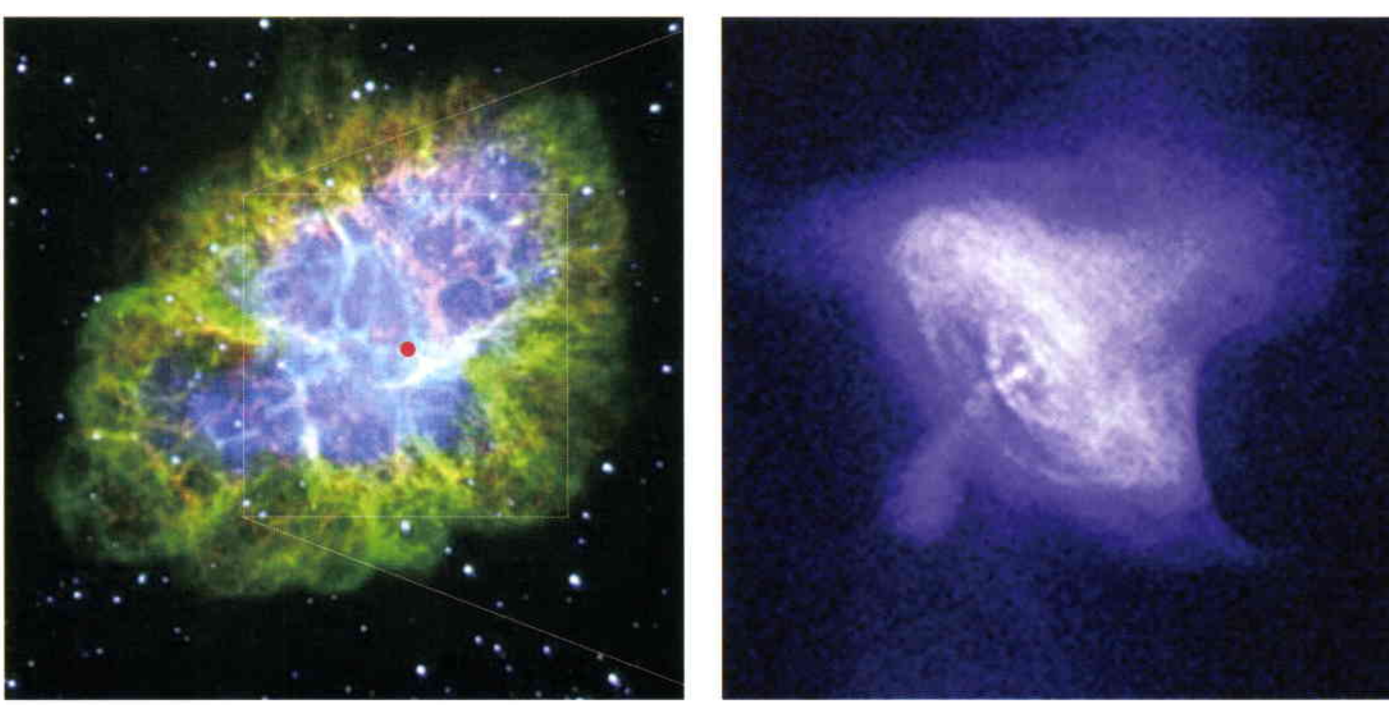


Figure 2. The Crab Nebula at optical (left) and soft X-ray (right) wavelengths. The red dot indicates the position of the pulsar – the remnant of a dead star which powers the nebulae through electron injection

astronomers observed this pulsar in visible light in early 2000 using the William Herschel Telescope in La Palma, Spain. The camera performed pulse phase spectroscopy on the light beamed from the tiny pulsar, only about 10 km in diameter, with unparalleled precision (cf. ESA Bulletin No. 98).

By contrast, the right-hand image of Figure 2 shows the central portion of the nebula viewed at soft X-ray wavelengths. The structures seen at these wavelengths are considerably hotter and are not at all apparent in the optical image. A swirling disk of hot particles and jet-like structures blasting out from the central pulsar are clearly visible. By using the spatially resolved colour information in this image, astrophysicists are now able to disentangle and isolate the energetically different emitting regions.

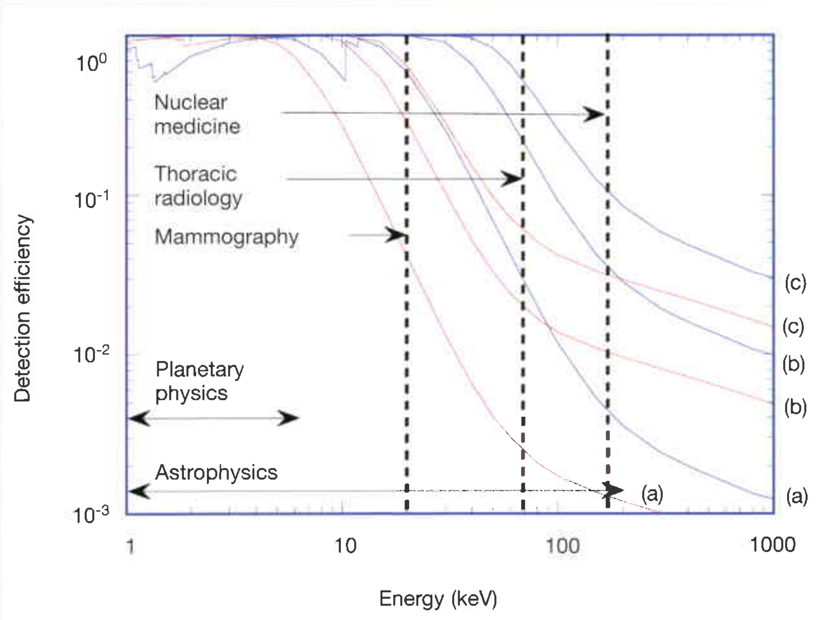


Figure 3. The calculated detection efficiency for three GaAs detectors (blue curves) with thicknesses of 40 microns (a), 325 microns and 1000 microns (c), compared to conventional silicon (red curves). The horizontal solid lines indicate the energy ranges of interest for space-science applications. The vertical dotted lines indicate the peak tube energies commonly encountered in clinical applications, such as mammography, thoracic radiology and nuclear medicine. The important point is that a system based on GaAs and specifically designed for astrophysics applications is also optimally designed for medical applications

Whilst the current generation of semiconductor devices based on silicon has provided sub-keV energy resolution near 1 keV, they are only sensitive in the UV and soft X-ray bands up to ~10 keV because of the low absorption power of silicon (cf. Fig. 3). For example, it is impossible to acquire the X-ray image shown in Figure 2(b) at energies above ~10 keV with ESA's XMM-Newton, simply because the telescope and the silicon CCD detectors lack efficiency at these energies.

Another point of note is that silicon detection systems require cooling to achieve low noise, which in turn means that the devices are quite bulky. For example, XMM-Newton's silicon-based CCDs are cooled passively by large radiators dumping the heat to space so as to achieve an optimum working temperature of minus 100°C. Clearly, this system is inappropriate for say intra-oral applications. These very practical considerations are crucial for the widespread use of new diagnostic instruments in medicine.

The key material requirements for future systems are: (a) high density to provide high detection efficiency, (b) a wide enough band-gap to ensure room-temperature operation, (c) a time response matched to the expected photon fluxes (potentially up to 10 million photons/mm^2/s for diffraction-enhanced imaging), and (d) a uniformity in spatial response in excess of 99.99% (a precision dictated by the dynamic range required for low-contrast imaging, e.g. mammography). Of the available materials suitable for hard X-ray detectors, compound semiconductors are the most promising, and in particular gallium arsenide (GaAs). Its band-gap is high enough that it does not require cryogenic cooling, but low enough that sub-keV spectral resolution is achievable at hard X-ray energies. The former attribute is highly desirable in a number of applications, e.g. intra-oral radiography, while the latter quality, when coupled with the inherent fast response of semiconductor detectors, offers real advances in fluoroscopy. Room-temperature operation is also an important consideration for X-ray systems designed for planetary exploration, since heat rejection is a real problem, especially for probes exploring the inner planets. The constituent elements of GaAs have high enough densities that its hard X-ray responsivity is much more closely matched to the spectral output of the standard X-ray tubes than either classical film or silicon-based detectors. This is illustrated in Figure 3 which shows the expected quantum efficiency for three thicknesses of GaAs imager as a function of X-ray energy, compared to silicon. All three thicknesses shown are under active development by ESA.

Note from Figure 3 how quickly the response of silicon (red curves) falls-off with energy above 10 keV, in fact a factor of 10 more than for GaAs (blue curves). The lower solid horizontal lines in Figure 3 indicate the energy ranges of interest for astrophysics and planetary fluorescence studies, while the vertical dotted lines indicate the peak tube energies commonly encountered in mammography, thoracic radiology and nuclear medicine. As can be seen, the 40 micron device is particularly well suited for planetary applications, whereas the 325 and 1000 micron devices would be suited for astrophysical and clinical applications. Specifically, a 325 micron device would have an efficiency at 20 keV of over 98%. This should be compared to 1% for radiographic film, or 60% for film-screen combinations. Thus, by default, an imaging system developed for ESA's planetary and astrophysics missions could have immediate medical applications. In fact, since medical imaging requirements are generally more stringent and global than those for space sciences, they make good yardsticks for future mission studies.

The Science Payloads Technology Division and the Agency's Directorate of Technical and Operational Support have worked for a number of years with industry (Metorex International Oy of Finland) to develop GaAs arrays for astrophysics and planetary applications, beginning with an extensive monolithic detector programme designed to probe basic material and technological issues. Steady progress has been achieved, with average room temperature full-width-at-half-maximum (FWHM) energy resolutions at 60 keV decreasing from ~10% keV at the start of the programme to ~1% eV at the present time. The FWHM is a very useful figure of merit for characterising a spectrometer system and essentially describes its ability to resolve colours. The FWHM is usually expressed in terms of a percentage or, alternately, in units of energy (keV). For both space science and medicine, 10% is good, 1% is excellent. As a precursor to producing large arrays, we have also produced a series of small-format pixel arrays. Information on this material-science and detector programme can be found at: http://astro.estec.esa.nl/SA-general/Research/Detectors_and_optics/home.html.

Detailed measurements are routinely carried out in ESTEC's laboratories and in close cooperation with synchrotron research facilities: HASYLAB in Hamburg (D), BESSY II in Berlin (D) and ESRF in Grenoble (F). These key European facilities are three of the few in the world that can produce highly monochromatic X-ray beams extending from 0.1 up to 100 keV. From a space science point of view, they provide the 'cleanest' X-ray sources with which to calibrate satellite-borne detectors, whereas from a medical point of view they allow scientists to experiment with advanced imaging techniques designed to reduce patient doses whilst also improving image contrast. In both cases, the information acquired can be used to better interpret astrophysical and planetary X-ray maps.

Figure 4 shows the first small array produced. The purpose of this phase of the research was to explore array fabrication techniques, particularly masking and etching, as well as possible implementations of the readout and front-end electronics. The array was fabricated by growing an ultra-pure 40 micron epitaxial layer onto an n+ semi-insulating substrate using the same chemical vapour-phase deposition (CVPD) techniques developed for the semiconductor industry. To reduce leakage currents, a 10 micron thick p+ layer was then deposited directly onto the epitaxial layer, forming a p-i-n structure. This layer was then patterned by etching, to create a 5 x 5 pixel structure surrounded by a guard ring (see figure). The pixel sizes are 250 x 250 micron^2, with an inter-pixel gap of 50 microns. The guard is 200 microns wide and is used to control surface leakage currents. The chip was bonded to a ceramic substrate and coupled to a two-stage Peltier cooler capable of cooling the array to -40°C. Two pixels were actually instrumented, contact with the chip being achieved by wire bonding. Measurements from 5.9 to 98 keV were carried out at HASYLAB, yielding room-temperature energy resolutions of 660 eV FWHM at 5.9 keV and 380 eV FWHM with only modest cooling (-40°C).

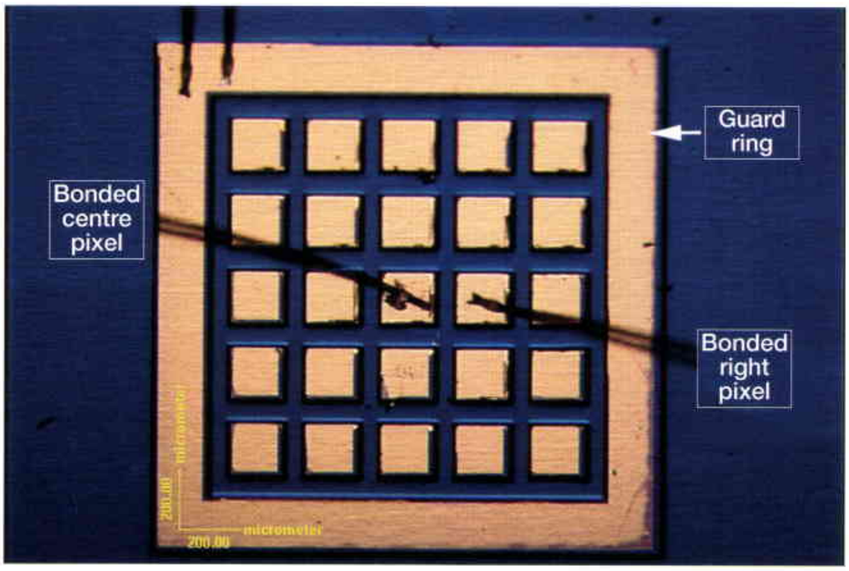


Figure 4. Nomarski photomicrograph of the first array produced. The device is 40 microns thick and has a pixel size of 250 x 250 microns. The bond wires to two instrumented pixels and the guard ring are clearly visible. This early prototype allows the array-processing techniques to be rapidly developed

Figure 5 shows a second-generation device produced in essentially the same way as the 5 x 5 device. In this case, a 4 x 4 array was patterned on thicker (325 micron) epitaxial material. However, unlike the previous device, all pixels were instrumented and read out by individual hybrid resistive feedback pre-amplifiers mounted directly onto an aluminium-nitride substrate along with the chip. To ensure low noise, the input stages utilise state-of-the-art low-capacitance tetrode FETs, also mounted directly on the substrate, but closer to the array. The mechanical layout of the chip, hybrid preamplifiers and substrate is shown in Figure 5.

The optimum performance in terms of energy resolution was found for pixel biases of +50 V, although the device would operate satisfactorily for biases as low as +5 V. The leakage currents

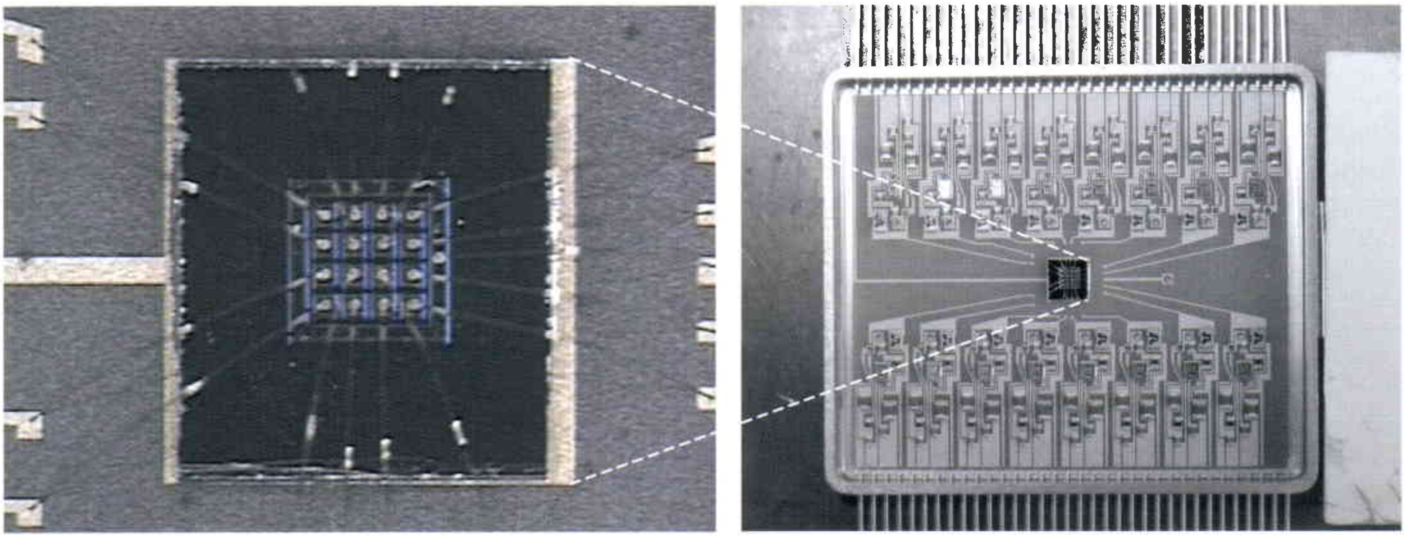
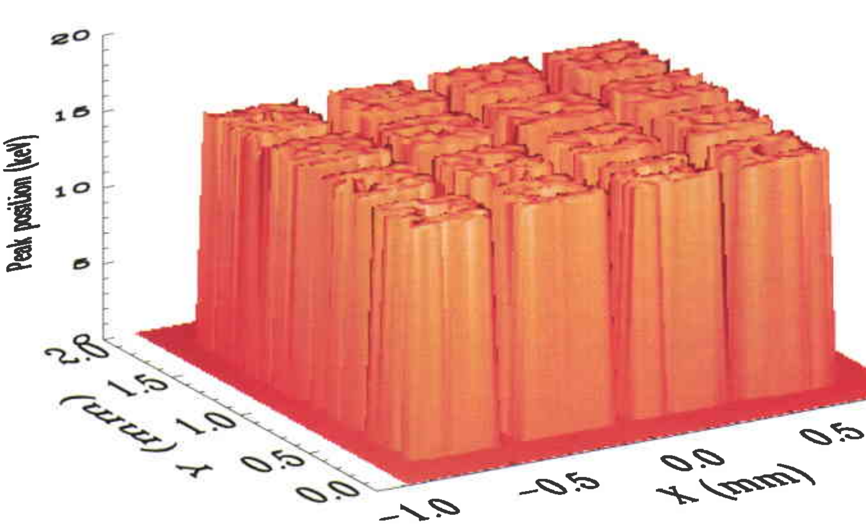


Figure 5. Left: Photomicrograph of a second-generation 4 x 4 GaAs detector assembly. The device is die-attached to the substrate, which in turn is mounted on a two-stage Peltier cooler. Right: Photograph of the completed GaAs array/hybrid/substrate assembly. While such an array is too small for space science or medical applications, it does allow issues related to pixel performance and inter-pixel communication to be studied. Note any large-format device would also use a dedicated ASIC rather than specific components for the electronic readout chain of each pixel

Figure 6. A surface plot of the spatial variation of the gain (i.e. the fitted centroid position) across the 4 x 4 GaAs array measured at HASYLAB using a 15 keV, 20 x 20 micron pencil beam. The spatial sampling in X and Y was 10 microns

were low enough to permit room-temperature operation (RT), with typical FWHM energy resolutions of 600 eV at 5.9 keV and 700 eV at 59.54 keV (pulse width = 550 eV). The energy resolution was found to improve with decreasing detector temperature. At ~ +5°C, for example, typical energy resolutions of ~410 eV FWHM were found at 5.9 keV with an electronic noise component of ~390 eV FWHM. At 59.54 keV, the corresponding resolutions were ~ 640 eV. The spatial uniformity of the array was tested explicitly at HASYLAB using a 15 keV 20 x 20 micron pencil beam, normally incident on the pixels. The beam was raster-scanned across this area with 10 micron spatial resolution in both dimensions. It was found that, apart from a slight depression in these parameters directly under the bond wires, their spatial distributions were very uniform over the surface of each pixel and the array. In fact, the average non-uniformity is typically no worse than 1% and is consistent with a flat response. Specifically, the variations seen in the gain across the array are consistent with the expected statistical variations alone to a level that would satisfy the uniformity requirements of low-contrast imaging. The fact that both the count rate and centroid responses are zero in the inter-pixel gaps, with no evidence of cross-talk, proves that it should be possible to replicate isolated and identical pixels, and thus potentially mega-pixel arrays. Figure 6 shows the resultant map of the 4 x 4 pixel array when illuminated with 15 keV X-rays.



Given that small arrays have demonstrated excellent performance, designs for practical applications in astrophysics, planetary remote sensing and medical imaging can now be considered. Figure 7 shows the first of these attempts, a 32 x 32 pixel array, produced as a technology demonstrator for a planetary mission. As with the 4 x 4 array, it was fabricated on 325 micron-thick epitaxial material. The left-hand image in Figure 7 shows the photo-lithographic mask, which contains the patterns of three 32 x 32 arrays and a large variety of small-format arrays and monolithics. The smaller devices are used to evaluate the quality of masking, lithography and etching as well as assess the electrical and isolation properties of potential detectors via IV measurements, X-ray testing and microscopy. The right-hand image in Figure 7 shows a Nomarski photomicrograph of a single 32 x 32 pixel array after dicing from the wafer.

Previous studies have shown that the p-i-n structure could produce near-Fano-limited performance in monolithic and small-format arrays by drastically reducing leakage currents. This in turn allowed the use of increasingly lower noise preamplifier designs, read-out through the p+ contact and positively biased via the n+ contact to ensure the efficient collection of holes. While such an approach is acceptable for research and development using small arrays, any practical application requires modifications to this structure for large-format arrays as well as

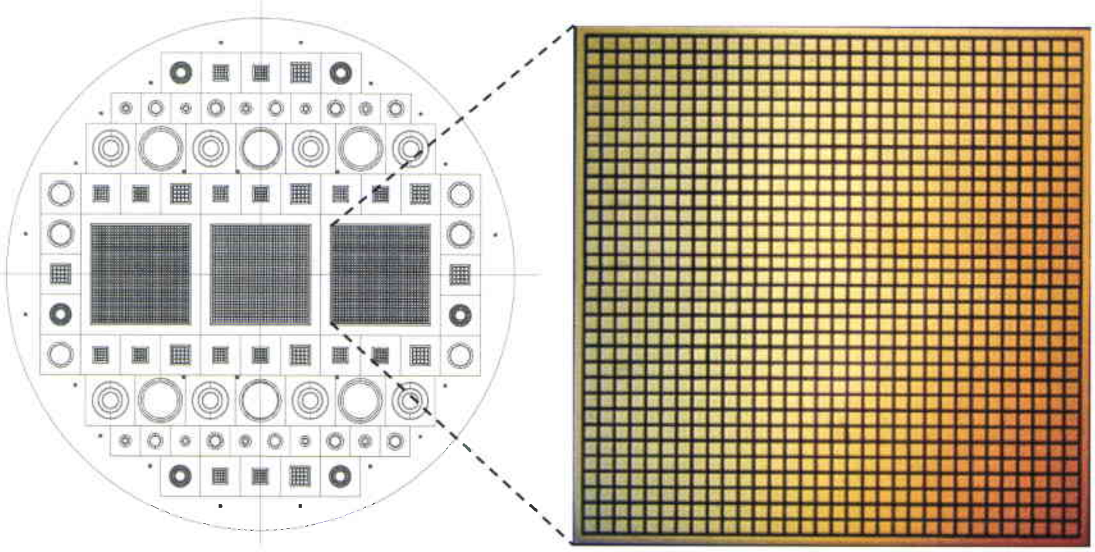


Figure 7. Left: The lithographic mask used to produce the large-format array. Note that a wide variety of smaller arrays, monolithics and test structures are also produced on the same wafer.
Right: A photograph of the array after dicing and prior to electrical probing and bonding of individual pixels

changes to the readout. It will be necessary to illuminate the arrays through the n+ electrode. Since each pixel in a large-format device must be read out individually, with its own electronic chain, the packing density is prohibitive for conventional electronics. Instead, the Division is developing a custom-built microchip to do this. The device is known as an 'Application Specific Integrated Circuit' or ASIC, which will be flip-chip, bump-bonded to the pixelated side of the detector. To avoid excessive X-ray extinction in the n+ layer, this layer will have to be substantially thinned or removed. Whilst the thinning process is being developed, the material and electronics development programme has continued by retaining a p-i-n structure on these prototype arrays and reading out the pixels via wire bonding to the p+ layer.

For the initial tests, four pixels were instrumented. The preliminary characterisation of the detector over the energy range 5.9 to 100 keV was carried out at ESTEC and HASYLAB. Typical FWHM energy resolutions of around 300 eV at 5.9 keV and ~550 eV at 59.5 keV were recorded for all four pixels at +24°C. For comparison, the electronic system noise was measured to be ~280 eV FWHM. The resolutions were found to decrease with decreasing temperature to ~250 eV at 5.9 keV and ~500 eV at 59.54 keV at ~+5°C. Below this temperature, there was no statistical improvement in resolution. Note, these results are representative of all pixels. It should be noted that the expected Fano noise at these energies (the limiting resolution given by the physics of the photo-absorption process) is ~130 and 410 eV, respectively.

Conclusion

This GaAs sensor research and development programme, originally intended for astrophysics and planetary exploration missions, has yielded such excellent performance figures that serious clinical applications can now be considered. In particular, the demonstration of good performance at room temperature, coupled with the fact that standard integrated-circuit fabrication techniques can replicate isolated and identical pixels, means that practical large-format compact cameras are not far away. The next key step is the coupling of the current, or even larger format, arrays with a readout system based on ASIC technology, leading to the volume production of compact X-ray cameras for routine radiological procedures.

An example of such a task is the detection and treatment of breast cancer. This cancer is best treated when detected at a rather early stage in its development, in particular before the disease has a chance to spread into to the lymphatic node system from a primary tumour. A compact X-ray camera based on a large-format GaAs array would allow the physician, through radio-isotope imaging, to determine the location of those nodes that are malignant. The GaAs array shown in Figure 7 is entirely suitable for this task. In the event of the detection of ductile carcinomas, the device could be used for staging, i.e. to assess how far the disease has spread by probing the auxiliary lymph nodes, as well as pin-pointing diseased nodes for surgical removal, in real time. Whereas present commercially available devices locate such tumours to a spatial accuracy of several millimetres, the array shown in Figure 7 would have a worst-case accuracy of 250 micron and, depending on statistics, potentially a lot higher.

Figure 1. Asteroid Ida and its moon Dactyl in enhanced colour. This colour picture is made from images taken by the Galileo spacecraft just before its closest approach to asteroid 243 Ida on 28 August 1993. The moon Dactyl is visible to the right of the asteroid. The colour is 'enhanced' in the sense that the CCD camera is sensitive to near-infrared wavelengths of light beyond human vision; a 'natural' colour picture of this asteroid would appear mostly grey. Shadings in the image indicate changes in illumination angle on the many steep slopes of this irregular body, as well as subtle colour variations due to differences in the physical state and composition of the soil (regolith). There are brighter areas, appearing bluish in the picture, around craters on the upper left end of Ida, around the small bright crater near the centre of the asteroid, and near the upper right-hand edge (the limb). This is a combination of more reflected blue light and greater absorption of near-infrared light, suggesting a difference in the abundance or composition of iron-bearing minerals in these areas. Ida's moon also has a deeper near-infrared absorption and a different colour in the violet than any area on this side of Ida. The moon is not identical in spectral properties to any area of Ida in view here, though its overall similarity in reflectance and general spectral type suggests that it is basically made of the same rock types.
(Credit: JPL, Galileo mission)

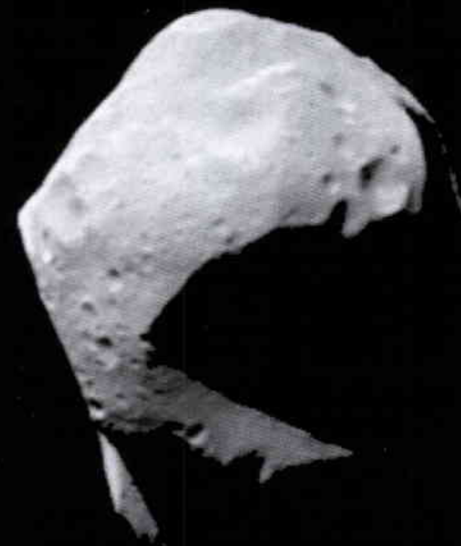


Figure 2. This image mosaic of asteroid 253 Mathilde is constructed from four images acquired by the NEAR spacecraft on 27 June 1997. The part of the asteroid shown is about 59 km by 47 km. Details as small as 380 m can be discerned. The surface exhibits many large craters, including the deeply shadowed one at the centre, which is estimated to be more than 10 km deep. The shadowed, wedge-shaped feature at the lower right is another large crater viewed obliquely. The angular shape of the upper left limb of the asteroid results from the rim of a third large crater viewed edge-on. The bright mountainous feature at the far left may be the rim of a fourth large crater emerging from the shadow. The angular shape is believed to result from a violent history of impacts.
(Credit: Johns Hopkins University Applied Physics Laboratory, NEAR-Shoemaker mission)

Figure 3. This picture of asteroid 951 Gaspra is a mosaic of two images taken by the Galileo spacecraft from a range of 5300 km just before closest approach on 29 October 1991. The resolution is about 54 m/pixel. Gaspra is an irregular body with approximate dimensions of 19 x 12 x 11 km. The portion illuminated in this view is about 18 km from lower left to upper right. The north pole is located at upper left; Gaspra rotates counterclockwise every 7 h. The large concavity on the lower right limb is about 6 km across, the prominent crater on the terminator, centre left, about 1.5 km. A striking feature of Gaspra's surface is the abundance of small craters. More than 600 of them, 100-500 m in diameter, are visible here. The number of such small craters compared to larger ones is much greater for Gaspra than for previously studied bodies of comparable size such as the satellites of Mars. Gaspra's very irregular shape suggests that the asteroid was derived from a larger body by nearly catastrophic collisions. Consistent with such a history is the prominence of groove-like linear features, believed to be related to fractures. These linear depressions, 100-300 m wide and tens of metres deep, are in two crossing groups with slightly different morphology, one group wider and more pitted than the other. Gaspra also shows a variety of enigmatic curved depressions and ridges in the terminator region at left.
(Credit: US Geological Survey, Galileo Orbiter)

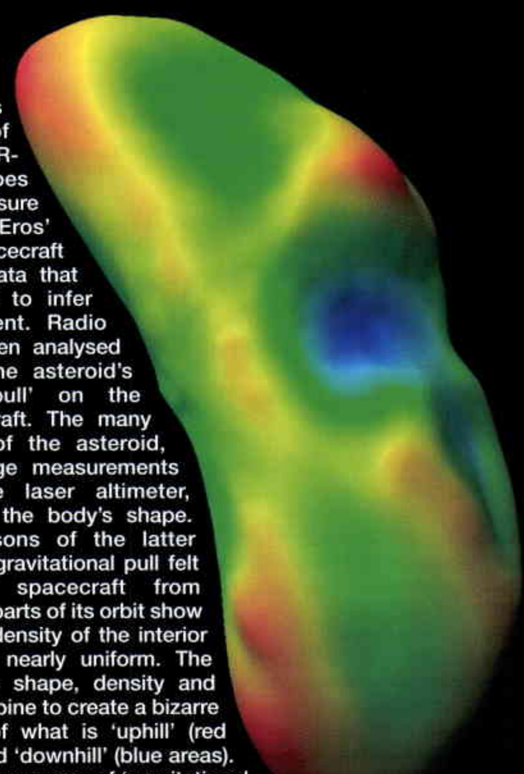


Figure 4. The ups and downs of Eros. While NEAR-Shoemaker does not directly measure gravity on Eros' surface, the spacecraft gathers other data that allow scientists to infer this measurement. Radio tracking has been analysed to determine the asteroid's gravitational 'pull' on the orbiting spacecraft. The many images of the asteroid, plus range measurements from the laser altimeter, measure the body's shape. Comparisons of the latter with the gravitational pull felt by the spacecraft from different parts of its orbit show that the density of the interior must be nearly uniform. The asteroid's shape, density and spin combine to create a bizarre pattern of what is 'uphill' (red areas) and 'downhill' (blue areas). In this view, a map of 'gravitational topography' has been painted onto a shape model. A ball dropped onto one of the red spots would try to roll across the nearest green area to the nearest blue area.
(Credit: Johns Hopkins University Applied Physics Laboratory, NEAR-Shoemaker mission)

ISO and Asteroids

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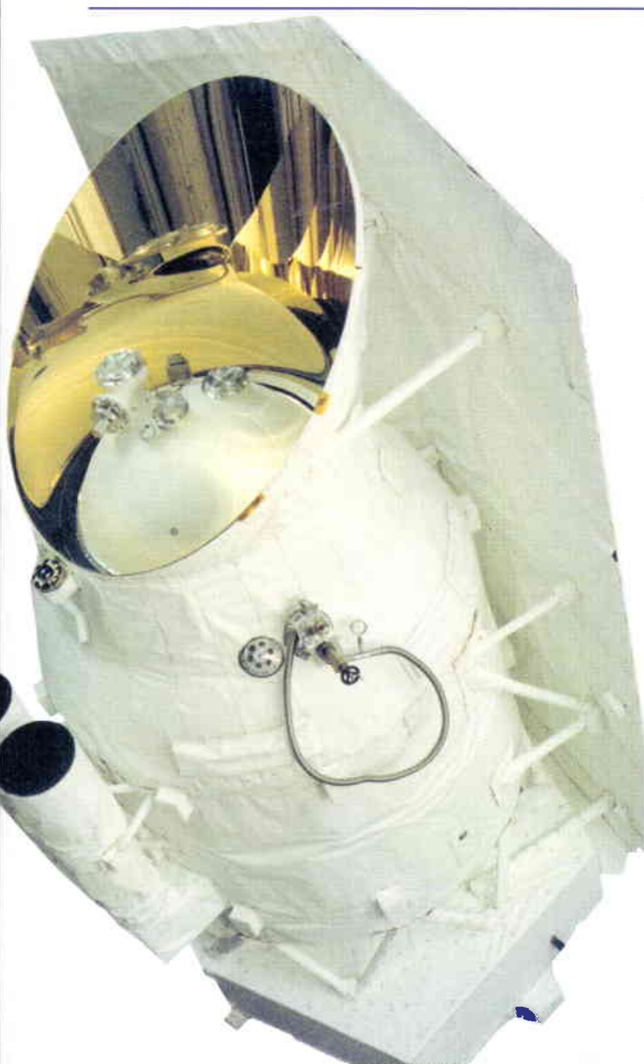
We are currently at the end of ISO's 3.5 year Post-Operations Phase and the start of the 5 year Active Archive Phase. Final automatic bulk processing of the observations has concluded and all observations are publicly available from the ISO archive.

Here, in addressing ISO's observations of asteroids we attempt a complete overview, from the original scientific ideas – to the current results – to what can be expected in the future. ISO has delivered a wealth of new and unexpected results concerning asteroids, but the archive still has many hidden treasures. In the near future, ISO's mid- and far-infrared data, in combination with other observations, will provide new advances in our understanding of the Solar System and new insights into the interrelations between meteorites, asteroids, comets and interplanetary material, all of which play fundamental roles in the Solar System's history and evolution.



Introduction*

ISO was the world's first true orbiting infrared observatory. Equipped with four sophisticated and versatile scientific instruments, it provided astronomers with a facility of unprecedented sensitivity and capability for the exploration of the Universe at infrared wavelengths from 2.5 to 240 microns. The Solar System programme comprised only about 1.4% of all science observations made by the ISO mission, and the astronomical community's expectations were not very high in relation to asteroids, comets and planets. During the last decades many satellites have studied several of our neighbouring objects in great detail, both in-situ and during close flybys – so what could be expected from a 60-cm telescope circulating just outside the atmosphere?

Now, however, the ISO results are on their way to making a big impact on our knowledge of objects on our celestial 'doorstep'. Spectacular results regarding the 'life-element' water in the Universe – not least its unexpected discovery in large amounts in the higher atmospheres of all giant planets – were already presented in ESA Bulletin No. 104, in November 2000. Here we maintain the Solar System theme, presenting ISO's results on asteroids.

*Units used in this article:
AU = Astronomical Unit, the average distance between Sun and Earth;
1 AU=149 597 870 km.
Jy = Jansky, flux density,
1 Jy = 1×10^{-26} Wm^{-2} Hz^{-1}.
Micron: wavelength unit,
1 micron = 1×10^{-6} m.

ISO was an ESA spacecraft launched on 19 November 1995 and operated in orbit until 16 May 1998, carrying instruments funded by the Agency's Member States (especially the countries of the instrument Principal Investigators (PIs): France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA. Additional information on ISO, including results galleries and how to retrieve data, can be found by following links from the ISO Home Page (*www.iso.vilspa.esa.es*); news items are also posted at *www.sci.esa.int*.

Previous ESA Bulletin articles have addressed:
- The ISO Mission – A Scientific Overview (ESA Bulletin No. 84, November 1984)
- The First Results from ISO (ESA Bulletin No. 86, May 1996)
- Looking Back at ISO Operations (ESA Bulletin No. 95, August 1998)
- The ISO Data Archive (ESA Bulletin No. 98, June 1999)
- ISO's Astronomical Harvest Continues (ESA Bulletin No. 99, September 1999)
- ISO and Cosmic Water (ESA Bulletin No. 104, November 2000).

These small pieces of rock (by celestial standards) have diameters of up to several hundred kilometres, with the majority orbiting between Mars and Jupiter. Some asteroids collisionally and gravitationally scattered into Earth-crossing orbits have made it in recent years into the newspaper headlines. The ISO results are of less immediate journalistic interest, but appear more and more in scientific journals and at specialised conferences, by virtue of the fundamental contributions that they make to a deeper understanding of these important constituent bodies of the Solar System.

Asteroids receive light from the Sun and what we see of them through amateur telescopes (and under certain circumstances also with the naked eye) is purely reflected light. Typically, however, only 10% of the incident light is reflected by the asteroid, the rest being absorbed and re-emitted as thermal radiation in the infrared. If we could see with our eyes in the thermal infrared (and subject to the assumption that the atmosphere would be transparent at such wavelengths), we would see a completely unfamiliar sky: hardly any stars, but thousands of bright asteroids forming a nice band in the ecliptic plane – the plane in which the Sun moves against the sky and which intersects the plane of our galaxy near the bright galactic centre and at the anti-centre. ISO's sensitivity range spanned the wavelengths at which asteroids produce the vast bulk of their thermal emission, and so it was capable of detecting 99% of the thermal emission of asteroids including, at the shortest wavelengths, part of the reflected sunlight. The main goal of astronomers observing asteroids with ISO was to analyse, by all possible means, this 'heat radiation', which contains the fingerprint of the asteroids' surfaces, and therefore traces of the history of our Solar System.

ISO and its data

ISO's four instruments were a camera covering the 2.5 – 17 micron band (CAM), an imaging photo-polarimeter (PHT), and the short- and long-wavelength spectrometers (SWS and LWS), covering the 2.4 – 45 micron and the 45 – 196.8 micron bands, respectively. The satellite was a great technical and scientific success with most of its subsystems operating far better than their specifications and with its scientific results impacting practically all fields of astronomy. At a wavelength of 12 microns, ISO was one thousand times more sensitive, and had one hundred times better angular resolution than its predecessor the all-sky-surveying IRAS. During its routine operational phase (from the 4 February 1996 to 8 April 1998), ISO made over 26 000 scientific observations (plus about 4000 calibration observations) of targets ranging from objects in our own Solar System right out to the most distant extragalactic sources. In addition to the dedicated observations, ISO obtained other serendipitous data in parallel during slews of the satellite or during long pointed observations.

The accuracy of ISO's pointing system was at the arcsecond level and allowed the tracking of Solar System targets up to apparent velocities of 120 arcsec/hour with respect to equatorial coordinates. This covered most Solar System targets: only a few near-Earth asteroids and comets in certain constellations were too fast and had to be excluded.

The data processing and calibration methods are mature and the archive is approaching the final legacy of the ISO project (final archive pipeline processing products will be released early in 2002). The accuracy of the automatically processed archive products depends strongly on the brightness of a source, on the source-to-background contrast, and on the instrument observing mode. For Solar System objects in particular, special care was necessary due to the source movement, the changing background contributions and, in many cases, non-default instrument configurations. Therefore, most of the results on asteroids are based on manual data processing of basic archive products, performed with the instrument-specific interactive-analysis software packages.

ISO asteroid observations

The titles, Principal Investigators and the targets of all asteroid programmes performed with ISO are summarized in Table 1. In total, 173 proposals were implemented within the 'Guaranteed Time'[1] and 925 within the 'Open Time'[2]. The proposals included several asteroid categories: (a) near-Earth asteroids with closest approaches to the Sun (perihelion) of less than 1.3 AU; (b) Main-Belt asteroids between 1.8 and 4.0 AU from the Sun; (c) Trojan asteroids at the Lagrangian points around Jupiter; and (d) Kuiper-belt objects populating space beyond Neptune. The main scientific goals comprised

[1] The various groups involved in the preparation and operation of the ISO mission received guaranteed observing time. These groups were: the four Principal Investigators and their teams, who built the ISO instruments; the five Mission Scientists; the Science Operations Team; the National Aeronautics and Space Administration (NASA), USA; and the Institute of Space and Astronautical Science (ISAS), Japan.

[2] The majority of ISO's observing time was made available via two calls for observing proposals, which were open to the astronomical community.

studies of the chemistry and mineralogy of asteroid surfaces, but also of great interest were questions about the links between asteroids, comets, meteorites and other interplanetary material. ISO allowed detailed studies of all aspects of asteroid thermal emission, as reflected in the proposal titles and in the variety of recent scientific results. More details about the proposals, including their scientific abstracts, can be found in the ISO Data Archive at *http://www.iso.vilspa.esa.es*.

Calibration observations performed with ISO have mainly been used for technical studies, but have also proved useful for scientific investigations.

In addition to the intentional science and calibration observations of asteroids, ISO serendipitously observed Solar System objects that happened to be in the field of view during slews or were seen by instruments in one of the parallel modes. Many other programmes

Table 1. Dedicated asteroid programmes

Programme	P.I.	Asteroids
A. Guaranteed Time Observations		
Observations of Galilean Satellites and Asteroids	Encrenaz, Th.	1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 10 Hygiea, 52 Europa, 65 Cybele
The Mineralogy and Chemistry of the Major Asteroid Classes	Salama, A.	1 Ceres, 2 Pallas, 52 Europa
Vesta Lightcurve Observations	Schulz, B.	4 Vesta
B. Open Time Observations		
IR Observations of Rosetta Asteroidal Targets: Albedo and Diameter Measurements of the Rosetta Target Asteroids	Barbieri, C.	2703 Rodari, 3840 Mimistrobel
Dark, Volatile-rich Asteroids: Possible Relation to Comets	Barucci, A.	10 Hygiea, 77 Frigga, 114 Kassandra, 308 Polyxo, 511 Davida, 624 Hektor, 911 Agamemnon, 914 Palisana, 1172 Aneas, 1437 Diomedes
The Composition of D-Type Asteroids	Fitzsimmons, A.	308 Polyxo, 336 Lacadiera, 498 Tokio
Rosetta Target Asteroids	Fulchignoni, M.	3840 Mimistrobel
Cometary Activity in Asteroids	Harris, A.	1980 Tezcatlipoca, 3200 Phaethon, 3671 Dionysus, 4015 Wilson Harrington, 4179 Toutatis, 5145 Pholus
A Survey of Kuiper Belt Candidates	Ip, W.-H.	5145 Pholus, 1992 QB1, 1993 SB, 1993 SC, 1994 JQ1, 1994 TB, 1996 TL66
Spectroscopic Studies of Volatile-Rich Asteroids	Larson, H.	1 Ceres, 2 Pallas, 13 Egeria
Polarimetry of Asteroids	Mueller, T.	6 Hebe, 9 Metis
A Comprehensive Investigation of the Thermal Properties and Rotational Thermal Variability of the Pluto-Charon Binary and Chiron	Stern, A.	2060 Chiron
Asteroid Size Frequency Distribution	Tedesco, E.	4 Positions at around (22h38min — 08d34min, f.o.v. of 214″ x 214″, 17′ x 17′ and 19′ x 19′
C. Calibration Observations		
ISOCAM Calibration Observations	CAM Team	10 Hygiea, 20 Massalia, 46 Hestia, 56 Melete, 65 Cybele, 150 Nuwa, 804 Hispania, 2062 Aten
LWS Calibration Observations	LWS Team	1 Ceres, 2 Pallas, 4 Vesta, 10 Hygiea
ISOPHOT Calibration Observations	PHT Team	1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 10 Hygiea, 54 Alexandra, 65 Cybele, 106 Dione, 313 Chaldaea, 532 Herculina
SWS Calibration Observations	SWS Team	1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 10 Hygiea

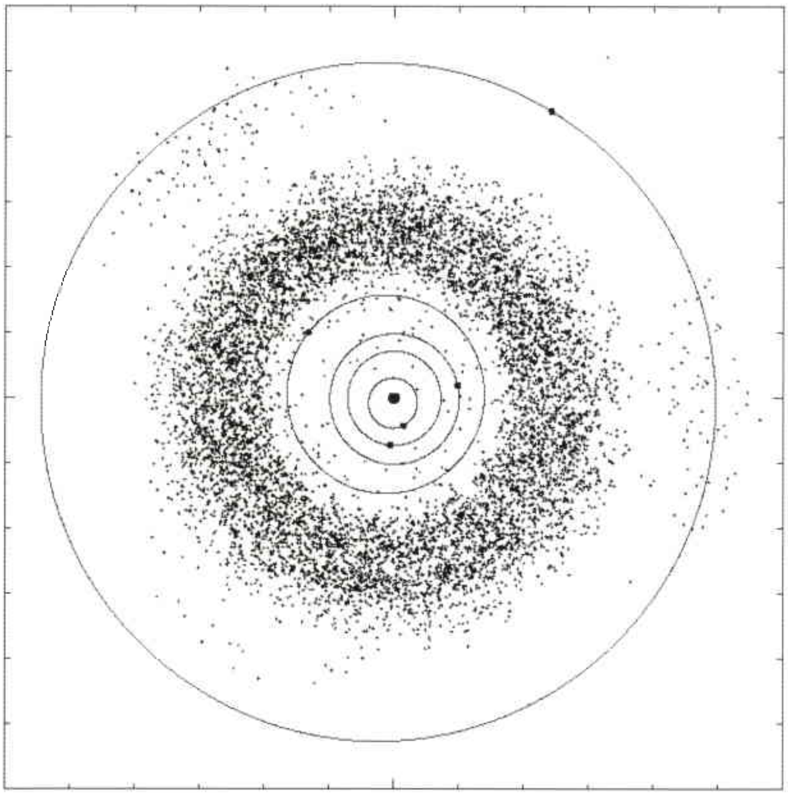


Figure 5. The positions of approximately 8000 asteroids and of the planets from Mercury through Jupiter, projected onto the ecliptic plane for 4 October 2000. The asteroid Main Belt between Mars and Jupiter is nicely visible. The two groups of Trojan asteroids are located at the Lagragian points in front of and behind Jupiter. We currently know the orbits of more than 100 000 asteroids.

provided indirect information on the asteroids, like those focussing on comets, on cometary transition objects (i.e. comets losing the last of their volatile substances and becoming asteroidal), on zodiacal light measurements, and on studies of the trails and tails of comets.

Scientific results

The ISO data archive contains spectroscopic, photometric, imaging and polarimetric measurements at infrared wavelengths between 2 and 240 microns of more than 40 different asteroids. Among the data are complete spectra from 2 to 200 microns of bright asteroids with spectral resolutions of 1000 – 2000 in the SWS range and about 200 in the LWS range. Imaging and photometric asteroid measurements are available and, for the first time, ISO also made polarimetric measurements of the disk-integrated thermal emission of asteroids at 25 microns. These observations and also those of the asteroids seen in parallel and serendipity modes, are the basis for current and future scientific investigations. The recent ISO results presented below are based both on data processed with the automatic-pipeline and with the interactive-analysis packages.

The special case of Vesta

Vesta is the third largest asteroid in the Main Belt. High geological interest arose from the discovery that howardite, eucrite and diogenite (HED) meteorites found on Earth could be samples excavated from its surface. These meteorites have spectral features common to Vesta and to a cluster of small (< 10 km diameter) V-type asteroids extending from the region surrounding Vesta to the edge of the 3:1 resonance[3] at 2.5 AU. Impacts may have excavated enough crustal material to form this widely scattered family of 'Vestoids': some of

[3] Objects with orbital periods close to a simple fraction (here 3:1) of Jupiter's 11.86-year period are in resonance due to the steady influence of Jupiter's huge gravitational attraction. Asteroids in these so-called 'Kirkwood gaps' have very unstable orbits.

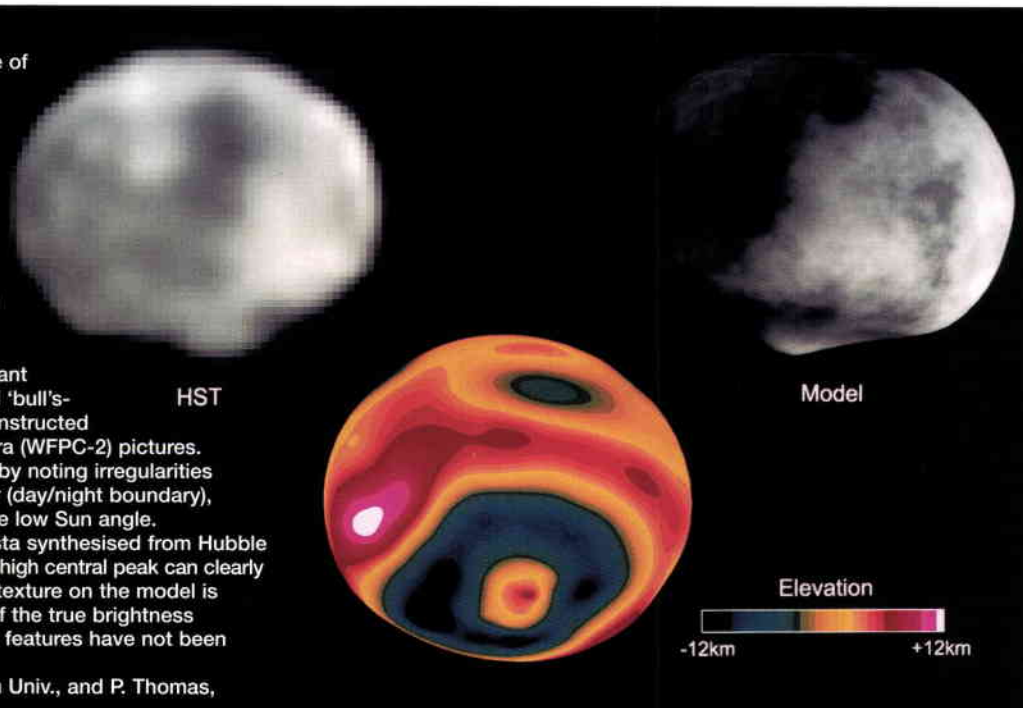


Figure 6. Hubble Space Telescope reveals a huge crater on the surface of Vesta.
Left: An HST image of the asteroid Vesta, taken in May 1996 when it was 110 million miles from Earth. The asymmetry of the asteroid and 'nub' and the south pole is suggestive that it suffered a large impact event. The image was digitally restored to yield an effective scale of six miles per pixel (picture element).
Centre: A colour-encoded elevation map of Vesta clearly showing the giant 285-mile diameter impact basin and 'bull's-eye' central peak. The map was constructed from 78 Wide Field Planetary Camera (WFPC-2) pictures. Surface topography was estimated by noting irregularities along the limb and at the terminator (day/night boundary), where shadows are enhanced by the low Sun angle.
Right: A 3-D computer model of Vesta synthesised from Hubble topographic data. The crater's 8-mile high central peak can clearly be seen near the pole. The surface texture on the model is artificial, and is not representative of the true brightness variations on the asteroid. Elevation features have not been exaggerated.
(Credit: B. Zellner, Georgia Southern Univ., and P. Thomas, Cornell Univ., NASA)

them approach the chaotic region associated with the 3:1 and v6 resonances[4], from which regions fragments can be rapidly transferred to Earth-crossing orbits. Based on HST images, a three-dimensional shape model was derived for Vesta, and mineralogical and albedo variegations on the surface were discovered.

Vesta has a large mountain on its south pole, surrounded by a ring of mountains stretching halfway to its equator (Fig. 6). This was interpreted as a huge crater with a large central peak rising 18 km above the crater floor. The discovery of substantial impact excavation on Vesta is consistent with the idea that the basaltic achondrite HED meteorites were excavated from its surface by impact processes. There are thus convincing observational and dynamical arguments to suggest that Vesta is the actual parent body for the suite of these meteorites, which represent about 6% of all meteorites falling on Earth. As such, Vesta would represent one of only four known Solar System bodies for which actual rock samples are available in terrestrial laboratories (Earth, Moon, Mars and Vesta).

The detailed studies of the high- and low-resolution ISO spectra of Vesta are still ongoing and are very promising. The observed structure at around 9.1 microns seems to be compatible with the presence of olivines on the asteroid's surface. However, material alteration, such as space weathering, aqueous alteration[5], and varying collisional history, complicate the unique identification of spectral features in the ISO data with laboratory spectra of HED materials. Here, the ISO data are expected to contribute significantly to our knowledge of the relationships between the meteorites that we have in our laboratories and their possible parent bodies.

The special case of Hygiea (courtesy of M. Barucci and co-workers)

Asteroid Hygiea (number 10 in the official asteroid numbering scheme) is the fourth largest asteroid in the Main Belt, with a diameter of more than 400 km. Hygiea rotates around its principal axis in a retrograde sense with an unusually long rotation period of 27.6 hours. Aqueous alteration products have been discovered in its near-infrared spectra, and also a compositional variation over the surface has been discussed. Hygiea was the only ISO target that was observed by all four ISO instruments on the same day. This provided interesting possibilities for intercomparison of the instruments' behaviours and for cross-calibration. It turned out that the overall thermal continuum emission has been nicely predicted by previous thermophysical modelling. However, the greatest interest arises when looking at the low-level spectral features, which are characteristic of the asteroid surface minerals. Hygiea is classified as a C-type asteroid with possible analogues in carbonaceous chondrite meteorites found on Earth. Extensive laboratory studies of different minerals and meteorites have revealed some similarities between ISO's Hygiea spectrum and Ornans and Warrenton meteorites (CO_3 meteorites) at small grain size (Fig. 7).

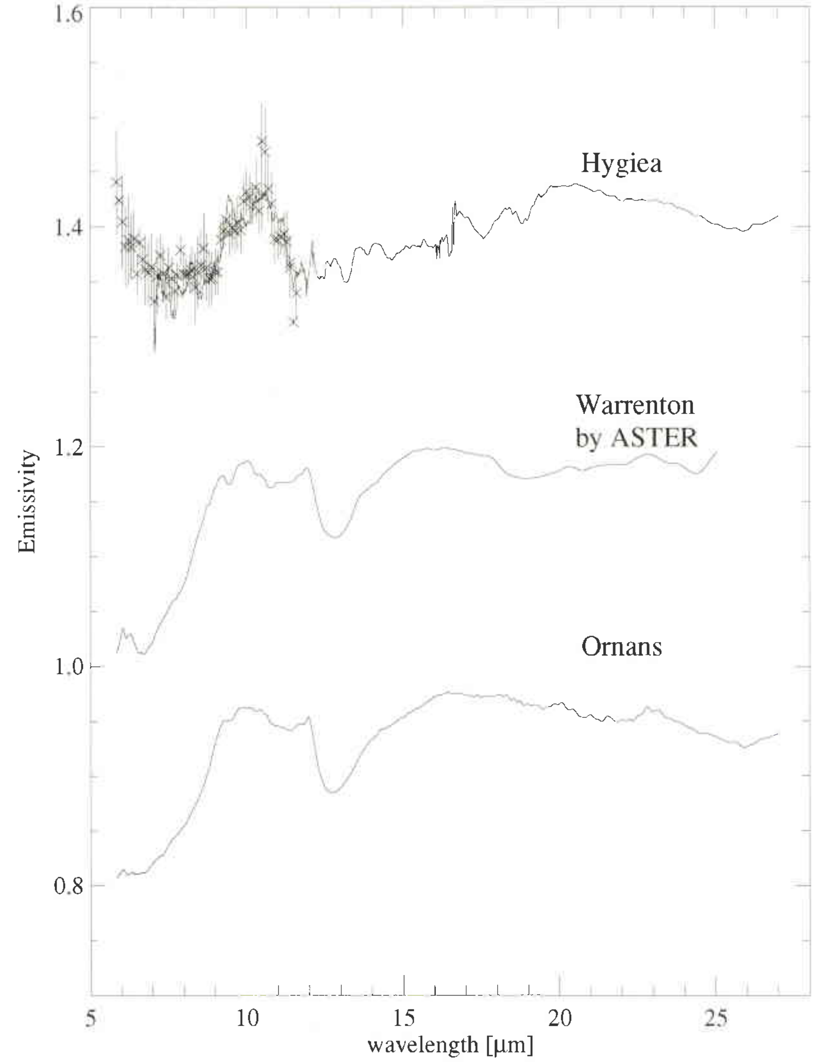


Figure 7. Comparison between 10-Hygiea emissivities measured by ISOPHOT-S and SWS, and laboratory emissivities of Ornans and Warrenton meteorites. (Credit: M. Barucci & co-workers)

The most indicative feature for this kind of comparison is the Christiansen peak, which occurs around 9.3 microns in the ISO data and in the above-mentioned two carbonaceous chondrite meteorites. The analogy is also supported by the comparison of the transparency features around 13 and 26 microns. If Hygiea is really compatible with CO

[4] Specific secular resonances.
[5] Aqueous alteration is a low-temperature chemical modification of materials by liquid water.

meteorites, this would imply that it is a 'primitive' object which has undergone some metamorphosis. ISO's large database of spectroscopic observations will allow more detailed studies of mineralogy and chemical composition of asteroids to proceed in the near future. The questions of surface alteration processes and the interpretation of spectroscopic features in the infrared are of great interest in the Solar System expert community.

Spectroscopic and spectrophotometric observation of bright asteroids

Spectroscopic and spectrophotometric observations of asteroids have been carried out with all four ISO instruments. The sub-solar and black-body temperatures have been computed for all observed asteroids based on different models. The five bright asteroids 1-Ceres, 2-Pallas, 3-Juno, 4-Vesta and 52-Europa are among the brightest and best-known Main-Belt asteroids, with spin vector, shape and size computed to a good precision. Their thermal continuum has been modelled using a thermophysical model. The spectral features above the thermal-emission continuum have been analysed and discussed in terms of surface composition of the objects.

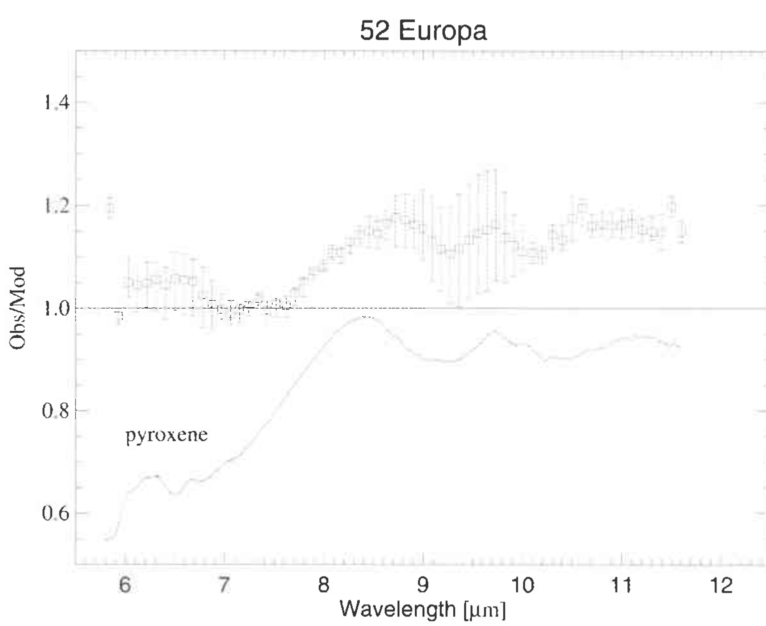


Figure 8. Comparison between 52-Europa emissivities measured by ISOPHOT-S and laboratory emissivities of typical asteroid minerals. (Credit: E. Dotto & co-workers)

The main features observable in the infrared spectral range, which are diagnostic of the mineralogical and petrologic assembly probably present on the surface of the observed asteroids, can be put into three classes: Reststrahlen, transparency and Christiansen features. The interpretation of these spectral features is neither easy nor unique. Since asteroid surfaces are composed of mixtures of minerals whose absorption features are combined following non-linear paths, asteroid spectra are affected not only by the chemical composition of the surface, but also by several undetermined physical parameters, such as density, mineralogy, particle size and packing. In order to investigate the surface composition of the observed asteroids, the spectra obtained have been compared with the emissivity of meteorites and minerals available in the literature, and with new laboratory spectra of a selected sample of minerals. The thermal emissivities of all of the five asteroids show a strong signature around 10 to 11 microns, suggesting the presence of silicates on the surface of these bodies. As an example, the observed emissivity of C-type asteroid 52-Europa and of pyroxenes and olivines obtained by laboratory experiments is shown in Figure 8.

The spectral behaviour between 8 and 11 microns suggests the presence of a mixture of pyroxenes and olivines on the surface of 52-Europa. In particular, the 8.8 micron maximum in the asteroid spectrum seems to be consistent with the Christiansen peak of olivine. At longer wavelengths, olivine and pyroxene exhibit two major reststrahlen bands separated by a band gap, which seems to be consistent with the ISO spectrum of Europa even though the error bars in this region are high.

Polarised thermal emission from asteroids

Depending on wavelength, refractive index and viewing geometry, the thermal-infrared emission from asteroids will originate at some depth below the surface. The radiation propagates through the porous regolith towards the surface, where it is refracted according to Fresnel's equations. As a consequence, the thermal emission becomes polarised. Due to symmetry, however, there can be no net polarisation in the disk-integrated flux from a circularly symmetrical temperature distribution. However, the non-zero thermal inertia of the asteroid, together with its rotation, causes an asymmetry in the temperature distribution. The effect increases with phase angle and for elongated asteroids. The contribution of subsurface emission to the total emission is wavelength-dependent, with the largest contribution at peak wavelength and beyond.

The disk-integrated mid-infrared polarisation parameters were computed by extending the new thermophysical model by J. Lagerros (Uppsala). The small-scale surface roughness was approximated by hemispherical segment craters covering a smooth surface. Analytical solutions were used for the multiply scattered solar and thermally emitted radiation inside the craters. The surface roughness enhances the emission in the solar direction, but lowers the polarisation due to a less sharp transition from the solid body to the vacuum. In general, the predicted degree of linear polarisation increases with higher refractive index, higher absorption coefficient, and a more elongated shape of the asteroid.

The asteroids 6-Hebe and 9-Metis were observed at a wavelength of 25 microns with ISOPHOT. The model absolute fluxes were in good agreement with the photometric results. Although no linear polarisation was detected, the upper limits, together with the extended model, allowed useful constraints to be placed on the regolith properties of the target asteroids. The derived detection limits were compared to model polarisation, by spanning a range in surface roughness, refractive index, and thermal-inertia parameter space. The Metis observations favour a low refractive index and high surface roughness, but the Hebe observations were inconclusive since they coincided with a minimum in the polarisation curve.

Fundamental thermal-emission parameters of Main-Belt asteroids

Based on a large, uniform, pre-ISO database of about 700 individual observations, ranging from 7 to 2000 microns, the thermophysical emission aspects of asteroids have been analysed. In this context, the ISO observations of the following objects have been studied in detail: 1-Ceres, 2-Pallas, 3-Juno, 4-Vesta, 10-Hygiea, 54-Alexandra, 65-Cybele, 106-Dione, 313-Chaldaea and 532-Herculina. A recent thermophysical model was applied to investigate surface roughness, heat conduction and emissivity over the thermal wavelength range. The model included aspects of observing geometry, illumination conditions, shape and spin vector and, if available, also the physical size and the albedo. The model parameters of thermal inertia and beaming were varied over a wide range in search of the best agreement between observations and model predictions. In a second step, the emissivity was determined as a function dependent on wavelength, to be fitted to the data.

The investigations indicated very rough surfaces, reflected in the beaming effect, and very low levels of heat conduction. These values were found to be much smaller than in the lunar case, mainly due to the different environment of the asteroid regolith (lower temperature, lower density) compared to the Moon. The derived thermal-infrared beaming model parameters in terms of 'surface slopes' and 'fraction of surface covered by craters' are in good agreement with theoretical considerations.

Due to scattering processes in the porous regolith, the emissivity varies significantly with wavelength. At the peak of the thermal emission at around 20 microns, the objects emit almost perfectly, and with a significantly lower efficiency at longer wavelength. In the case of Vesta, emissivities as low as 0.6 in the far-infrared/submillimetre region were found. Redman and co-workers suggested that this is an indication of the presence of a dusty, porous regolith. Scattering processes by grains within the regolith reduce the emissivity in a wavelength-dependent fashion. However, the interpretation of the results in terms of grain-size distribution, regolith structure and material is still ongoing.

The excellent agreement at all flux levels over the full thermal-emission spectrum of Ceres at different epochs confirms that the derived values for the thermal properties are well-determined. Figure 9 shows SWS and LWS observations of Ceres taken at different times. The thermophysical model predictions are over-plotted.

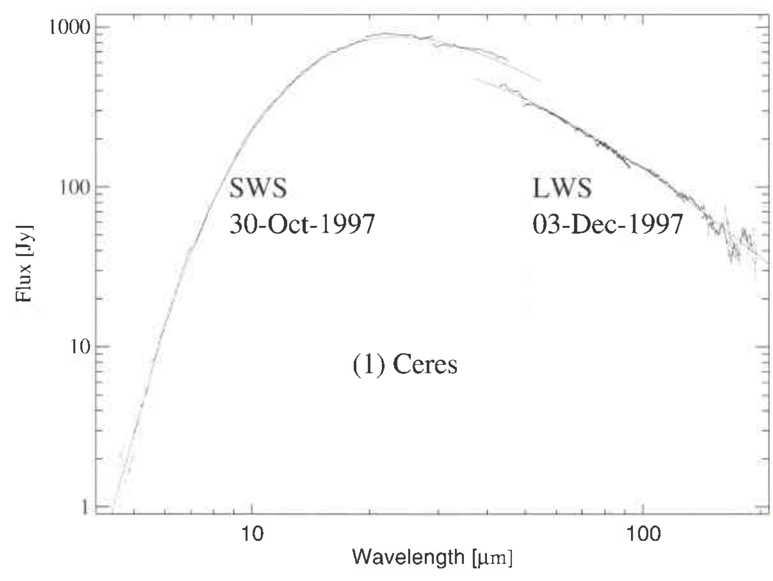


Figure 9. The asteroid 1 Ceres, observed by ISO's short- and long-wavelength spectrometers SWS and LWS. The TPM predictions are over-plotted as solid lines.

Further preliminary tests of these values against other asteroid observations show that the thermal description of Ceres is also valid for other Main-Belt asteroids. This means that the thermophysical model parameters allow a prediction of the thermal emission with a high accuracy for all Main-Belt asteroids where the shape and reflected-light properties are known.

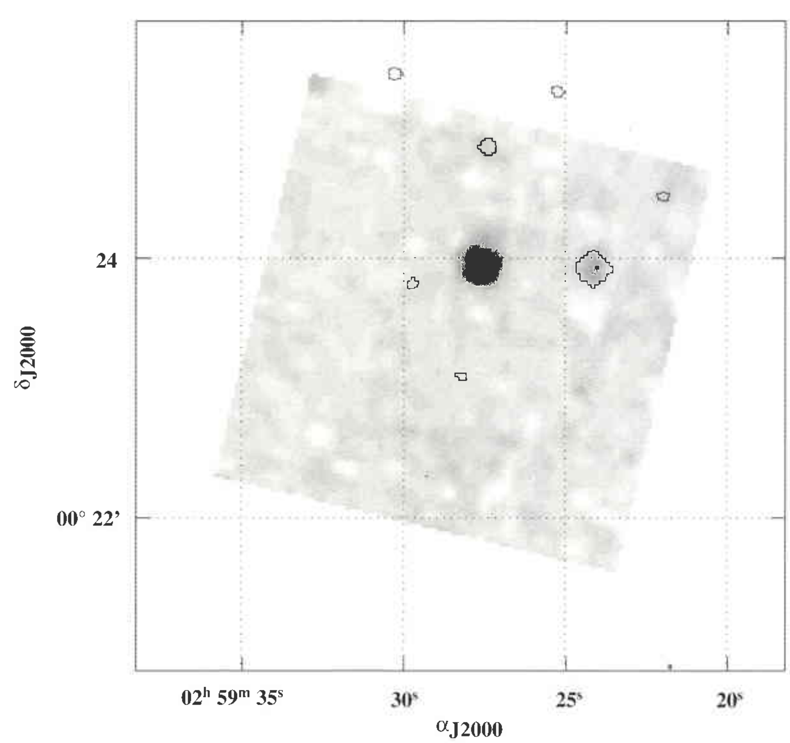
Cometary activity in asteroids

Five near-Earth asteroids have been observed in dedicated programmes with ISOCAM to search for cometary activity. A preliminary analysis of the region around 1980-Tezcatlipoca, 3200-Phaethon, 3671-Dionysus, 4015-Wilson-Harrington and 4179-Toutatis showed no extended emission. It was expected, at least for some of the targets, that weak cometary activity would be seen in the form of dust comas. The non-detection of activity has implications for our understanding of the transition between asteroids and comets, and for the possible scenarios for extinct comets. The CAM photometry was very useful. It has been employed to improve the physical characterisation of these objects, and their albedos and diameters have been derived from a model recently developed especially for near-Earth objects (courtesy of A. Harris, Berlin).

Asteroid size-frequency distribution (courtesy of E. Tedesco, TerraSystem Inc., USA)
Two deep maps of a 12 arcminute square field on the ecliptic using the ISO 12 micron 'IRAS' filter (ISOCAM LW10 band) were made in June 1996, and another four in June 1997. The positions of the fields and the timing between the exposures had been chosen to enable recognition of moving sources with typical Main-Belt apparent velocities below 1 arcmin/hour.

Based on the Minor Planet Center's database, as of October 2000 two known asteroids had been identified in the 1996 field, but none in the 1997 field. Of the seven probable asteroids identified in this field, the two that appear to correspond to 1999-AQ23 and 1999-JZ50 are the brightest and third-brightest in the field. The apparent velocities of the sources are appropriate for Main-Belt asteroids (as seen from ISO).

Figure 10. Asteroid 729 Watsonia as serendipitously observed in the ISOCAM parallel mode.



As an upper limit, it was found that there are about 400 asteroids per square degree at the ecliptic plane above the 12 micron detection threshold of the observations. This threshold is about 0.9 mJy, i.e. it corresponds to diameters greater than about 1.1 km at mid-belt. To put these results into perspective, the IRAS limiting sensitivity was about 150 mJy at 12 microns, whereas most of the asteroids detected by ISO are more than 100 times fainter than that!

The same sky areas were simulated with the Statistical Asteroid Model developed by Tedesco and co-workers. The model gives only lower limits, because it does not include the near-Earth asteroids or asteroids beyond the Hilda group and it terminates abruptly at an asteroid diameter of 1 km. It predicted values of around 200 asteroids per square degree at the ecliptic plane above the 12 micron detection threshold. If smaller asteroids were included, some of these would have 12 micron flux densities greater than 1 mJy if they were close to the Earth. Nevertheless, the ISO data imply that the actual number of kilometre-sized asteroids is significantly greater than previously believed, and in reasonable agreement with the Statistical Asteroid Model.

Asteroids serendipitously seen by ISO
During the ISO mission many surveys and large observing programmes were conducted. Surveys with observations close to the ecliptic plane, performed by CAM and PHT, include many asteroids. The detection of asteroids at thermal wavelengths has many applications. For well-known objects, thermal-model predictions can be tested against the measured infrared brightness. In all cases, radiometric diameters and albedos can be determined and compared, if available, with direct size determinations and/or IRAS results. The mid-infrared CAM observations allow further studies of beaming and surface structure properties, while the far-infrared measurements provide clues about the so far unknown emissivity behaviour of asteroids.

A first analysis of the approximately 40 000 CAM parallel observations between 6 and 15 microns revealed infrared fluxes for about 50 asteroids, most of them not seen by IRAS. Many additional objects are expected to be included in other CAM surveys, with some of the deep observations being sensitive enough to detect 1 km-diameter objects in the asteroid mid-belt.

PHT performed observations at 170 microns while the ISO satellite was slewing from one target to the next. This so-called 'PHT Serendipity Survey' covered approximately 15% of the sky, with a limiting sensitivity of 1 Jy. A total of 56 asteroids were predicted to be bright enough to be seen in the slew data. However, an accurate flux determination was not possible in all cases, mainly due to the structured and bright celestial cirrus background. Nevertheless, the new 170 micron fluxes allowed thermophysical model analysis and improvements of the PHT serendipity calibration through reference to well-known asteroids. For some objects, diameter and albedo estimates became possible for the first time.

The ISO database can now be searched systematically for Solar System objects with known orbits. The flux determination will allow thermophysical investigations and the derivation of surface parameters. However, ISO also saw moving targets for which no counterpart in the Minor Planet Database is known so far. For these objects, only a statistical analysis is possible at the moment, at least as long as the orbits and the visual brightness are not known.

Asteroids as new standards in the thermal infrared

Celestial standards play a major role in astronomy. They serve as references for all kinds of measurements where absolute values of physical properties are investigated. In the visible, many stellar sources are available, with Sirius and Vega as main references. In the mid-infrared (i.e. at wavelengths shorter than 35 microns), a 'self-consistent radiometric all-sky network of absolutely calibrated stellar spectra' was recently established (courtesy of M. Cohen, P. Hammersley and co-workers). At submillimetre and radio wavelengths, observers usually use planets as primary standards and H II regions and planetary nebulae as secondary standards. With the launch of ISO in 1995 the far-infrared window was opened, and for the first time observations out to 200 microns were possible. At the same time, it became necessary to establish a set of new celestial standards for the photometric calibration of instruments in the far-infrared.

The extension of stellar reference spectra to the far-infrared provided for the calibration of faint objects, while the planets covered only the very brightest targets. The gap between the two types of calibrators had to be filled by new objects. A set of asteroids fulfilled all requirements:

- they filled the brightness gap between stars and planets in the far-infrared
- at least a few of them were always available during the ISO mission
- they have a smooth thermal-continuum spectrum with only minor emission and absorption features
- the flux changes due to rotation and changing observing geometry can be modelled
- the absolute-brightness predictions are accurate to better than 10% in most of the cases.

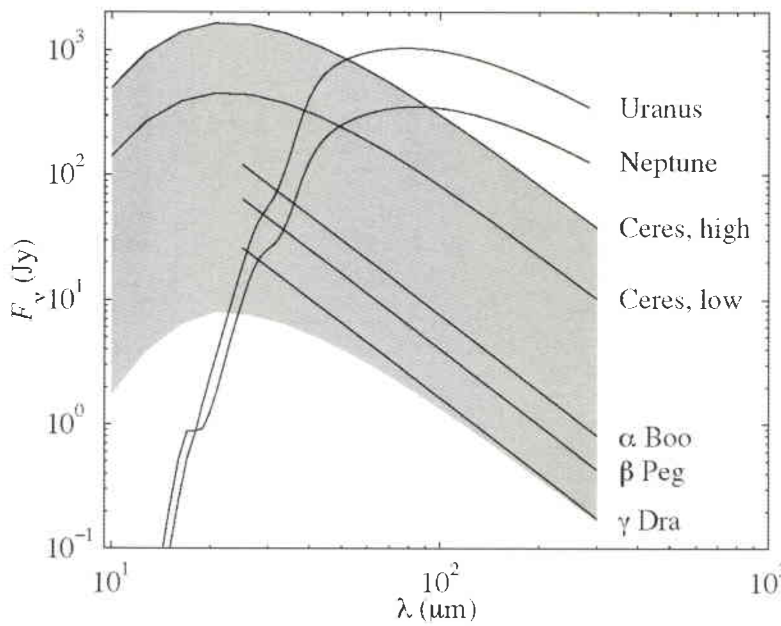


Figure 11. The brightness of different celestial standards. The shaded area indicates the range covered by the selected asteroids. The predictable flux variations of the asteroid, due to rotation, are in the order of 5-30% on time scales of several hours. The changing Earth-asteroid distance can cause a flux increase or decrease of one order of magnitude on a yearly scale (see Ceres: high and low). Uranus and Neptune cover the upper flux range.

In support of ISOPHOT, a set of 10 asteroids was intensively studied and established as new calibrators. Figure 11 shows the three brightest stellar reference sources. It shows Uranus and Neptune (at the upper end of the ISO brightness scale) and also a shaded area representing the selected set of asteroids. Ceres, as the brightest one, is shown at opposition and at conjunction to demonstrate the flux increase or decrease on a time scale of a year.

To establish asteroids as photometric standards, it was necessary to model geometric and illumination effects, surface structures and porosity, and the thermal behaviour for non-spherical objects. The essential model input parameters were derived from many ground-based observations at mid-infrared and submillimetre wavelengths, from Kuiper Airborne Observatory data and from special ISO measurements.

The following parameters are crucial for accurate flux predictions: asteroid size, shape and spin vector; the infrared beaming behaviour caused by surface roughness; the thermal inertia, and a wavelength-dependent emissivity. A comparison of thermophysical

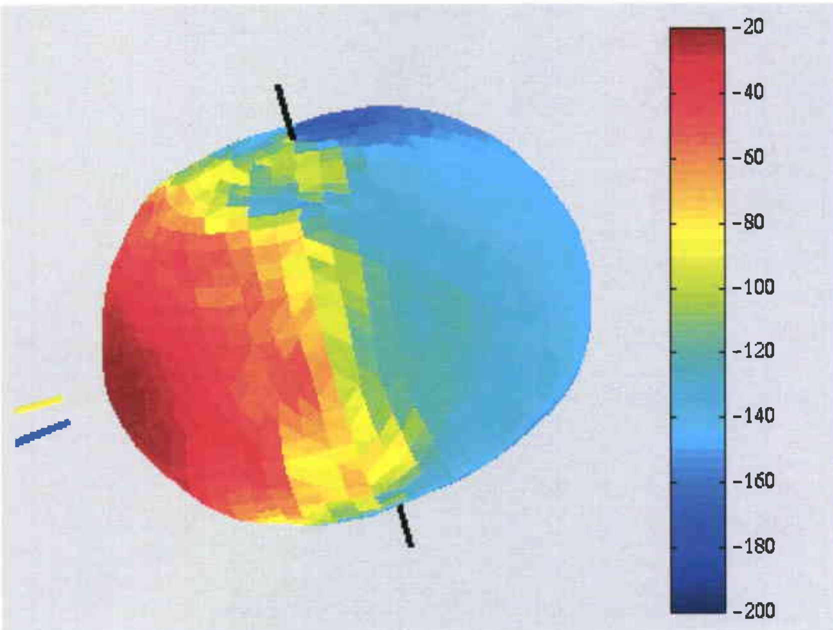


Figure 12. The asteroid 4 Vesta on 6 May 1996 (produced by J. Lagerros). The shape was derived from HST observations (by N. Thomas and co-workers), the temperature coding is in centigrade, the spin vector is marked with a black line, the direction to the Sun with a yellow line and the direction to the Earth with a blue line.

model predictions against spectroscopic data from 5 to 200 microns showed an excellent agreement. The uncertainties of the absolute calibration depend on the individual object and the wavelength interval. In the far-infrared ISOPHOT wavelength range (50 – 200 microns), an accuracy of between 5 and 20% has been achieved. One result of the thermophysical modelling is shown in Figure 12, where the surface temperature of Vesta has been calculated.

Asteroids were widely used later on for calibration purposes for all four ISO instruments. Future applications for ground-based submillimetre, airborne and spaceborne experiments are expected.

Outlook

Only a small fraction of the ISO archive has been exploited in terms of asteroid research. There are still several dedicated programmes for which the astronomers involved have not yet announced their results. The final archive will facilitate this work in the future, and support to the ISO user community is assured for the next five years through provision for an Active Archive Phase for the mission. Nevertheless, the main directions of ISO asteroid research can be seen from the previous overview section: 'astro-mineralogy' is the new topic in the astronomical world. Based on ISO's spectroscopic data from mid- to far-infrared and the corresponding laboratory analysis, many research groups have started to investigate asteroid surface compositions, their interrelation with meteorites, with comets, with the interplanetary and the interstellar medium, and with protoplanetary systems. ISO not only provides the 'key' observations to connect meteorites to asteroids, it also provides means to study the alteration of surface minerals in space.

ISO has also shown the high potential of thermal-infrared observations for the analysis of physical properties of asteroids through thermophysical modelling. The understanding of the thermal behaviour is a prerequisite for the interpretation of surface-mineral signatures in the thermal spectra. As in ISO's case, an excellent understanding of the thermal behaviour of well-known asteroids can be used to calibrate instruments in the far-infrared, where celestial calibrators are extremely rare.

Since the majority of the targets are Main-Belt objects, that is where the biggest improvements can be expected. Moreover, the few dedicated measurements of near-Earth objects will provide new clues to help answer important questions like the fate of extinct comets, or the real sizes and albedos of objects in Earth-threatening orbits. The serendipitous and parallel observations most likely include near-Earth objects, and surprises are not impossible.

It can be imagined that the ISO Data Centre and Archive might become involved with broad initiatives within the astronomical community, such as the Astrophysical Virtual Observatory (AVO), which will allow new and spectacular ways of using ISO observations together with observations at other wavelengths. In terms of the discovery of objects on Earth-crossing orbits, ISO's infrared observations, in combination with information from the visible, lead to an accurate diameter determination, which allows a better judgement of the impact risk and, if necessary, to evaluate mitigation scenarios.

ISO spent less than 100 hours in total on asteroid observations, or about 0.7% of the total available observing time. However, due to the uniqueness of the data and the great spectroscopic and polarimetric possibilities of ISO, these observations will remain state-of-the-art for many years to come, and future projects like SIRTF, SOFIA, ASTRO-F, and Herschel will benefit greatly from the ISO results. Our knowledge about the formation and evolution of asteroids has changed with ISO, and the picture of our Solar System will, from now on, retain many nuances injected by ISO.

Acknowledgement

The results described above are the work of a large number of astronomers, who for reasons of space could not all be individually credited throughout the article.

Technology R&D Programme Support to Future ESA Science Missions

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ESA's Directorate of Scientific Programmes has recently introduced a novel approach aimed at reducing the costs and minimising the risks associated with the procurement and implementation of its missions. This approach hinges on two complementary elements: technology preparedness and new management practices. The first aims at reducing the risk of unavailability of key technologies during the actual project development phases and thus avoiding substantial delays and cost increases. The second focuses on the need to lower overall mission-management costs.

ESA Bulletin No. 95 (August 1998) reported on the new management practices, and so this article focuses on the technology-preparedness aspect. It provides an overview of the objectives, the main challenges, the programmatic aspects and the current status of the recently approved Science Technology R&D Programme that ESA is pursuing to support its future missions.

The ESA Science Technology R&D Programme

The strategic need to achieve technology preparedness can be considered from two different points of view, which in turn imply two different but complementary objectives. On the one hand, technology preparedness can be seen as a 'means', aimed at consolidating the 'realism' of the ESA Science Programme. The first main objective is thus:

"To develop the necessary technologies on time and within budget, by reaching a readiness level equivalent to an elegant breadboard or an electrical model, tested in the relevant environment before the beginning of Phase-B, with the aim of minimising schedule delay and cost increases, at a late stage in the programme".

On the other hand, technology preparedness can be considered as the 'scope' itself of the Technology R&D Programme. The second main objective is therefore:

"To maintain and expand European technological knowhow, by setting up a coherent and ambitious R&D Programme, in order to increase the competitiveness and the technological independence of Europe from to the other world players in the space sector".

The future ESA science missions and their technology challenges

On 13 September 2000, the Science Programme Committee (SPC) was presented with the results of the studies carried out during the previous three years, which defined the mission concepts and identified the technology needs for the four 'Cornerstones' of the ESA Science Programme:
- BepiColombo: a planetary mission to Mercury
- GAIA: an astrometric mission to unveil the origin and evolution of our Galaxy
- DARWIN: an interferometric mission for the detection and spectroscopic characterisation of terrestrial exoplanets
- LISA: a fundamental-physics mission for the detection of low-frequency gravitational waves.

The bulk of the Science Technology R&D Programme is completed by development activities related to two other missions:
- SMART-2: a Small Mission for Advanced Research in Technology, a precursor of DARWIN and LISA, which will flight-test some of their key enabling technologies
- XEUS: an X-ray imaging and spectroscopy mission, to establish the evolution of the early Universe.

Finally, at a lower level, resources have been made available also for technology developments within the framework of the NGST (Next-Generation Space Telescope) mission, and for long-term activities not yet related to a specific mission.

The BepiColombo mission
BepiColombo is a mission to Mercury, the innermost planet of our Solar System, aimed at characterising its internal structure, its surface features and composition, its magnetic field and planetary environment. It consists of three scientific elements, namely two orbiters and a lander.

The first orbital element, the Mercury Magnetospheric Orbiter (MMO), provided by ISAS (Japan), is a small spinning spacecraft, which will be placed in an elliptical orbit (400 km by 12 000 km) around Mercury. It will be equipped with a range of field and plasma experiments to allow analysis of the magnetospheric physics of the planet. The Mercury Planetary Orbiter (MPO), a three-axis-stabilised spacecraft, is the second orbital element and will be placed in an elliptic polar orbit (400 km by 1500 km). It will carry a range of remote-sensing instruments to study Mercury's surface and interior. The Mercury Surface Element (MSE) is the lander element, which will analyse the planet's chemical and surface properties for a period of at least 7 days. Transfer to Mercury is achieved using a combination of planetary swing-bys, solar electric and chemical propulsion.

BepiColombo's launch is currently foreseen for summer 2009. More information about the mission and its scientific objectives can be found at:
http://sci.esa.int/home/bepicolombo/index.cfm

Two main drivers have dictated BepiColombo's pecific technology domains:
- the harsh thermal and radiation environments to which the model payloads will be subjected
- the need for miniaturisation and mass reduction due to the high Delta-V.

As far as the first driver is concerned, the main technological domains encompass:
- thermal-control technologies, including insulation materials, thermal coatings, heat pipes, optical solar reflectors, dichroic elements, and louvers; solar-array technologies, encompassing development at cell, module and array level, and testing under high temperatures and high light-insolation conditions
- antenna system technologies: reflector materials; RF components like wave-guides, feeds, rotary joints; two-axis steering and de-spin mechanisms.

The second driver requires that significant technology development, for mass and power saving, has to be carried out in areas such as: landing systems (to alleviate the shock at touchdown); avionics systems and vision-based descent and landing navigation systems; high-energy-density batteries; cameras and robots for in-situ geochemical and geo-physical measurements.

A total of thirty-three activities, involving an overall investment of more than 25 MEuros, have been identified for the BepiColombo Technology Programme, to be developed in the 2001–2003 time frame in line with the start of the programme's main design phase (Phase-B).

Figure 1 illustrates some of main features related to BepiColombo technology development.

The GAIA mission
GAIA's primary scientific goal is to clarify the origin and evolution of our Galaxy. The mission will provide unprecedented positional and radial velocity measurements with outstanding accuracy (10 μarcsec at 15 mag and 5 km/s at 18 mag, respectively). Such demanding requirements are necessary in order to make a stereoscopic and cinematic census of about one billion stars in our Galaxy, which represent about 1% of the galactic stellar population.

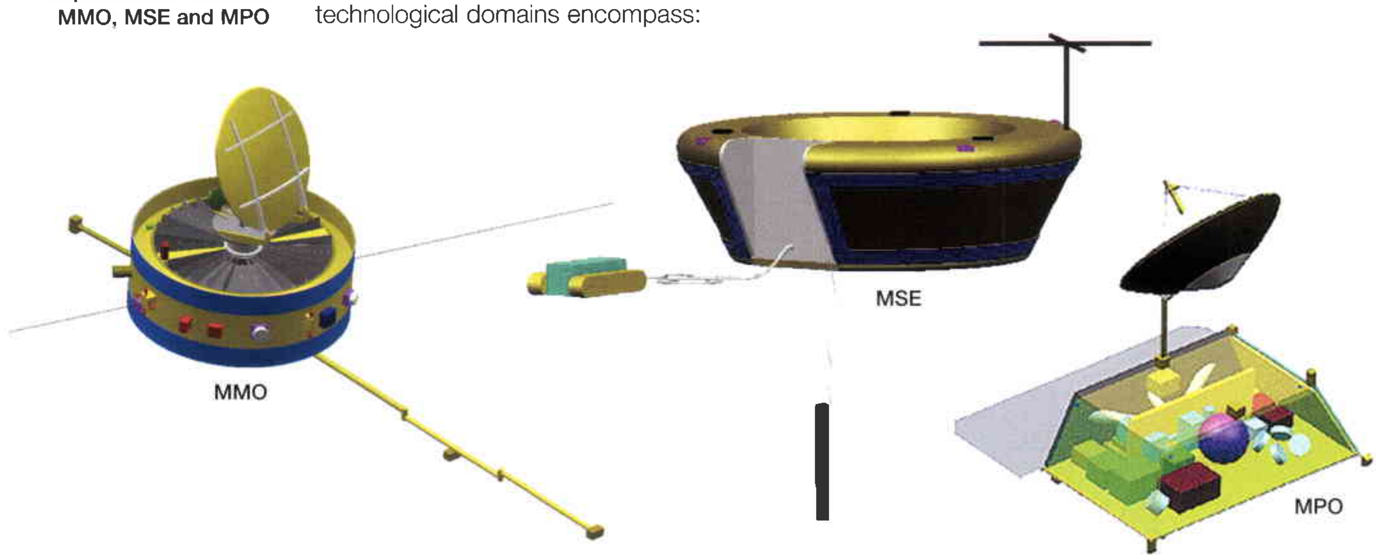


Figure 1. The scientific elements of the BepiColombo mission: MMO, MSE and MPO

Combined with astrophysical information for each star, provided by the onboard multicolour photometry, these data will have the precision and depth necessary to address key questions associated with the formation of the stars in the Milky Way and the distribution of so-called 'dark matter' in our Galaxy.

The three-axis-stabilised spacecraft will use its onboard propulsion system to reach its final orbit, around the L2 Lagrangian point of the Sun – Earth system, after about 200 days of cruise. For 5 years, the 1700 kg spacecraft will scan the heavens at a rate of 2 arcmin/sec, and will deliver an equivalent science data rate of about 1 Mbps, corresponding to an impressive overall data volume of several Terabytes (10^{12} bytes).

At its October 2000 meeting, ESA's Science Programme Committee recommended a launch date for GAIA of no later than 2012. More information about the mission and its scientific objectives can be found at:
http://sci.esa.int/home/gaia/index.cfm

Three demanding design features drive the requirements of the GAIA payload:
- a complex and compact optical design, which features two identical three-mirror telescopes, plus two astrometric instruments and a third three-mirror spectrophotometer (Fig. 2)
- an array with a very large number of CCDs (~250) in each of the three focal planes, with associated video lines (>300), which in turn implies demanding onboard real-time data-handling requirements
- an opto-mechanical bench with extreme thermal-stability requirements (30 μK over 3 hours) comprising a large octagonal structure (4 m in diameter) equipped with a large mirror made of the same material (Fig. 2).

The 13 MEuro investment spread over the fifteen development activities identified for the GAIA Technology Programme reflects these technological challenges and includes the development and manufacture of:

- a large (1.7 m x 0.7 m), lightweight, silicon-carbide mirror
- a large mosaic of CCD arrays (700 mm x 600 mm), needed for the three Focal-Plane Assembly instruments
- a metrology system for the measurement and active control, down to few picometres accuracy, of the relative positioning of the two telescopes
- high-speed, low-power data-handling electronics and related software for data readout (several Mbps), thresholding, compression and storage (300 Gbit), before safe transmission to the ground at about 3 Mbps.

Other GAIA technology development activities include the qualification of a reaction-control system based on Field-Emission Electric Propulsion (FEEP) technology for spacecraft attitude control during observations, and the development of a representative prototype of the large Deployable Solar Array/Sun Shield assembly (9 m in diameter).

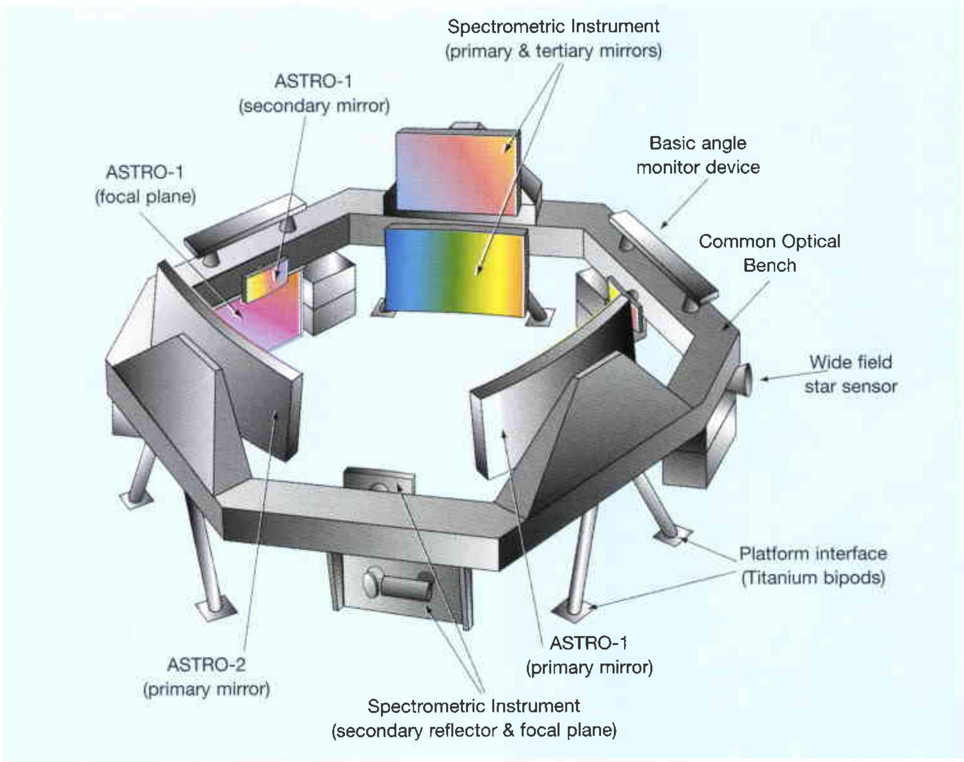


Figure 2. The GAIA three-mirror spectrometer

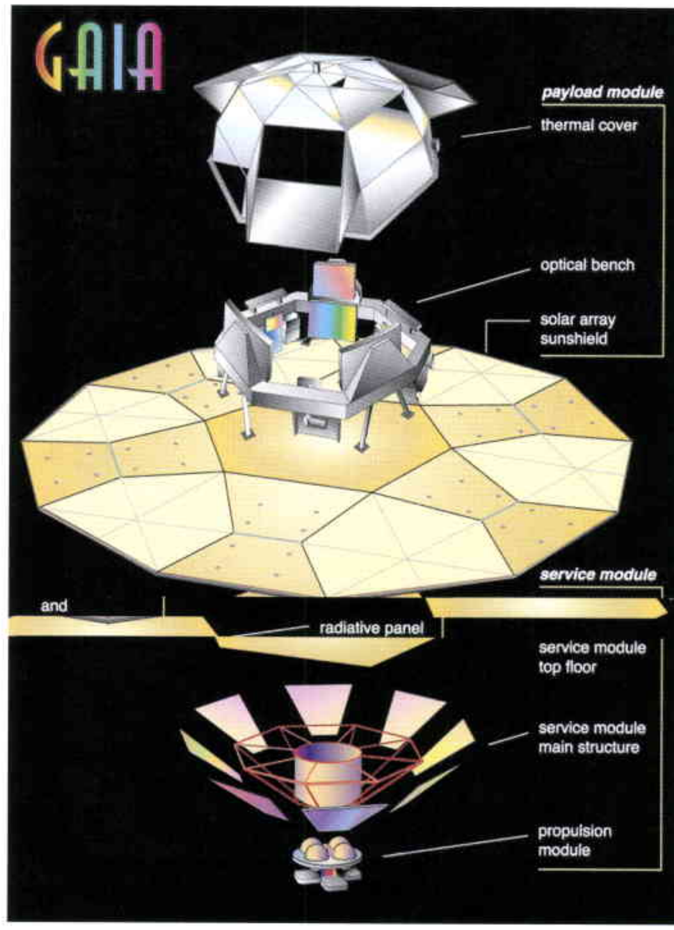


Figure 3. Exploded view of the GAIA satellite

Figure 3 is an exploded view of the GAIA satellite, with some of the main features related to GAIA technology development indicated.

The DARWIN mission

DARWIN (Detection and Analysis of Remote Worlds by Interferometric Nulling) is a multiple-spacecraft mission to perform nulling interferometry in the medium- and far-infrared wavelength bands, with the prime objective of detecting and spectroscopically characterising terrestrial exoplanets. It consists of six free-flying spacecraft in a hexagonal configuration, each equipped with a 1.5 m-diameter telescope that collects the incoming photons and transmits them to a seventh beam-combining spacecraft. The latter, positioned at the centre of the satellite formation, is equipped with optical benches for both the nulling interferometry and imaging functions. An eighth spacecraft is dedicated to overall management of the constellation, data handling and communication to and from the Earth and the other seven spacecraft (Fig. 4).

A dedicated Ariane-5 launch, together with a suitable chemical or electric-propulsion stage for cruise and orbit insertion, will place DARWIN at the L2 Lagrangian point of the Sun-Earth system.

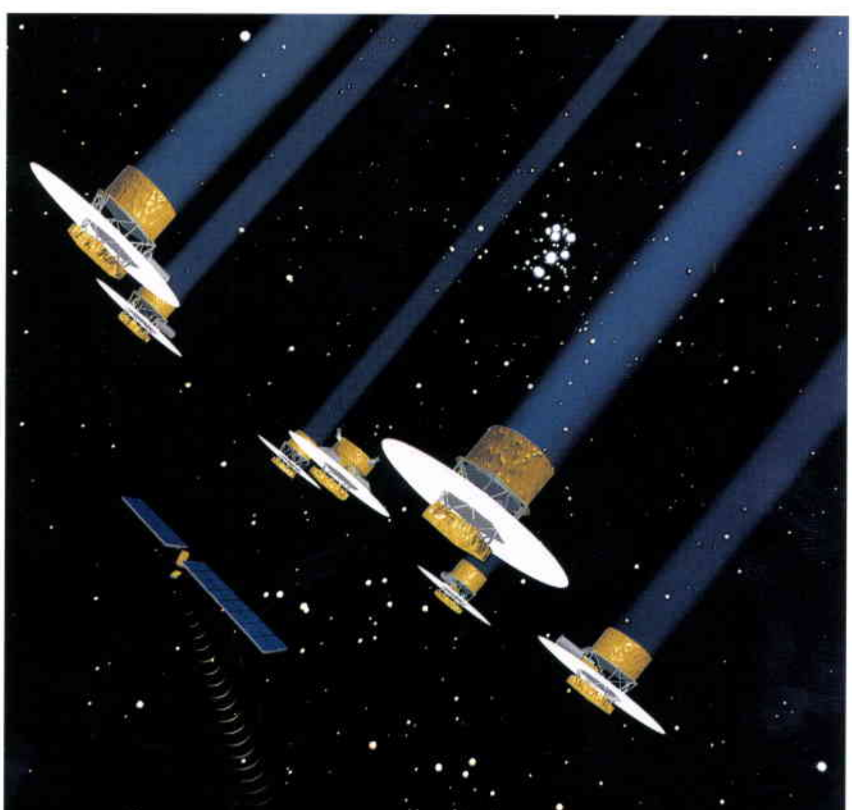


Figure 4. The Darwin multiple-spacecraft mission

Formation flying will be achieved by a combination of GPS techniques, high-precision laser metrology, and accurate low-thrust electric propulsion, keeping the optical path differences between spacecraft below 20 nm. On-axis star light will be cancelled by using suitable phase-shifting techniques, while planetary light collected by the different telescopes will have a phase difference proportional to the off-axis angle of the planet and will thus not be nulled.

DARWIN is scheduled for launch in the 2014 time frame.

More information about the mission and its scientific objectives can be found at:
http://sci.esa.int/home/darwin/index.cfm

Such a complex satellite configuration, combined with the demanding scientific requirements, has imposed the need to initiate an ambitious technology programme. Over the next three years breadboard developments will take place in several areas:
- Radio-frequency (RF) ranging and goniometry systems, together with laser metrology and an interferometric fringe tracker, are needed

to acquire and maintain the six-telescope constellation geometry and to point it precisely towards the selected target. The actual geometry of the constellation will have to be measured with linear and angular accuracies of a few nanometres and a few microarc-seconds, respectively.

- Field-Emission Electric Propulsion (FEEP) systems, with their ability to provide extremely low, accurate thrusts (10^{-6} Newton), will be developed to counteract the tiny forces disturbing the constellation geometry.
- Medium- and far-infrared detectors ($\lambda = 6$ – 25 micron) technology and related front-end electronics need significant development in order to provide the required low dark current and good quantum efficiency at temperatures compatible with standard passive cooling techniques.
- As an alternative solution, vibration-free, low-power (10 mW) coolers need to be developed for the focal-plane detectors.
- Optical components and assemblies mounted on the beam-combining satellite and including achromatic phase shifters for nulling interferometry; integrated optics for combining in single monolithic devices functions like beam-splitting, front-end filtering, beam combining; fibre-optics for wave-front filtering, operating in single mode over the infrared spectral range ($\lambda = 1$–20 micron); dichroic components; optical delay lines; and high-stability optical benches.

Although DARWIN is not due to be launched before 2014, substantial development and verification of key technological issues needs to be carried out via precursor experiments. For this reason, in collaboration with the European Southern Observatory (ESO), ESA will develop a nulling-interferometer breadboard, equipped with a suitable optical target simulator for its validation. The breadboard will be integrated into the Very Large Telescope Interferometer. This nulling-interferometer precursor will be operational in 2005 and will characterise the DARWIN targets with respect to exo-zodiacal light.

In parallel, the SMART-2 mission, to be launched in 2006, will provide in-orbit demonstrations of other key technological challenges.

More than twenty activities have been identified for the DARWIN Technology Programme, for an investment of some 12 MEuro.

The LISA mission

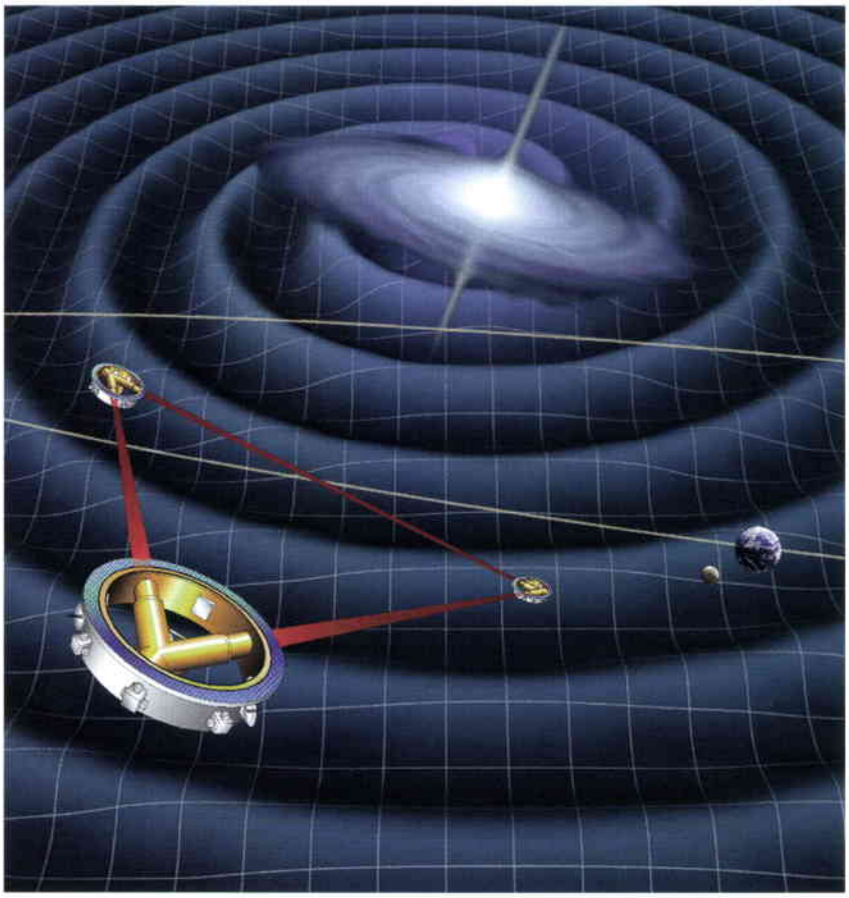
Predicted already at the beginning of last century by Einstein's Theory of General Relativity, gravitational waves have so far eluded actual detection. The Laser Interferometry Space Antenna, or LISA, is the first ESA Cornerstone mission in 'Fundamental Physics'. It has the daunting objective of detecting tiny changes in relative distance due to the passage of gravitational waves.

To do this, three spacecraft will be positioned at the vertices of an equilateral triangle, with sides about 5 million km long (Fig. 5). Each spacecraft will contain two 'proof-masses', which will be kept in a 'free-fall' environment shielded from all forces except gravity. The mutual position of each proof-mass with respect to its 'companion' in the other spacecraft 5 million km away is continuously measured by means of a sophisticated optical system. The configuration forms a giant Michelson-type interferometer with three arms, in which the proof masses are effectively adjustable elements. The passage of gravitational waves will move the proof-masses by a fraction of an Angstrom (10^{-10} m), changing the length of the optical path of one arm of the interferometer with respect to the others.

The LISA mission is planned as a joint venture with NASA, with a launch in 2010. More information about the mission and its scientific objectives can be found at:

http://sci.esa.int/home/lisa/index.cfm

Figure 5. LISA: Laser Interferometer Space Antenna



LISA's scientific objectives make it one of the most complex ESA Cornerstone missions. Like DARWIN, it requires both a considerable technology development plan and the verification of key technologies by means of a precursor mission, namely SMART-2. The technology needs stem mainly from the necessity to distinguish between relative displacements between the two proof masses induced by gravitational waves and those induced by spurious forces.

LISA is heavily reliant on the development of a series of technologies that include:

- Inertial acceleration sensors, based on capacitive displacement measurement of the proof masses with respect to the spacecraft, for which the spectral amplitude of the inertial acceleration should be measured and kept below $3x10^{-15}$ m sec^2 $Hz^{-1/2}$.
- A Field-Emission Electric Propulsion (FEEP) system capable of providing thrusting at micro-Newton levels (10^{-6} N). Such a system, commanded in a feedback loop by the inertial acceleration sensor, is baselined for the precise control and positioning, with nanometer accuracy, of the LISA spacecraft with respect to the proof masses. In this way, the masses can be kept isolated from spurious forces and in a 'free-fall' condition.
- Thrust-measurement instruments with $1x10^{-9}$ N accuracy for the characterisation of the above FEEP system.
- A high-power, high-stability Nd:YAG laser.
- Pointing systems for two separate lasers 5 million kilometres apart with nano-radian angular accuracy.
- Laser interferometry between the proof masses using heterodyne techniques and a slowly varying phase difference between the two laser beams. Critical elements in such a subsystem include high-sensitivity photo-diodes, ultra-stable oscillators, etc.

The complete LISA Technology Development Programme is made up by more than fifteen activities to be developed in the next four years, at a cost of 11 MEuro.

The SMART-2 mission

The Small Missions for Advanced Research in Technology are tasked with testing key technologies for future ESA Science Corner-stone missions. While SMART-1 has been conceived for demonstrating the feasibility of electric propulsion for deep-space propulsion, preparing the way for missions like BepiColombo, SMART-2 will pave the way for DARWIN and LISA.

As a mission involving two spacecraft flying in formation, SMART-2 will demonstrate LISA technology in three areas: inertial sensor performance, spacecraft position control, and laser interferometry between proof masses (Fig. 6). SMART-2 will also demonstrate DARWIN technology in terms of the formation-flying performance of two spacecraft capable of sustaining nulling interferometry. It is envisaged that coarse metrology (based on RF ranging and goniometry) and intermediate metrology (based on a laser metrology system), capable of positioning the spacecraft with micron accuracy, will be demonstrated, together with the related FEEP actuators and guidance, navigation and control system.

More information about the SMART-2 mission and its scientific objectives is available at:
http://sci.esa.int/home/smart-2/index.cfm

The XEUS mission

The X-ray Evolving Universe Spectroscopy (XEUS) mission will be the powerful successor

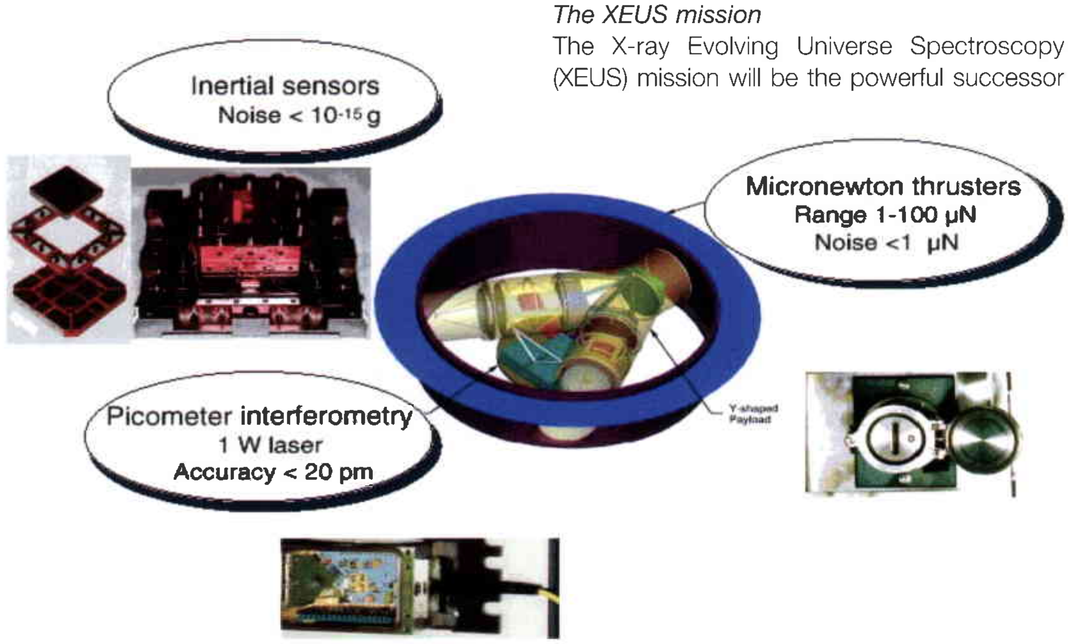


Figure 6. SMART-2 key technologies

Figure 7. XEUS: the X-ray Evolving Universe Spectroscopy mission

to the European and American X-ray observatories XMM-Newton and Chandra. The formation and evolution of the Universe is at the heart of the XEUS science case. Supermassive black holes, which emit most of their energy in the X-ray band, seem to have played an important role in the formation and present structure of our Universe. They can probably only be detected in the electromagnetic band in which XEUS operates because of their high contrasts with respect to other objects and their low absorption by the intergalactic medium.

XEUS is characterised by a large, free-flying, grazing-incidence mirror assembly of some 20–30 m^2 collecting area at 2 keV, with an angular resolution of about 2–5 arcsec and a spectroscopic resolution of about 2 eV. The X-rays collected by the mirror assembly are focussed 50 m or more away onto a separate free-flying detector assembly, equipped with novel semiconductors and superconductor detectors. Both assemblies will be flying in formation in a low Earth orbit (Fig. 7).

When completed, the XEUS facility will be some 250 times more sensitive than the XMM-Newton telescope. It will be constructed in stages, using the International Space Station (ISS) as a base. Launch of the first stage is planned around 2012. For more information about the mission and its scientific objectives, visit:
http://sci.esa.int/home/xeus/index.cfm.

The highest priority for the XEUS Technology Programme are the X-ray optics, based on open-surface Wolter-I mirror elements integrated into units called 'petals'. The mirror technology development has benefitted from the extensive investment already made by ESA in the X-ray optics for the XMM-Newton mission, allowing European industry to acquire a world-leading position in this field of technology.

However, further developments are required to meet the XEUS mirror requirements in terms of new mirror geometry and methods for their support, lower mass, higher spatial resolution (< 2 arcsec), and cost-effective production.

The potential instrument detectors include semiconductor wide-field imagers, narrow-field cryogenic superconductors and bolometric spectrometers, will also require substantial research and development. Proper cooling of the detector arrays to cryogenic temperatures (50 mK), with adiabatic demagnetisation techniques and the development of low-noise, large-bandwidth front-end electronics, based on a Superconducting Quantum Interference Device (SQUID), will also need to be developed.

At the spacecraft level, the major technology developments will focus on compatibility with the International Space Station (ISS) and the formation-flying of the two spacecraft, including the solar-electric-propulsion elements.

The complete XEUS Technology Development Programme is made up of thirteen activities to be developed over the next four years. The total investment plan corresponds to about 11 MEuro.

The preparation and harmonisation of the R&D programme

The Future Project Studies and Technology Office, in co-ordination with the other ESA Directorates, has set up a complete, coherent and realistic R&D Programme, following a three-step plan. The first step focussed on an assessment of the technology requirements for each future mission. During this phase, the study managers, together with the study scientists from ESA Space Science Department (SSD), critically reviewed and selected the technology activities proposed by the industrial contractors, who were responsible for the preliminary system designs for the different future missions. In a second phase, with the support of the Industrial Matters and Technology Programmes Directorate, the selected activities were harmonised by identifying overlaps and synergies with the other ESA Technology Programmes. The third step concentrated on the more detailed definition of the various technology activities. Together with the staff of the Technical and Operational Support Directorate, considerable effort was devoted to the clear identification of the objectives for each technology activity. In-depth definition of the technical requirements, detailed assessment of the duration of each activity and a critical review of allocated budgets were at the centre of this exercise.

The plan that has emerged for Science is thus an integrated element of the ESA-wide Technology Plan.

This co-ordinated effort has led to the establishment of a complete set of Technology Schedules for each future mission, and and of a detailed Technology Work Plan covering the 2000–2004 time frame. The latter was submitted to and unanimously approved by ESA's Industrial Policy Committee (IPC) in December 2000. Both the technology schedules and the Work Plan can be accessed via the ESA Science web site :

http://sci.esa.int

At the same time, the evolution in the procurement approach for the future missions foresees the selection of two Prime Contractors for each mission-definition phase. Both Primes will be closely associated, via ESA, to the development of the technology activities. They will support ESA in the analysis and assessment of their progress, and will inject relevant requirements and constraints stemming from mission-level design. This approach should lead to the development of the technology activities being fully in line with the assumptions at spacecraft system level, and if successfully developed, to their endorsement. Last but not least, it should allow the Primes provide a more reliable bidding price, because of their increased knowledge of, and confidence in, these key mission-enabling technologies.

Financial envelope

The ESA Science Technology Work Plan for the years 2000-2004 comprises more than 110 technology development activities, with a total budget of more than 80 MEuro. It builds upon activities identified and funded by the various ESA Technology Programmes, which can be summarised as follows:

- Activities carried forward from the previous plans, funded by the Technology Research Programme (TRP) and the General Support Technology Programme (GSTP) budgets.
- Activities currently identified in the 2000-2002 TRP plan.
- Activities identified and funded in the Science Core Technology Programme (CTP).
- Activities identified as 'mission preparatory'.

These technology activities, funded from different budgets, generally have different goals in term of technology maturity or readiness. The feasibility demonstrations and breadboarding are usually funded from the Technological Research Programme budget. The Science Core Technology budget will mainly be used to reach a higher technology maturity level (electrical model), while the Mission Preparatory Activities will address the adaptation of mature technologies to specific mission requirements.

The Work Plan is long-term oriented. Reviews and updates in support of newly approved scientific missions, potential candidates for future missions or specific projects' needs, are foreseen at periodic intervals. The objective is to ensure a constant level of resources to allow a consistent technology development effort in the years ahead. Although the current approach foresees linking technological research activities to specific missions, in order to provide a framework in terms of schedule and end-product, many technologies will have much wider ramifications and relevance. This is particularly true for technologies that will be developed within the framework of the LISA, DARWIN and XEUS missions.

Management tools

One of the key requirements when working on projects involving many organisations and individuals is the need for easy on-line access to and dissemination of accurate, up-to-date information. In this regard, a special Information System has been created for the Science R&D programme in order to gather and rapidly distribute all of the information related to the 113 activities, which involve more than 100 people in various ESA Directorates at ESTEC. This Information System includes:

- a Technology Development Activities Database
- a Technology Document Management System.

From an initial Microsoft Access application, the Development Activities Database has rapidly evolved into a web-based Oracle database, now known as the Science Technology Information System (STIS), which all of the parties involved can easily access. The system allows the user to browse through the information for each activity, ranging from the technology objectives to technical notes, reports and requirements documents, from costs to programmatic assumptions and schedules, from the list of people involved to its current status. It can be used both as an archive to find the details concerning specific activities, and as a reporting tool for system-level analysis and assessments.

The Technology Document Management System (DMS), developed within the ESA Scientific Programmes Department, complements the Database. Its main functions include:

- Registration: recording all information regarding a document, and maintaining version control.
- Archiving: safe and controlled storage of electronic document files.
- Search: location of documents through registration attributes.
- Retrieval: on-line availability of electronic document files.
- Distribution: electronic distribution of documents.
- External Collection: integration of documents sourced externally (files, e-mails, faxes).

Figure 8 shows the DMS screen layout with available search functions.

Present status, prospects and conclusions

Since December 2000, when the Science R&D Technology Plan was approved by the Industrial Policy Committee, the Future Projects and Technology Office has initiated an intense plan of action. In close co-ordination with Directorate of Technical and Operational Support, Space Science Department, and Directorate of Industrial Matters and Technology Programmes staff, considerable effort has been focussed on trying to speed-up the preparation, review and final issue of the technical and contractual documentation needed for the timely award of the industrial contracts.

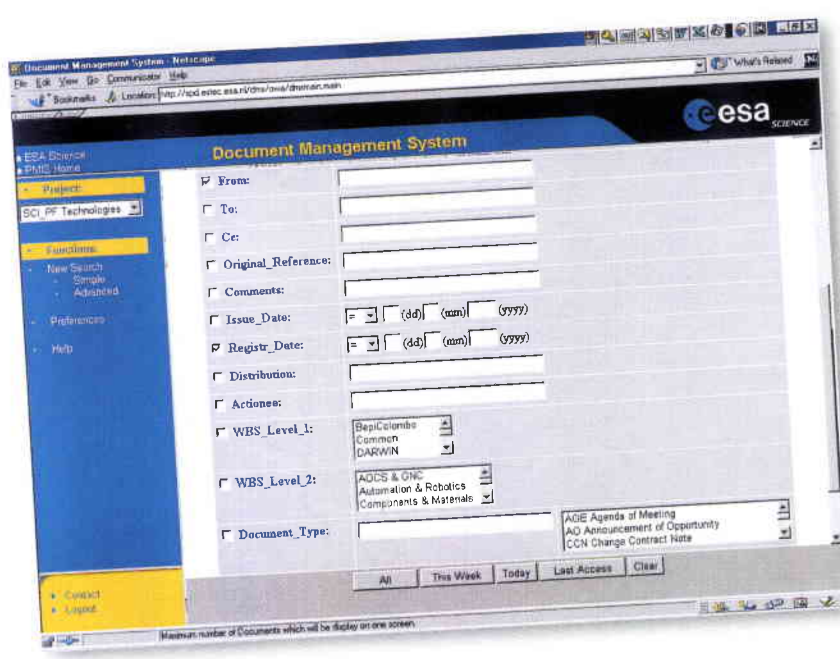
In the meantime, the System Definition Phase for BepiColombo has started in May 2001, with the two Primes already engaged in the assessment of the technology activities. The System Definition Phase for SMART-2 has just started, in September.

It is still premature to judge, on the basis of the present results, whether the Science R&D Programme will achieve the overall objectives outlined at the beginning of this article. However, the results obtained so far allow us to maintain a confident outlook for the successful implementation of this huge and challenging programme.

Acknowledgements

The Future Projects and Technology Office wishes to acknowledge the substantial efforts of the many colleagues in ESTEC, working in D/TOS, D/IMT and SSD, who have contributed greatly to the creation of this Technology Programme and hopefully to its successful implementation.

Figure 8. The Technology Document Management System (DMS)



Solar Sailing – Mission Opportunities and Innovative Technology Demonstration

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Solar sailing is a unique and elegant form of propulsion that transcends reliance on reaction mass. Rather than carrying propellant, solar sails acquire momentum from photons, the quantum packets of energy from which sunlight is composed. In addition, since solar sails are not limited by reaction mass, they can provide continual acceleration, limited only by the lifetime of the sail film in the space environment. Therefore, solar sails can expand the envelope of possible missions, enabling new high-energy mission concepts that are essentially impossible with conventional reaction propulsion, and enhancing current mission concepts by lowering launch mass and reducing trip times.

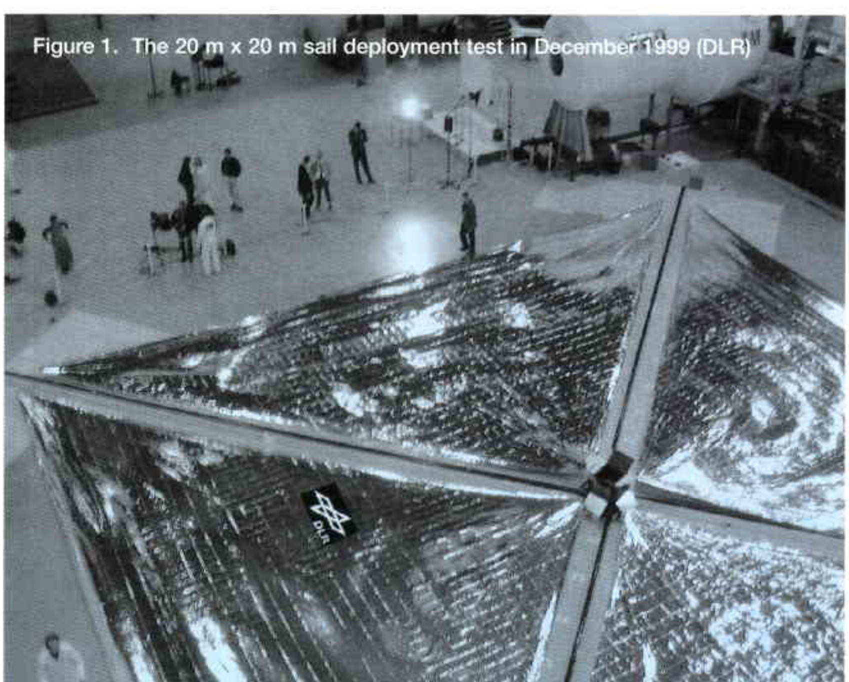
Figure 1. The 20 m x 20 m sail deployment test in December 1999 (DLR)

Introduction

Solar-sail technology was developed to some extent by NASA/JPL during the mid-1970s for a proposed rendezvous mission with Comet Halley. Although not attaining flight-readiness, the study sparked international interest in solar sailing for future mission applications. More recently, due to advances in payload miniaturisation and a recognition of the need for high-energy propulsion for demanding future missions, NASA is again aggressively pursuing the development of solar-sail technologies. A strong interest in solar sailing is also emerging in Europe, supported by a successful joint ESA-DLR ground deployment test of a 20 m x 20 m solar sail (Fig. 1) and a series of ESA-funded mission studies at the University of Glasgow (UK).

Since the momentum transported by an individual photon is extremely small, solar sails require a large surface area in order to intercept a large flux of photons. Furthermore, to generate as high an acceleration as possible from the momentum transported by these intercepted photons, solar sails must also be extremely light. For a future solar sail, the mass per unit area of the entire spacecraft, the so-called sail loading, may be of order 20–30 g/m^2. In addition to the sail loading, the sail assembly loading is a key measure of technology. This parameter is defined as the ratio between the mass of the sail structure plus reflective film (excluding the payload and bus), and the sail area. A goal for mid-term solar sails for large planetary or space-physics missions would be an assembly loading of order 10 g/m^2, although near-term missions would be less demanding.

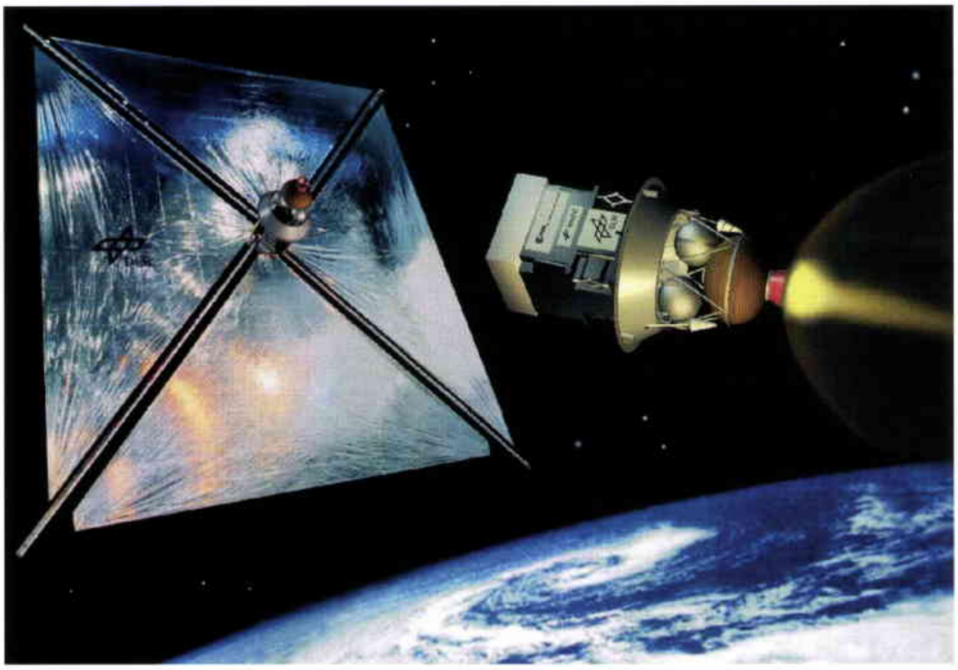

Figure 2. Solar-sail in-orbit deployment demonstration

Not only must solar sails have a small mass per unit area, they must also be near-perfect reflectors. Then, the momentum transferred to the sail can be almost double the momentum transported by the incident photons. By adding the forces due to incident and reflected photons, the total force exerted on the sail is directed almost normal to its surface. By controlling the orientation of the sail relative to the Sun-line, the sail can gain or loose orbital angular momentum. In this way the solar sail is able to spiral outwards or indeed inwards along the Sun-line. Achieving a useful characteristic acceleration (acceleration at 1 AU) of order 0.1 – 1 mm/s^2 from solar radiation pressure poses great engineering challenges in terms of innovative technology demonstration of low-mass deployable structures, thin-film sails, and also importantly payload miniatur-0isation.

Innovative technology demonstration: the project challenge

While the major technology challenge of entering the field of solar sailing is to build extremely light, large-area deployable structures and to combine them with micro-spacecraft for carrying out science exploration missions throughout our Solar System and beyond, the programmatic challenge is to cleverly subdivide the big leap in technology needed into technically and programmatically manageable project steps. Mass-efficient space hardware of many kinds is well known, but a vehicle with a mass per area ratio of only a fraction of that of writing paper is something unusual and a new challenge in itself, and one beyond the usual approach taken in spacecraft engineering.

In order to carry out a first and vital European flight-hardware step in the direction of developing solar sails, ESA's Industrial Policy Committee (IPC) at its March 2001 meeting approved a procurement proposal to develop and launch a solar-sail in-orbit deployment demonstrator. This deployment demonstrator, as the first step in solar-sailing validation, is concentrating on the successful functioning of sail deployment, which is compromised on the ground by the 1g environment and where in-orbit anomalies have been experienced with a number of large deployable structures.

The demonstrator has booms sized for the deployment of a 40 m x 40 m sail, but considering the low-cost approach adopted for this demonstration mission, the deployed sails will be only 20 m x 20 m. The design of the deployment module and the envisaged material for the 40 m x 40 m sail target an overall assembly loading in the order of 35 g/m^2. Further reductions appear feasible in view of the advanced sail films under study in the USA. In its stowed launch configuration, the demonstrator will be only 60 x 60 x 80 cm^3. Within this box envelope there is room to accommodate a future miniaturised spacecraft also. Four coiled booms, each about 14 m long, and four triangularly shaped sails will be deployed consecutively and form a 20 m x 20 m flat square sail.

The profile and scope of the mission are fully geared to the demonstration of the in-orbit deployment (Fig. 2). All elements of this technology project, including mission definition, hardware and software development and manufacturing, launch and in-orbit operations will be focused towards this single goal. Given the limited budgetary resources available, the project's implementation from the ground demonstration model to the flight hardware will be challenging. A successful solar-sail deployment demonstration will imply that important challenges associated with designing, building and operating a large, complex, multifunctional lightweight mechanism and the associated sails have been achieved. Mastering this first important technological step in European solar sailing will therefore establish the required confidence in solar sailing as a viable technology for the promising mission scenarios described below.

Potential applications for science missions

When we examine the potential benefits that solar-sailing technology may provide for future science missions, several promising future mission scenarios for the exploration of our Solar System and beyond can already be identified.

A mission to study the Earth's magnetosphere – Geosail

While some planetary exploration missions will require rather large solar sails, a number of science missions closer to home have been identified that require only modest sail areas. This incremental approach therefore builds on the sail deployment demonstration mission described above and allows the technology to develop in a mission-focussed manner. The Geosail example is therefore described here not only as a demonstration of solar-sail technology beyond that of simple in-orbit deployment, but also of the ability of such sailing techniques to enable totally new science mission concepts to be undertaken.

Conventional geomagnetic-tail missions require a spacecraft to be injected into a long elliptical orbit to explore the length of the geomagnetic tail. However, since the orbit is inertially fixed, and the geomagnetic tail points along the Sun–Earth line, the apse line of the orbit is precisely aligned with the geomagnetic tail only once per year. Approximately 4 months of data can be acquired when the spacecraft is in the vicinity of the tail, but only about 1 month of accurate data when on the tail axis itself. Artificially precessing the apse line of the elliptical orbit to keep the spacecraft in the geomagnetic tail during the entire year would simply be prohibitively demanding using chemical propulsion. In a scientifically meaningful elliptical orbit of 10 x 30 Earth radii, for example, a Δv of order 3.2 km/s per year of operation would be required for apse-line rotation.

Although the total Δv for apse-line rotation is large, only a small acceleration continuously directed along the apse line is needed in principle to achieve the necessary orbit change. Calculations and simulations have shown that a continuous acceleration of only 0.14 mm/s^2 is required for such an orbit. Since the precession rate of the orbit's apse line is chosen to match that of the Sun-line, the sail normal can be directed along the latter. This has significant operational advantages, since such a Sun-facing attitude can be achieved passively. The evolution of the mission orbit over 50 days is shown in Figure 3.

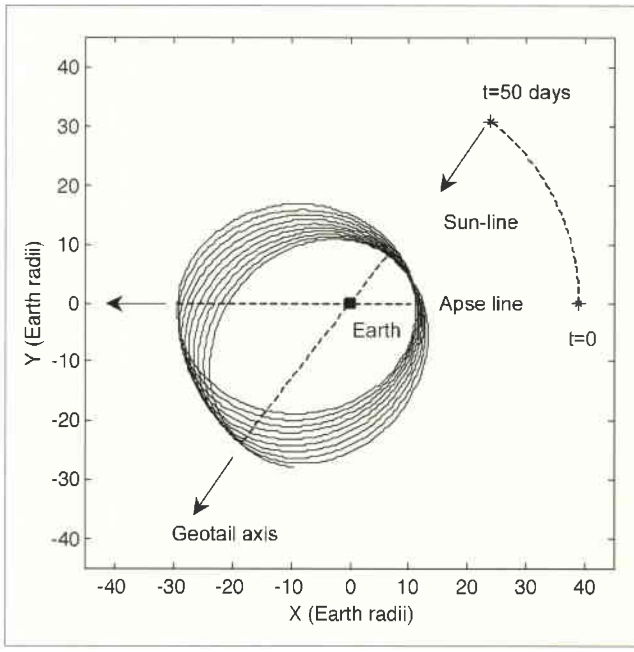

Figure 3. A 10 x 30 Earth radii orbit rotating with the Sun–Earth line

Table 1. Mass budgets for the Geosail mission

SAIL	(kg)
Booms (100 g/m)	11
Sail film (7.5 µm)	15
Coatings (Al + Cr)	0.5
Bonding	2.5
Mechanisms	20
SAIL TOTAL	49
PAYLOAD	
Instruments	5
Bus	25
Adapter	1
PAYLOAD TOTAL	31
LAUNCH MASS	80

Having established the acceleration requirements, it is now possible to size the sail. First we have assumed a micro-satellite of about 30 kg mass for the bus and payload, which could be appropriate for a low-mass space-physics payload with a magnetometer and plasma instruments. The instrument mass is assumed to be of order 5 kg with a 26 kg spacecraft bus (i.e. the instruments are about 20% of the spacecraft dry mass; cf. Table 1). This is far less than the mass of a single ESA Cluster spacecraft, which is around 1200 kg: 72 kg payload, 480 kg spacecraft bus and 650 kg propellant necessary to reach and then modify the orbit during the mission. Thus, in the case of Cluster, the payload-to-spacecraft mass ratio is similar to that of the micro-satellite. One can, however, now identify the necessary parallel development of low-mass technology solutions at spacecraft and instrument level. With this caveat in mind, we have sized the sail at 38 m x 38 m so as to generate a characteristic acceleration of 0.14 mm/s^2. This is therefore a modest evolution over the 20 m x 20 m demonstration sail. The booms are assumed to be of CFRP with a specific mass of 100 g/m, while the sail film is assumed to be commercially available 7.5 micron thick kapton, vapour-coated with aluminium on one side and chromium on the other for thermal control. The total launch mass is about 80 kg, which also falls within the mass budget of an Ariane-5 ASAP auxiliary payload.

The spacecraft can be delivered to the 10 x 30 Earth radii orbit by simply using the solar sail itself to spiral from geostationary transfer orbit (GTO). For a standard Ariane-5 midnight launch, the apse line of the orbit is directed sunward, opposite to the geomagnetic tail. A six-month (or 18-month) orbit-raising phase is therefore required while the solar sail manoeuvres to the required operational orbit, and the apse line aligns with the geomagnetic tail. During this time, the orbit plane must also be rotated so that the final orbit lies in the ecliptic plane. Long-term orbital integration studies of the solar sail in a 10 x 30 Earth radii orbit, which includes a geopotential model as well as the lunar-solar gravitational perturbations, has demonstrated the validity of precessing the operational orbit.

Alternative launch scenarios can be considered which, after its delivery into GTO, would inject the sail and spacecraft-bus package directly into the operational 10 x 30 Earth radii orbit using a dedicated launcher or a piggy-back launch with a chemical kick-stage. With this scenario, if the sail deployment were to fail, the spacecraft bus could be separated to perform a conventional, albeit scientifically degraded geomagnetic-tail mission without apse-line precession, although the launch costs would of course be increased. The risk of using solar-sail technology on such a first science mission would, however, be significantly reduced.

The above mission concept is extremely attractive since it provides a scientifically useful application for a solar-sail technology-demonstration mission.

A mission to study a planet in our Solar System – Mercury-Sail

BepiColombo is an ambitious ESA Cornerstone science mission to explore Mercury comprehensively using a diverse array of instruments. It requires solar-electric propulsion, chemical propulsion and multiple gravity assists to deliver a large payload with a single Ariane-5 launch. The payload consists of a 360 kg planetary orbiter, a 165 kg magnetospheric orbiter and a 44 kg hard lander. The three-axis-stabilised orbiter will perform global imaging of the planetary surface using visible and infrared cameras, while a range of spectrometers will determine surface composition. These remote mapping functions will be complimented by a radio-science payload. The smaller spin-stabilised magnetospheric orbiter will investigate the interaction of Mercury's magnetic field with the solar wind from a long 400 km x 12 000 km elliptical orbit using a three-axis magnetometer and a range of plasma instruments. Finally, the hard lander will deliver a small rover plus imager and science package to explore the physical properties of the planetary surface.

The mission profile required to deliver such a large payload centres on the use of solar-electric propulsion (SEP) and multiple gravity assists to reach Mercury, while orbit capture is performed using a chemical bi-propellant stage. Launch opportunities occur every 1.6 years with a 2.2–2.6 year trip time for the SEP option with a Venus swingby, depending on the particular launch window selected. The total launch mass is some 2500–2800 kg, which could be delivered with a hyperbolic excess speed of order 3 km/s by an Ariane-5 launcher, or with two Soyuz-Fregat launchers, which would launch the MPO (1255 kg) and MMO+MSE (1265 kg) separately.

We can use this BepiColombo mission as a reference to assess the potential benefits of solar sails for future planetary exploration missions. It has therefore been reconfigured for delivery by solar-sail propulsion alone. To allow for a realistic comparison, the solar-sail solution must provide a comparable trip time to the baseline SEP mission without lunar swingby, i.e. 2.5 years. It was found that a characteristic acceleration of 0.25 mm/s^2 is adequate for the Mercury orbiter mission, but a figure of 0.3 mm/s^2 has been selected to provide some margin. A typical 2.4 year trajectory to Mercury is shown in Figure 4. The trajectory begins with a launch energy C_3=0 and therefore does not require any hyperbolic excess to be delivered by the launch vehicle. In addition, the launch window for such a solar sail mission is in principle unconstrained because gravity assists are not required.

Assuming the chosen acceleration of 0.3 mm/s^2 and a total spacecraft mass (bus + payload) of 590 kg (planetary orbiter, magnetospheric

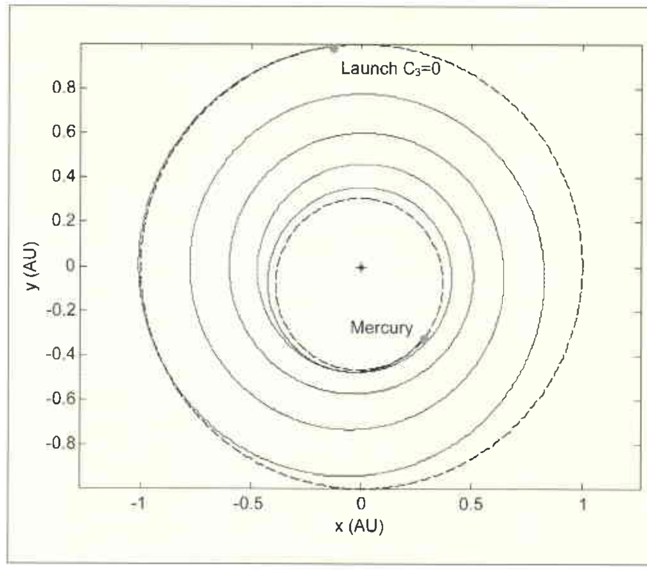

Figure 4. A 2.38 year trajectory to Mercury , with a characteristic acceleration of 0.3 mm/s²

orbiter and lander), the sail size needed and the mission launch mass can be determined. First, the sail assembly loading, which is a function of the level of solar-sail technology available, must be established. A representative value for mid-term missions is likely to be of order 10 g/m². To achieve this, a sail substrate thinner than the commercially available 7.5 micron kapton proposed for the initial demonstration missions is required. A 3 micron substrate, similar to that fabricated by NASA/JPL for a range of near- and mid-term solar-sail applications, will therefore be assumed, with a front aluminium and rear chromium coating and a 10% mass penalty for bonding the sail segments. In addition, CFRP booms with a specific mass of 150 g/m (some 50% heavier than those used for the ESA–DLR ground deployment test) have been assumed. For such large sails, film mass is dominant and the sizing is relatively insensitive to boom properties in that any increase in boom mass can be accommodated via a modest reduction in sail-film thickness. The overall mass of the sail assembly, comprising the coated sail film, the deployable booms and the associated mechanisms turns out to be around 319 kg.

A mass-breakdown comparison for the solar-sail and SEP powered BepiColombo missions is shown in Table 2. The solar-sail option offers significant advantages in that the total mission launch mass is reduced to 872 kg, below the C_3=0 capacity of a Soyuz/Fregat launcher and the mission payload mass fraction is significantly improved, from 0.24 to 0.63.

Table 2. Mass budgets for the Mercury-Sail and Mercury-SEP missions

SAIL	(kg)	SEP	(kg)
Booms (150 g/m)	76	Ion stage	675
Sail film (3 μm)	136	Chemical stage	140
Coatings (Al + Cr)	12	Xenon fuel	433
Bonding	19	Bi-propellant fuel	332
Mechanisms	76	Margin	139
SAIL TOTAL	319	SEP TOTAL	1719
PAYLOAD		PAYLOAD	
Planetary orbiter	463	Planetary orbiter	463
Magnetospheric satellite	59	Magnetospheric satellite	59
Lander	31	Lander	31
PAYLOAD TOTAL	553	PAYLOAD TOTAL	553
LAUNCH MASS (C_3=0)	872	LAUNCH MASS (C_3>0)	2272

While this example really highlights the benefits of the solar-sail approach for such deep-space scientific exploration missions, the extended and flexible mission scenarios that it allows can provide additional scientific return. For example, in the case of the Mercury mission it would allow several additional follow-on 'end-of-life' applications. If, for instance, the mission profile were modified such that the planetary orbiter and lander are jettisoned at Mercury, but the magnetospheric orbiter remains attached to the sail, the magnetospheric orbiter can subsequently be used for other secondary exploration missions. After the planetary orbiter and lander are jettisoned, the characteristic acceleration of the solar sail increases significantly to 0.69 mm/s².

From the Mercury magnetospheric orbit, the solar sail and magnetospheric orbiter could spiral in to a close orbit around the Sun and use the onboard suite of field and particle instruments to investigate the plasma environment near the solar co-rotation region. This co-rotation region occurs at an orbital radius of 0.172 AU, where the circular orbit period of 26 days is equal to the solar equatorial rotation period. With the increased solar-sail characteristic acceleration, the trip time to a 0.2 AU circular orbit would be only 80 days. Clearly, the sail would experience significant thermal loads, but such end-of-life mission applications, attempted only after the primary mission is complete, add little risk and are clearly highly cost-effective. A dual mission, in which delivery of a Mercury orbiter and a close solar orbiter are part of the primary mission, would clearly have an impact on the engineering of the sail and payload. One can even consider other secondary mission scenarios in which the spacecraft in its circular 0.2 AU orbit initiates a new manoeuvre. Essentially the sail can crank up its orbital inclination to a solar polar orbit in a further 290 days.

Finally, an alternative end-of-life mission application is to spiral from Mercury and return to Earth orbit in only 1.2 years to demonstrate the round-trip capabilities of solar sailing for future sample-return missions.

A mission to study the Sun's inner heliosphere – Solo-Sail

The Solar Orbiter mission Solo is a ESA F-class (flexible) mission to view the Sun from a close solar orbit (0.2 AU) and from out of the ecliptic plane. To reach a high-energy orbit in order to meet these demanding mission objectives, a combination of solar-electric propulsion and multiple gravity assists is required. The mission requires a single Soyuz-Fregat launch to an Earth-escape trajectory with a hyperbolic excess of 2.4 km/s. The spacecraft then uses SEP to reduce its orbit's semi-major axis and target multiple Venus gravity assists to decrease the perihelion radius and increase the orbital inclination. A total flight time of 1.9 years is required to reach an initial elliptical science orbit, with a perihelion radius of 0.21 AU and an aphelion radius of 0.89 AU. Thereafter, additional gravity assists are used to crank the orbital inclination to 30 deg after an additional 2.9 years, and possibly to 38 deg for an extended mission requiring a further 2.3 years of flight time. The spacecraft will deliver an X-ray and EUV imager, along with a range of field and particle instruments, for a total mission launch mass of 1510 kg. Approximately 634 kg of this can be attributed to the spacecraft bus and science payload.

Again as an example of the advantages of solar sailing for future missions, we consider the Solar Orbiter mission profile in the context of using solar-sail propulsion to transport a payload to a close circular orbit, deep within the Sun's gravity well. This is a mission that is essentially impossible with chemical propulsion and would involve an extremely large launch mass with a solar-electric propulsion system. The ideal mission orbit is at a heliocentric distance of 0.172 AU, where the local circular orbit period is 26 days, synchronous with solar equatorial rotation. The primary science goals of this sailing mission are the same as those of the current Solar Orbiter mission to ensure a reasonable comparison. In the case of the solar-sailing mission, the closer circular orbit provides a better vantage point than the elliptical baseline orbit. In particular, the unique 26-day solar synchronous orbit allows continuous observations of particle acceleration above active regions. Although the primary science goals are achieved once on station in the 26-day orbit, useful cruise science can begin from the start of the mission during the inward spiralling phase.

The proposed sailing mission concept assumes that the stowed solar sail is delivered by the launch vehicle to an Earth-escape trajectory and spirals inwards to the mission orbit using an optimal, minimum-time trajectory. To provide a reasonable transfer time to the initial mission orbit, a sail characteristic acceleration of 0.25 mm/s^2 is selected. This provides a 3.1 year transfer to 0.172 AU, as shown in Figure 5. From this initial orbit, the solar sail can rapidly crank the orbital inclination to a solar-polar orbit after an additional 1.7 years, as shown in Figure 6.

In the initial 26-day orbit, the equilibrium sail temperature is in the order of 300°C, assuming a chromium rear coating, which is close to the operating limits of most polyimide films. Therefore, high-emissivity coatings are required to provide adequate thermal control for the sail.

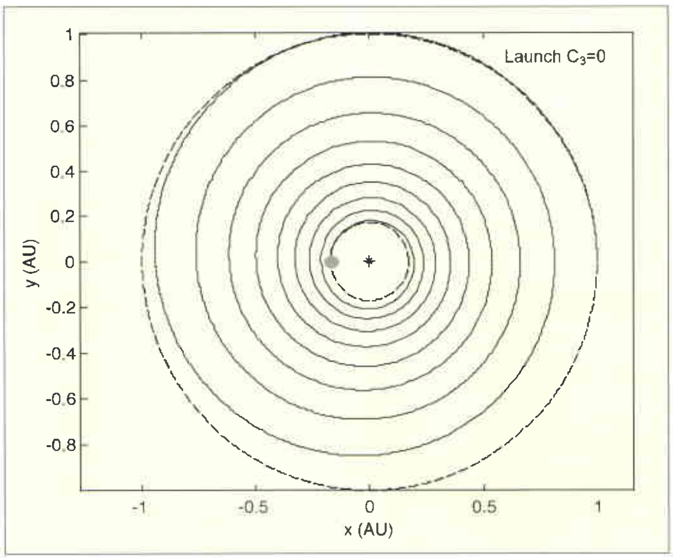

Figure 5. A 3.12 year trajectory to 0.172 AU, with a characteristic acceleration of 0.25 mm/s^2

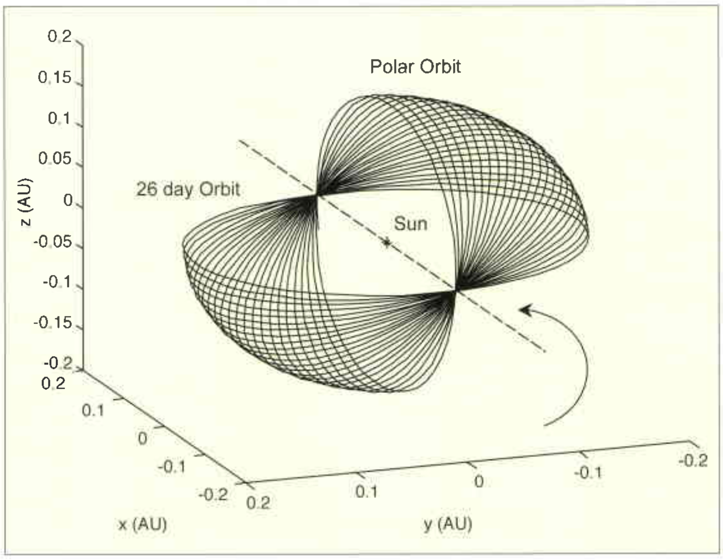

Figure 6. A 1.7 year cranking to solar polar orbit

The thermal loads on the payload are also extreme, although the sail may be utilised as a sunshade. They can be reduced by increasing the initial orbit radius from 0.172 AU, at the expense of maintaining strict Sun-synchronous orbital conditions. For illustrative purposes, however, we maintain a 26-day orbit.

The baseline 634 kg spacecraft bus and payload are used for sizing the solar sail, with only an appropriate mass reduction to eliminate SEP-specific components. Again, a sail-assembly loading of 10 g/m^2 is assumed. Since the required characteristic acceleration is now only 0.25 mm/s^2, a 167 m x 167 m solar sail is required, with a total launch mass of 911 kg. Table 3 compares the mass breakdowns for the solar-sail mission and the current mission using SEP. It can be seen that the solar-sail approach offers a launch-mass reduction of over 300 kg, allowing a significant increase in payload mass. Again, the launch mass is to a C_3=0 trajectory with an unconstrained launch window due to the absence of gravity-assist manoeuvres. More importantly, the use of a solar sail leads to a significant increase in the quality of the science from the mission by achieving a true solar-polar orbit, and offering the opportunity to reach the solar co-rotation region. As solar sail-technology develops, therefore, future solar missions could benefit significantly from this approach.

A mission to study the Earth – Polar Observer

Geostationary orbit provides a convenient location for communications satellites, providing a fixed line-of-sight from the satellite to ground terminals. Being located high above a fixed point on the equator, geostationary orbit is also an ideal vantage point for Earth observation, providing coverage of large geographical regions. While the advantages of geostationary orbit for communications and Earth observation are clear, there are operational limitations. Due to their location over the equator, geostationary satellites do not have a good vantage point from which to view high-latitude regions. Imaging of the latter is degraded by foreshortening, while the poles are entirely excluded from view. Likewise, communications satellites are extremely difficult to view for users at high latitudes due to their close proximity to the horizon, and indeed are below the horizon for latitudes above about 81 deg.

It can be shown that solar sails may be used to generate families of artificial equilibrium solutions (Lagrange points) in the Sun–Earth three-body system. Artificial out-of-plane equilibria may be used for continual, low-resolution imaging of the Earth's high-latitude regions. In fact, if the artificial Lagrangian point is located high enough above the ecliptic plane, the solar sail may be stationed directly over the north pole, or indeed the south pole, during the summer solstice. The solar sail can be stationed directly over the north pole at the summer solstice, as shown in Figure 7, but will not remain over the pole during the entire year due to the tilt of the polar axis. From this unique vantage point, a constant daylight view of the north pole is available at the summer solstice, but six months later at the winter solstice the polar regions are in permanent darkness (Fig. 8).

The solar-sail performance needed can be minimised by appropriate selection of the polar altitude. It can be shown that an equilibrium location some 3.8 million km (~600 Earth radii) above the North Pole will minimise the demands on the solar sail's performance. Closer equilibrium locations are possible using larger or higher performance solar sails, or by selecting a less demanding viewing geometry. While this is clearly a long path length, a number of applications can be identified.

In this example, we have assumed that a 100 kg bus and instrument payload will be necessary to support a 35 kg optical imager with 65 kg of associated subsystems in the proposed orbit. To station the payload at this unique polar viewing point requires an 139 m x 139 m square solar sail, with a total launch mass of 299 kg, assuming a sail-assembly loading of 10 g/m^2 (Table 4). The booms are again assumed to be made of CFRP with a specific mass of 100 g/m, and the sail is assumed to be

Table 3. Mass budgets for the Solo-Sail and Solo-SEP missions

SAIL	(kg)	SEP	(kg)
Booms (150 g/m)	71	Thrusters	25
Sail film (3 µm)	119	PPU	27
Coatings (Al + Cr)	10	Tanks	34
Bonding	17	Cruise power	155
Mechanisms	61	Xenon fuel	299
SAIL TOTAL	278	SEP TOTAL	540
PAYLOAD		PAYLOAD	
Instruments	145	Instruments	145
Structure	131	Structure	131
Orbiter power	64	Orbiter power	64
Common systems	182	Common systems	182
Mechanisms	46	Mechanisms	67
Harness	10	Harness	34
Pyros	6	Pyros	10
Adapter	50	Adapter	50
PAYLOAD TOTAL	634	PAYLOAD TOTAL	683
LAUNCH MASS (C_3=0)	912	LAUNCH MASS (C_3>0)	1223

NASA/JPL-developed 3-micron aluminised film. The total launch mass is suitable for delivery to a C_3=0 escape trajectory from a range of small launchers. The sail is used to spiral from the escape trajectory to the artificial equilibrium point high over the Pole.

Although the solar sail's distance from the Earth is large for imaging purposes, there are potential applications for real-time, low-resolution imaging for continuous viewing of large-scale polar weather systems, along with Arctic ice and cloud coverage, for global climate studies. Although such images can be acquired by assembling a mosaic of instrument swaths from a conventional polar-orbiting satellite, many high-latitude passes are required to form a complete image. High resolution is then possible, but the completed image is not acquired in real time. Similar applications for real-time, low-resolution whole-Earth imaging are being developed for the NASA Triana mission located at the classical L1 Lagrangian point, sunward of the Earth.

For a 30 cm-aperture instrument stationed 3.8 million km from the Earth and operating at optical wavelengths, a minimum ground resolution of order 10 km is possible, assuming near-diffraction-limited optics. In practice though, the actual resolution obtained will be degraded due to such factors as the pointing stability of the camera. Higher resolution is possible if an equilibrium location closer to the pole is selected, at the expense of increased demands on the solar sail's performance. Other applications of these orbits include line-of-sight, low-bandwidth communications to high-latitude users. Applications for continuous data links to Mars polar landers and surface rovers have also been explored for a solar sail stationed high above the poles of Mars.

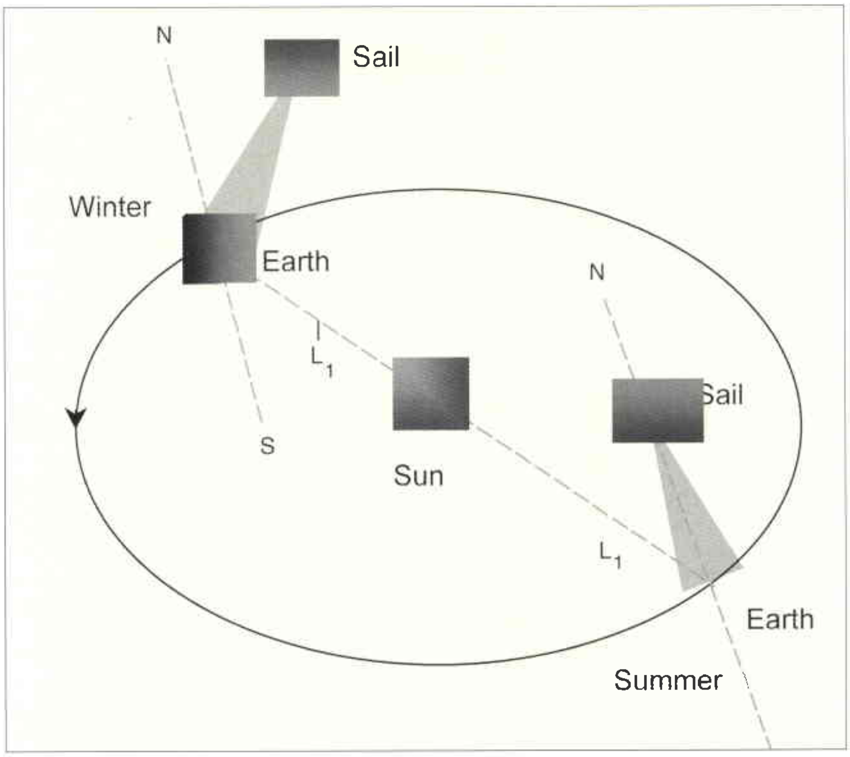

Figure 7. The Polar Observer mission concept

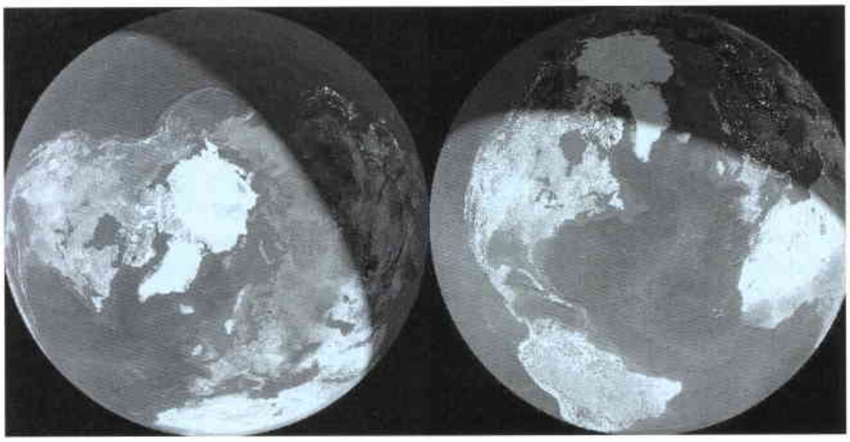

Figure 8. Summer and Winter Solstice views

Table 4. Mass budgets for the Polar Observer mission

SAIL	(kg)
Booms (100 g/m)	39
Sail film (3 μm)	84
Coatings (Al + Cr)	7
Bonding	9
Mechanisms	55
SAIL TOTAL	194
PAYLOAD	
Instruments	35
Bus	65
Adapter	5
PAYLOAD TOTAL	105
LAUNCH MASS	299

Conclusions

By assessing the mission scenarios of a range of future space missions, very promising opportunities for potential mission applications for solar-sailing propulsion have been identified. This low-cost delivery system with basically unlimited Δv capability holds promise for significantly enhancing or even enabling space-exploration missions in the new millennium. Clearly, the readiness of the solar-sailing technology for implementation in an actual space mission will require the technological demonstration of in-orbit deployment, orbit raising and navigation of a solar sailcraft. The first essential step will be achieved through the in-orbit deployment demonstration project now in progress.

A New Propulsion Concept for Interplanetary Missions

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When tons of payload must be brought back from the planets to Earth, the current launch-system technology hits size limitations. The huge Saturn-V launcher that enabled the Apollo missions to go to the Moon would be dwarfed by a single launcher capable of sending men to a destination like Mars and bringing them back. Keeping interplanetary missions within a reasonable size and cost therefore requires technological progress in terms of both vehicle weight reduction and propulsion efficiency.

Introduction

Today's propulsion-technology know-how makes it possible to explore the celestial bodies of our Solar System with automatic probes. However, the design of the propulsion system becomes more critical when the mission includes the return of even a few kilogrammes of rock from other planets, because the total velocity increment required is so much higher. The sample-return capsule must be accelerated from Earth to escape velocity, decelerated upon arrival according to a trajectory suitable for a soft planetary landing, re-accelerated from the planet to escape velocity, and finally decelerated again to reenter the Earth's atmosphere. The high total velocity increment required strains the propulsion design, but remains feasible with classical means, albeit at the expense of long mission durations. It is still envisaged, for example, that Martian soil samples will be returned to Earth around 2013 using chemical propulsion.

Today's known categories of propulsion are shown in Figure 1. Classical chemical propulsion yields good acceleration capabilities, but its development is now asymptotically reaching the theoretical performance limits. New propulsion principles must therefore be harnessed.

As Figure 1 shows, electric propulsion can be interesting when the level of thrust required is low. It therefore finds application for satellite station-keeping, or orbital propulsion of automatic probes such as Smart-1. For manned interplanetary missions, however, the total trip time must be minimised. Current plans for a total duration of 3 years for a mission to Mars should not be exceeded, and should

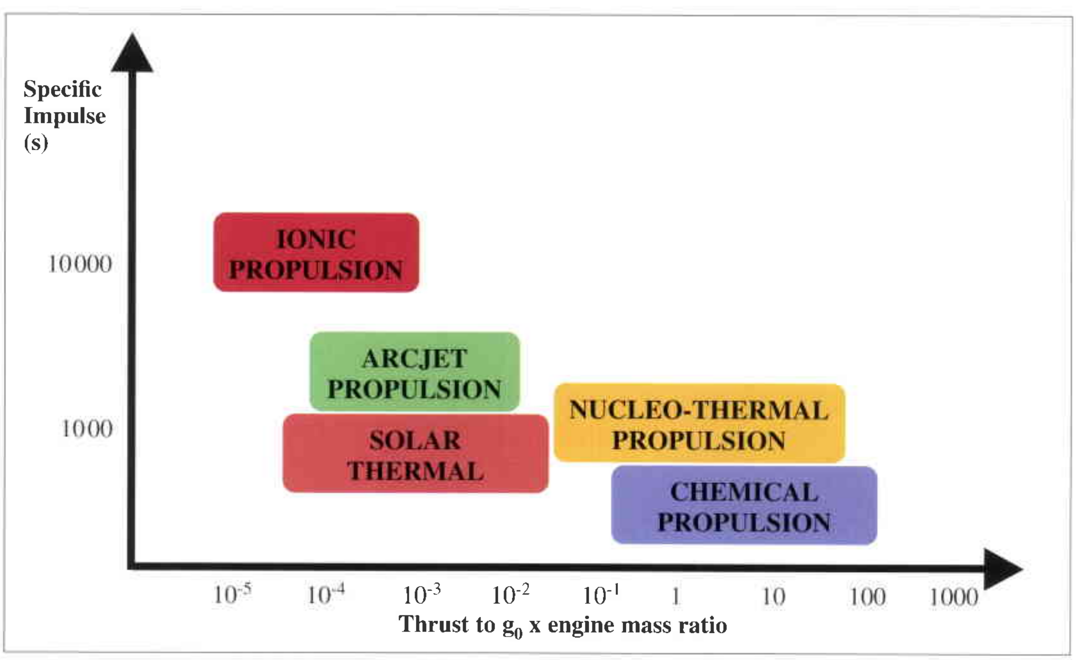

Figure 1. Performances of various types of rocket engines as a function of their thrust-to-mass ratios

preferably be reduced, owing to the psychological stresses on the crew and to the effects of cosmic radiation during interplanetary travel. Therefore, both a high thrust and a high specific impulse are required for manned interplanetary travel, and this high performance cannot be achieved at the cost of reliability and therefore safety.

Nuclear propulsion, which was studied in the USA and the Soviet Union in the sixties, yields a high level of performance, but its reliability has not yet been proved to be satisfactory. The development of nuclear propulsion was stopped at an already advanced stage, partly because the on-ground testing could not be continued under environmentally acceptable conditions. The core degradation during some tests showed that with the current technology the engine's lifetime was insufficient when operating at maximum performance.

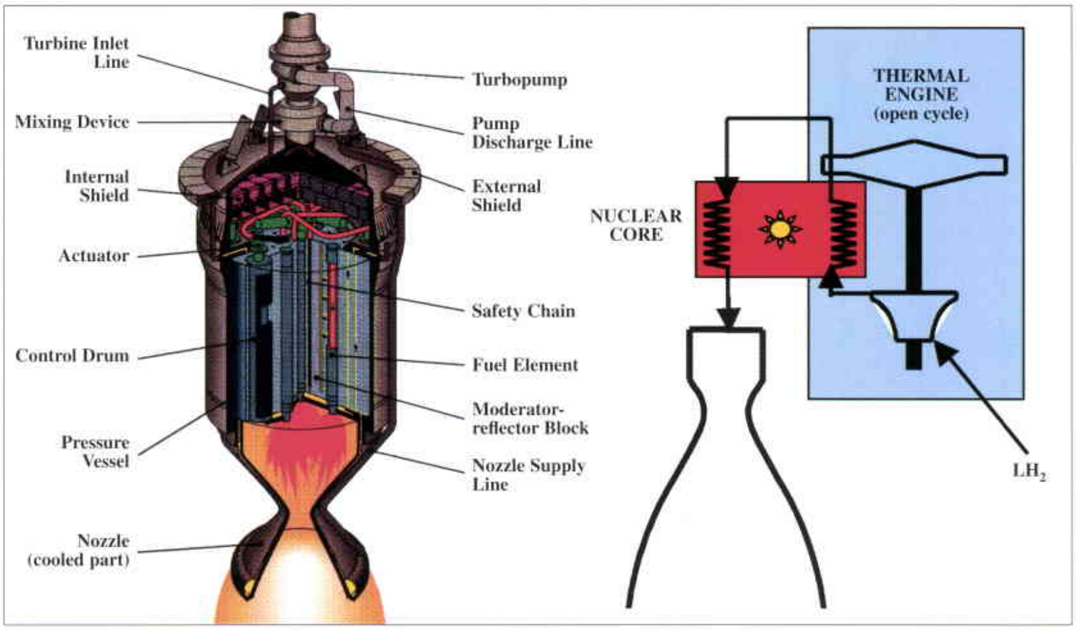

Figure 2. A state-of-the-art nucleo-thermal engine

Several possible solutions are currently under study around the world. The nuclear thermal propulsion concept described in this article features:
- a rocket-engine concept with a performance level at least equivalent to, and potentially better than that of the nuclear thermal engines developed in the sixties
- a design that provides a large technological margin for the operating temperature of the nuclear core, to achieve good reliability over a long engine lifetime
- a closed-loop test facility enabling long-duration on-ground testing of the engine without the rejection of nuclear contaminants.

How do nuclear thermal engines work?
Figure 2 (right) shows a schematic of the thermodynamic cycle of a state-of-the-art nuclear thermal rocket engine. The engine on the left was studied by the French CEA organisation in the framework of the MAPS project in 1990. Liquid hydrogen is first pumped at high pressure and used to cool down the core envelope and nozzle of the engine. Then the heated hydrogen is expanded in a turbine which drives the pump. This subassembly constitutes an open-cycle thermal engine. The hydrogen is then heated in the nuclear core at high temperature (up to 2500 K or more), and expanded through a rocket nozzle which produces the thrust.

The gas exhaust velocity V_e, which characterises the engine's performance, is given by the equation:

$$V_e \approx \sqrt{\frac{2R}{M}\left(\frac{\gamma}{\gamma-1}\right)T_c\left[1-\left(\frac{\Pi_e}{\Pi_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where γ is the ratio of specific heats, and R the universal gas constant.

This equation shows that maximum performance is obtained with:
- the propellant gas of lowest molar mass M, which is why hydrogen is used
- the highest possible temperature T_c in the core region, the practical limit being set by the core material's degradation
- the highest possible nozzle expansion ratio Π_e/Π_c this parameter being limited by the external nozzle's bulk, while increasing it beyond classical values has only a limited effect.

In practice, an engine specific impulse in the 850–900 sec range can be obtained with current materials technology, accepting some core-material degradation.

How were these engines tested?

Developmental testing is a real problem for this kind of engine. In the sixties, numerous tests were performed in the deserts of New Mexico during the NERVA programme. The hot hydrogen was exhausted upwards directly to the atmosphere (Fig. 3), but nowadays this kind of test is no longer acceptable from an environmental point of view.

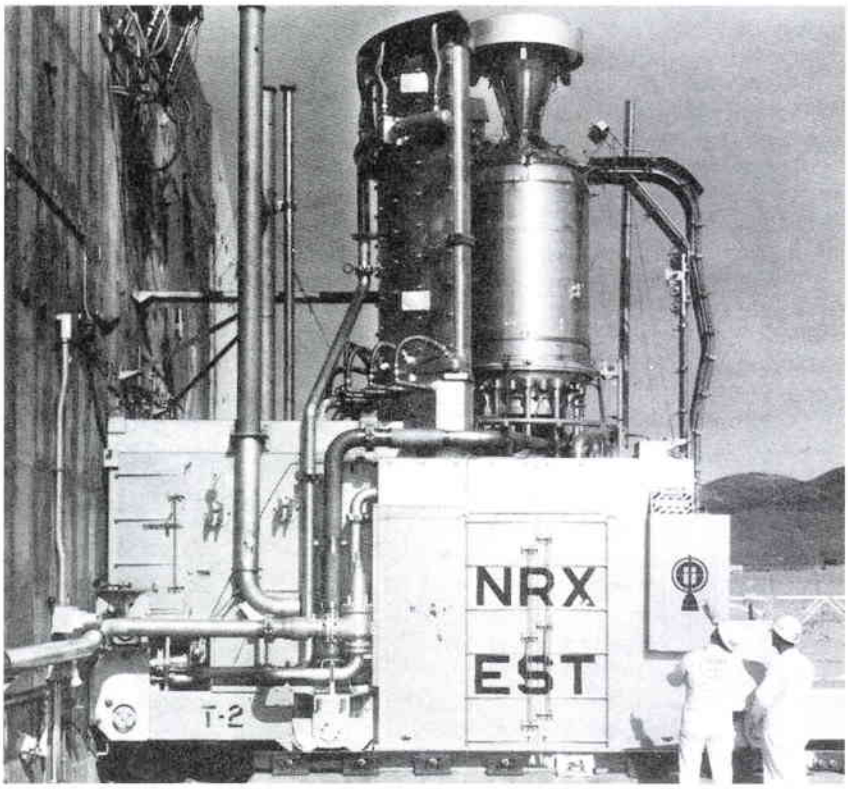

Figure 3. Nucleo-thermal rocket testing in the New Mexico desert

Evolutionary engines with improved performance, reliability and safety

The first step in the possible evolution of these engines is shown in Figure 4. It is simply an improvement of the turbopump cycle of the nuclear thermal engine. Since the liquid-hydrogen flow provides a cold source and the nuclear core a hot source, it is possible to engineer a closed-cycle thermal engine between the two which will drive the hydrogen pump. A Brayton cycle is preferable, using a mixture of helium and xenon as the closed loop's working fluid to take advantage of the low reactivity, high specific heat, and low sonic speed of this mixture. The advantage of this thermodynamic cycle is that it works between 15 and 2000 K, and therefore yields an excellent overall engine efficiency (better than 50%).

In a second step, realising that an extremely large quantity of heat can be obtained from the nuclear core and that, assuming a hydrogen mass flow of a few kg/s, a very large quantity of heat can be absorbed by the liquid hydrogen, the thermal engine's power output can be increased to several tens of Megawatts. This power can be used to drive an alternator which produces electricity. As described in an ESA patent, this huge amount of electric power can then be sent via a supercooled wire to a coil installed around the nozzle to produce an alternating electromagnetic field in the exhaust jet. In this region, the supersonic exhaust flow is reheated by magnetic induction. The

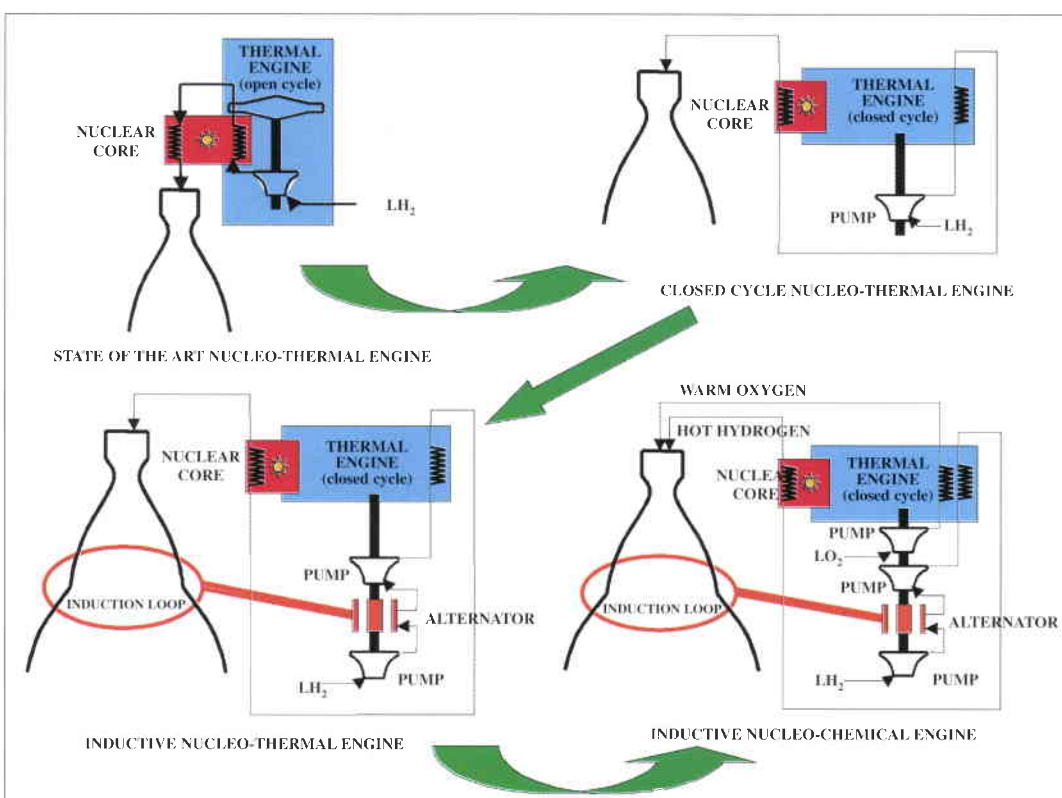

Figure 4. A possible evolution towards safer nuclear propulsion

induction coupling requires the flow to be seeded upstream, for example with caesium. The reheated flow is then expanded again in a downstream nozzle extension, thereby producing an increased thrust, somewhat like the afterburners on a jet fighter.

The gas exhaust velocity for this new type of 'inductive nucleo-thermal engine' is given by the following equation:

$$V_e \approx \sqrt{\frac{2R}{M}\left(\frac{\gamma}{\gamma-1}\right)\left[T_c + \frac{P_i}{Q\left(\frac{\gamma}{\gamma-1}\right)\frac{R}{M}}\right]\left[1-\left(\frac{\Pi_e}{\Pi_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where Q is the exhaust mass flow rate, and P_i the power introduced into the exhaust gas through magnetic induction.

The terms of the previous equation can easily be recognised. A term has been added which is proportional to P_i. It is clear from this formula that, for a given core temperature T_c, the added power P_i increases the gas exhaust velocity V_e. Alternatively, the same engine performance V_e can be achieved with a lower nuclear core temperature T_c thanks to the power P_i introduced in the nozzle. The last step in the proposed evolution is the injection of oxygen in a combustion chamber sited up-stream of the nozzle of the inductive nucleo-thermal engine.

The result, called an 'inductive nucleo-chemical engine', harnesses three heat sources simultaneously: nuclear, chemical, and electric inductive. Table 1 shows the effect of increasing the oxygen/hydrogen mixture ratio: the engine's thrust is increased, due mainly to the higher mass flow rate, but its specific impulse decreases, due to the increase in the exhaust gas mean molar mass. Consequently, oxygen injection is of interest only when extra thrust is required for a short period, for example during planetary take-off or for orbit injection.

The idea of harnessing both nuclear and chemical power on a rocket is not new. It was pictured by Hergé in 1953 in his famous cartoon 'Tintin: Objectif Lune' (Fig. 5).

Table 1. Effect of oxygen addition

Mixture ratio Q_{O2} / Q_{H2}	Specific impulse (s)	Normalised thrust
0	930	1
1	700	1.5
1.5	650	1.75
2	610	2
4	510	2.8
5	480	3.1

Why is the inductive nuclear engine safer and more reliable?

A state-of-the-art nucleo-thermal engine running with an average gas temperature of 2750 K in the core yields a specific impulse in vacuum of the order of 930 seconds. This temperature is close to the practical limit of the known materials for nuclear core design, bearing in mind that the temperature distribution in the core is not uniform and could locally reach 3000 K. Under these conditions, the lifetime of the engine is very short.

The same specific impulse of 930 seconds can be obtained using the inductive nucleo-thermal engine design with an average gas temperature of 2200 K in the core. With these conditions the lifetime of the core is unlimited, and there is even room for increasing the core temperature to improve the engine's performance. In fact, no element of the inductive nuclear engine ever reaches a temperature equal to the stagnation temperature of the exhaust flow. This is due to the fact that the induction energy is added to the flow only when it has already started to cool down, following its expansion in the nozzle.

How can one test an inductive nuclear engine on the ground?

The problem of the ground testing facility is illustrated in Figure 6. For a conventional nuclear thermal engine, the hydrogen entering the core is very cold. At the nozzle exhaust, the

Figure 5. An 'early' nucleo-chemical rocket concept

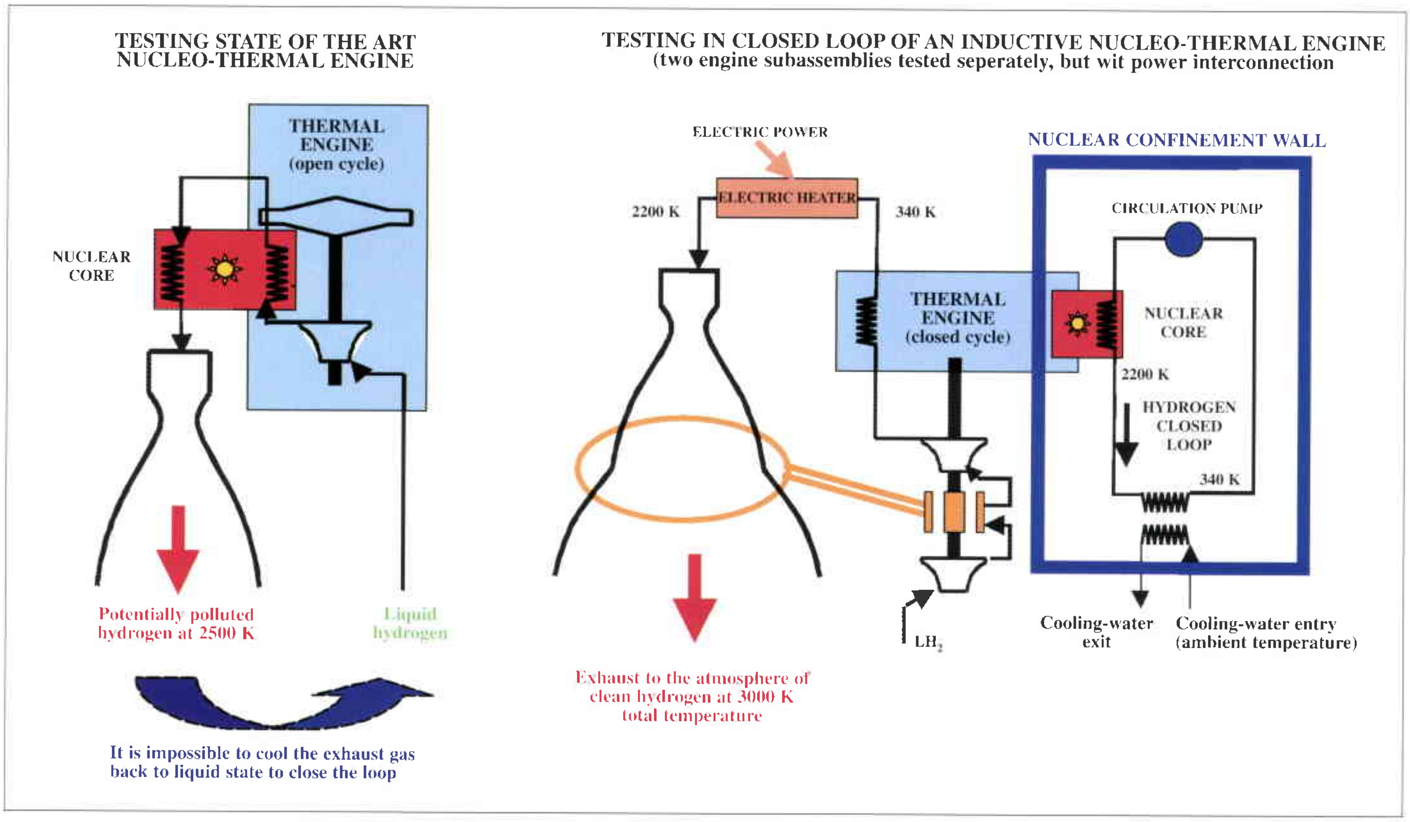

Figure 6. Testing facilities for nuclear propulsion

stagnation temperature is 2500 K or higher. It is therefore unrealistic to cool the exhaust hydrogen and liquefy it to re-inject it into the pump. Since the loop cannot be closed, the exhaust gas is dumped to the atmosphere, and part of its potential nuclear contaminants too, even when the gas is scrubbed.

The situation is quite different with inductive nuclear propulsion. Two independent fluid circuits go through the core. The Brayton cycle helium/xenon loop is already closed by design, and therefore creates no risk of pollution. In the propellant circuit, the hydrogen enters the core at 340 K and exits it at 2200 K. At this point the hydrogen can be cooled by a heat exchanger with external water at ambient temperature, brought back to 340 K, pumped through an auxiliary circulation pump, and sent back to the core to close the hydrogen loop. The nuclear core and any potentially dangerous loops are then entirely enclosed by a confinement wall, as shown in Figure 6. The nozzle and induction parts can be tested separately, fed by clean hydrogen that has been heated using an electric arc jet. The exhaust gas is dumped to the atmosphere or to a rocket altitude-test chamber. The resulting gas-heating and exhaust-pump installation looks very much like that of the recently developed Scirocco facility in Italy.

Hence, the inductive-propulsion concept can be qualified on the ground in two separated subassemblies, under environmentally clean and safe conditions, and with no duration limit except that resulting from the liquid-hydrogen storage.

Future prospects

From the dawn of humankind, the need to explore has driven human expansion across our planet. Expansion towards other planets in the Solar System is already underway with 'virtual explorers', namely robotic spacecraft. The question is, will human expansion continue? In the public consciousness, this is only a matter of time.

By 2020 to 2030, an international human mission to Mars may be a reality. It may use the Moon as a staging post to prepare for the great leap. The feasibility of such a mission is already being assessed, though the necessary technologies and capabilities still need to be developed. ESA's Aurora Programme is designed to define and develop the strategic technologies in which Europe has to invest in order to be a key player in this international endeavour.

Today, it is too early to decide in favour of one specific type of propulsion. Trade-off studies will continue for some time. However, it is clear that current state-of-the-art chemical and electrical propulsion would impose very severe limitations on a human Mars mission and it is therefore necessary to continue to explore all options that might lead to an efficient and safe solution.

The nuclear-inductive propulsion concept described above may constitute a possible step in this direction. It builds on competences that already partially exist in Europe, for instance in the fields of turbo-machinery, nuclear furnaces, electric induction, high-power cryogenic circuitry and commutation, test facilities, and many other technical domains. The elements that need to be developed for this kind of concept may have spin-offs to applications in our day-to-day lives. Current research for a new generation of nuclear powerplants includes the consideration of high-temperature gas loops similar in design to the proposed Brayton-cycle nuclear power loop. High-power induction in a supersonic flow would assist in the design of higher enthalpy wind tunnels, while cryogenic high-power alternators are needed for a multitude of applications.

Current status

Once the new propulsion concept had been patented by ESA, a preliminary analysis of its feasibility was performed by SNECMA (F). As a result, a number of design issues have been shortlisted which require deeper investigation, but no clear technical showstopper has been found. At this stage, the most significant unknowns relate to:

- The possibility of heating the gas under supersonic conditions by induction: A fundamental study is needed into this still-unexplored aspect of physics. Is there a minimal residence time for molecules to increase their energy by induction heating? A simple low-cost experiment at the Von Karman Institute's facilities could provide the answer. But even if the supersonic heating is found to be impossible, the concept can also be adapted for subsonic heating, as SNECMA has already shown.

- The overall mass of an engine of this type: The mass can be realistically estimated only after a deeper pre-design study, which has still to be carried out.

Conclusions

The advanced concept for future interplanetary propulsion that has been described above offers the prospect of high performance at reduced core temperature, together with improved lifetime and reliability. A test facility that allows the engine to be qualified on the ground under environmentally clean and safe conditions has also been described. Today the development of the concept is still at the working-principle level, and further pre-design work is needed to confirm its true advantages and practical feasibility. Simple physical experiments are also needed to confirm the feasibility of the supersonic induction.

Acknowledgement

The contribution of Mr Dominique Valentian of SNECMA to the analysis and improvement of the nuclear inductive propulsion concept is gratefully acknowledged. He also proposed the idea of a closed-loop ground-testing facility.

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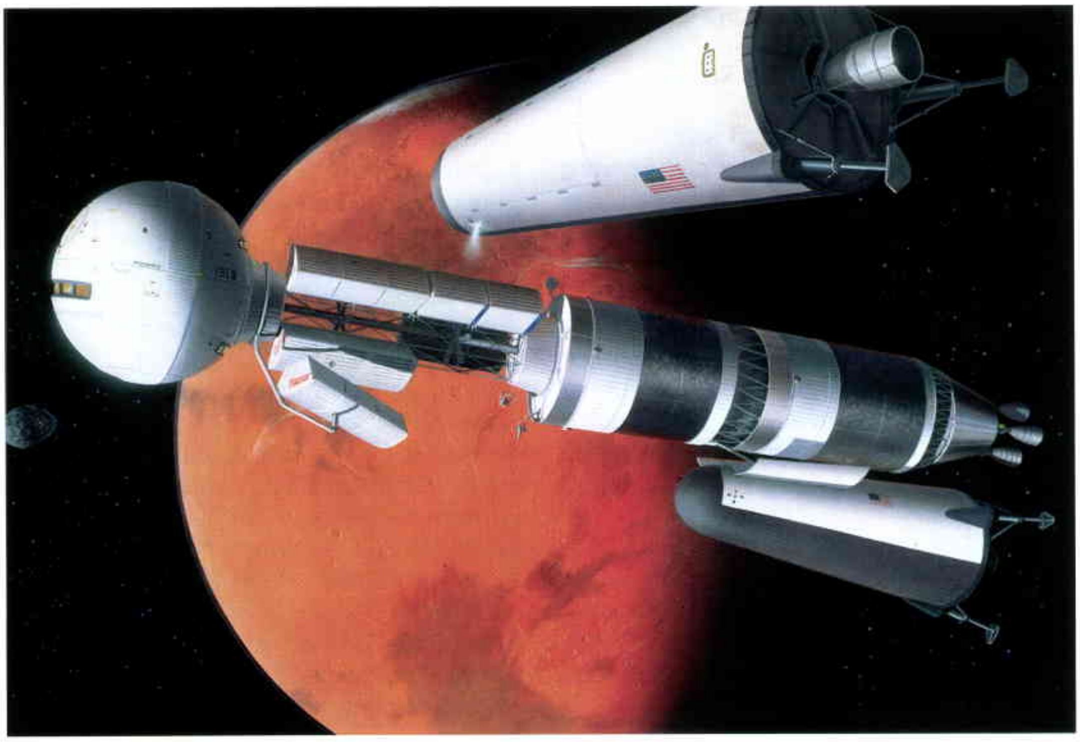

Figure 7. Arrival of an interplanetary vehicle in Mars orbit (artist's impression, NASA/NIX)

Promoting ESA Software as a European Product: The SCOS-2000 Example

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ESA has been allowing re-use of the high-quality software that it has developed for its own operational purposes by granting non-exclusive licenses within the Member States for the software's use for space research and technology purposes. The licensing is normally free of charge and is seen as a good way of allowing the European space community to benefit from ESA-developed assets. This article looks at an initiative to take this approach further through the promotion of ESOC's latest SCOS-2000 mission control infrastructure as an ESA product.

ESOC software products and their marketing

ESOC develops high-quality software for its core business of spacecraft operations. This includes:
- mission-control software
- flight-dynamics packages
- mission-analysis packages
- simulator software, etc.

Much of this software is used and rigorously tested in the demanding arena of supporting spacecraft operations. Such software falls within a relatively small 'niche' market, which consists primarily of spacecraft operators. It is developed using European funding and because of ESOC's need to apply it to many missions, it is designed for reuse. The question then arises: Why not encourage other spacecraft operators to use this software and benefit from the investments that have been made?

In fact, ESA has been doing this via the licensing of its software for many years, although the idea of promoting software as a supported 'product' is relatively recent. If we define 'productisation' as the activities needed to make ESA software usable by a wider community that includes external users, its advantages are that:
- the software can be improved further by enlarging the user community: this benefits both ESA and the user community as a whole
- wider use of such products can contribute to the consolidation of European space technology and can help make European industry more competitive (in Europe and globally)
- such use can also help save money, by avoiding unnecessary repetitive, and possibly risky, re-development
- better use is made of European public funds, both by better leveraging of the products developed using these funds and by avoiding waste through unnecessary redevelopment.

SCOS-2000 as a software product

At ESOC, it has been the practice for over 25 years to use a generic mission control system as the basis for the control system of each mission. The control system is a potentially expensive and tricky system to develop. It supports the monitoring and control of the spacecraft, including the various displays and facilities that one sees in a typical mission-control facility, like ESOC's Main Control Room (Fig. 1). Having a generic system significantly lowers costs and risks. The rub, of course, is that developing a generic spacecraft control system with adequate flexibility and performance for all missions is difficult and is itself a very costly investment. ESOC has developed such a generic control system using the latest software technology: the Spacecraft Control and Operations System SCOS-2000.

The SCOS-2000 development effort had the following main strategic aims:
- ease of configuration and/or customisation, thereby lowering associated costs

Figure 1. The Main Control Room at ESOC

- functional richness, reducing the need for mission-dedicated functions and thus lowering mission-specific costs
- scalability, allowing the system to be adapted to missions of any size or for any phase of a mission, e.g. by adding work stations according to the performance required or the number of users; scalability provides flexibility
- vendor independence, which reduces or avoids the need for periodic porting exercises as hardware platforms or commercial off-the-shelf (COTS) software become obsolete.

All four aims have been achieved and as a consequence the costs of the ESOC control systems have come down by a factor of between two and three. Vendor independence has also been largely achieved with the recent acceptance of the so-called 'evolution version' of SCOS-2000.

Work started on SCOS in about 1992 and it supported its first ESA missions – Huygens, Meteosat (MTP) LEOP and Teamsat – in 1997. Since then, the software has been continuously improved with the re-engineering of the telecommanding chain in 1998–2000, numerous functional improvements, and the recent evolutionary work to improve vendor independence. The total investment in SCOS-2000 to date, including internal ESA effort in managing the project and supporting studies, is of the order of 15 MEuro.

Since SCOS-2000 has been developed to cope with the wide ranging demands of ESA missions, from the simple to the most complex, it can obviously be of benefit to other spacecraft operators outside ESA. Hence the decision to promote it as a specific software product.

Pre-conditions

Candidate software for 'productisation' must be:
- fit for its intended use
- well-defined
- vendor-independent, or at least supported on popular platforms.

It is also desirable that it has long-term support from ESA, so users know that it will be maintained and kept up-to-date.

SCOS-2000 satisfies all of these criteria. It has been specified and designed to meet the needs of ESOC-supported missions, which range from relatively simple ones to complex earth-observation and scientific missions. It is fully defined in documentation available on an electronic database. Its functional and other requirements are detailed in software-requirements documents and its architecture is well specified (Fig. 2). Figure 3 shows the available external interfaces.

SCOS-2000 was originally developed to run on Sun Solaris platforms, compatible with Unix

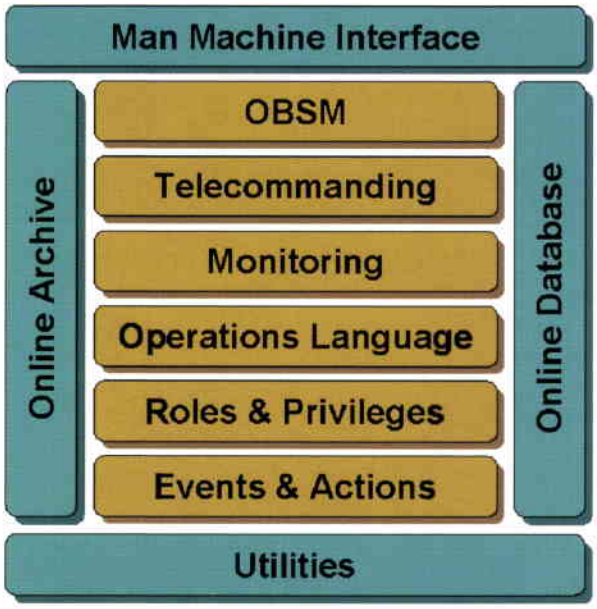


Figure 2. The SCOS-2000 architecture

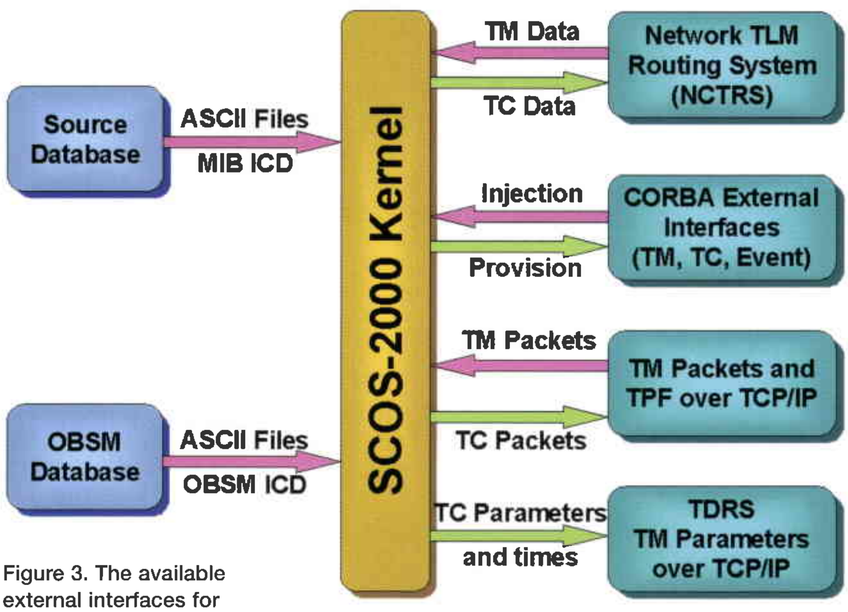


Figure 3. The available external interfaces for SCOS-2000

System V Release 4. While this represented increased vendor independence compared with the earlier Vax VMS systems, vendor independence was still limited because of dependencies on the Solaris environment, and the use of potentially changing COTS software. To address this first point, SCOS-2000 was modified so that it could run under the Linux operating system, which has a good track record for mission-critical systems, and is a Unix variant not very different from the original SCOS-2000 platform, Solaris. However, Linux also runs on Intel PCs, which is an important point since some potential users require a PC-based control infrastructure. Last but not least, Linux is itself 'open-source', and therefore by definition vendor-independent.

SCOS-2000 in its 'classical' form used three major COTS products: ObjectStore, Orbix and ILOGViews. The first two of these were subsequently replaced by open-source equivalents: POST++ and Omniorb, respectively. ILOGViews, which supports the graphical user interfaces, will eventually be replaced by Java technology, but this is not urgent in view of this product's modest cost.

SCOS-2000 will be used for all future ESA missions and will be fully maintained and supported for many years to come. It is intended to retrofit it for some of the older missions that are currently based on an earlier infrastructure. SCOS-2000 will be used, for example, to support the Rosetta mission, which extends up to 2013. Certain features introduced by the many missions expected over this period will be considered generic and will be incorporated into the product, which will also benefit from ongoing R&D funded by the Agency's various study programmes.

Licensing aspects

The current ESA licensing scheme

Normally, ESA's special conditions concerning intellectual property and associated rights assign the International Property Rights (IPR) for software developed under ESA contract to the contractor, with ESA having full rights to use the software for its own purposes. The rules also define a category called 'operational software', for which ESA may claim full IPR. This 'operational software' clause is usually applied for software needed in operations, which requires, for example, full inspection rights for the source code, or the possibility of passing software from one contractor to another (say from development to maintenance). Claiming IPR for 'operational software' also safeguards the Agency's independence from the original author and so helps the long-time support of the software. For software for which ESA owns the IPR, it may grant a non-exclusive licence to a Member State body for use of the software for peaceful purposes in fields of space research and technology. Such licences are normally free of charge.

A further complication relates to the rights given in the licence, and these depend on the objectives of the licensee. Basically, licences can either allow use of the ESA software unchanged or with minor changes – leaving the IPR with ESA – or permitting the licensee to gain IPR for changed code or modules under certain conditions. This second approach was used for the licensing of ESOC's Multi-Satellite Support System (MSSS), but was later found to have drawbacks: for example, it can result in 'forking', which may generate a different product from that licensed, and then there is little feedback to help to improve the original product.

In the absence of detailed rules for writing licensing agreements, ESOC has in practice adopted three different types of licences:

- Run-time Licences, granted for temporary use and trial, without the right to change the software or investigate the source code.
- Development Licences, granted for upgrade developments of existing 'operational software' for ESOC's own use and under ESA contract, including work on the source code.
- Full Licences, to make developments based on the software, e.g. to develop a product. They also allow the licensee to make changes to the software.

The future ESA licensing scheme
The Agency's rules concerning information, data and IPR are presently being revised. The policy document prepared by the IPR Drafting Committee has been submitted to ESA's Administrative and Finance Committee (AFC) and Industrial Policy Committee (IPC). The novel feature introduced in this paper is a scaled and differentiated treatment of information, data and IPR with respect to the body which has borne the cost of its development. Different treatments are foreseen for the result of activities fully-paid by the Agency, not fully-paid by the Agency, and for partnerships.

For 'operational software', however, there will be no change in the licensing approach and so the impact for SCOS-2000 promotion will be negligible.

Open-source licensing
Because of the aforementioned shortcomings, the product approach for SCOS-2000 has caused us to look at an alternative 'open-source' licensing model, in which the source code is accessible and may be modified, albeit with some obligations depending upon the particular open-source licence used.

The advantages of the 'open-source' approach are that:

- the source code is open to inspection by everyone
- the programmer community tests the software and fixes bugs
- new features are added to the software by the programmer community; indeed features may be added that could not possibly have been foreseen by the original authors.

Open-source software is in an 'intellectual marketplace', in the sense that peer review improves the software quality in a kind of 'survival of the fittest' scenario. The economic basis for the open-source approach has been explained in the book 'The Cathedral and the Bazaar', by Eric S. Raymond. Another economic model advocates the 'give away the recipe, open up a restaurant' approach, i.e. provide your software as open source, but sell services around it, such as packaging, consultancy, integration and applications. This is the model that external licensees of SCOS-2000 may adopt.

SCOS-2000 licensees will be encouraged to accept 'open-source-type' conditions, i.e. to hand back improvements made in the SCOS-2000 kernel. The intention is to reflect this in licensing agreements, replacing the older IPR transfer scheme discussed earlier. However, it cannot be imposed and has to be done by agreement. Industry is also free to develop add-on products that inter-operate with SCOS-2000 using the defined interfaces; in such cases they may wish to reserve full IPR over the products of their own investment.

Market aspects
As mentioned earlier, mission-control software, and indeed any kind of space-operations software, falls into a specialised or niche market, dominated by a limited number of space agencies and satellite operators. However, there are a surprisingly large number of commercial geostationary (GEO) and low Earth orbit (LEO) missions, run by organisations such a Intelsat, Inmarsat and Eutelsat. The main products currently on the market come from US commercial suppliers such as Integral Systems, Storm and Braxton Technologies. The first two in particular have solid track records with satellite operators, with a large existing customer base for commercial GEO and LEO missions. Their products have attractive user interfaces, and integrated tools are often available to work with them (e.g. simulators, basic flight-dynamics tools). Their disadvantages are that they are:

- closed systems
- licence fees are incurred, as with all COTS products
- customers have limited or no control over product evolution
- customisation costs may be significant for new classes of missions, since it has to be done at commercial rates by the vendor.

This contrasts with SCOS-2000, which is open in terms of external interfaces and customisability, as well as being open-source within the ESA Member States.

There do not appear to be any European mission control packages, at least ones that are being actively promoted commercially, making the US products the main competition for SCOS-2000.

Support requirements

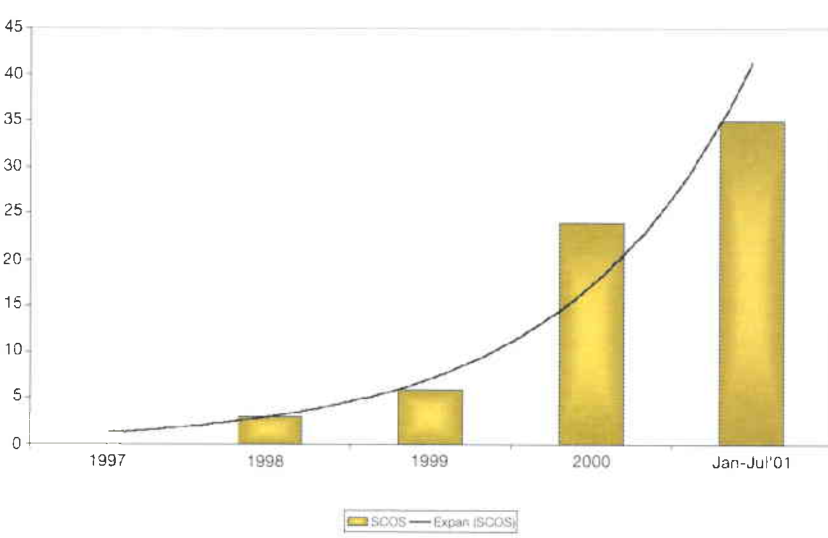
It has to be recognised that if a piece of ESA software is promoted as a product, considerable efforts and important responsibilities are incurred on the Agency's side. For example:
- Promotional effort.
- Setup and maintenance of a user-community organisation, to allow consultation on product evolution.
- Provision of access to product information.
- Provision of customer technical support in terms of a user help desk.

For SCOS-2000, measures have been taken in all of these areas:
- Product promotion is carried out through meetings with potential customers and also through supporting Industry to make bids to other spacecraft operators based on SCOS-2000.
- A user organisation has been set up.
- Access to documentation is currently provided via an FTP server. A web site is under construction and will be available before the end of the year. It will carry documentation, answers to Frequently Asked Questions (FAQs), registration for different user categories, a software-problem report database, release plans, and an on-line demonstration.
- A help desk has been set-up as part of SCOS-2000 maintenance; users can subscribe to this service for a fee.

We also anticipate possibilities for training courses, installation assistance, consultancy, and specific developments of customer-requested features.

In terms of relations with the user community, ESOC will take the initiative, but the user community is also expected to contribute. ESOC and the user community will be partners in that:
- On the one hand, ESOC will be the custodian of the product, maintaining it, fixing faults (inevitable in a complex system with many users), and keeping it up-to-date with changes in the computer platforms and operating systems. ESOC will also implement new features or integrate features that have been developed by user missions or external users under the open-source approach. ESOC will also conduct the R&D needed to keep the product up to date with technological advances.
- On the other hand, the users will propose new requirements based on their operational experience and will contribute to the product via the open-source approach, e.g. by submitting code updates or coding for new features.

Figure 4. Cumulated number of licences issued at the end of the periods indicated



Experience so far

Nearly 100 people from outside ESA attended a very successful SCOS-2000 Users Workshop, held for the first time in April 2001. At this Workshop, which included presentations on the product, plans for its evolution and the proposal to set up a SCOS-2000 User Community, the users also gave presentations on their experience with the product. The proposed open-source approach received a generally positive response.

A number of the companies involved in the development of SCOS-2000 have been marketing the product to other spacecraft operations organisations. This has resulted in the decision by the German Space Operations Centre (DLR) to use SCOS-2000 as the basis of its control centre infrastructure. The Principal Investigators of the Herschel Planck science-mission payloads have also decided to use SCOS-2000 in building their instrument check-out equipment. The changes to SCOS-2000 to enable it to support spacecraft or instrument checkout were pioneered for ESA's Proba (Project for On-Board Autonomy) spacecraft, and have recently been introduced into the evolution version of SCOS-2000. There are also other commercial prospects in the pipeline.

In the meantime, SCOS-2000 has already become the 'best-selling' software product licensed through ESOC's Contract Service. In a little over two years, some 30 licences have been granted, as shown in Figure 4.

What has been found is that breaking into new markets involves considerable effort. Firstly, there is the need to compete against the established suppliers of COTS mission-control systems. This involves convincing potential customers of the benefits of using SCOS-2000, and this will become easier as it establishes a track record with organisations or customers outside ESA. Secondly, preparing bids usually involves demonstrating compliance with a set of customer requirements, frequently expressed in different terminologies from that employed at ESOC and possibly reflecting different operational practices or concepts. With such a functionally rich and flexible system as SCOS-2000, preparing a compliant proposal is usually possible. ESOC has been giving help to some of the companies in preparing such analyses.

Our experience has also led us to look at two other aspects – certification and extension to further platforms:

- Together with the ESA Quality Department, we are starting an activity to 'certify' SCOS-2000. This will involve an independent evaluation of the software against a set of agreed quality criteria. The certification method has been customised for space software from ISO Standard ISO 9126 ('Information Technology: Software Quality Characteristics and Metrics') among others. The method has been developed under a study contract with TUV Cologne, which will perform the certification. Certification of space software is a new discipline and we are pleased that SCOS-2000 will be in the vanguard of this. Obviously, certification will be help in SCOS-2000's promotion.
- We have also carried out a short study into the feasibility of porting SCOS-2000 to 'Windows®', keeping the common-source approach that was applied with the earlier Linux porting. This would make the product more attractive to organisations with a Windows® PC infrastructure. This is frequently the case for spacecraft and payload checkout, and is also true of some spacecraft operators. The study has shown that it is indeed feasible, although as yet no decision has been made on proceeding further.

Conclusion

This article has reported an initiative to promote a highly successful ESA mission-control system as a commercial product. There is, however, a significant body of ESA software. For example, from ESOC alone, 93 software products have been licensed in 94 Member State bodies, involving more than 220 licences in total. Given that there is a significant reservoir of such software, the approach has strong potential for being extended to other ESA software to improve the effectiveness of its promotion and use.

EIROFORUM – Building the European Research Area

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In early 2000, the Commission of the European Union (EU), through its Commissioner for Research, set out to establish a 'European Research Area' (ERA). The purpose of this initiative is to give Europe a structured network of expertise with which to efficiently promote regional research projects. EIROFORUM, the European Inter-governmental Research Organisations Forum, has been created in the context of the ERA for the purpose of fermenting ties between some of the most active and influential research entities in Europe, namely: the European Organisation for Nuclear Research (CERN), the European Fusion Development Agreement (EFDA), the European Molecular Biology Laboratory (EMBL), the European Space Agency (ESA), the European Southern Observatory (ESO), the European Synchrotron Radiation Facility (ESRF) and the Institut Laue-Langevin (ILL).

This article focusses on the background to the EIROFORUM initiative and the evolutions that have made EIROFORUM a necessity, highlighting how the EU's interest in space and research has recently crystallised, and how EIROFORUM may influence ESA's activities.

The European Union
The European Economic Community (EEC) is a regional inter-governmental organisation, which has the particularity of exercising some supra-national prerogatives, established by the 1957 Rome Treaty, and whose name was modified to the European Community (EC) by the Maastricht Treaty of 7 February 1992. The European Union itself, as a polity created by the Maastricht Treaty, encompasses the three Communities of the European Coal and Steel Community, Euratom and the EC, together referred to as the first pillar of the EU, as well as the second and third 'pillars' (the common foreign and security policy and the police and judicial co-operation in criminal matters, respectively).

Historically, the EEC has given only minor attention to space research and development. Indeed, the first 25 years of the EEC were primarily dedicated to the essential political objective of building the Common Market. It is only after 1971, once the political crisis linked to the United Kingdom's accession was resolved, that the EEC really began looking into space activities. In 1984, the EEC Council approved the First Framework Programme (1984-87), funding research and development initiatives such as ESPRIT, RACE and BRITE. The following year, the EEC Commission participated in the Eureka Programme.

However, the most significant tie between the EU and space research is the entry into force of the Single European Act in 1987, which extended the Commission's competence to research and development activities organised through the Framework Programmes by adding a new 'Research and Technological Development' title to the 1957 Rome Treaty. The Single European Act's Research and Technical Development (RTD) title was further significantly broadened by the 1993 Maastricht Treaty, stating that EC competence now applied to 'all the research activities deemed necessary by virtue of other Chapters of this Treaty.' In addition, a new title on the environment expanded the EEC's competence while generally providing for the Community's use of scientific and technical remote-sensing data. There are clear signs that in practice the European Commission is no stranger to space activities. The EU is competent, whether exclusively or not, in the areas of transport, environment, industrial policy, trade, and other areas that de facto have repercussions on space activities.

EIROs
In parallel with the European integration process, European States have committed themselves to research and development by creating specialised regional organisations. In 1997, European multilateral public RTD organisations accounted for approximately 11% of European public expenditure on research and development, twice the amount committed by the EU RTD Framework Programmes. Such inter-governmental research institutions have several specific added-value characteristics, including the ability to provide their Member States with gateways to scientific and industrial communities in other countries. This enables Member States with less-developed scientific infrastructures to build and use the organisation's own capabilities, allowing Members to participate in infrastructures that are international centres of excellence, catalysing world-class science in Member States, etc. Among these are the EIROFORUM participants.

ESA is an International Organisation established by its Convention signed on 30 May 1975, and which entered into force on 30 October 1980. The purpose of the Agency is to *'provide for and to promote, for exclusively peaceful purposes, co-operation among European States in space research and technology and their space applications, with a view to their being used for scientific purposes and for operational space application systems'*, while promoting the competitiveness of European industry. In order to achieve its mandate, the Agency co-ordinates the European space programme and national space programmes.

ESO was established in 1962 to build and operate an astronomical observatory located in the Southern Hemisphere. ESO's task is to provide the best scientific instruments available and to promote and organise co-operation in astronomical research, equipped with powerful instruments, with the aim of furthering and organising collaboration in astronomy. ESO operates the La Silla observatory in the Atacama desert, 600 km north of Santiago de Chile, where fourteen optical telescopes with diameters up to 3.6 m and a 15 m sub-millimetre radio telescope (SEST) are now in operation. In addition, ESO is in the process of building the Very Large Telescope (VLT) on Paranal, a 2600 m high mountain approximately 130 km south of Antofagasta, in the driest part of the Atacama desert.

ESRF is a large experimental facility for basic and applied research in physics, chemistry, materials and life sciences, and is licensed to operate a powerful source of light in the X-ray range. The construction of the ESRF began in 1988 and the opening of the first 15 beam lines to scientific users took place in September 1994. Today, the ESRF operates 40 beam lines, 24 hours per day and 7 days a week, in 'User Service Mode'.

ILL, an international research centre and one of the World's leaders in neutron science and technology, was set up in 1967 to provide a high-flux neutron source and instruments for physics, chemistry, materials and life-sciences studies. Over 800 experiments selected by a scientific review committee are performed at ILL every year.

EMBL was established in 1973 to promote co-operation among European States in fundamental research, in the development of advanced instrumentation, and in advanced teaching in molecular biology as well as in other related areas of research. To this end, it concentrates its activities on work not normally or easily carried out in national institutions. EMBL was founded in the light of a four-fold mission: to conduct basic research in molecular biology; to provide essential services to scientists in Member States; to provide high-level training to its staff, students and visitors; and to develop new instrumentation for biological research.

With respect to CERN, Article II of its Convention, which entered into force on 29 September 1954, reads that *'the Organisation shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto.'* Article II further extends the Organisation's mandate to several different activities relating to nuclear research.

Finally, EFDA allows co-operation activities in the field of controlled thermo-nuclear fusion by magnetic confinement. The Joint European Torus (JET) Joint Undertaking was established in June 1978 to build and operate the JET machine, the largest single project within the European nuclear-fusion programme of its time. Since 1 January 2000, the JET programme has been managed by EFDA, an agreement that is scheduled to remain in force until the end of 2002 and very possibly beyond. The JET has been co-ordinated by the European Atomic Energy Community (Euratom) and the project soon became the flagship of the Community Fusion Programme. Furthermore, JET became the first fusion facility in the World to achieve significant production of controlled fusion power, back in 1991.

Over the years, it became increasingly apparent that these EIROs evolved and worked independently from each other. Links among EIROs existed but remained scarce, making European research a fragmented arena with no real institutionalised or coherent co-ordination. Indeed, some analysts pointed out that multilateral research organisations in Europe have few horizontal links between them, due to the fact that they can be analysed as extensions of Member State activities allowing national scientific communities in Europe to interlock and, in several cases, co-operate on a global basis. In addition, observers have noted that these organisations have a tendency to compete against each other, trying to distinguish their own institution from other research entities. Horizontal links have therefore historically been mainly confined to 'exchanges of information', although there have been substantial exceptions.

Research in Europe

Hence, two different dynamics currently characterise European research: the increasing involvement of the EU, and the fragmentation of infrastructures and resources. European analysts have concluded that this fragmentation of efforts impairs the competitiveness and quality of research in Europe, especially with respect to the United States (USA). Meanwhile, the Commission is alarmed that the gap between the USA and the Old Continent will increase further if meaningful resource co-ordination is not implemented in Europe.

Indeed, the average research effort in the EU is currently only 1.8% of Europe's GDP, compared with 2.8% in the USA and 2.9% in Japan. This worrisome trend is expected to increase, as the difference between total public and private expenditure on research in the USA and Europe amounted to a gap of some 60 billion Euros in 1998, against 12 billion in 1992, an alarming five-to-one ratio. Furthermore, statistics show that Europe has had a high-technology-product trade deficit of 20 billion Euros per year over the past decade, and there is no clear indication leading one to argue that the trend will reverse in the short term.

The ERA initiative

Against this alarming picture, the EU is striving to implement proactive policies to bring research and technology back to the forefront of European priorities. Indeed, research and technology account for 25 to 50% of economic growth, while also having a strong influence on competitiveness, employment and the quality of life for Europeans. Philippe Busquin, the European Research Commissioner, has therefore set out to create a 'European Research Area', detailed in a Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee, and the Committee of the Regions, adopted on 18 January 2000, whose aim is to *'contribute to the creation of better overall framework conditions for research in Europe.'*

Commissioner Busquin's basic contention is that Europe is ill-equipped to rival the USA, which is contributing more funds to scientific and technological research, while US spending in these areas is expected to grow 9% in 2001. In addition, the Commission feels that the prospects in life sciences and technologies are promising. Indeed, the information and communications sciences and technologies are playing an increasingly fundamental role for competitiveness, living conditions in Europe, as well as food safety and sustainable development efforts, issues that are all central to the agendas of European policy-makers. As an illustration, the aforementioned 18 January 2000 Communication states that:

'........scientific research and technological development more particularly are at the heart of what makes society tick. More and more, activities undertaken in this domain are for the express purpose of meeting a social demand and satisfying social needs, especially in connection with the evolution of work and the emergence of new ways of life and activities.... Science and technology play an increasingly important role in the implementation of public policies, particularly Union policies. They are involved in various forms in the drafting of regulations and can be found more and more in the policy-making process, at the heart of trade negotiations and at the centre of international discussions in fields such as, for example, safety in its various forms or the various aspects of sustainable development... The European research system must be organised in such a way as to pre-empt and take account of needs arising at the different stages of implementation of public policies: drafting, decision-making, implementation, monitoring. Policy-makers must be able to draw on precise knowledge which is as complete as possible and constantly updated and validated.'

The EU's research policy is implemented through its Framework Programmes. Thus far, these RTD Framework Programmes have been described as instruments *'to promote co-operation and support collaboration'*. The Sixth Framework Programme (2002–2006) (FPVI), also referred to as the 'New Framework Programme', currently in its draft version, is bolder than its predecessors in that this Programme *'is designed to enable it to step up its contribution to the development of scientific and technical excellence in Europe'*, while *'increasing its impact on the innovation process in Europe and reinforcing its contribution to the efforts to integrate European Research'*. However, the ERA initiative seeks to provide more than just EU funds through its Framework Programmes. It seeks to create a process through which a European research policy can be elaborated with the support of every concerned European actor, including EIROs. The ultimate goal of the ERA is therefore to elaborate a comprehensive collaborative effort in Europe in order to make research more efficient through extensive and meaningful co-ordination between research entities via the elaboration of networks and the identification of common goals and needs. The means that the Commission is looking into in order to make the ERA a reality are: networks of excellence, integrated projects, and the participation of the EU in programmes carried out jointly by several Member States.

EIROFORUM

Origin and structure

The EIROFORUM initiative was created in this context so as to strengthen the foundations of the ERA. Initially, the EIROFORUM endeavour included six members: CERN, EFDA, EMBL, ESA, ESO and ESRF. These founding members then invited ILL to join as its seventh Member.

Historically, Commissioner Busquin launched the idea in early 2000 during an informal Research Council held under Portuguese Presidency. The initiative to gather the EIROs came from Antonio Rodotà, ESA's Director General, who invited the highest representatives of the EIROs to discuss the proposal. A working group was thereafter established to analyse the ways and means by which the EIROFORUM initiative could be implemented. The initial working group, chaired by Mr Rodotà during the second half of 2000, had already accomplished substantive work by the time EIROFORUM was officially launched in the spring of 2001.

The structure of EIROFORUM is straightforward and underlines a balanced distribution of responsibilities between the participating EIROs. It brings together the highest authorities of each participating entity, in a forum where the main policy orientations are discussed and where further courses of action are analysed. EIROFORUM meets several times a year, to assess the progress of the initiatives thus decided.

The 'EIROFORUM Working Group', whose participants are senior staff members from the different organisations, assists the EIROFORUM. This Working Group is entrusted with the task of implementing the EIROFORUM measures, while looking into further issues of interest to the EIROFORUM. In addition, the Working Group acts as the Secretariat for the EIROFORUM.

The Chairmanship of the Working Group follows the yearly cycle of EIROFORUM. The Chair (currently CERN) of EIROFORUM nominates the Working Group Chairperson. The Secretariat function of the Working Group is assigned for a period of three years.

Purpose

As the EIROFORUM Charter states, a primary goal of EIROFORUM is:

'to play an active and constructive role in promoting the quality and impact of European Research. In particular the group will be a basis for effective, high-level inter-organisational interaction and co-ordination. It will mobilise its substantial combined expertise in basic

research and in the management of large international projects for the benefit of European research and development. This will be possible by exploiting the existing intimate links between the member organisations and their respective European research communities'.

In pursuance of this task, the EIROFORUM has first analysed the current relations between EIROs as well as with the EU from a legal and technical standpoint. In parallel, the EIROFORUM has produced several position papers regarding the pressing issues facing European research organisations today, namely: information technology and computation, instrumentation, technology transfer, new materials, outreach activities. Other topics were also raised and dealt with, including accession procedures, enlargement, the brain drain, fellowships, the FPVI, relations between EIROs and the EU as well as with the European Science Foundation, Japan, the USA and Eastern Europe.

Specific thematic meetings have already taken place in which each EIRO's experts have been able to discuss and provide inputs regarding areas where co-operation ought to be sought. A first meeting of the 'EIRO Outreach Network' was thus held at ESO in April 2001, and further topical workshops on instrumentation and materials are forthcoming.

This mechanism underlines the potential of EIROFORUM: a high-level representation of the EIRO's Director Generals sets the pace in EIROFORUM, the EIROFORUM Working Group implements these actions and recommends further courses of action to EIROFORUM, while topical workshops are held to co-ordinate specific tasks and measures.

Relations with the European Commission

The second fundamental function of EIROFORUM is to ferment vertical relations – to serve as a forum where EIROs can communicate and discuss their policies, goals and needs with the European Commission. Several formal and informal meetings have already taken place between EIROFORUM and Philippe Busquin as well as with Dr. Mitsos, Director General of the EC's DG Research. These meetings allowed the EIROs put forward their common views and ideas on how the Commission could best help rationalise and support the work of EIROs for the benefit of European society and to tackle the stakes of a knowledge-based society.

In addition, these EU officials have invited EIROFORUM Members to analyse the draft Sixth Framework Programme (FPVI) and relay their inputs and suggestions to the Commission. This consultation with the EIROs illustrates how the Commission and EIROs can best work together to rationalise research initiatives in Europe, and how EIROs are central players who can meaningfully influence EU policies and support, whether financial or otherwise.

Conclusion

Hence, EIROFORUM's added-value is to have the most influential European research and development institutions in Europe pinpoint common goals and common needs in a forum where issues are comprehensively dealt with by its Members for further referral to the EU. If the stakes and the means are well defined by the main players in European research activities, then it becomes easier for the Commission to focus on the areas where its actions will reap the most benefit for European society. EIROFORUM therefore institutionalises two types of relations: horizontal relations between the EIROFORUM Members, who thus have a forum in which they can interact and discuss co-operation activities, and vertical relations between EIROFORUM as a group and the European Commission.

The EIROFORUM initiative cannot be singled-out from a broader strategic policy direction leading the EU and ESA closer together. Indeed, following the endorsement of the European Strategy for Space by the European Research Council and by the ESA Council at Ministerial Level in Brussels on 16 November 2000, a Joint Task Force (JTF) was created to monitor the implementation of the strategy, and to propose a framework enabling ESA to act as implementing agency with respect to EU policy on space. The EIROFORUM and the JTF complement each other well in the sense that EIROFORUM handles research matters as a whole within an intergovernmental framework, dealing directly with hands-on research collaboration initiatives in Europe, while the JTF looks into a better EU–ESA collaboration both at the institutional and programmatic levels.

The possibilities for discussion within EIROFORUM are endless. In order to take full advantage of the EIROFORUM initiative, its participants should endeavour to make this initiative widely known to their different departments, to publicise the fact that a forum now exists for the exchange of ideas with other European institutions, and that a common group has close relations with the Commission.

The ESA Data Warehouse: A Tool for Effective Management Reporting

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A data warehouse is a data reporting and analysis system that, thanks to its specific functional and architectural features, provides uniform and flexible access to a wide range of data. The ESA Data Warehouse project was brought about by the combination of growing requirements from administrators and managers, and the limitations of the data reporting and analysis capabilities of traditional information systems. The system has been made available incrementally and is now being used extensively by all Directorates. The project as originally defined is now in the final stages of implementation.

Introduction

Management information relies on well-organised, easily exploitable data. As managers need more information, their data reporting and analysis requirements become more stringent. At the same time, traditional information systems are often not in a position to deliver the information required, chiefly because they specialise in one functional area – and have as a result a limited data scope – and because their functional focus is on data entry and processing, not reporting. As their reporting and analysis needs outgrow the capabilities of traditional information systems, therefore, organisations like ESA are turning to Data Warehouses to fulfil their needs.

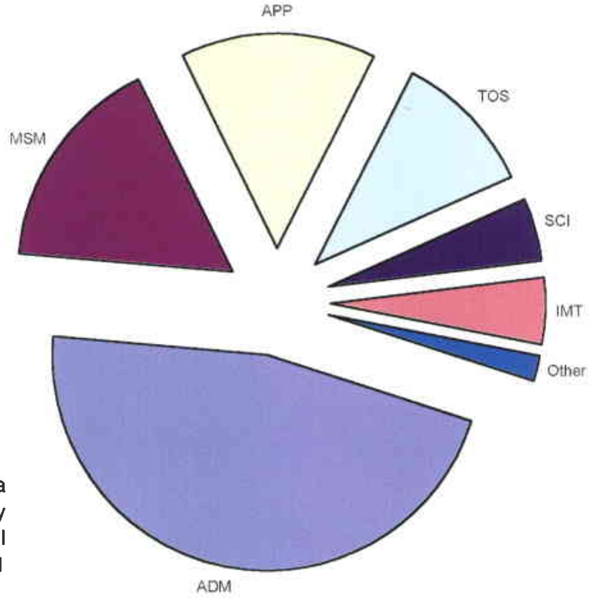


Figure 1. ESA Data Warehouse usage by Directorate, status April 2001

The major features and benefits of the ESA Data Warehouse fall into three broad categories:
- cost and operational aspects
- data integration aspects, and
- the time dimension.

The Warehouse's functionality has been has been made available incrementally so that value would be delivered to users as it became available. From the precursor systems to the full deployment by the end of 2001, the system has been increasingly popular for both administrative and management tasks (Fig. 1). Now that the initial project is nearing completion, the Warehouse is offering further opportunities, taking advantage of the structure, data and tools readily available.

The problem with reporting

Despite their name, Management Information Systems (MIS) often fall short of providing managers with the full supply of information they require. The reasons for this are linked to the very purpose of traditional information systems and fall into three categories:

- A MIS is created to fill a specific, operational data-processing need in some organisational process. It must focus on the process, the corresponding data and related calculations. Data outside the specific functional scope of the system is handled only to the limited extent of the process interfaces. A MIS is therefore a specialised system that handles a limited scope of data.
- The functional focus of a MIS is on the processing to be performed, which often includes data entry by the end-users. This leads to technical choices in which reporting needs cannot be the main driver. For example, the data structure will normally be optimised for responsiveness in data entry at the expense of reporting. When necessary, older data no longer needed for day-to-day transactions, but still useful for reporting, will be purged to make room for new data.

- Even if the combined MIS available could cover the data span required for management, it would be a frightening prospect to have to master all of the different systems, with their idiosyncrasies, access limitations, licence costs, etc., when all you need is to extract information.

On the other hand, management requires an integrated view of management data, with a single reporting environment and powerful analysis tools spanning the whole spectrum of data, from finance to contracts to programme management, and from past to current to planned. A data-warehouse system has specific features that address the reporting problem.

Features and benefits

A data-warehouse system specialises in collecting, storing and rendering administrative and management data. Manual data entry or transaction processing are deliberately beyond the scope of a data warehouse: the data is collected from existing sources like transactional systems or archives – obviously after formal agreement between the data owners and the users of the data warehouse. The data is refreshed in principle once a day, at the end of the working day to avoid any impact of the refresh process on the response time of the data sources.

The Conceptual Data Model (CDM) of the data warehouse represents the data entities handled in the warehouse and their relationships. The representation of each data entity is unique, follows a single set of standards and conventions, and brings together all the data attributes and relationships regardless of their source system.

The physical database of the data warehouse reflects CDM closely, with some redundancies added to optimise rendering, typically in the form of pre-calculated aggregations. This is a major difference between a data warehouse and a transactional, data-entry-oriented system: the former is optimised for providing information *to* the end user, the latter for obtaining and processing information *from* the end user. The result is a single database, structured to reflect functional constructs, and seamlessly merging data from a variety of source systems.

At the user end, the data is made available to end users and client applications – within the limits prescribed by the original owners of the data. The client applications fetch data as input to their own operations. The end users exploit the data by means of the various query, reporting and analysis tools, collectively known as 'IRMA'.

The most notable of those tools is Business Objects (BO), a market leader among so-called 'business intelligence tools', which has been introduced to allow users without knowledge of the technical data structure to perform ad-hoc queries on the data, and such analyses as 'drill-downs' from aggregate into detailed information.

This architecture leads to three families of features and benefits, related to:
- data integration
- time dimension
- operations and costs.

Data integration

Classical information systems automate the processes of one business unit: within ESA, these are AWARDS for Finance, COSY for Contracts, IPMS for Personnel, etc. To achieve this, they store and manage data of specific relevance to the business process they support: contracts, budgets, and staff information. They offer reporting functions centred on this business process data. This creates a double driver for data integration.

The first driver comes from the need, in every system, to handle data of ESA-wide relevance, like lists of Outputs, Directorates and General Headings – and data produced by other systems: industrial-return calculations in SYSTRI are based on commitments created in AWARDS.

The natural solution – building peer-to-peer interfaces – is costly to put in place and to maintain because of the number of interfaces required. If a system receives data from p providers and supplies data to r recipients, the interface cost for this particular system in a peer-to-peer approach is $p+r$.

The Operational Data Store (ODS) is the part of the DW that acts as a broker between the partner systems. On the basis of Data Exchange Agreements established between provider and recipient, ODS collects, integrates and stores the data from one and makes it available to the other. No matter how many providers and recipients there are, the cost to each individual system is reduced to one or at most two interfaces.

The second driver for data integration comes from those users who need broader data visibility than is provided by a single system. The data warehouse caters for these users, allowing, for example, seamless navigation between financial data and related contractual data: the user is not aware that the data originates in different systems.

Time dimension
Retaining a memory of the past is necessary for various reasons. Not only does the legal status of ESA require that at least the last 8 years' worth of financial data be available for on-line consultation, but there are also many other functional uses for historical data.

The term historical – as opposed to operational – refers to data that is no longer kept in its original transactional system, either because it was purged to make room for fresh data (as happens in AWARDS), or because the original system is no longer in operation. The latter is notably the case of EFSY, the predecessor of AWARDS as ESA's financial management system.

The data model of the data warehouse reflects the functional concepts of the transactional systems, but not the technical idiosyncrasies of these systems. This has made it possible (if not easy) to collect, structure and store together data coming from EFSY and AWARDS, which are functionally similar but technically totally different systems. Furthermore, the data warehouse is designed in a way that allows many years' worth of data to be stored and retrieved without penalising performance.

There is more to handling historical data than just accumulating records. It is one thing to accumulate many individual records, created over many years and never changing, like transaction records. It is another to handle information which evolves with time, like the status of commitments. For this, it was necessary to equip the system with a 'snapshot' function able to freeze the status at any given time. Depending upon the type of information handled, the granularity retrievable from the data warehouse ranges from a month to a year. The time interval between snapshots is an adjustable system parameter.

A further dimension to the problem of handling historical data is that the referential data changes over time. These are the pointers used to classify and retrieve the data: lists of Directorates, Establishments, Outputs, etc. After a reorganisation, you need to be able to retrieve the data both through its original reference (former Directorate) and through the new one.

By combining these capabilities, the data-warehouse user can run the exact same queries and reports that are available on current data on data dating back to 1988. These standard queries and reports bear upon the data of one particular year, but if requested an analysis of trends spanning many years could be implemented on the same basis.

Operational and cost-related benefits
Having no data entry makes it possible to optimise the data structures of the data warehouse for efficiency in querying and reporting rather than data entry and transaction processing, which are the main drivers in designing transactional information systems. This is how complex reports can be obtained in the data warehouse with a response time that could not be matched by a transactional system.

Distributing the data entry and the reporting functions over different systems offers the additional benefit that the load can be balanced and the respective systems sized much more accurately. The population of users involved in data entry is a fraction of the population of report users: why bear the costs of a transactional system sized to support both?

Moreover, the separation of the reporting and data-entry functions provides many read-only users with access to reporting functions that they would otherwise not exploit, particularly when the transactional system is a commercial product. Quite a proportion of report-only users would be deterred by the cost of the necessary user's licence, the time needed to learn the idiosyncrasies of the system, or lack of the necessary privilege to use the transactional system.

Finally, the data structure and technical environment of transactional systems can be very complex, which requires development and maintenance personnel with specialist technical knowledge of the transactional system in question and makes it very costly to develop and maintain pre-defined queries and reports under diverse and complex environments. The data warehouse smoothes out the development and maintenance costs by operating in a standard technical environment, and only with the subset of the data structure that has functional relevance.

Value to ESA
The value of a data warehouse to an organisation is measured by the data available from it and the usage that is made of its services within the organisation. The ESA Data Warehouse handles about 150 different data entities, not counting ancillary or technical data. The domains covered (and corresponding partner systems supplying or reading data) currently include:

- finance (AWARDS)
- contracts (COSY)
- missions (MOS)
- personnel, excluding confidential data (IPMS)
- geographical return (SYSTRI)
- invoicing (EFIS).

Table 1. ESA Data Warehouse usage statistics

Number of IRMA active users: 257

Number of Business Objects/WebIntelligence IRMA universe users: 73

Number of FRS Financial reports produced

	May 2001	June 2001	July 2001
Total number	3982	4090	4045
Average per working day	181	195	184

The 5 most used FRS financial reports

Total number of instances produced from April 1999 to August 2001:

Accounting Situation of Expense Lines (582)	26 411
Current Status of Obligations (567)	26 374
Budget Summary (566)	25 546
List of Invoice Lines (574)	18 201
Expenditure by Directorate, Establ. and EPA (564)	2 045

The 5 most used tables in the Corporate Data Browser (BAR)

Total number of calls from December 2000 to date:

Commitments	7905
ESA Staff Missions	6564
Invoices	4958
Budget by Item	4565
Allocations	1698

Programme management systems are gradually appearing. AMS (TOS), AIMS (APP) and IPCDB (MSM) are already retrieving data from the Data Warehouse and have taken steps towards supplying data as well.

Figure 2 shows the data flows currently supported by the ESA Data Warehouse. The user community is comprised of end-users and application owners. The blend of pre-defined reports and guided queries and free-hand analysis tools helps hundreds of users with their administrative and managerial information needs. Table 1 presents some usage statistics. Figures 3a,b show examples of pre-defined report and user-driven data analysis that can be obtained from the same environment.

The two salient examples of AWARDS and SYSTRI show how applications can derive value from the Data Warehouse. AWARDS has delegated most of its reporting and interfaces to it. As a result, it was able to concentrate more on its core function of managing ESA's financial processes. And as its data base was threatening to become clogged up with data still required for reporting but not for day-to-day operations, it also archived 2 years' worth of data into the Data Warehouse and thereby avoided performance degradation. The Warehouse seamlessly absorbed this data and no difference was visible to the end-users.

SYSTRI, the system used by ESA's Industrial Policy Office (IPO) to calculate the industrial

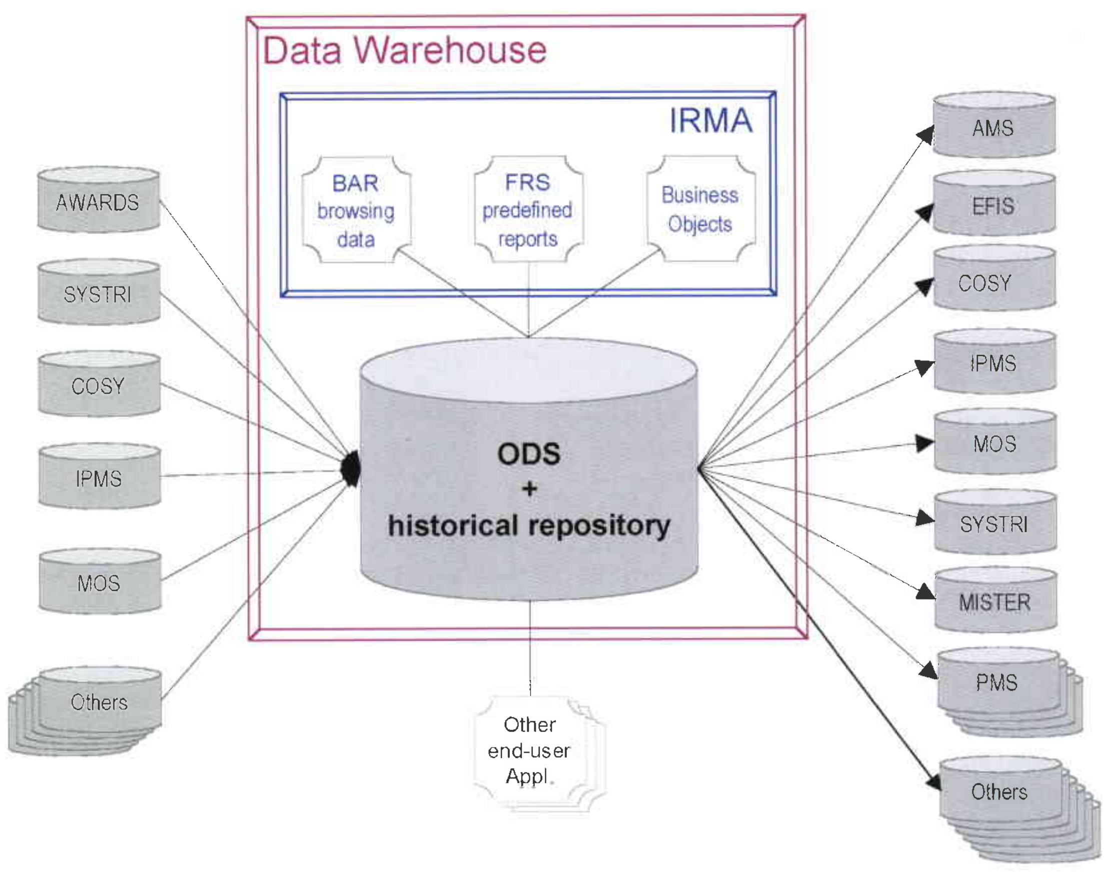
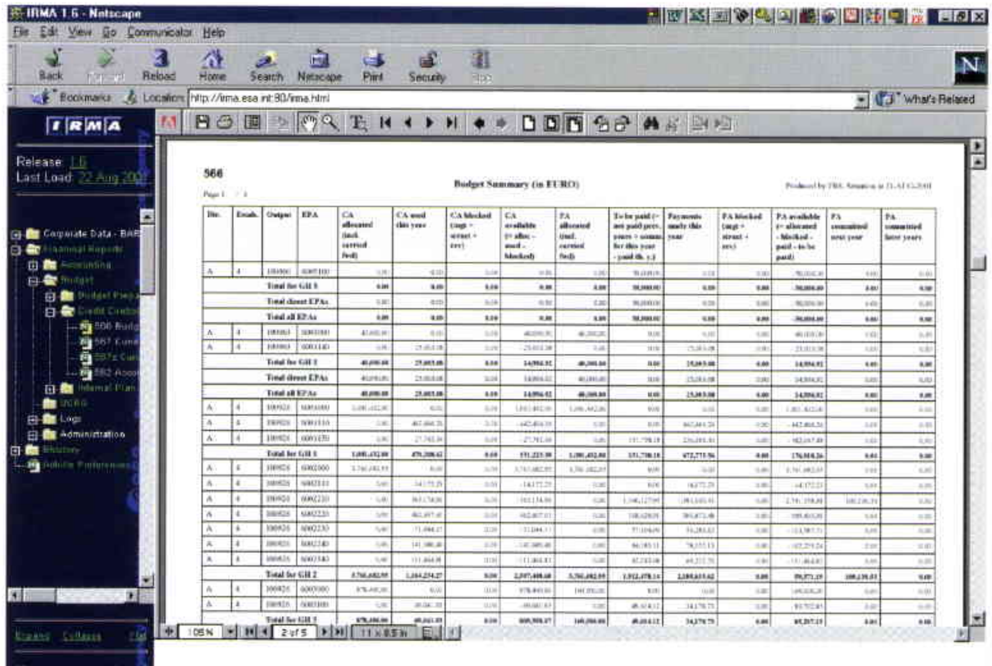
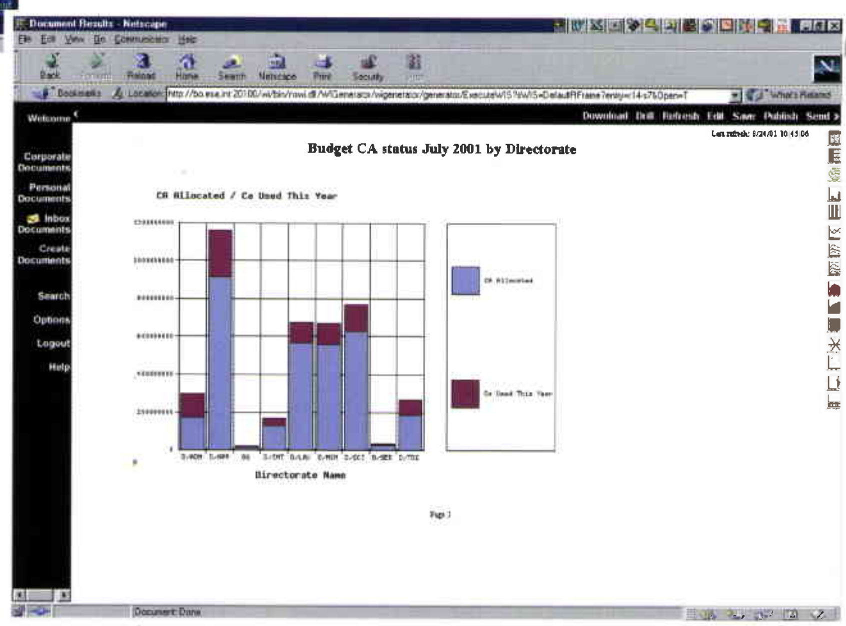


Figure 2. Data flows currently supported by the ESA Data Warehouse

return to Member States from the Agency, relies on data entered by end-users in IPO and in the Programmes, and on a large amount of data centred on the financial commitments. A lot of the basic data handled in SYSTRI are also in the Data Warehouse, and require a similar structuring and archiving approach. This has allowed a high degree of synergy and integration between the two systems, reflected by the commonality of large parts of the conceptual data models as well as the physical data and the use of the same user environment and user tools, in particular Business Objects.





Figures 3a,b. Examples of a pre-defined report and a user-driven data analysis obtained from the same environment

The next wave of project-controller-oriented functionality in SYSTRI, including the management of Work Breakdown Structure data below the financial output level, will be a new opportunity to share data, techniques and tools between the two systems.

Intangible benefits
In addition to these tangible benefits, the introduction of a data warehouse, through the use of a corporate conceptual data model as its foundation:
- fosters the use of a common language throughout the organisation
- facilitates the circulation and common understanding of information, and
- minimises the duplication of inconsistent data repositories.

Having hundreds of users from all Directorates use information based on one logical representation of ESA's data structure promotes a common language and effective communication. It also reduces ambiguity in information exchange and learning curves in cases of staff mobility.

There is still a lot to do in this domain, as can be seen from the multiplicity of interpretations of even such basic and ESA-wide concepts as the financial 'output'. This can be achieved by complementing the corporate data model with a user-readable data dictionary, which is part of the more general 'meta-data management'. The corporate data model, which is the foundation of the Data Warehouse, is also a major enabler of further evolution.

Evolution
The ESA Data Warehouse as it was initially defined will be complete by the end of 2001, with the implementation of outgoing incremental interfaces for the partner systems reading data out of ODS, and the addition of features to enhance availability. Because of the Warehouse's careful design, enlarging its coverage to include additional data types and providing the corresponding capabilities for reporting and analysis comes at an ever-decreasing marginal cost. Now that the major referential entities (financial outputs, Directorates, OBS, EPA, etc.) are in place, adding new data is like adding a piece to an existing jigsaw puzzle. Business Objects, originally a powerful but novel tool, is now past its 'running in' stage, and the roles and procedures around the exchange of data through ODS are starting to be well understood.

Of course, further evolution will be dictated by demand. Two major fields of application are provided by high-level reporting in Executive

Information Systems (EIS) and by the management of the full life cycle of obligations.

Executive Information Systems

Executive Information Systems (EIS) is a generic name for reporting systems that rely on large amounts of data and provide an aggregated and summarised view of it for use by top management. Since ESA's core business is in its programmes, an EIS that would:

- bring together planned data from Programmes
- integrate it with actual and past data from administrative systems, and
- provide reporting and analysis capabilities

could provide a consolidated view of ESA's situation and outlook with respect to payments, commitments, or other parameters.

The challenge is in reconciling the various data structures used in the various Directorates. The concepts used in the central system must be 'compatible' with those used in the individual Directorates and their local management systems, and with the Data Warehouse itself: there must be an unambiguous way of relating the data together. For example, while every programme should remain free to the concepts of project or activity at its convenience, a standard level must be defined in relation to the hierarchy of financial outputs for reporting purposes.

Management of obligation data throughout its life cycle

Before an activity formally becomes a row in the AWARDS commitment database, it follows a period of gestation as a planned activity. It then takes the shape of a contract, translating into commitments, invoices and payments according to a milestone payment plan. The stages of this life cycle are supported by different specialised systems in ESA: various local management tools (LMT) are used in the planning phase (and beyond), COSY handles contracts, AWARDS financial commitments, and EFIS receives milestone payment plans, invoices and payments.

Two major functions would help the end-to-end management of obligations in ESA. The first is the tracking of the obligation through its various stages of planning, contracting and executing. This would allow following the various stages of the 'activity', with the whole history available from one user environment. That environment could act as a portal, opening an access to specialised systems like COSY or EFIS to see more detail or take action on an obligation. A corollary function would aggregate the amounts 'accumulated' at the various stages of the life cycle of the activities.

Another major function will come out of SYSTRI users' initiative to link the obligations to a breakdown of work packages below the level of the outputs. The user group is in the process of defining the required functionality. Depending on the requirements, other structures can be envisaged in addition to the WBS as axes of analysis: Product Tree, Organisation Breakdown Structure, Cost Breakdown Structure, etc. Any structure with at least its top level defined at corporate level is a candidate axis for aggregation and analysis.

As for EIS, further endeavours are contingent on a degree of coordination, so that:

- regardless of local differences in management processes, a number of well-defined aggregating concepts should be used identically throughout ESA; e.g. each programme should be free to define its WBS as it sees fit, but the concept of a work package should have one corporate meaning
- objects that users need to track throughout their life cycle should be assigned unique identifiers at the start of the life cycle and these should never be reused.

Conclusion

Like many organisations, ESA has equipped itself with a Data Warehouse to address its growing needs in the reporting and analysis of administrative and management data. The development originally planned has reached its final stages. The user functions, reporting, analysis and interfacing have been made operational gradually throughout the development and are already very popular. Additional value lies in the common language and improved communication brought about when data structures of corporate interest are standardised ESA-wide.

The data-warehouse concept provides a guarantee of maintaining the historical memory of an essential ESA management data set in periods of change in management information systems, ensuring proper access to the data in a coherent and understandable way. In addition to its current value, the data warehouse offers a wealth of well-structured data that serves as a platform for evolutions whenever required. Of particular interest is the possibility of aggregating programme-management data from the Directorates. This function can yield powerful results if a simple approach to standardisation is followed.

Further information on the features of and access to the ESA Data Warehouse can be obtained from the ESRIN Help Desk. esa

ESA Education on the Web

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Education activities at ESA are developing at a fast pace. The Education Office itself has been enlarged to co-ordinate all education-linked activities at the Agency. However, all ESA Directorates are developing their own activities, and many partners outside ESA are also active in this field. There is thus a need to develop tools to present the different activities in a coherent way to allow anyone, especially young people and teachers, interested in space education to easily find the information that they need. For this reason, the ESA Education Office is developing a web site that will cover all activities linked to education, whether they are proposed by ESA or by some of our partners. This article provides an overview of the main topics that will be developed over the next five years.

The missions of the Education Office
Education is important. According to the ESA Convention, it is one of the Agency's mandatory activities, and it was also specifically mentioned in the second Long-Term Space Policy Committee Report, endorsed by the ESA Council at Ministerial Level (see ESA SP-2000, Actions 18 and 20).

The role of the Education Office was further emphasised at the end of 2000, when the organisation of the Directorate of Administration was revised. The Office is *'responsible for proposing and following up the implementation of education activities aimed at reinforcing in a pan-European manner ESA's contribution to promoting education in the space field'*, and more specifically:

- developing co-operation and partnership agreements with national agencies, government bodies, universities, associations, etc., including the European Union
- administering agreements with organisations such as ISU or EURISY, managing issues related to contributions
- developing ESA educational 'outreach' activities for university students by:
  - fostering the creation of possibilities for students to actively work on space projects before graduating
  - offering them the opportunity to work on real projects together with professionals from ESA, national space agencies and European industry
- organising educational measures for younger students by:
  - promoting space-related activities to attract the attention of young people (primary, secondary and post-secondary levels)
  - developing special projects, programmes and promotional competitive actions
- developing a programme of high-level post-graduate scholarships for staff, nationals of Member States and international candidates, in cooperation with the Personnel Department
- co-ordinating the education activities of other ESA Directorates and consolidating the necessary resources.

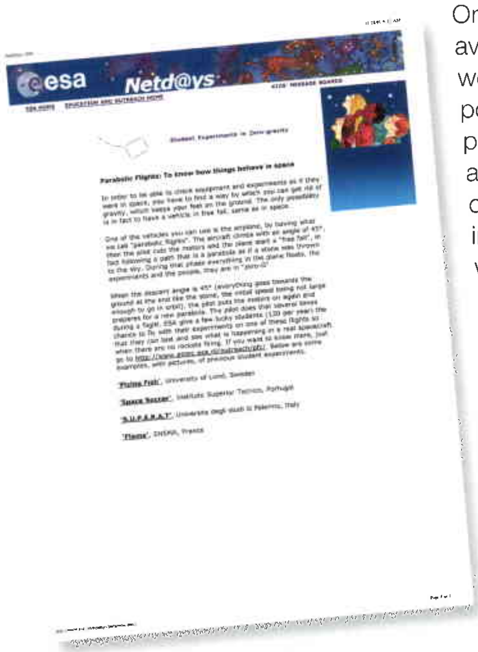
2nd report of the Long-Term Space Policy Committee:
Action 18: *European Space Education Programme*
Purpose: Contribute to the creation of the talented work force needed for the 21st century by providing a European focus for Education on space matters, and stimulating interest in science and technology.

Action 20: *European Space Policy Institute*
Purpose: Create a European focal point for the analysis and academic discussion of European needs, capabilities and long-term prospects in space.

* Based at ESTEC in the Netherlands

In order to fulfil these tasks, the Education Office is now composed of four permanent staff, two of whom work at ESTEC in Noordwijk (NL) and two at ESA Headquarters in Paris, with a fifth one joining at ESTEC in 2002. Up to eight Young Graduate Trainees are also part of the Office and are responsible for specific projects. Each Directorate also has some education activities of its own, and one of the roles of the Education Office is to coordinate the various activities so that all of the efforts within ESA are exploited in the most efficient way. Corporate projects will also be carried out by pooling resources.

Why emphasis is being put on the Web
All actions in the field of education need to be advertised and explained in a coherent way. One of the most efficient tools available in this respect today is the world-wide web. It allows a single portal, or gateway, to be used to present all of the different educational activities carried out at ESA. It constitutes a unique address for informing and contacting everybody who is interested. It also provides links to the web pages detailing the education activities of other ESA Directorates and to the activities of partners outside ESA. All activities concerned with space in Europe can thus be found via the ESA Education web site.



Target audience
The target audience for this Education web site will be young space enthusiasts, because they are the ones we want to reach, encourage and inspire. Many young people in the ESA Member States and around the World are already very interested in space. On our site, they can get information, ask questions, find a job, be put in contact with other space enthusiasts throughout the ESA Member States, obtain help with networking, and much more.

Today, fewer and fewer young Europeans are choosing to study and work in science, and there is a great risk that there will not be enough trained scientific or technical staff for the needs of the 21st century. Space is one of the few subjects that grabs almost everybody's interest, and it is one of the best examples not only for explaining science and technology, but also for motivating the younger generation to study these topics.

The target age group for the ESA education activities is 6 to 28 years, that is from primary level to the end of their studies. This gives us a chance to cover the whole education process and to reach as many young Europeans as possible. Girls, who have to be specifically encouraged to study what are unfortunately traditionally considered as 'male' subjects, will profit from an early start at primary-school level.

If we want to reach all young space enthusiasts, one of the challenges that we have to face is language. We will put a lot of effort into translating the material into as many languages as possible, and arrange for experts of all nationalities to answer questions from all across Europe. ESA's Member States and the European Commission will play an important role in that respect, either by generating material in their official languages or by providing translations.

Main elements
The web site will have many 'chapters' in order to cover all aspects of education and address all possible questions. A short description of what is planned for each section is given below:

1. Learn about space

"Information" will give the basic information on space and space programmes (e.g. information on what space is, what is it used for, and the ESA programmes), using words, drawings and animations easily understandable by even the youngest readers. Links will be provided to the more specialised pages of the Programme Directorates for those who want more detailed information, and to information on sites of external partners.

"What is space" will include the basics about the space environment and its characteristics, the basics of spaceflight (e.g. different orbits and their various uses). The main elements of a spacecraft will also be explained (mechanics, thermal control, orbital control, power…).

"What is it used for?" will give examples of the various disciplines that benefit from space. There will be links to the corresponding ESA Programmes.

The Programmes too will be explained in simple terms, with links allowing those who want to know more to go directly to the pages of the appropriate ESA Directorate and the full explanation. Drawings will show the different parts of the spacecraft and how they are used.

"Past education projects" and their results will also be presented, as they can provide ideas for future projects and form part of the information on space. For example, descriptions of the experiments flown on previous Student Parabolic Flight Campaigns will explain the purpose of the experiment, why it was important to do it under microgravity conditions, and its results.

As many questions are related to working in the space sector, such as 'How can I become an astronaut?', we are including a section about ***professions*** at ESA and in the space sector in general. It will give young people an idea of the studies involved and the nature of the work. It will of course not be limited to astronauts, but will include engineers and all their different disciplines, scientists, lawyers, administrative support, technicians, translators, and many others. The information may be purely factual, but may also be in the form of an interview with someone doing the job.

Young people want and need to see in order to understand. We cannot limit ourselves to words, drawings and photographs. ***Small videos*** of or ***virtual visits*** to the most interesting or impressive venues will be included, such as the ESTEC Test Centre, the ESOC Control Rooms or the launches in Kourou. Seeing Envisat on a vibrating table or Artemis inside the Large Space Simulator at ESTEC has a much greater impact than just an explanation of the tests.

A ***Space Quiz*** with some 90 questions is already available in French and English. It will be improved in the coming months and links added to more detailed answers, so that it will not be only a game, but also a way of learning more. The game encourages the young people to reflect, more than when reading pure information, to analyse the question and think about it before answering.

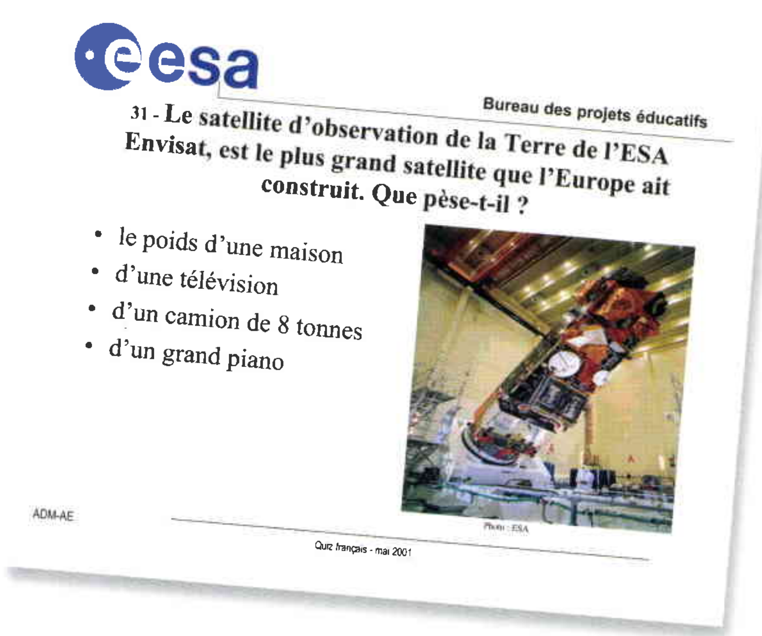
2. Projects that ESA offers or sponsors

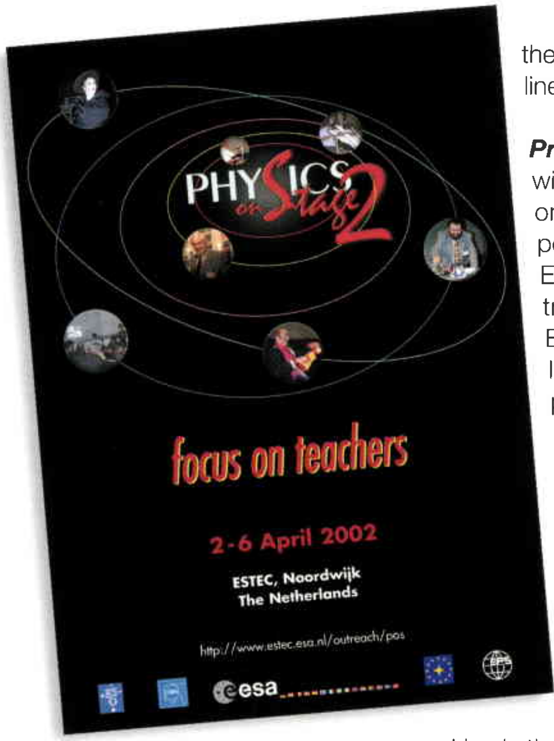
The ESA education projects listed here, some of which will have external sponsors, are directed towards the youth themselves, teachers, schools, associations or any institution that deals with young people. They include conferences/courses given by ESA staff or partners in the schools, programmes to train teachers, outreach projects and training positions within ESA. The goal is to ensure that whatever good ideas are put forward are widely advertised and promoted.

The following are examples of existing or planned projects that might appear in this chapter on the web site:

Organising conferences/courses in universities and schools, with the emphasis on space. These can be courses in the schools of the children of ESA staff, or in the vicinity of ESA Establishments, and can be given in any Member State language. Courses or discussions can also be organised remotely using the video-conferencing facilities available in all ESA Establishments, and could even include transmissions from the International Space Station for 'direct-from-space' discussions. Courses may be recorded on videotape and DVD for further distribution. When ESA staff attend conferences or congresses, they could contact the local schools to arrange a visit.

Training teachers, and encouraging them to exchange experiences through initiatives like 'Physics on Stage', held for the first time in November 2000 at CERN in Geneva (a similar event will take place in April 2002 at ESTEC), or offering courses on space to European teachers to greatly increase the number of students being reached (multiplier effect). Support will be given to these teachers after





their courses, in the form of on-line help, teaching material, etc.

Proposing training positions with all information needed (and on-line registration for the positions proposed directly by ESA) concerning end-of-study training, fellowships (within ESA or at universities), the International Space University programme, and the future European Space Policy Institute.

Co-ordinating the Young Graduate Trainee (YGT) programme, which gives students who have recently graduated the opportunity to gain one or two years of work experience. The YGTs working in the Education Office, for example, are responsible for many of the Office's outreach projects.

Outreach projects for university students, such as participation in the annual International Astronautical Federation (IAF) Congress (100 to 400 students depending on the location), the SSETI initiative (teams of students across Europe design a complete spacecraft via the Internet), yearly parabolic-flight campaigns (carrying experiments developed by student teams), participation in the International Space Station Programme (1% of the European resources will be allocated to student experiments), the 'Teach and Track' project (sending students to developing countries with a small, autonomous satellite receiver in their backpack to teach young people there about space and the benefits of space technology), and many others.

Conferences/Courses that can be given by ESA staff in various languages (non-exhaustive list):

ESA in general
Detailed project or subject (XMM, biology, Space Station, environment...)
Occupations in the space sector
ESA and its partners
What is a spacecraft and how does it work?
What is space used for?
Life in space
Space and law
Technologies in the space sector
Technology Transfer – benefits on Earth
How to finance international organisations

Outreach projects for primary/secondary level students promote school or group projects so that space is studied more intensively, combining different disciplines to help the students understand the complexities of the subject. On-line courses will be offered in a next step for easier contact with the experts. These courses will also be offered on videotape and DVD. The projects also include integrating space into school curricula, through a dialogue with the Ministries of Education and publishers and providing accurate and attractive elements to be included in the school books.

3. Publications and Other Material

The broad spectrum of ESA Publications and material from other sources will be listed here, including PDF files downloadable via the Web. Other items, such as the colouring books prepared by the Technology-Transfer and Science areas, will also be listed so that children can easily order them.

We will also be developing supporting material for dissemination either free of charge or against a nominal charge via ESA Publications Division or the ESA Space Shops. Some of this material will be distributed to space museums or associations at cost price. This will include postcards of some of the best ESA images from the Science and Earth Observation Programmes, for example, and cardboard mock-ups of ESA spacecraft (with an explanation of the spacecraft and its mission in as many languages as needed). Specially tailored video material will also be prepared to support courses and discussions.

4. Contests and exhibitions

Special events like launches will regularly be accompanied by contests for children. Although they cannot be classified directly as 'educative', such contests are important for attracting many children. One can then easily add education information around these contests. The contests will of course be on the web, together with information on exhibitions linked to space in Europe. Details about rentable ESA exhibitions will also be provided.

5. Partners

External partners – National Space Agencies, the Directorates for Research and for Education and Culture of the European Commission, associations, school networks – will be listed here, with links and basic information about what they offer. Links with the youth pages of the National Space Agencies will be included, as well as information about the types of partnerships that ESA has with universities and space-related associations, such as the support to the International Space University and Astrorama (training of teachers and classes for children on space).

6. Ask an expert

An important element will be the new service 'Ask an Expert'. On-line sessions will be organised for special occasions (e.g. in the framework of the EC's *Netd@ys*). All questions posted to the *education@esa.int* mailbox will be answered by experts, and the most interesting ones will be published, either by integrating the answers into the 'Learn about Space' or 'Frequently Asked Questions' sections.

7. Friends of ESA

It is planned to set up a special network of young European space enthusiasts, who can serve as ambassadors for ESA in their schools, universities, etc. Teachers will also be invited to register and to indicate what they expect from us.

Older university students will also be able to register as candidates for the Young Graduate Trainee programme. Today, only two selections per year are made and interesting candidates may be lost because they have been recruited elsewhere in the meantime. With this new registration process, the database will be refreshed and applications examined and followed up much more regularly.

Internal and external networks

The task of co-ordinating the ESA activities implies the existence of an internal network, formed by all staff involved directly in education activities. In addition, a database will be maintained of all staff volunteering assistance, indicating the subjects that they can teach, the languages they speak, the geographical areas to which they can easily go or where they go regularly, and the courses they have already taught.

As ESA is not the only organisation in Europe dealing with space education, for maximum impact it needs to pool its efforts with those of the other players also. The external network should therefore include the Member State space agencies, space associations, schools, Ministries of Education or Science, the European Commission, etc. There are also potential partners outside Europe, for example the International Space Station Partners. Hopefully we will be able to link to their activities and they to ours, in order to organise common/joint activities. Part of this external network will be built with the help of the newly created Advisory Committee on Education (ACE), formed by representatives of the Member States and staff of the Education Office.

Time-frame

A lot of work has been done since the creation of the Education Office, but many projects still need further development. Some will take several years to reach fruition. Basically, what has been presented forms the basis for a five-year plan. The various activities and networks will be built progressively. The number of young people interested in space in Europe is impressive, and the first ones to join the 'Friends of ESA' team will have the chance to help shape the web site and its content. They will also act as 'guinea pigs', in helping us to be sure that the activities that we are proposing are well tailored to their needs and interests.

Closing remarks

The final aim is that any young European or educator who needs information about space or wants to start a project about space will know that they will find the information and help that they need on the ESA web site. ESA will be the place where all information about European space-education activities will be brought together. This will save time and no important information will pass unnoticed. We will need the help of all ESA staff and all ESA partners to build these networks and provide full information about what is going on in space in a comprehensive and easily comprehensible manner for children and students of all ages. This is the only way to make sure that we reach as many young Europeans as possible and have the best chance of helping them to learn about space, science and technology. We will also be helping to train them to manage the space projects of tomorrow!

For further information concerning the ESA Education Office, or to contribute to its projects, write to *education@esa.int* or visit *www.esa.int/education.*

Bed-Rest Studies for the International Space Station

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The microgravity experienced during space flight induces physiological changes that affect astronauts' health and performance. Simulations such as prolonged bed rest can mimic some of these changes and provide study conditions that are more accessible than during space flight itself. Previous studies, including several long and short-term bed-rest campaigns supported by ESA, have yielded significant medical data on the physiological changes induced by space flight. These data are being used extensively to study the effects of various countermeasures on those physiological changes.

Introduction

Bed rest is a recognised tool for validating countermeasures on healthy subjects on the ground before applying them to the astronauts who will live and work on the International Space Station (ISS). It also serves to identify where there are differences between the true effects of space and those of simulation situations, as a means of achieving a better understanding of the profound mechanisms at work within the body's control functions.

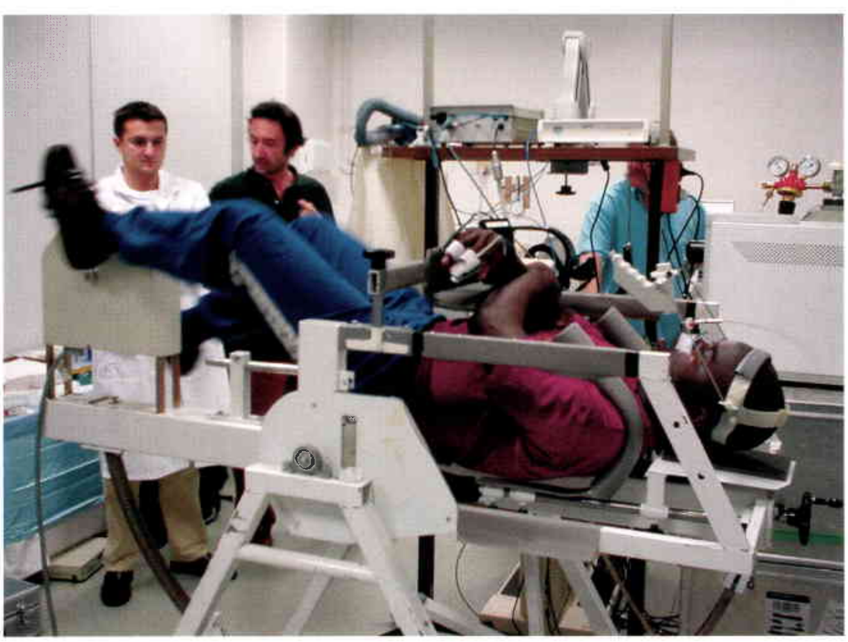

Figure 1. Tilt Table – testing responses to horizontal and upright exercise

For the first time ESA, together with DLR, CNES and NASDA, is performing extensive studies using short- and long-duration bed rest. The short-duration study, which involves a period of two weeks with 10 subjects, is examining the importance of reduced caloric intake on physiological de-conditioning (multiple changes resulting in reduced physical fitness). The long-duration bed-rest study, lasting three months, undertakes a variety of investigations involving 28 subjects. It focuses on countermeasures, studying the effect of an anti-osteoporosis drug as a medical countermeasure and resistive exercise as a physical countermeasure, to determine their suitability for use during long space journies.

The scale and duration of these studies is attracting interest from other international partners such as the USA and China. The physiological changes recorded during space flight and bed rest also mimic those observed as a result of certain diseases and as part of the ageing process. Significant clinical application is therefore expected as a direct result of these and similar future studies.

Background

Space life-sciences research (both at ESA and elsewhere) is predominantly focused on the effects of the space environment on physiological and biological mechanisms. The main aim of such research is to develop areas of basic or fundamental scientific investigation in order to improve the understanding of life, and to apply this knowledge to solve medical problems and support the development of biotechnology. The European Research Plan for Life and Physical Sciences and Applications in Space supports this aim by including initiatives for both preparatory and supporting research, such as access to European facilities for ground-based research and bed-rest studies.

A top-level objective identified in this research plan is 'Improving Health', through basic and applied research related to problems incurred as a result of ageing, disease or disability. Within this objective, the first priority is to understand the body's response to changes in load and mobility both in space and in the clinic. This requires a wide range of studies during space flight and through clinical investigations, e.g. bed-rest studies. The physiological changes occurring in microgravity, although differing in origin, are often similar to those due to certain diseases and to the ageing process, thereby providing new insight into the body's regulating mechanisms. These changes include:

- major changes in the circulatory system, such as altered blood-pressure and heart-rate control
- decreases in muscle mass and in the neuronal control of muscle activity
- differences in posture and locomotion control
- altered perception and cognition strategies in the brain
- bone loss, exceeding 1% per month in weight-bearing bones, in addition to potentially unrecoverable changes in structure
- changes in metabolism such as nutrition absorption and control of excretion of water and salt.

The second priority is to develop counter-measures, often tested using bed rest as the space-flight analogue, and to adapt their use for clinical rehabilitation on Earth. Nearly all space-flight-induced physiological changes observed to date have been well documented. This knowledge base is supporting specific studies on the effectiveness of counter-measures in reducing or eradicating the detrimental effects of microgravity and the absence of loading and mobility. Some current experiments in this area are focussing on resistive exercise, anti-osteoporosis drug testing, forcing appropriate blood and fluid distribution, and the use of vibration devices to trigger bone metabolism. These research areas have a large application potential in rehabilitation medicine.

A third priority is the testing of advanced instrumentation for monitoring and diagnostics. In this area, applied research is being performed in close collaboration with industry, mainly Small and Medium-sized Enterprises (SMEs) working in the biomedical field. Examples include:

- portable devices for non-invasive cardio-pulmonary monitoring
- tele-diagnostics using echocardiography and other relevant methods
- advanced gas sensors for fitness checks
- microcomputer tomography for fine bone-structure determination
- advanced techniques for measuring the electrical activity of muscles (electro-myography).

Why bed rest?

The American and Russian space programmes in the 1960's gave significant impetus to bed-rest research. Before that, a few studies had been conducted on bed-rested patients and on normal, healthy subjects starting as early as 1855. Physicians had used prolonged stays in bed to immobilise and confine patients for rehabilitation and restoration of health even before that time. The horizontal position relieves the strain of the upright posture, often used in situations of acute circulatory situations (syncope), bone fractures, muscle injuries or fatigue. However, adaptive responses occurring during bed rest proceed concomitantly with the healing process.

More recently, adaptive physiological responses have been measured in normal healthy subjects in a horizontal or slightly head-down-tilted supine position during prolonged bed rest as analogues for the adaptive responses of astronauts exposed to the microgravity environment. The recumbent position and prolonged continuous bed rest result in loss of most hydrostatic pressures, virtual elimination of longitudinal compression of the spine and long bones of the lower body, reduced muscular force and psycho-social changes. Bed rest is therefore considered a valid analogue for a number of aspects of space-induced physiological changes leading to de-conditioning.

Figure 2. Micro-neurography registration of electrical signals in a single nerve fibre

The 2001/2002 ESA DLR Short-Term Bed-Rest Campaign

Two bed-rest studies have been initiated in 2001, one short-term described here, and one long-term described in the next section.

Stimulated by findings that with few exceptions space crews lose bodyweight during longer stays onboard an orbiting spacecraft, this phenomenon has been investigated extensively over the last decade. Initially, even up until 1993, it was assumed that the weight loss was due to loss of body water, as its magnitude could easily be explained in that way. The so-called 'fluid shift' – whereby a major part of the fluid in the lower part of the body would move to the upper body in space due to lack of the pull normally exerted by gravity – was the basis for this very plausible assumption, in that the body would attempt to get rid of the excess of fluid in the trunk region. This theory also supported the observation that the circumference of the legs became smaller when in space.

It has now been shown via accurate metabolic studies, however, that the water-loss hypothesis does not hold. It appears that water and also salt are retained in the body to a greater extent than on the Earth; this observation cannot therefore justify maintaining the loss-of-water hypothesis. Instead, the same metabolic studies show that less food is being ingested per day on average during a space flight, and it is speculated that this relative under-nutrition could be a reason for some of the other negative effects observed, and specifically those related to muscle and bone metabolism. Nutritional aspects, coupled with the general unloading in space, which is the primary parameter simulated by using bed rest, may be two main factors causing the weight-loss and tissue changes. A potential effect on the manner in which the circulatory system maintains its responsiveness when exposed to gravitational stress may also be linked with the nutritional state.

Figure 3. Measuring food intake

Figure 4. Analysis of metabolic turn-over

The 2001-02 Short-Term Bed Rest study is composed of four equally long study periods, three months or more apart, investigating the same ten subjects in each of them. It addresses the nutrition-related questions raised above.

In a so-called 'crossover randomised study design' (randomisation of the sequence in which subjects perform the four phases), each person goes through four phases identical in duration and type of examination, but varying in terms of: (a) body position and (b) nutritional state. Each bed-rest study needs a set of control values gathered during an upright-body phase, while the nutritional state includes both a normal state and a state of relative under-nutrition.

By performing the same experiment and examinations during these four, time-wise-identical phases, and observing each of the four possible combinations of body position and nutritional state, the goal is to describe the differences in the observed parameters, which investigate: (a) potential changes in the way in which circulation is controlled under these conditions, (b) changes in the metabolism of bone, muscle and fat tissue, (c) whether there are changes to the kidney's function in regulating excretion of fluid and salt, (d) stress-related factors, and (e) general markers for energy turnover and food intake.

Overall, this short-term bed-rest study is expected to provide very important data on the effects of body position and nutrition on the different body functions, based on very accurate monitoring of the effect of food intake.

The 2001/2002 ESA–NASDA–CNES Long-Term Bed-Rest Campaign

Weight loss is one of several adverse effects of longer space flights. General 'adaptation' to weightlessness, which takes the form of de-conditioning or deterioration of many of the body's systems, involves a long list of additional changes, for which a good understanding of the basic mechanisms involved could help in developing suitable and effective counter-measures.

Another aspect of pure scientific research is that the effects of microgravity on humans are unique in nature. This means that changes, as an effect of continuous unloading, only occur with that particular speed (fast!) and with that particular characteristic when the subject is 'weightless' onboard a spacecraft for a longer period, i.e. several days or more.

The development of countermeasures has been a major goal since the early days of longer-duration space flight. Large variations in the seriousness of the microgravity-induced symptoms from one crew member to another, and the fact that in certain cases very large losses of bone mass or severe deterioration in muscle performance, balance function or circulation control over a period of three to six months can be observed, have been the prime reasons for seeking to understand the underlying mechanisms. The goal is to use this knowledge to develop the most effective countermeasures, but this has proved be a very ambitious goal because there are still serious gaps in our understanding of the basic mechanisms involved. Such countermeasures are therefore what the 2001-02 Long-Term Bed-Rest Study at the Space Clinic MEDES in Toulouse is focussing on.

A general serious constraint, which limits the speed with which progress can be made in this field, is the small number of observations possible due to the limited number of astronauts flying. In principle, each individual can only serve once for the observation of a certain variable, whereas a number of observations are necessary to draw valid conclusions. This is why a highly focused selection process is extremely important when choosing crew-based experiments. A further complication during the ISS construction phase is that crews generally have such a heavy work schedule that time for other research is very limited.

Some responses can be provoked better by using the bed-rest simulation model than others. The focus of the study started in August 2001 at MEDES has been on bone and muscle tissue. The changes seen in space crews bear similarities with the effects of being bed-ridden for long periods. Bone loss in astronauts has similarities with osteoporosis, which is an age- and to a significant extent also a sex-related disease, which particularly afflicts women over the age of fifty or so. A particularly important finding is that while osteoporosis normally occurs later in life and affects persons belonging to a certain risk-group, astronauts are usually younger, healthy individuals who suddenly begin to exhibit bone-mass loss when in the space environment.

In this co-operative study between the Japanese Space Agency NASDA, the French Space Agency CNES and ESA, one Japanese and nine European teams from five European countries have been selected. They will look, in particular, into the effect of bed rest on muscle and bone tissue, but at the same time will study whether exercise- and medication-based countermeasures are effective in counteracting the effects of immobilisation. They will simulate the situation in space by keeping fourteen volunteers in a six-degree head-down tilted position for three consecutive months. The volunteers will be divided into three groups: one will be the control group, one will undertake a certain type of exercise three times a week, and the last group will receive medication for the stabilisation of bone tissue.

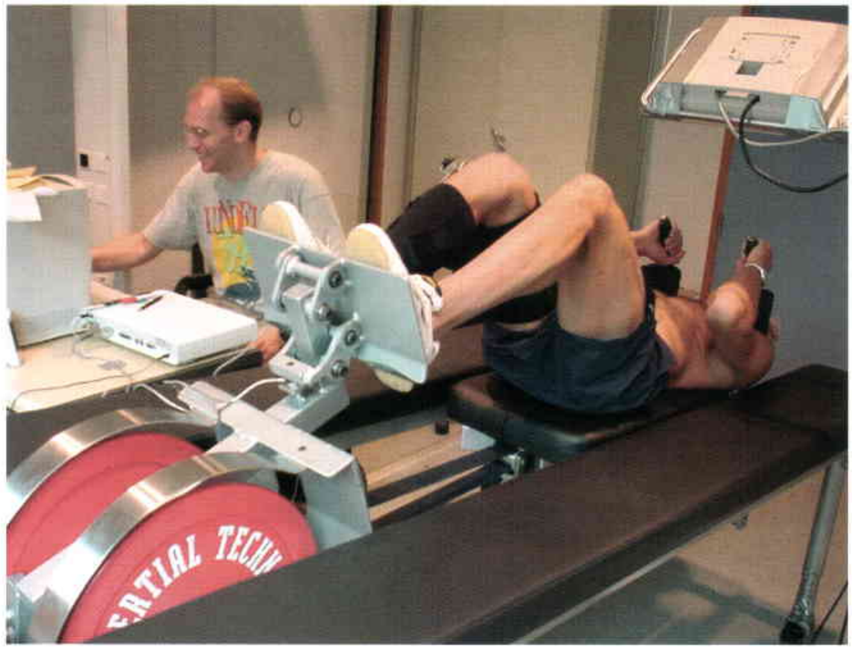

Figure 5. The exercise countermeasure – leg force pushing a set of flywheels

Bed-rest studies of the sort described are in many respects just as complex a those during a space flight:
- planning begins 1–2 years prior to the start of the study
- experiment selection is very similar to that for a manned space flight, in terms of combination of disciplines and relative interdependence

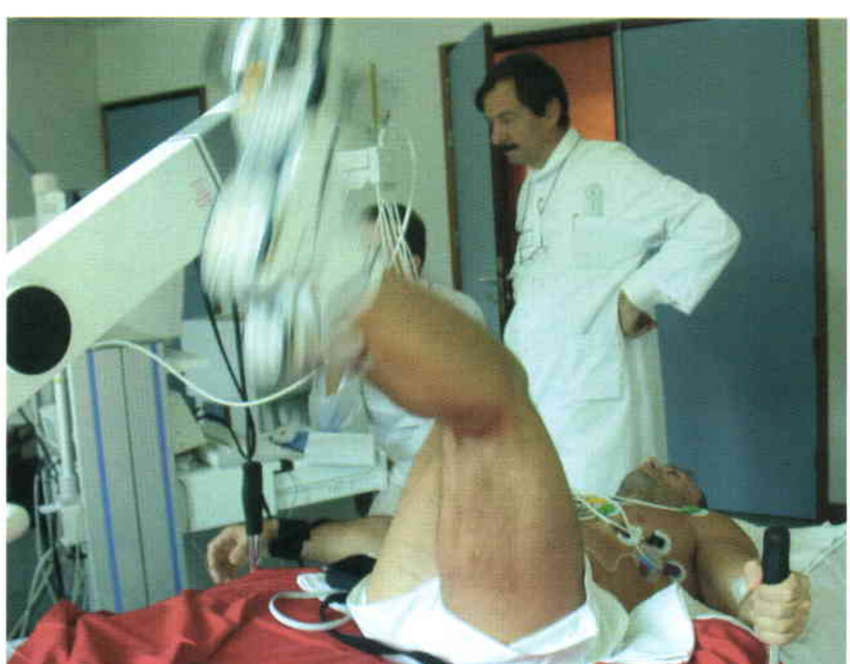

Figure 6. Regular control of dynamic exercise capacity

- the same constraints as for a manned spacecraft apply in terms of general logistics, limited resources, general personal load estimation, ethical aspects, time and availability limitations, etc.

Consequently, space-agency personnel with the relevant experience and research groups who have experience of manned space flights are best-suited for managing such an undertaking.

Clinically, the study should prove extremely important. In particular, we expect to make crucial findings regarding how to maintain muscle mass while immobilised during long-term bed rest, which will benefit millions of patients. The other main focus of the study is to investigate and carefully describe the migration of calcium, bone's main building block, by exploiting a new combination of methods and tools.

Figure 7. Localised QCT: high resolution analysis and imaging of a slice of the forearm

In particular, this is the first time that a combination of nutrition monitoring, X-ray scanning (Dual X-ray Absorptiometry, DEXA, the gold standard) and Quantified Computer Tomography (QCT) have been combined in a single study, whilst at the same time testing different countermeasures on parallel groups. It is believed, for instance, that calcium is released from the bound state in the loaded part of the skeleton as a result of exposure to microgravity and then migrates dissolved in the blood, but the basic mechanisms involved are not at all well understood.

The study is to be seen firstly as a simulation of the present-day length of crew visits to the ISS, and secondly as a first step to investigating the effects and possible countermeasures when crews will be travelling in space for much longer periods, for instance to visit Mars. In addition, apart from their direct importance for manned space flight, such study activities tend to attract the involvement of more and more clinical experts who have had no prior exposure to the effects of space.

Older people who have to be bedridden for long periods have an increased risk of sustaining bone fractures thereafter. Astronauts who are otherwise completely healthy can lose bone structure very fast when exposed to microgravity. Bed rest and the development of bone-tissue changes in healthy young individuals combine these two situations, in a scientifically, trans-disciplinary and sophisticated manner. An added quality of such a study is that the overall effect on the major body systems is investigated, whereas traditional medical research is not geared to this level of ambition. This is because clinical research has the relative luxury, compared to the manned-space-flight situation, of having a large number of volunteers available and therefore tends to address narrower questions, in much smaller 'steps'.

Once this study has been completed, we hope to be able to contribute valuable new ideas on how to reduce the risks associated with clinical bed-rest situations on the ground, and also to develop more modern techniques for maintaining healthy bone and muscle tissue throughout life.

Future work

Following a recent Call for Ideas for simulation models, the need to continue using bed rest as an analogue to space flight is clear. Other analogues will also be looked at in the near future. The problems to be addressed are numerous and a long-term commitment to such studies will be put in place.

In anticipation of future manned space travel within the Solar System, preparatory activities are envisaged within the strategic framework for European space exploration, especially in the new Aurora programme. Here the use of 'space analogues' other than bed rest, such as Antarctic bases for example, is a must. Analogues for confinement and isolation are essential to address such scientific and technical issues as advanced life-support systems, habitability, communications and medical, physiological and psychological problems, which cannot all be fully tested using the ISS only. The use of Antarctic bases for 12–16 months of isolation is also the most suitable analogue for manned missions to Mars.

The European Drawer Rack for the ISS and its Scientific Capabilities

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The European Drawer Rack (EDR) provides accommodation for small and modular experiments, as well as distributing Columbus laboratory services to the EDR payloads. One of its fundamental goals is to support the development of smaller sub-rack payloads through the provision of accommodation and flight opportunities for quick-turnaround missions. The EDR's design is oriented towards user-friendliness and flexibility of experiment accommodation and operation. This article describes its accommodation in the Columbus laboratory, the services that it offers to its payloads, as well as briefly addressing EDR operations and some of the logistical aspects of payload integration and exchange.

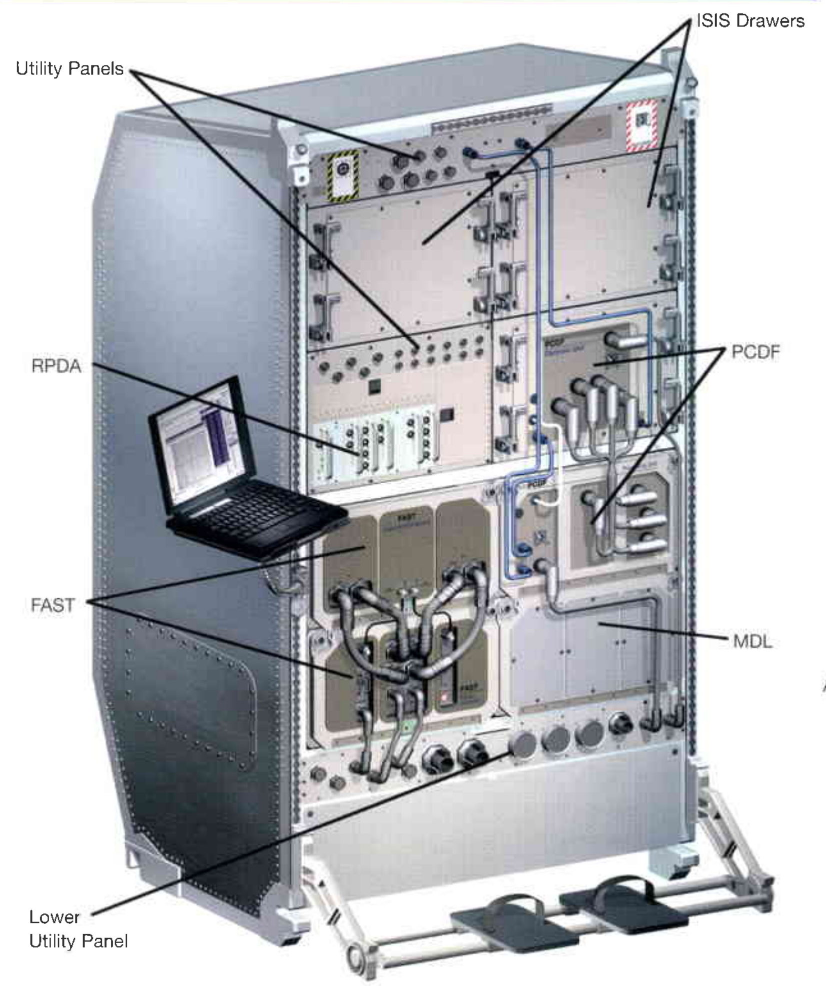


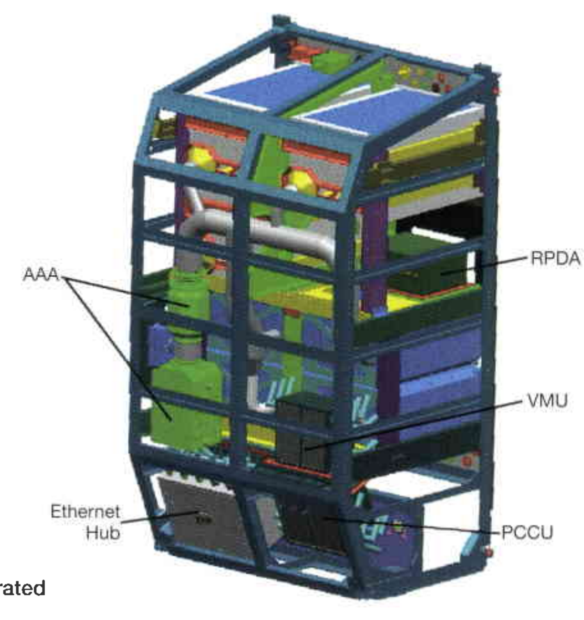
Figure 1a. Artist's impression of the EDR with two payloads (PCDF and FAST) integrated

The design concept

The European Drawer Rack (EDR) is part of the initial Columbus laboratory launch configuration. It incorporates International Sub-rack Interface Specification (ISIS) Drawers and ISS Lockers to allow the easy accommodation of small- to medium-size type payloads (so-called 'Class-II' payloads). This use of standard drawers and lockers will provide a rapid-turnaround capability and hence a greater number of flight opportunities for the user community. The EDR will include a first set of drawers and lockers equipped with experiments selected through European and international Announcements of Opportunity.

The EDR is a multi-user facility (Fig.1) that provides the infrastructure for accommodating and servicing Class-II payloads in an International Standard Payload Rack (ISPR). Modularity and standardisation have been major design drivers for the EDR, both to

Figure 1b. Rear of the EDR with major subsystems



provide a maximum of flexibility and interchangeability for the payloads, and to make optimum use of standardised technology development for the Space Station. At present the Rack can accommodate up to three ISIS drawers and up to four ISS lockers in parallel. In order to service a large number of small, quick-turnaround payloads, its design is optimised for the parallel accommodation of three to four payloads, i.e. each requiring an average of two drawers and/or lockers. A larger number of small payloads can always be accommodated, albeit with the possibility of resource distribution and utilisation restrictions. The resource management at EDR level includes the monitoring/supervision of resources to individual payloads, but not process control for individual experiments, which are in general expected to provide their own intelligence and processing capabilities.

Accommodation in Columbus

EDR will be accommodated in an International Standard Payload Rack (ISPR), manufactured by Ishikawajima-Harima Heavy Industries (IHI) of Japan, which is the current rack standard for European payloads on Columbus. The ISPR will be modified to allow locker accommodation and achieve compatibility with the ISIS standard.

The EDR will be launched with Columbus, with an initial payload complement integrated into the rack, to respect the 500 kg EDR launch-mass allocation. Once in orbit, the overall EDR mass will be limited by the mass-carrying capability of the ISIS drawers and ISS lockers to approximately 650 kg.

Resources provided by Columbus to the EDR include: main and auxiliary power, data uplinking and downlinking, thermal control, and gas and vacuum supplies and venting.

Major development challenges

During the EDR design phase, considerable effort has been made to maximise the number of standard containers (lockers and drawers) available to payloads. Simple payload exchange also requires that payloads be installed and removed by front access to the rack. This necessitated the accommodation of EDR carrier subsystems in the back of the rack, which in turn led to very crowded arrangements with serious difficulties in servicing and repair. Some design constraints and access requirements of standard equipment to be used by EDR turned out to be incompatible with the access constraints imposed by a tilted rack, so that finally one payload drawer 'slot' on the front of the rack had to be allocated to EDR subsystems.

The very limited space available for EDR subsystems and the constraints imposed by the standardised support equipment made it necessary to optimise the allocation of resources to payloads. It turned out to be impossible to route all available resources to all payload slots in parallel. Safety constraints also had to be respected. The actual routing of cabling and piping to payloads itself turned out to be a major design constraint. While ISIS drawers allow most electrical connections to be routed through self-mating connectors at the back of the drawer, the operating concept for ISS lockers necessitates that all resources except air cooling be connected to the front of the locker. This leads to a very large number of connectors – electrical, water, gas and vacuum – being on the front of the rack. Consequently, the assessment of resource distribution to EDR payloads is still on-going.

EDR services and resources

The distribution of centralised resources is mainly realised using five EDR subsystems:

- Power Distribution Unit (PDU)
- Process Control and Command Unit (PCCU)
- Ethernet Hub
- Video Management Unit (VMU)
- Avionics Air Assembly (AAA).

Water, nitrogen and vacuum resources are simply routed to so-called 'Utility Distribution Panels' (UDPs) at the front of the rack, but there are no active control elements in the EDR carrier for these resources, other than a manual shut-off valve for the nitrogen line. The payloads will have to provide the necessary connectors, jumper cables and piping to access the resources at these interface locations, as well as all payload-internal connections between drawers and/or lockers via the front of the rack. A laptop computer, which will not be physically integrated into the EDR rack, provides the main interface for the crew to monitor, control and command the EDR system.

Physical accommodation

EDR payloads are to be accommodated in combinations of standardised 8-Panel Unit ISIS drawers and/or ISS lockers, the main mechanical characteristics of which are given in Table 1. The exact combination of drawers and lockers depends on the EDR payload complement and has to be agreed with the EDR payload integrator. A first set of drawers and lockers will be procured as part of the EDR development effort and may be made available to users; subsequently, payload developers will be expected to procure their own drawers and/or lockers.

Power distribution

The EDR PDU receives Columbus main power at 120 V DC, converts it partially into 28 V DC and distributes both voltages to the EDR subsystems and drawer/locker interfaces. The PDU is based on the Remote Power Distribution Assembly (RPDA), which is an ESA standardised and configurable system. Each ISIS drawer will have a 120 V DC power connection to the PDU. At least one drawer supply will be rated for 10 A. The 120 V DC connectors to the drawers are self-mating at the back of the drawer.

There will be four 28 V DC/10 A outlets at the front of the rack, which are primarily intended to supply the ISS lockers. Three of these outlets are branched in parallel to self-mating connectors at the back of the ISIS drawers. However, for each outlet only one branch of the 28 V DC supply may be used at any time. The 28 V power supply thus becomes a time-lined resource.

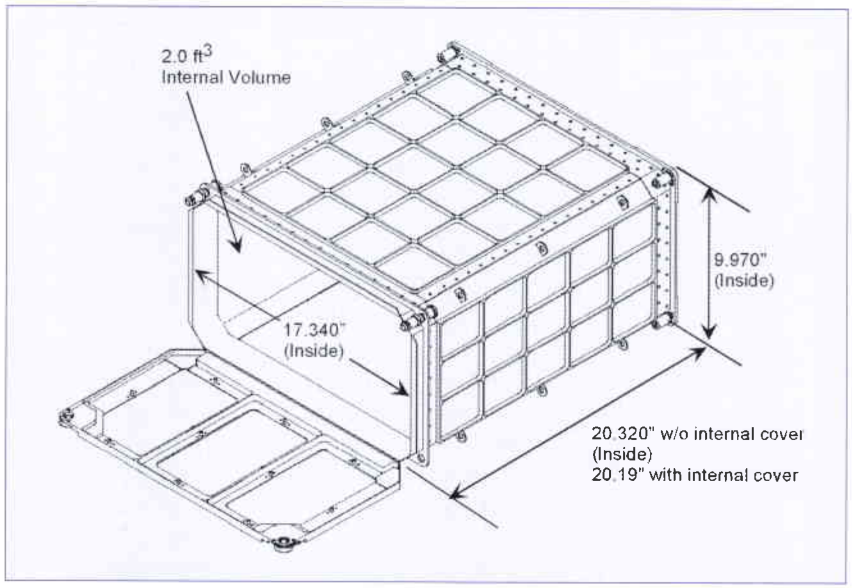


Figure 2a. ISS locker

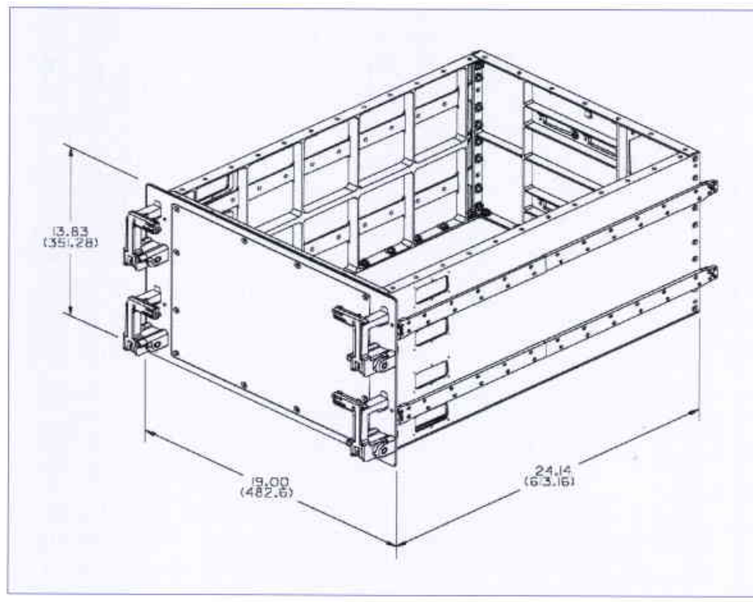


Figure 2b. 8-Panel Unit ISIS drawer

Table 1. Mechanical characteristics of ISIS drawers and ISS lockers

ISIS Drawer Characteristics	
Number of ISIS drawers in EDR	3 (8-PU size)
Volume per drawer available to users (L x W x H)	72 litres 574 x 387x 327 mm^3
Nett mass available to users	39.5 kg
ISS Locker Characteristics	
Number of ISS lockers in EDR	4
Volume per locker available to users (L x W x H)	57 litres 516 x 440 x 253 mm^3
Nett mass available to users	27 kg

The 28 V DC power supply is limited to 280 W per outlet. In principle, it will be possible to route more than one outlet to any given locker or drawer, but payloads wishing to use this feature would have to observe very stringent grounding requirements to avoid ground loops and cross-talk between power supplies. Similar considerations hold for the possible combination of 120 and 28 V DC supplies in any given ISS drawer. The overall power consumption of the EDR payload complement will be limited to 2200 W. Constraints imposed by the EDR thermal-control system may, however, limit the usable power to lower values under certain circumstances. In case of main power loss, approximately 600 W of auxiliary power can be made available to EDR payloads via a manual switch-over. Use of auxiliary power will usually be limited to thermally controlled storage, and must not be proposed for safety-critical operations.

Data handling and commanding

The central data processing system of the EDR, the PCCU, is a standardised system based on the Standard Payload Computer (SPLC). The PCCU software allows reconfiguration in orbit for each new payload increment by uplinking the necessary changes to the system and payload application software.

The main functions of the PCCU include:
- management of the communication interface with Columbus
- management of the laptop interface
- management of the communication interface with EDR payloads
- EDR monitoring and control at system level

- monitoring and control of EDR payload resources
- EDR subsystem management and control
- downlinking of EDR payload data (except high-data-rate connection, which uses the VMU described below)
- distribution of external commands (ground and/or crew) to payloads
- distribution of Columbus time and ancillary data to payloads.

The communication protocol to be used in between the EDR PCCU and the EDR payloads will be the NASA Express Rack protocol. The payload side of this interface has been developed as part of the SPLC industrial contract, and the relevant software will be available directly from the SPLC developer.

The sampling rate of the PCCU for payload housekeeping and scientific data is selectable up to 1 Hz. As EDR will in general accommodate autonomously operating payloads, only very limited processing capabilities will be provided for simple payloads that do not possess any dedicated intelligence. On the EDR Utility Distribution Panel there are connectors for the direct acquisition of four temperatures (thermistor voltages) and four discrete status signals. The EDR will also be able to send up to four discrete commands to such payloads.

The EDR PCCU receives Columbus ancillary data (e.g. loss-of-signal, GPS, microgravity values) and provides these data to EDR payloads as required. It also provides at least 50 Mbytes of memory for temporary storage of EDR housekeeping and payload scientific data, mainly intended for bridging communication outages.

Video Management Unit (VMU)
The EDR VMU is intended to handle a wide range of high-data-rate information from the EDR payloads, be it analogue video, digital video or any other high-rate digital data stream. To support this, it provides NTSC interfaces and IEEE 1355 high-speed serial lines. To limit the volume of downlinked data, the VMU allows one to select a reduced field of view (for digital images) and to perform data compression (both digital and digitised analogue images) using the JPEG standard. The VMU can also support uncompressed data transmission and video storage using any format, including 12- and 16-bit pixel depths. S-video compatible inputs may be displayed on the laptop computer connected to the EDR.

The VMU provides a mass storage capability of 72 Gbytes, the main application of which is expected to be the on-line storage of high-speed or high-resolution video, which cannot be transmitted directly to ground due to downlink limitations. After an experiment run, the user can identify particular frames, sequences, etc. for offline downlinking.

Thermal control
The EDR provides both air cooling and water cooling to payloads. The air-cooling concept is based on the AAA heat exchanger interacting with the Columbus primary water loop, while for the water cooling the primary water loop is directly routed to payloads. The overall thermal load to be dissipated from the EDR payload complement is limited to 2200 W.

The preliminary concept for EDR air cooling foresees that cold air exiting from the AAA heat exchanger will be blown into the back part of the EDR rack and will be routed to ISIS drawers through the gap between the drawers and the ISPR side walls. Each drawer requiring air will have air inlet grids on its side walls near the front of the drawer. For lockers, the air inlet will be at the back of the locker ('rear breather' concept). An air outlet at the back of each drawer/locker will be connected by tubing to the AAA fan, which will suck the exhaust air from each air-cooled box.

The amount of air cooling made available to EDR payloads will depend on the sharing with water cooling for each payload configuration. However, the maximum amount of air cooling that can be made available to the EDR payload complement is presently limited to 700 W. The maximum cooling-air flow rate available to a single EDR drawer/locker is 1500 litres/min.

There are two sets of water connections (two inlets and two outlets) at the Utility Distribution Panel on the front of the rack. The water from the Columbus ISPR interface will be routed directly to these interfaces. Payloads utilising water cooling will have to regulate their throughput to a 0.4 bar pressure difference between inlet and outlet for the maximum water flow rate anticipated. Payloads requiring dynamic flow control of cooling water will have to provide this capability internally. The maximum cumulative heat load that may be dissipated on both sets of water interfaces is 2000 W.

EDR control via the laptop
The EDR laptop will serve as the primary interface between the flight crew and the EDR with its integrated payloads. The laptop supports all functions necessary to monitor and control the EDR, its operation and its resource-usage envelopes, including the ability

to control and command experiments. Although under nominal conditions the EDR should not require crew support, the laptop provides a standardised 'look-and-feel' Human Computer Interface (HCI) for facility control as commonly defined for the Space Station.

Fire detection and warning
The EDR will incorporate a smoke-detector assembly, which will serve as the primary fire-detection tool for the EDR system and all air-cooled payloads within it. In addition, the EDR payloads are advised to include parameter monitoring to give advance warning of a potential fire condition.

EDR payloads that do not make use of air cooling and do not provide adequate air exchange with the AAA will have to base their own fire detection exclusively on parameter monitoring. The payload providers will be responsible for verifying the adequacy of such parameter monitoring via their own safety-review process.

EDR fire suppression will be accomplished through the interface for the Portable Fire Extinguisher on the Fire Detection and Suppression Panel installed on the front of the EDR.

EDR operations
The key to efficient payload operations onboard the ISS will be optimum use of available resources, including power, cooling, telemetry, commanding, crew support, etc. all of which must be shared. As indicated in Figure 3, resources will be allocated hierarchically, starting at the overall ISS level, then to each partner's module, and finally to individual payload facilities. As one of the main drivers for EDR is to allow concurrent experiment operation, resources must be further shared among individual instruments resident in the EDR drawers and lockers. While at the ISS level resources will be relatively firm, a certain flexibility may be expected in the allocation available to a particular facility at any given time.

The EDR utilisation scenario relies on close co-operation between the supporting ground facilities. These include the Facility Responsible Centre (FRC), which is in charge of the overall EDR, and the User Home Bases (UHBs), which are dedicated to the support of individual payloads or experiments. These centres will together be responsible for preparing the EDR operations plan, and controlling and processing housekeeping and science return data.

The EDR is intended to support a relatively quick turnaround for 'small' payloads. It will be possible to exchange complete drawers or lockers (while EDR is powered down) without requiring modification to existing payloads or to the core facility. Such flexibility requires an implementation approach whereby the majority of the intelligence for payload operation is delegated to the individual payloads, with the EDR dedicated to resource allocation and initiation and monitoring of experiment execution.

The software and communications architecture allows in-orbit uploading and reconfiguration of both the EDR and experiment-container software. The main element of the carrier software is the EDR timeline, responsible for the overall scheduling of experiment- and EDR-related software sequences dedicated to the control of individual subsystems and experiments.

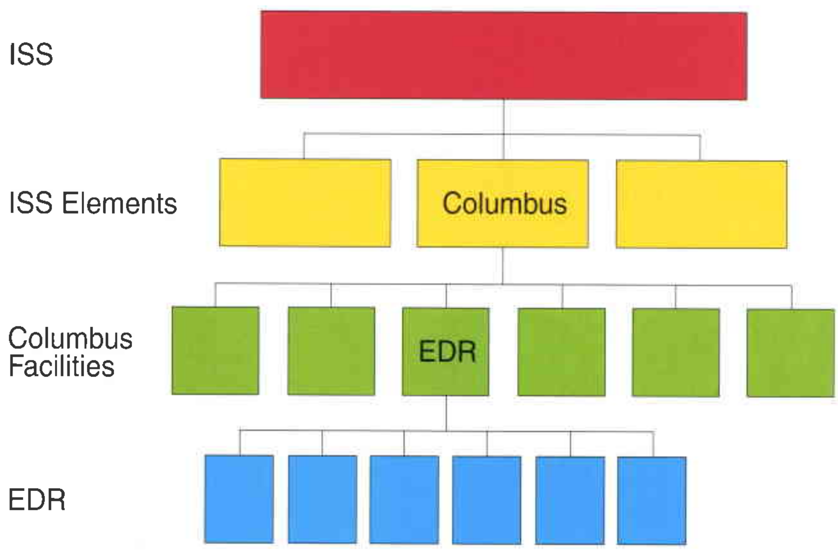


Figure 3. Space Station resource distribution

The master timeline element will be established according to a given EDR operations plan. The latter, which will be verified on the ground, will provide the best match between available EDR resources and those required for experiment execution, the goal being to maximise the number of experiments in concurrent operation.

A key EDR feature will be the ability to control experiments from the ground, allowing any combination of automatic and interactive (telescience) modes of execution.

EDR logistics
The EDR and its initial payload will be integrated into the Columbus laboratory as part of the initial payload complement, termed the 'EDR 1st Mission'. In parallel with this first mission, the preparation and ground testing of new payloads/experiments will result in new

drawers and lockers to be transported to orbit. Transportation of ISIS drawers will nominally be in a NASA Express Transport Rack (ETR) in the Multi-Purpose Logistics Module (MPLM). For the ISS lockers, the nominal means of transport will be the MPLM for unpowered lockers and the Space Shuttle mid-deck for those requiring power during transport.

Drawers and lockers will be exchanged in orbit and payloads/experiments will be processed as part of so-called 'EDR Follow-on Flights'. This implies an on-board configuration evolution, and maintenance of the subsystems and components. A payload utilisation plan will define and schedule the uploading/down-loading of EDR payloads and reconfiguration activities.

EDR payloads will be tested on the ground at various sites at drawer/locker level, using dedicated support equipment to emulate the EDR interfaces. Payload developers will therefore have to deliver ground models of their payloads to the Facility Responsible Centre (FRC), to remain in the EDR ground model for future reference testing as long as the related flight model is in orbit.

Outlook for the EDR

At the time of writing, the EDR Preliminary Design Review (PDR) is being prepared. The EDR flight unit is expected to be delivered for initial payload integration in early 2003.

The EDR's flexible design will allow shorter mission-preparation times than the 'classical' multi-user facilities and provide quick return and delivery of mission products. The payload testing and integration process is expected to be both fast and easy, and payload processing onboard of the Columbus laboratory should make optimum use of the resources allocated to the scientific users. The payloads themselves are being designed for fast and frequent turnaround, moderate use of resources, and flexibility of operation in order to fully exploit the EDR principles of payload exchange and parallel operation of small- and medium-sized payloads.

Acknowledgement

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Programmes under Development and Operations

(status end-September 2001)

In Orbit

Under Development

Integral

The flight-model environmental test campaign has started at ESTEC (NL). The spacecraft containing the Spectrometer (SPI) and Optical Monitoring Camera (OMC) flight models has successfully passed the sine-vibration and shock tests. After integration and functional verification of the remaining flight-model instruments, the test campaign will continue at the beginning of 2002 with electromagnetic compatibility (EMC), acoustic and thermal testing.

The Imager (IBIS) and X-ray Monitor (JEM-X) instrument teams have made good progress in assembling their flight models. JEM-X FM1 has already been integrated on the spacecraft and the delivery of FM2 is planned for December. IBIS has successfully completed its acceptance campaign and is undergoing calibration, with delivery to ESTEC expected, on schedule, in November. The currently foreseen IBIS and JEM-X FM2 delivery dates are fully compatible with Integral's planned October 2002 launch date.

The mission analysis has been updated to match this new launch date. Good progress has been made regarding ground-station coverage during the transfer-orbit injection. The ground-segment verification activities are progressing as planned.

The Proton launcher manufacturing and adaptation activities are also progressing satisfactorily. The Russian Space Agency has confirmed that it can provide a launcher to suit the recently revised Integral completion schedule. A detailed launch-system-development and launch-campaign schedule has been agreed with our Russian partners.

The mission's Time Allocation Committee (TAC) has finalised its work concerning the observation proposals in response to the Announcement of Opportunity (AO-1). The observation programme for the first year of the nominal mission is now defined.

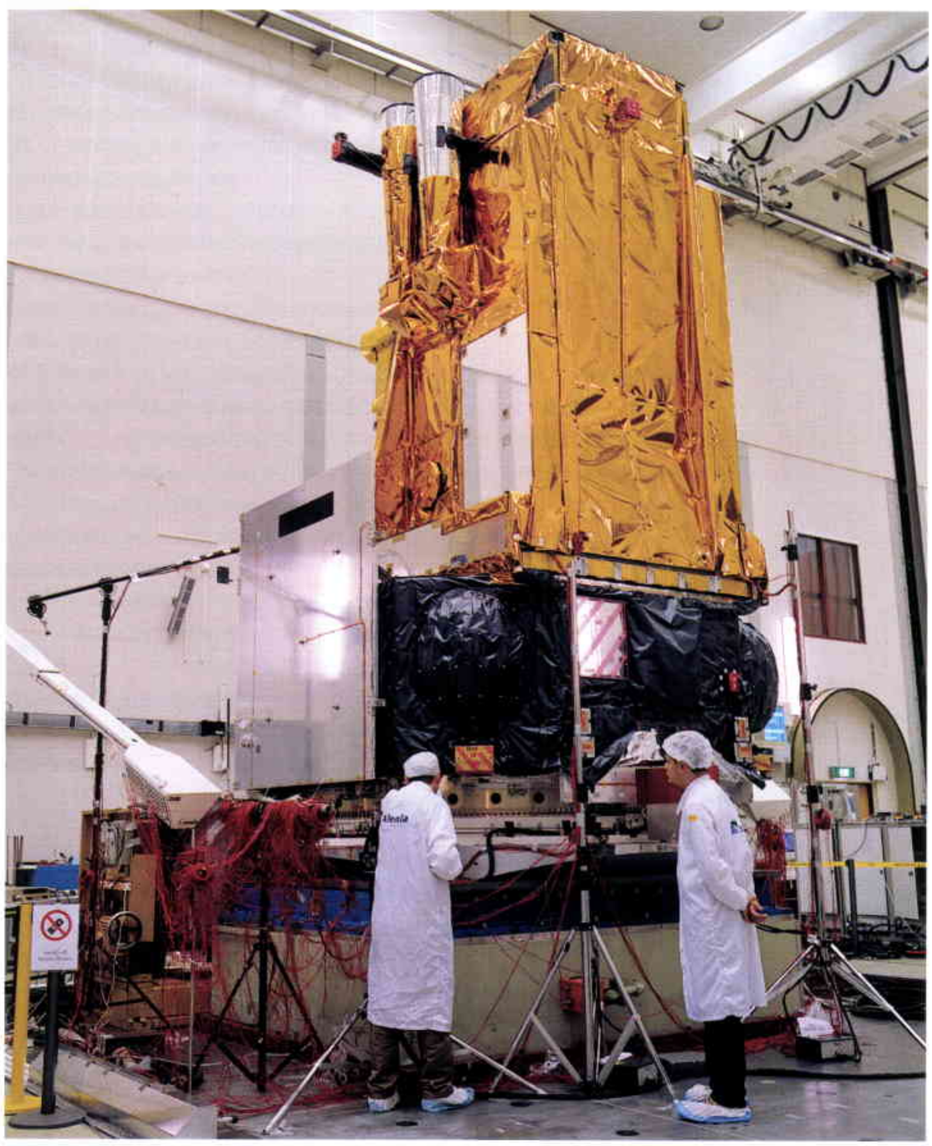
Mars Express

Three main activities took place during the third quarter of the year. Firstly, the structural model, consisting of flight structure, flight propulsion system and subsystem mass dummies, was shipped from Alenia in Turin (I) to the Intespace test facility in Toulouse (F). In September and October, the entire mechanical qualification programme was successfully completed. This campaign included the vibration, acoustic, shock and clamp-band-release tests, as well as other activities. Meanwhile, the structural model is already back at Alenia, and the start of the flight-model programme is awaited.

In parallel with the activities at Intespace, electrical testing of all subsystems continued on the Electrical and Functional Verification Bench at Astrium SAS in Toulouse. Also this task is now nearing completion with the preparations for the final Integrated System Test, foreseen for late-October/early-November, having been completed. Immediately after the successful conclusion of this test, the bench will be dismantled and the hardware transported to Turin for the flight-model programme.

Last but not least, the Mission Critical Design Review was held in early July. Chaired by two senior ESA managers, the Review Board looked at all aspects of the mission, i.e. spacecraft, payload, ground segment, launcher and science operations. The Board made several recommendations to the Project and concluded that the review was successful.

In close collaboration with the launch-service provider, the launch and cruise phase to Mars has been optimised, allowing an extension of the launch window. Its opening, and thus the most likely launch date for Mars Express, is now 23 May instead of 2 June 2003.



Integral sine-vibration test being successfully completed in the ESTEC facilities in Noordwijk

Herschel/Planck

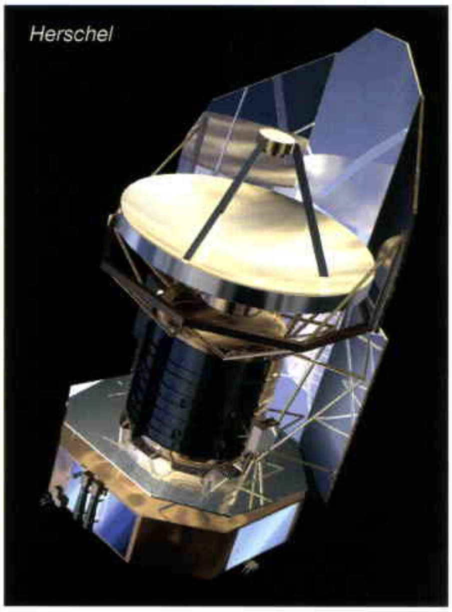
The technical work within the industrial core team, with Alcatel Space Industries as Prime Contractor, which initiated the industrial development and implementation phase for Herschel and Planck, continued throughout the summer period. The focus now is on the consolidation of the conceptual designs for both spacecraft, taking due account of the challenging technical needs and the review of the requirements to be placed on the lower level subcontractors. The major achievement within the last few months was the successful completion of the first system-level review, namely the Herschel/Planck Requirements Review. Started on 1 August with the distribution of the documentation, it was successfully completed with the Review Board meeting on 12 October.

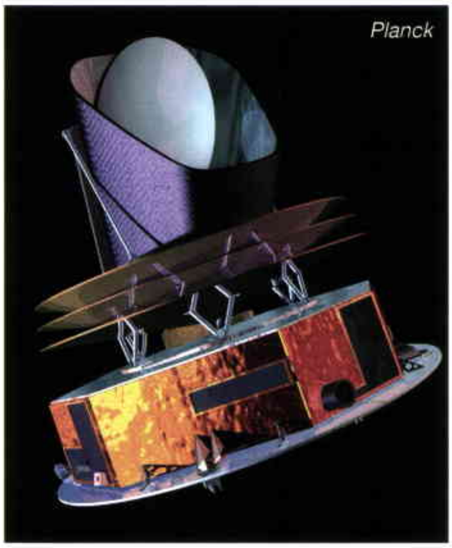
The second main activity, the build-up of the complete industrial consortium up to mid-2002, has started well with the selection of the subcontractors for the first of the four procurement batches. The procurement process, from preparation of the ITT documentation all the way through to the archiving of the winning bid once the contract is kicked-off, is being conducted by Industry under rigorous guidelines set by the ESA Project Team in order to guarantee a fair and competitive procurement process.

Outside the main development contract for the Herschel/Planck spacecraft with Alcatel Space Industries, it is worth noting that the evaluation of the offer for the 3.5 m silicon-carbide telescope for Herschel, a direct delivery from ESA to the Prime Contractor, was also completed in this period. Following the successful contractual negotiations between ESA and Astrium SAS, the development work for this activity has started.

On the telescope of the second spacecraft, where the telescope reflectors are provided via a collaboration with the Danish Space Research Institute (DSRI), progress has also been made and a development contract has been awarded to Astrium GmbH (Germany) after a competitive tender action.

With respect to the scientific instruments, progress is according to plan and the instrument teams are heading towards their major next formal review, which will


Herschel


Planck

release the start of manufacture of the first hardware-development models. The critical development issues identified in the recent instrument reviews are being followed up and closed out one by one. The consolidation of the instrument interfaces with the spacecraft will be completed by year's end.

The co-ordinated parts procurement for Herschel and Planck, originally initiated by ESA to support the scientific-instrument development, has now been handed over to the Prime Contractor and will also include the other parts procurement for the two spacecraft.

The activities initiated with CSL (Liege) for the development of a facility to allow vibration testing of the Herschel instrument's focal-plane units at cryogenic temperatures is approaching the Critical Design Review. The facility will be ready for instrument-unit testing by the end of 2002.

Artemis

The spacecraft is still in its parking orbit at an altitude of 31 000 km. The start of the orbit-raising phase, using the ion-propulsion system on board has been postponed until about mid-December. The new software that has to be written to support the revised operating modes has turned out to be more complicated, and is consequently taking more time to prepare, than expected.

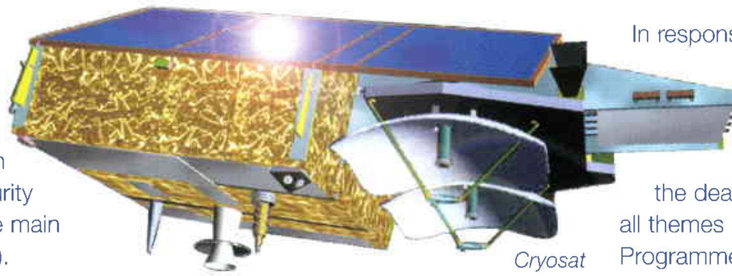
However, whilst in parking orbit, the sspacecraft bus subsystems have been fully commissioned and the satellite's good health has been confirmed. Also, the ion-propulsion elements have been tested and operated for some time, demonstrating their ability to function over longer periods than planned, which will be required for the orbit-raising manoeuvres.

In the course of November, preliminary payload check-outs will be conducted. These tests can be performed for short periods only (a few hours every five days), because the frequencies allocated can only be used from the satellite's nominal position. At other times, when the satellite is drifting along its orbit, the transmitters have to be off to avoid interfering with other satellites in the geostationary arc.

In its parking orbit, Artemis is drifting around the Earth at a rate of 3 deg/hour. To maintain contact with the satellite, therefore, a network of tracking stations has had to be set up around the world – in Fucino (Italy), Dongara (Aus.), South Point (Hawaii) and Santiago (Chile) – to ensure full satellite control at all times. This network will have to be maintained until Artemis reaches its nominal operating position. This major milestone should be achieved in June 2002, provided the planned orbit-raising manoeuvres can indeed be initiated in December.

Earth Observation Envelope Programme (EOEP)

During the last months, Astrium GmbH, the Prime Contractor for the CryoSat project, has concentrated its activities on consolidation of the satellite design resulting from Phase-B. Thanks to the technical contributions provided by some 25 industrial partners, the design has now reached a level of maturity that will form the baseline for the main development phase (Phase-C/D).



Cryosat

Concerning SIRAL, the CryoSat Radar Altimeter, Alcatel (F) has successfully demonstrated the performance of the Solid-State Power Amplifier on a dedicated breadboard. This important milestone validates the technology of one of the most critical elements of the SIRAL instrument.

The GOCE space-segment industrial activities have continued to focus on the consolidation of the satellite configuration and associated budgets and on the competitive selection process for the various equipment suppliers. The efforts spent on the satellite configuration have allowed an overall configuration to be identified in terms of volume, shape, dimensions, etc., capable of accommodating either a micropopulsion assembly based on cold gas or one based on Field-Emission Electric Propulsion (FEEP). However, it will only be possible to complete the satellite design activities to the level of detail necessary for holding the GOCE Preliminary Design Review (PDR) after the final selection of the micro-propulsion technology, which is still pending. The GOCE PDR will therefore have to be shifted to the first quarter of 2002.

The Proceedings of the first International GOCE User Workshop at ESTEC have been distributed to the participants and individual papers have also been made available publicly on the GOCE Explorer web site.

The preparations for Earth Watch led to the adoption of the Earth Watch Declaration and Implementing Rules by the Earth Observation Programme Board (PB-EO) on 20 September.

Support to Eumetsat has continued within the post-MSG consultation activities. In particular, ESA experts are reviewing the observation requirements established by the user application experts.

After evaluation of the two proposals for the Aladin instrument second phase (manufacturing and testing of pre-development model), Astrium SAS has been selected as the contractor for this phase, with the kick-off taking place on 8 October. The PDM development and test contract should last two years.

The Invitation to Tender (ITT) for the APEX instrument's Phase-C/D was issued in August, with a submission deadline of 25 October. To ensure optimum coordination with the EOEP-funded elements, ESA will perform the technical management of Phase-C/D.

In the market-development area, five new short-term contracts and five new longer-term contract opportunities have been selected as a result of two ITTs issued in May and in July. All of these activities target the exploitation of the new capabilities offered by Envisat.

Earth Observation Preparatory Programme (EOPP)

Step 2 of the implementation mechanism for the second cycle of Earth Explorer Core Missions (mission assessment) has been completed. The five ESA Reports for Mission Assessment (ESA SP-1257) have been published and will be presented at the Third Earth Explorer Consultation Meeting in Granada, in Spain, in October. After this Consultation Meeting, the Earth Science Advisory Group (ESAC) will make its recommendation for the selection of the three missions for which Phase-A activities should be started. Following the ESAC recommendation, the Executive will submit an implementation proposal to the Agency's Earth-Observation Programme Board (PB-EO) for discussion at its November meeting.

Coordination with NASDA on EarthCARE has continued in the context of the recent ESA – Japan Meeting held in Tokyo in September.

In response to the Call for Proposals for the second cycle of Earth Explorer Opportunity Missions, 29 outline proposals were received by the deadline. These proposals address all themes of ESA's Living Planet Programme and use a variety of active and passive remote-sensing techniques, exploiting the full electromagnetic spectrum. They are backed by hundreds of scientists from Europe, Canada and elsewhere. The proposed missions require single-satellite, satellite-formation or satellite-constellation implementations, in low Earth orbit and in geostationary orbit. The massive response illustrates the very high interest in the programme.

The Phase-A for SMOS is proceeding according to plan. A Preliminary Requirements Review is planned in October. The scientific review will proceed in parallel. After these two reviews, the proposal for full implementation will be submitted to the PB-EO in November.

International Space Station

ISS Overall Assembly Sequence

Three assembly flights have taken place in the third quarter of 2001. The Airlock 'Quest', the third MPLM logistics flight (which included ESA's Advanced Protein Crystallisation Facility) and the Russian Docking Compartment 1 'Pirs'. The third crew, Expedition-3, is already in orbit. In addition, two Russian 'Progress' logistics flights have been launched. To date, 15 of the planned 49 assembly flights have been completed.

The first scientific experiments have been operated, principally after the MPLM flight in August, and the ESA Global Time System (GTS), which was successfully installed on the Russian Service Module 'Zvezda', should be switched-on later this year.

The ISS Assembly Sequence was updated in June to include some detailed changes to flights up to early 2004 and the deletion of the Propulsion Module from the configuration. The Columbus launch remains scheduled in October 2004.

An independent high-level task force, the ISS Cost and Management Evaluation

Panel, has been appointed to evaluate the serious projected cost overrun of the NASA part of the Space Station and to propose corrective future actions.

Columbus Laboratory

The integrated mechanical flight-unit assembly (the so-called 'PICA') has been transported from Turin (I) to the Prime Contractor in Bremen in an Airbus Beluga. There, the flight unit will be equipped with the functional boxes and the acceptance testing will commence next year. Meanwhile, the electrical test model is undergoing functional qualification testing, including Columbus/ISS interface tests with NASA. Qualification tests should be completed in the first quarter of 2002.

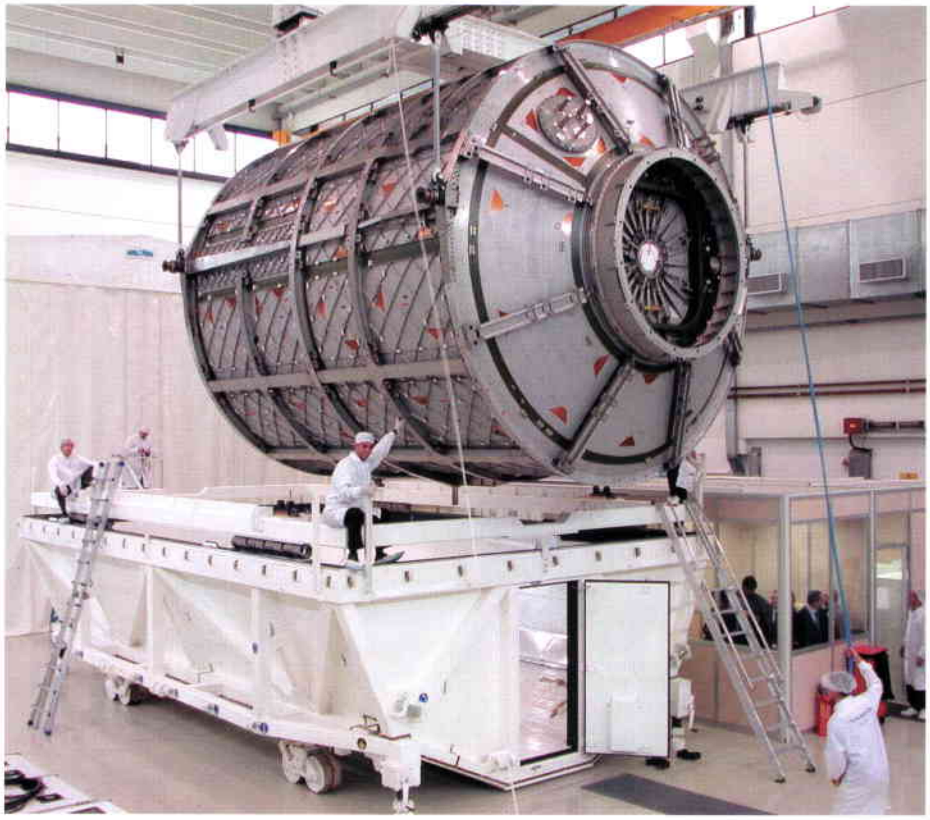
Columbus Launch Barter

Nodes-2 and -3

The system-level modal-survey test has been successfully conducted and the flight-unit integration of Node-2 has been initiated. The harnesses have all been delivered, as has much of the secondary structure. The Node-3 Critical Design Review (CDR) is planned for Spring 2002 and preparation for this is now underway.

Crew Refrigerator / Freezer (RFR)

The Preliminary Design Review (PDR) has been successfully completed.



PICA arriving in Bremen, Germany

Arrival of the ATV at the ESTEC test facilities for environmental testing

Cryogenic Freezer (CRYOS)

The System Requirements Document (SRD) agreement with NASA should be finalised in November.

Cupola

The Neutral Buoyancy Test in the NASA/JSC pool has been successfully conducted and the few minor recommended changes are being incorporated into the design. The CDR has been completed, with no serious discrepancies being found. Manufacture of the flight-unit cylindrical and dome sections is underway, as is that of the window frames.

Automated Transfer Vehicle (ATV)

The pressurised cargo-carrier structural/thermal model (STM) has been delivered to ESTEC in Noordwijk (NL) in preparation for environmental tests. The STM's electrical and propulsion bays are nearing completion and will be integrated with the cargo carrier at ESTEC, before testing begins at the end of the year. Equipment and subsystem CDR campaigns have been initiated.

X-38/CRV and Applied Re-entry Technology (ART)

The X-38 deliveries are continuing and the integration of the orbital flight-test vehicle (V201) is well underway at the integration site at NASA/JSC.

Negotiations have been advanced with industry for the initial CRV activities, and the PATP contract has been agreed with the new joint prime contractors.

Following up a request from NASA, discussions have taken place on a potentially expanded role for Europe in the overall CRV programme. This would change the basis of ESA's participation from that of supplier of interesting technology elements for the vehicle to fundamental participation in the system design, system functions and the delivery of major assemblies (which would still include the technological items).

Ground-segment development and operations preparation

In response to the Request for Quotation (RFQ) for the Columbus Control Centre, DLR (D) has released the lower-level subsystem RFQs. After their evaluation, an integrated offer for the Control Centre will be submitted.

The RFQ for the ATV Control Centre is being prepared for release in the last quarter of this year and the offer for the ATV Control Centre Operations Preparation Definition Phase has been received from CNES (F). The RFQ for the equivalent contract with DLR (D) was released in July and the offer is expected in October.

Utilisation

Preparation

Meeting on 13 September, the European Utilisation Board (EUB) focussed on the issue of access policy for the Space Station. There remained some open points, mainly related to revenue policy and utilisation rights.

Later in the month, the Space Station User Panel (SSUP) advised on how an Announcement of Opportunity (AO) for technology payloads on the ISS could be formulated, emphasising innovation and technology topical teams.

On 27/28 September, the International Microgravity Strategic Planning Group met and the Agencies involved in the recent global AO converged on a shortlist of projects that will require definition studies. Bilaterally with ESA, NASA indicated a clear intention to co-operate in the joint utilisation of ESA-developed facilities.

Hardware development

A study has shown that relocation of the Atomic Clock Ensemble in Space (ACES) to the Columbus External Payload Facility is feasible and a proposal for the Micro-wave Link is now under evaluation.

The System Requirements Review for the SOLAR/EXPORT facility was successfully completed in September.

Phase-C/D of the European Technology Exposure Facility (EuTEF) was kicked-off in August and the PDR for the European Drawer Rack (EDR) is planned for December.

The Requirements Definition Phase for the User Support and Operation Centres (USOCs) is nearing completion and an ESA-led review is planned for end-2001.

Astronaut activities

'Principles regarding Processes and Criteria for Selection, Assignment, Training and Certification of ISS Crew Members', covering increment and visiting crews including non-professional visitors, have been presented by the Multilateral Crew Operations Panel to the Multilateral Control Board.

ESA Astronauts R. Vittori and F. De Winne (backup) started training on 6 August in Star City for a Soyuz Taxi Flight to the International Space Station in April 2002.

For the second period of ISS Advanced Training at Johnson Space Center (JSC), P. Nespoli was proposed to replace R. Vittori. Due to severe NASA security restrictions, the start of his training period was delayed until October.

Preparations for the Andromède mission, with Claudie Haigneré on board, are on track (see 'In Brief', elsewhere in this issue, for the latest news). The crew has passed all tests and examinations and is ready to fly the mission, which is scheduled to take place from 21 to 30 October.

Early deliveries

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

The in-orbit operation of DMS-R is proceeding nominally.

European Robotic Arm (ERA)

The ERA flight model is undergoing functional qualification testing at the Prime Contractor. The work on the Mission Preparation and Training Equipment is experiencing further delays, which will have an impact on the ERA system-level schedule. A credible ERA launch date is not expected before next Spring.

Preparations in progress for the Andromède mission (21 - 30 October), with ESA Astronaut Claudie Haigneré and the two Russian crew members

Laboratory Support Equipment (LSE)
The first flight unit of the –80°C Freezer (MELFI) is undergoing final verification, and shipment in October of the Microgravity Science Glovebox (MSG) to NASA is being prepared.

The engineering unit of the Hexapod pointing system is currently under test.

ISS Exploitation Programme
A Multilateral Commercialisation Group has been set-up and is currently establishing the programme guidelines for commercial utilisation of the ISS. NASA has provided their draft Commercialisation Policy as an input to this activity.

The approach for a Public-Private Partnership between ESA and private or institutional investors has been agreed and industry has offered the Agency their possible contributions in kind and/or cash, which are in excess of 30 MEuro. The Exploitation Contract RFQ has been released to industry. Due to changes in content established during the elaboration of the Exploitation Programme Proposal for the Ministerial Council, it was agreed that industry would provide, in October, a binding offer only for Period-1 of the exploitation phase. At the same time, a high-level commitment for the entire programme, in line with the approved Programme Proposal, will be provided and a formal binding offer will follow early in 2002.

Microgravity

EMIR programmes
Preparations have continued for ESA's participation in the STS-107 Spacehab mission, which has been delayed until June 2002.

Discussions with NASA have continued regarding the uncertain status of the future R-2 Spacehab mission, which would be a major flight opportunity for ESA payloads. At the same time, investigation of other flight opportunities has begun.

An Inquiry Board has reported on the parachute failure during the re-entry of the Maxus-4 sounding-rocket flight and preparations have continued for the Foton-M1 mission.

The Advanced Protein Crystallisation Facility (APCF) was flown to the ISS's Destiny module in August and has operated well since then.

In discussions with representatives of the NASA Office of Biological and Physical Research, an Agreement has been reached on enhanced co-operation in the Life Sciences area.

Microgravity Facilities for Columbus (MFC)
Manufacturing and assembly of the engineering models of Biolab, the Fluid-Science Laboratory (FSL) and the Materials Science Laboratory (MSL) are well advanced. Manufacturing of the flight models of these facilities has started and closeout of the Critical Design Review (CDR) for MSL was successfully completed.

The results of a study of the feasibility of accommodating the Biolab in the US Destiny module, as a possible early flight opportunity in co-operation with NASA, are positive and further assessment is continuing.

Mechanical qualification of the Standard Active Containers for the European Physiology Module (EPM) has been completed and early work on the Electromagnetic Levitation Furnace for the MSL has started.

Ariane-5 Plus

ESC-A
The modal-survey test campaign for the upper composite, including the ESC-A stage's full-scale mechanical model

Artist's impression of Ariane-5 Plus

(known as the 'Maquette Dynamique', or MD) was completed in July. The results were generally close to the predictions. After refurbishment, the MD stage model alone will be submitted to the vibration test campaign. In parallel, integration began of the 'Maquette Ergols' full-scale model dedicated to testing all of the electrical and fluid systems, as well as the ground-handling procedures at CSG.

Manufacture of the first flight hardware items has started. Besides some small items, which are still in the final design phase, the main attention is on the design justification, considering the final load data set. The re-use of existing equipment, in this case developed for Ariane-4 and re-used on Ariane-5, is again proving to be less simple than expected, especially when trying to justify the design and identify the margins within the new environment. The cycle of qualification reviews will start during the last quarter of 2001.

ESC-B, Vinci

For ESC-B, the development activities are focusing on some fundamental architectural and system choices, such as the attitude-control system. In parallel, the main launcher system inputs are being elaborated, and they are to be reviewed during the system concept review later this year. The development of the ESC-B Vinci engine has now completed a first important phase, which involved the successful achievement of all of the major subsystem Preliminary Design Reviews (PDRs). This has allowed the development logistics and the associated planning to be harmonised. Currently, more component tests are being realised (i.e. powder metallurgy impeller, ceramic bearings, casting process, etc.) in order to prepare for the subsystem development tests, which represent the next major milestone.

Vega

The major milestone foreseen for 2002 is the placing of the Vega Development Contract with the company ELV, a joint venture between the Italian Space Agency and Fiat Avio. Before committing to the full development activities, an intense launcher System Preliminary Design Review was conducted in June and July 2001.

The conclusions reached by the Review Board recognised that very significant efforts have been made by Industry and the ESA Project Team during this initial phase of the Vega launcher's development. The preliminary system definition, the development plan and design-to-cost and organisation aspects were among the main technical and programmatic issues that were reviewed. The Board assessed the design of the Vega launcher as being sound and largely based on proven technology, and it concluded that it provides a correct basis for the Request for Quotation for the Development Contract.

As far as the Vega ground segment is concerned, a Joint Working Group composed of representatives from ESA, CNES, Arianespace and ELV was tasked with reassessing the choice of a launch site for Vega in Kourou, in the light of the new schedule and on additional technical and operational factors. The Group completed its activity at the end of June. Both the ELA-1 and ELA-2 sites (the latter becoming available for Vega after the conclusion of Ariane-4 launches) were considered, in combination with various options for the implementation of the Control Centre required for Vega.

Although the ELA-3 solution had the advantage of meeting the requirements of the programme better in terms of synergy and of facility sharing with Ariane-5, it was felt that it would be difficult to optimise without putting a strain on investment costs. The combined operations of Ariane-5 and Vega would have made ELA-3 a single-point failure within the European space transportation system. The ELA-2 solution was felt to be too expensive in terms of initial investment, in association with the costs of dismantling Ariane-4 infrastructure. A schedule conflict was also identified, which would lead to a shift of 18 months in the timing of Vega's first flight. The Working Group therefore concluded that, for the integration and launch of Vega, the ELA-1 solution is the cheapest option and the only one that fits within the programme budget allocations for this segment.

As far as the launch Control Centre is concerned, the group concluded that the use for Vega of a dedicated centre accommodated within the existing CDL-3 would allow substantial investment savings without incurring additional exploitation costs.

Finally, the P80 (Vega's first stage) management scheme assigning project-management responsibility to CNES in Evry (F) has been agreed in detail, and it has already been adopted at working level pending its formalisation. The Request for Quotation for the full P80 Development Contract was prepared according to the ESA procurement procedure, and was issued to Fiat Avio on 9 July, resulting in the industrial proposal being under evaluation during the month of October.

From the P80 perspective, the Vega System Preliminary Design Review has been positive insofar as no major incompatibility has been identified between the first-stage motor and the overall launcher system.

The build-up of the management team both at ESRIN in Frascati (I) and at CNES in Evry (for the P80) has progressed significantly, with the recruitment of ESA internal and external staff, with the Italian Space Agency (ASI) and CNES contributing three and one additional staff member, respectively.

PROBA

Following a three-week launch campaign at Shar in India, PROBA was successfully placed in orbit on 22 October by a PSLV launcher provided by ISRO/Antrix.

Contact with the spacecraft was established during the first orbit. Following verification of the spacecraft's health, the commissioning activities were started from a dedicated ground segment located at ESA's Redu station in Belgium. Commissioning should be completed by the end of the year.

esa

Launch of PROBA on 22 October

In Brief

First European woman on ISS

Mission accomplished: The crew of the Russian-French Andromède mission returned safely to Earth on 31 October after a ten-day trip to the International Space Station (ISS). The taxi flight to exchange the Soyuz "lifeboat" on the ISS brought the first European woman to the Station: ESA's Claudie Haigneré described the mission as a "challenging and intensely fulfilling experience". She was also the first non-Russian woman to fly as flight engineer on a Soyuz spacecraft.

Claudie and her fellow crew members Victor Afanassiev and Konstantin Kozeev spent eight days on board the Station and performed a number of experiments in life sciences, biology, material science and earth observation. Their main task was to deliver a new Soyuz vehicle, the Station's lifeboat, and take the one that had been attached to the Station for six months for their return flight to Baikonur in Kazakhstan.

Since August the ISS has hosted the first European experiments. First to arrive was the Advanced Protein Crystallisation Facility (APCF); shortly after followed the Granada Crystal Box Experiment. The ESA funded Granada Crystallisation Facility, in which protein crystals had been growing since the arrival of the mission, has returned to Earth with Claudie, just like some extraordinary passengers on the Soyuz spacecraft: frog and salamander larvae in the Aquarius containers.

But the ESA astronaut was not only busy with scientific experiments, she also had a lot of PR to do. During her stay on the ISS

Claudie spoke to the French Minister for Research Schwartzenberg, participated in the ceremony for the Prince of Asturias award via an in-flight call to Spain, answered questions from young students in the Cité de l'Espace in Toulouse during a TV downlink, and gave several interviews to TV, radio and newspapers.

"The Space Station is a remarkable feat of engineering, and is taking shape day by day. We were able to set up experiments and carry out a series of medical tests," said Claudie after her return. "Europe is playing a significant role in the development of the Space Station, which will be a key facility for space-based science and technology development in the coming years". esa

Artemis and Spot-4 chat with laser light

During the night of 21 November, two satellites communicated with each other for the first time through a laser beam. ESA's Artemis satellite, currently in a parking orbit at 31 000 kilometres altitude, and the CNES Earth observation satellite Spot-4, in an orbit at an altitude of 832 kilometres, are the first satellites to exchange data using an optical data transmission link. The Astrium-built SILEX system, with terminals on both spacecraft, is responsible for this novel event.

Through the laser data link, images taken by Spot-4 can be transmitted in real time to the image processing centre at Spot Image in Toulouse, France, via Artemis. This drastically reduces the time between taking the picture and its delivery to the centre. The transmission is possible whenever the two satellites are in line of sight. Without the Artemis relay the images are stored on board in Spot-4's memory and dumped to the ground stations.

The experiment performed in the night of 21 November consisted of establishing the link four times: in the course of four successive Spot-4 orbits, the SILEX terminal on board Artemis activated its optical beacon to scan the area where Spot was expected to be. As soon as contact was made, Spot-4 responded by sending its own laser beam to Artemis. On receiving the Spot-4 beam, Artemis stopped scanning and the optical link was maintained for a pre-programmed period lasting from 4 to 20 minutes.

During the period when the two satellites were "communicating", test data were transmitted from Spot-4 to the ground via Artemis at a rate of 50 000 000 bits per second (50 Mbps). ESA's test station in Redu (Belgium) and the Spot-4 receive station in Toulouse confirmed the extremely high accuracy of the data stream. The main challenge in establishing an optical link between satellites is to point a very narrow beam with extreme accuracy to illuminate the partner spacecraft flying at a speed of 7000 miles per second.

Before Christmas, the ion-propulsion phase is expected to start moving Artemis to its final geostationary orbit at an altitude of 36 000 km. Once the spacecraft has reached that orbit, in the middle of next year, the operational phase will begin and the link between the two satellites will be established at least five times a day. esa

ESA stimulates scientific and industrial relations with four East European countries

The Czech Republic, Hungary, Poland and Romania are going to participate more closely in ESA programmes. The aim of the new agreement between ESA and the four States is to stimulate relations with interested European countries, to expand the overall European scientific and industrial base and to enrich ESA as a research and development organisation.

In September the Agency held a workshop in Paris with representatives from the four European Cooperating States (ECS) with the objective of presenting the possibilities of the ECS status and understanding the different views and possible concerns of the countries. To be a candidate for this new agreement, a country must be European and must already have signed a Framework Agreement with ESA. The new ECS Agreement is a bilateral engagement between that country and ESA, and it allows the partner country to participate indirectly in all ESA procurements and activities. In each case, the participation is to be defined in a five-year Plan for a European Cooperating State (PECS) to be jointly agreed by ESA and the country concerned.

Henk Olthof, ESA programme manager, explains, "this new Agreement opens up the possibility to increase the potential synergy between ESA programmes and the future plans in the space field for our four European partners, the Czech Republic, Hungary, Poland and Romania. The ECS Agreement suits their current industrial and financial capacities better than the closer Associate Membership. It creates a natural extension of the existing very fruitful collaboration and allows the four countries to participate in all Agency programmes and enables ESA to benefit from their expertise". esa

World record for ESA

The Dutch solar car Nuna won the World Solar Challenge, a 3010 km race right across Australia for cars powered by solar energy. Having set off from Darwin on Sunday 18 November, Nuna crossed the finish line in Adelaide on Wednesday 21 November in a record-breaking time of 32 hours and 39 minutes.

Day 1

Preparing for the start

The average speed of the car was 91.7 kilometres per hour, also a new record. On the fourth day Nuna had to travel 830 km – the longest distance ever accomplished by a solar car in one day. Nuna pushed the limits by driving at a top speed of more than 100 km per hour, setting a new record by finishing in well under 4 days.

43 racing cars were at the start of the 6th World Solar Challenge in Darwin, Australia. The streamlined Nuna verhicle was built by eight Dutch students from the universities of Delft and Amsterdam. It uses advanced space technology, provided to the team via ESA's Technology Transfer Programme, enabling the car to reach a theoretical top speed of over 160 km per hour.

The aerodynamically optimised outer shell consists of space-age plastics to keep it light and strong. The main body is made from carbon fibre, reinforced with Kevlar, a material used in satellites, but nowadays also in high performance equipment like bulletproof vests.

The car's shell is covered with the best dual junction and triple junction gallium-arsenide solar cells, developed for satellites. These cells have an efficiency of about 24%. ESA will test these cells in space in early 2003, when the technology-demonstrating SMART-1 mission is launched to the Moon.

Nuna also carries Maximum Power Point Trackers, small devices that guarantee an optimal balance between power from the batteries and the solar cells, even in less favourable situations like shade and cloud. Many satellites carry these devices, for instance ESA's Rosetta mission to Comet Wirtanen.

A small strip of solar cells on the side of the car is very special for a different reason: the communication equipment is powered by this strip of cells that were originally on the NASA/ESA Hubble Space Telescope. These cells were part of a large ESA-provided solar array, retrieved by ESA astronaut Claude Nicollier and brought back to Earth in 1993 on a Space Shuttle.

"If Nuna wins the race, it will be due in part to the use of space technology" Ramon Martinez, a mechanical engineering student at the Technical University of Delft and leader of the Alpha Centauri Team, explained beforehand. "But much more important, due to the hard work and dedication of a group of students, it will make a dream come true!"

To fulfil their mission, the student team collected an impressive line-up of supporters. ESA not only provided them with engineering support via its Technology Transfer Programme, but also with general support via the Education Office, headed by former ESA astronaut Wubbo Ockels, who was also adviser to the team. Eric Trottemant, from the Education Office, who developed the strategy software, also joined the team. Dutch energy company Nuon was the main sponsor, and the association of plastic producers APME and the Technical University of Delft strongly supported the team.

After this success, an extensive tour is planned to visit schools in the ESA Member States. This educational programme will emphasise the value of space technology for a more sustainable world and show in a tangible manner how the dreams of youngsters can become reality.

Overtaking 'Aurora'

'Mission Control'

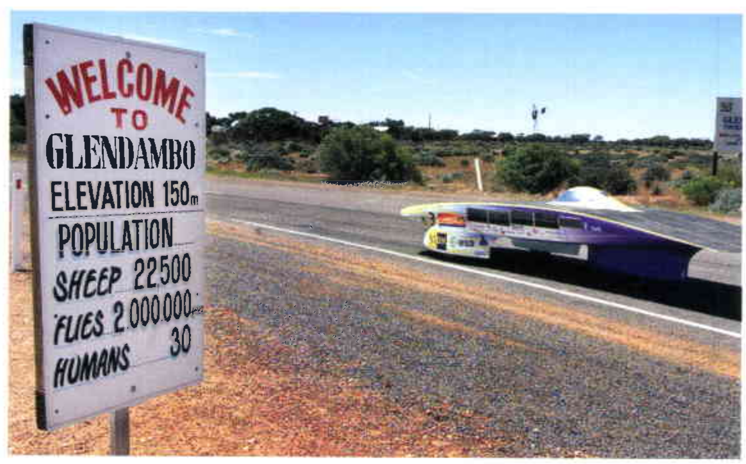
First stop

Day 2

Photos courtesy of: ANP/EPA/Pictor

Charging the batteries

Day 3



Day 4

Royal visit to ESTEC, royal award for the ISS

King Juan Carlos and Queen Sofía of Spain, on a state visit to The Netherlands, came to ESTEC on 25 October with their host Queen Beatrix to see Europe's space agency in action. The royal visitors listened with interest as Antonio Rodotà, ESA's Director General, explained the Agency's role, and watched a wide-screen video presentation summarising current ESA projects. Then the royal party was taken around a life-size replica of Europe's Columbus module, due for launch in 2004.

Three ESA astronauts currently based in Noordwijk - Italy's Umberto Guidoni, Spain's Pedro Duque and André Kuipers from the Netherlands - were on hand to explain from first-hand experience just how things worked. "They were all very enthusiastic. I was surprised how much they were interested in the technology as well as the business of living in space", said Kuipers.

Pedro Duque, who has met King Juan Carlos three times before, was less taken by surprise. "He always asks intelligent questions. He's very enthusiastic about space." ESA's Director General and the astronauts met the King again the next day in Oviedo in Spain to receive the 2001 Prince of Asturias Award for International Cooperation together with representatives of the other ISS partner space agencies, from the United States, Russia, Canada and Japan.

Royal visit to the Columbus module at ESTEC.

The Prince of Asturias Foundation granted this Award in recognition of the efforts made "to achieve international cooperation that have been necessary to turn this enormous orbiting laboratory for scientific research for a greater understanding of our planet into a reality". esa

King Juan Carlos and Queen Beatrix chatting with astronauts Pedro Duque and André Kuipers.

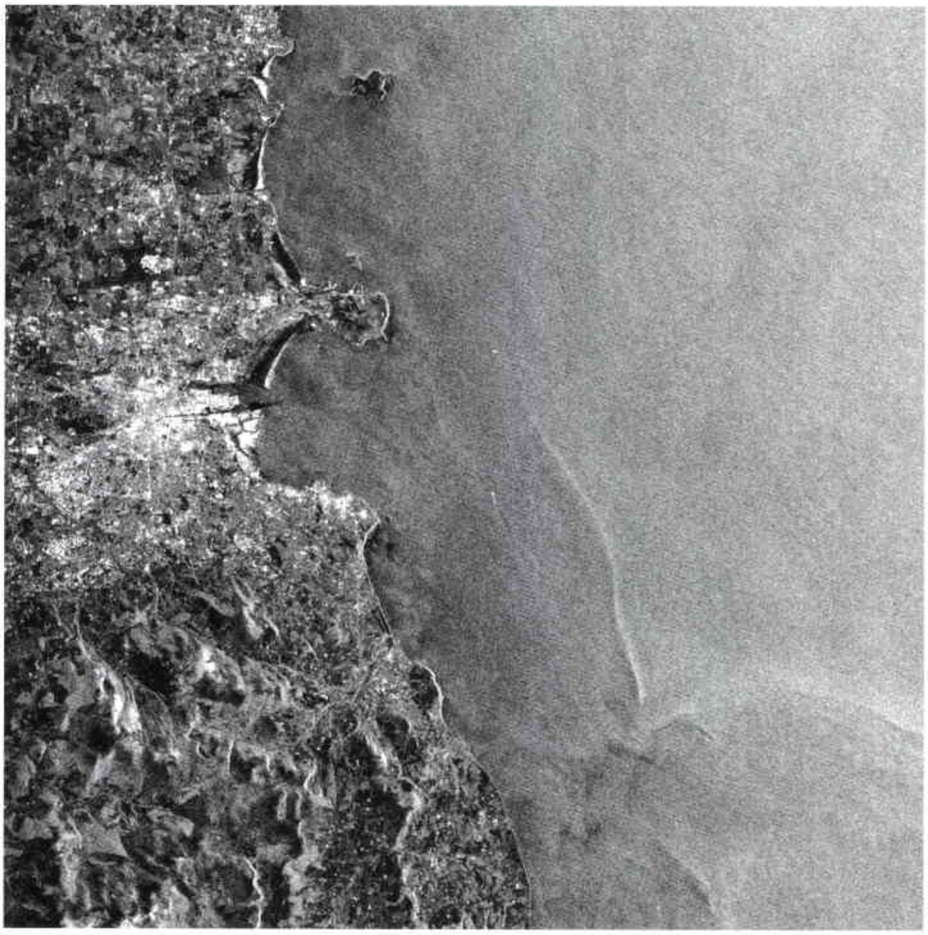
ERS-2 goes gyro-less

ESA engineers have developed a new technique to navigate satellites without the help of gyroscopes and saved the life of ERS-2, the European Remote Sensing Spacecraft launched in 1995. This mode allows ERS-2 to measure the satellite's pointing through the digital earth sensors and payload data, and has led to a considerable improvement on the yaw pointing of the satellite. By January 2000, the spacecraft's gyroscopes – needed to keep the satellite steady in all three axes – had lost their spin; only one still functioned correctly. A team from ESA and Astrium wrote new software to make the new "zero gyro mode" method work: they also had to rearrange onboard memory to free space for the new software, written in an antiquated language from 15 years ago, when ERS-2 was first designed.

The software was exhaustively tested on simulators before being uplinked to the satellite. Even then, they only dared run it in pieces, over the course of a week. Part of their design involved a device called the Digital Earth Sensor (DES), set to our planet's horizon for extremely basic positioning checks. But the engineers knew they could get a lot more precise data out of the DES than just the horizon line. The DES signal was cleaned up to filter out noise, and then used to estimate pitch and roll errors.

That still left the final yaw (or downward) pointing error, which could no longer be measured by the gyro-less spacecraft. The team realised they could check yaw drift themselves, by analysing Doppler frequency shifts in the ERS-2 radar instrument signals. They monitored ERS-2 over a 105-day 'shakedown cruise', totalling three 35-day repeat tracks over the Earth's surface. Recurring patterns of spacecraft 'depointing', caused mainly by terrestrial magnetic field variations as well as pressure from the solar wind, were rendered into a detailed model uplinked to the satellite. This enables depointing to be anticipated and compensated for.

The gyro-less technique should extend the lifespan of numerous other ESA missions, and preserves ERS-2 to operate with its scheduled successor Envisat and to provide wind measurement until Metop-1 takes over in 2003. esa



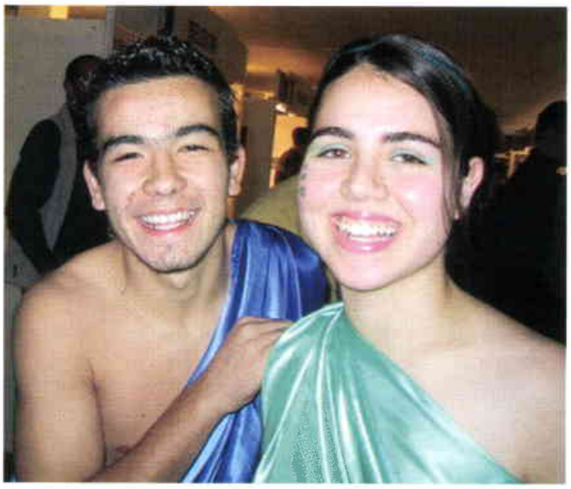
Ireland: Dublin Bay
Image taken by ERS-2 on 10 September 2001 at 11:19 GMT

Future engineers fly to Kourou

Life in the Universe, an event planned by the same organisations as last year's Physics on Stage, was another huge success. Students from all across Europe designed websites, wrote essays, performed scientific studies, created artwork, theatre plays and even musical compositions – all about life in the Universe in the widest sense. The final event, held at CERN in Geneva from 7 to 10 November, brought together the more than 200 finalists from 23 participating countries and science experts in search of extraterrestrial life. In a fair, in presentations and workshops the 14 to 18 year-olds presented their ideas and opinions – all of them extremely impressive and often innovative. The organisers CERN, ESA and ESO had originally planned to sponsor two first prizes for the best projects, but were so impressed with the quality and originality of the students' ideas that they spontaneously decided to offer four additional second prizes.

The winners are the Austrian team of Jan Stuller and Felix Ferdinand Mikl, who won a trip to ESA's Kourou Spaceport in French Guiana to see an Ariane-5 launch. Their project was a design proposal for a self-sustainable human settlement in space, called "Columbiat". The winners of the artistic category were Mihály Kristóf, Katalin Lövei and Adám Orbán from Hungary, with their imaginative board game "Entropoly". They won a trip to the European Southern Observatory's Paranal facility in Chile.

Second prizes were awarded to: Ricardo Moreno Luquero, Alberto Orejana Martin and Roberto Sanchez Garvin from Spain, for their project, 'Meteorites, Craters and Life in the Universe'; Edwin Kite from the United Kingdom for his investigation, 'Could Mars support advanced Life?'; Vitor Ferreira, Joao Dias, Cristiana Azevedo and Catia Lopes from Portugal for their theatrical performance, 'Science Please!', and Ivar Marthinusen from Norway for his essay 'The Caricon from Oxium'. esa



The participants from Portugal who won a second prize for their performance "Science Please!"

Glovebox to the States

The Microgravity Science Glovebox (MSG), one of the first ESA elements for conducting science on the International Space Station, has been shipped from the European Astium consortium in Bremen to NASA's Kennedy Space Center (KSC) in Florida

The MSG will enable astronauts on board the ISS to perform a wide variety of materials, combustion, fluids and bio-technology experiments and investigations in the microgravity environment. It is slated for launch in the mini pressurised logistic module in May 2002.

This science facility provides an enclosed and sealed work volume fitted with lighting, mechanical, electrical, data, gas and vacuum connections, and thermal control for the operation of experiments. The work volume is accessible through built-in gloves which isolate the experiment from the environment and the operator. The MSG is integrated into an International Standard Rack (ISPR) and can operate in open mode, with air circulating from the work volume to the Space Station cabin, or in closed mode, with air circulating within the MSG only. In addition, the MSG has the capability to maintain an inert atmosphere with dry nitrogen such that the oxygen volume is kept equal to or less than 10%.

The MSG facility was built for NASA for a projected operational use of ten years. It will be accommodated initially in the United States Laboratory (USLab) but could be moved later to ESA's Columbus Laboratory. ESA will have utilisation rights over this facility and will pre-screen European proposed experiments that could be accommodated by it.

After arrival at KSC, the MSG will undergo a long series of tests on interfaces with the Space Station. If all goes according to plan, on 18 February 2002 the MSG will be installed in the mini pressurised logistic module and will be ready for its long operational life on board ISS. esa

Space research could save babies' lives

Technology used in space could help to prevent Sudden Infant Death Syndrome (SIDS), commonly known as 'cot death'. The Belgian company Verhaert Design and Development and the University of Brussels (ULB) have developed a new type of pyjamas that monitor babies during sleep.

In the United Kingdom, cot death affects around four out of every 10 000 healthy babies, 86% of whom are less than six months old, while in the United States more than 2500 babies die each year within the first 12 months of life from suspected SIDS.

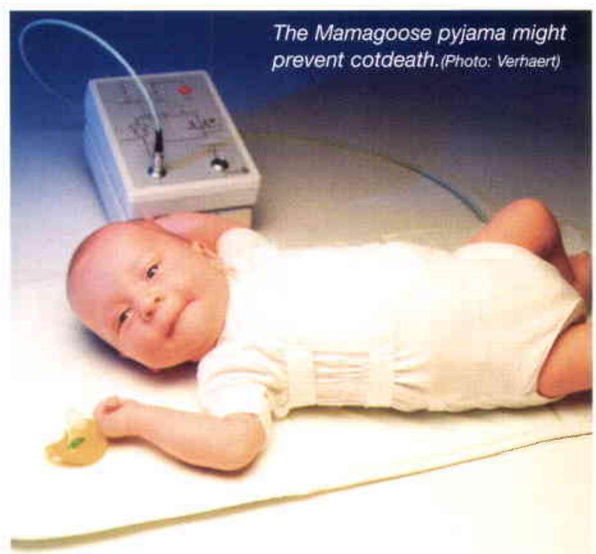
The new pyjamas are very aptly called "Mamagoose", and they draw on technology used in two space applications: the analogue biomechanics recorder experiment and the respiratory inductive plethysmograph suit. This transfer of technology designed for space to Earth application is part of the ESA Technology Transfer Programme. The Mamagoose project is also partially financed by the German Space Agency and IWT, the Belgian institute for the promotion of scientific and technological research in industry.

The Mamagoose pyjamas have five special sensors positioned over the breast and stomach: three to monitor the infant's heart beat and two to monitor respiration. This double sensor system guarantees a high level of measuring precision. The special sensors are actually built into the cloth and have no direct contact with the body, thus creating no discomfort for the baby.

The pyjamas are made of two parts: the first, which comes into direct contact with the baby, can be machine-washed and the second, which contains the sensor system, can be washed by hand. The pyjamas come in three sizes, are made of non-allergic material and have been especially designed to keep the sensors in place during use.

The control unit with alarm system is connected to the pyjamas and continuously monitors and processes the signals received from the five sensors. It is programmed with an alarm algorithm which scans the respiration pattern to detect unexpected and possibly dangerous situations. If found, an alarm system is activated. In addition, the selective memory records data for a certain period before and after the alarm to help physicians to make a diagnosis.

Mamagoose prototypes have been tested on many babies in different hospitals, environments and conditions. These include babies of various weights and sizes, when they are in different 'moods' such as calm, nervous or upset, and when they are sleeping in different positions. To date, the results have been extremely promising.



The Mamagoose pyjama might prevent cotdeath. (Photo: Verhaert)

Verhaert will be responsible for producing Mamagoose clothing once the tests currently being carried out in Germany have been completed. The biomedical physics laboratory of ULB will be responsible for improving the processing algorithm and for providing paediatricians with feedback on the research results

According to Stefaan Devolder from Verhaert Design, the plan is to have the first Mamagoose products on the market within the next year, and Verhaert and ULB are already in negotiation with potential distributors interested in commercialising the product. Once in production, Mamagoose will be an important tool in increasing understanding of the cause of and in preventing cot deaths. esa

Simulation of a Manned Martian Mission in the Arctic Circle

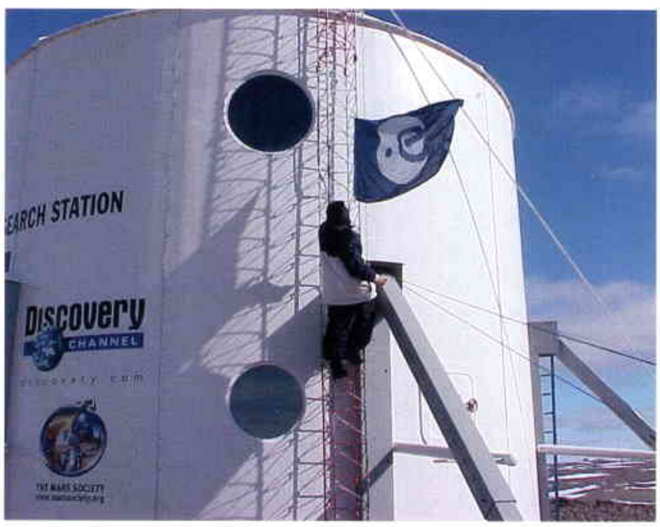
The closest you can get to a Mars landscape down on Earth is on Devon Island in Canada. It isn't exactly a holiday resort, but a group of six scientists, engineers, space enthusiasts and journalists nevertheless decided to spend a week in the cold to simulate a Mars mission. Author Vladimir Pletser was one of them.

Devon Island is an uninhabited island in the Canadian province of Nunavut, at a latitude of 75 degrees North in the Arctic Circle. This island is as large as Sicily, and the Haughton Crater, a geological structure about 20 km in diameter, formed by the impact of a meteorite 23 millions of years ago, is its most impressive landmark. Devon Island's strange geology and ecosystem and the harsh climatic conditions make you think of a Martian environment, except for the presence of a breathable atmosphere. Polar bears and a few other arctic animals are the only sign of life on this island.

NASA took an interest in using this Mars analogy on Earth several years ago. Research programmes have been initiated by the NASA Ames Center and the SETI Institute under the umbrella of the NASA-Haughton Mars Project (HMP). Last year, The Mars Society, a privately funded non-profit organisation, joined the NASA-HMP to establish a Martian Habitat, the Flashline Mars Arctic Research Station (MARS), on the rim of the Haughton Crater.

In this framework, the Mars Society organised this summer an international simulation campaign of a Martian mission consisting of several human crews living and working in a confined environment. International crews of mixed gender and professional qualifications had the same tasks that would be on the to-do list of a Martian crew, including scientific field experiments. Operations were performed just like during a real mission to Mars, including delays in radio communications with the Mission Control Center (located in Denver, Colorado) and Extra-Vehicular Activities (EVA) with specially designed unpressurised suits.

Some 250 scientists, engineers and space enthusiasts answered the call for volunteer candidates issued in November 2000. Only ten candidates, including three Europeans, were selected to join scientists and engineers from The Mars Society, NASA-HMP and the SETI Institute. The author was selected to be a crew member in the second rotation from 10 to 17 July 2001.



The Flashline MARS Habitat with the ESA flag (Photo V. Pletser).

One of the objectives of future Mars missions is the search for water. Water on the surface of Mars exists as ice in the polar caps, but cannot exist in its liquid form due to the low atmospheric pressure. However, liquid water is suspected to exist under the surface, possibly in underground pockets or trapped in rocks. Detecting liquid water under the Martian surface at a depth accessible to a human crew would be important for two reasons. First, under the adage "Find the water, and you may find life", detecting liquid water would increase the chances of finding evidence of past or present life, possibly in a bacterial form somehow similar to terrestrial extremophile bacteria. Second, water sources close to the first Martian human settlements would help to sustain the presence and operations of human crews in terms of consumption and fuel generation.

One of the experiments during this simulation campaign was proposed by Dr Philippe Lognonné (Institut de Physique du Globe de Paris, IPGP, Institute of Geophysics of Paris), Dr Véronique Dehant (Royal Observatory of Belgium, ROB) and the author: "Subsurface Water Detection by Seismic Refraction". It aimed at assessing the feasibility of a human crew conducting an active seismology experiment to detect the presence of subsurface water. A line of 24 seismometer sensors was deployed in several directions on the surface of the edge of the Haughton Crater to record seismic signals generated by a mini-quake, similar to experiments conducted in the past on the Moon. The seismic instrumentation was provided by the IPGP. This experiment can be seen as a possible continuation of the future automatic Seismology and Gravimetry Experiment (SEIS) aiming at characterising the deep internal structure of Mars and its subsurface and searching for the presence of water. The SEIS experiment will be conducted by teams from IPGP, ETHZ (Switzerland), JPL (USA) and ROB scientists during the Netlander mission, a cooperative programme between France, Germany, Finland, Belgium and the USA, to be launched in 2007.

It took us two and a half days to reach the Canadian Arctic. The distance travelled within Canada from Edmonton to Resolute, the most northern Canadian city frequented by regular airlines, was greater than the transatlantic crossing. Upon arrival in Resolute on Wednesday 5 July in the early morning, we were amazed by the constant daylight and the apparent absence of vegetation and fauna. All human activities in the Arctic, also travelling, are very much conditioned by the ever-changing weather. The warm (5 to 10 degrees) sunny summer weather changed to snow, sleet and rain for the next three days, grounding the one plane that could fly to Devon Island. The weather eventually cleared up on Sunday

The purposes of The Mars Society are "to further the goal of the exploration and settlement of the Red Planet, by:
(1) broad public outreach to instil the vision of pioneering Mars;
(2) support of ever more aggressive government-funded Mars exploration programs around the world;
(3) conducting Mars exploration on a private basis."

morning, allowing the crew gathered in Resolute to fly to Devon Island. After landing on a muddy track in front of the NASA-HMP base camp, one of the first things we learned was the use of the camp shotguns, handy to know in case polar bears get too close, and riding the four wheel ATVs (All Terrain Vehicles) used for transportation and expeditions outside the base camp. The base camp consisted of three large tents and the "tented village", made of individual sleeping tents where thick sleeping bags provided a warm welcome. One of the large tents was used as kitchen, mess and warm gathering place; the second was used as a working area by Mars Project researchers involved in field work. The third large tent served as a TV studio for Discovery Channel crews following the simulation campaign. All waste was collected and returned by plane to Resolute in order to preserve as far as possible the pristine conditions of this desert island.

After two days of exploring the area, verifying the scientific equipment and conducting a dry run with the seismic experiment, the second rotation crew was ready to enter the Flashline MARS Habitat, on which the ESA flag was mounted. The Habitat is a cylindrical building with two floors, approximately 6 m in diameter and 6 m high, with two doors. The first floor accommodates the working and living area, with a kitchen and six small rooms just large enough for a sleeping bag. The ground floor is made up of a laboratory and working area, an EVA preparation room, two unpressurised airlocks, a small bathroom, and an incinerator toilet. Problems in the setting-up of satellite links did not allow the delayed communications with the Mission Control Center in Denver. Contact with the outside world was only possible by radio with the base camp and by e-mail with the Control Center and the rest of the world.

Our crew of six consisted of Robert Zubrin (Mars Society President and Simulation Commander), William Clancey (Computer Scientist, NASA-Ames), Charles Cockel (Biologist, British Antarctic Survey), Stephen Braham (Simulation Chief Engineer, Simon Fraser University, Canada), Katy Quinn (Geologist, MIT, Boston), and myself. The scientific programme included several field expeditions under simulated EVA conditions for biology and geophysics experiments and participation as subjects in various psychology and human factors investigations.

We conducted our first, two-hour EVA on Wednesday, 11 July, to collect rocks in search of fossils and other biological evidence of past life. During the second, four-hour EVA on Thursday, 12 July, a three-member crew conducted the seismic experiment in rough rain and wind conditions. The 24 sensor line was deployed in the Haynes Ridge plain in front of the Flashline MARS Habitat and we made three tests with mini-quakes generated by sledge hammer blows. The third, three-hour EVA took place on Saturday, 14 July, to deploy radio-biology dosimeters inside the Haughton Crater. During the EVA we also visited other potential locations for deployment of the seismic experiment inside the crater. The fourth, two-and a half-hour EVA expedition on Sunday, 15 July, was a scouting EVA to find other locations to deploy the seismic experiment in the Von Braun Planitia, a few kilometres away from the Mars Habitat and the NASA-HMP base camp. After assessing the merits and disadvantages of several locations visited, taking into account the seismic interest, the access possibilities by ATVs and the terrain conditions – which were rather muddy in some places due to the severe rains of previous days – we decided that the fifth EVA of Monday, 16 July, would take place in the Haughton Crater. It would be the most ambitious EVA planned, with deployment of the sensor line in two perpendicular directions and six tests, including sledge hammer blows and thumper gun shots at each of the test locations. The four-member EVA crew left for the crater in the morning. When we were inside the Haughton crater, the trailer with the 130 kg instrumentation got stuck in the Arctic mud to a depth of half a metre. We lost more than one hour trying to pull the trailer out. After this, we were exhausted and the terrain conditions had become even worse, so we decided to abort the EVA and to return to the Habitat. On the way back, the instrumentation trailer got stuck a second time in the mud and was salvaged again only after quite some time. This EVA eventually lasted three and a half hours and was concluded, alas, without any results. The sixth and last EVA took place on Tuesday, 17 July, and lasted two and a half hours. A three-person crew deployed the seismic experiment in the Haynes Ridge plain, at the same location as the second EVA, allowing a complete three-dimensional characterisation of its underground structure.

We could not find any water under the Haynes Ridge ground despite the humid conditions at the surface. However, a first result analysis showed that the average signal velocity was 2600 m/s, consistent with Calcium Carbonate and Dolomite, commonly found in this area. Other results of this campaign simulation concerned the ergonomics of the equipment used, which was not initially adapted for use with EVA suits and required the use of extra tools like screwdrivers and pliers to activate switches, turn knobs and push on computer keyboards. We noticed as well

Geologist K. Quinn using the sledge hammer in the rain during the second EVA on 12 July, while V. Pletser operates the IPGP acquisition system under the supervision of R. Zubrin; the MARS Habitat is visible in the background (Photo V. Pletser).

that conducting the seismic experiment under EVA conditions was physically very demanding. This has a direct consequence on the choice of conditions for the interplanetary travel between Earth and Mars that would last several months. An interplanetary flight under microgravity conditions would have well-known debilitating effects on the musculo-skeletal system to a point where a crew, after landing on Mars, could no longer carry out physically demanding activities. Therefore, an Earth-Mars mission would benefit from either effective counter-measures during a 0g flight or an artificial gravity system in the design of the interplanetary spacecraft.
In view of the success of this first simulation campaign, the Mars Society intends to conduct further simulation campaigns in the coming years and to install other Mars Habitats in remote locations on Earth, one of them also planned in Europe (Iceland or Greenland). Several ESA project teams have also expressed their interest in conducting tests in similar extreme polar environments. So in small steps, Mars is getting closer.

Vladimir Pletser
Microgravity Projects Division,
ESA Directorate of Manned Space and Microgravity

Further information can be found at:
http://www.arctic-mars.org
http://arctic.marssociety.org
http://www.arctic-mars.org/team/2000/index.htm

R. Zubrin and V. Pletser pushing the instrumentation trailer out of the mud in the Haughton Crater during the fifth EVA on 16 July (Photo Discovery Channel).

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

ESA Newsletters

REACHING FOR THE SKIES NO. 24 (NOVEMBER 2001)
NEWSLETTER OF THE ESA DIRECTORATE OF LAUNCHERS
WILLEKENS PH. & BENAITIER F.
(EDS. SAWAYA-LACOSTE H. & BATTRICK B.)
NO CHARGE

ON STATION NO. 6 (SEPTEMBER 2001)
NEWSLETTER OF THE DIRECTORATE OF MANNED SPACEFLIGHT AND MICROGRAVITY
ED. WILSON A.
NO CHARGE

ON STATION NO. 7 (DECEMBER 2001)
NEWSLETTER OF THE DIRECTORATE OF MANNED SPACEFLIGHT AND MICROGRAVITY
ED. WILSON A.
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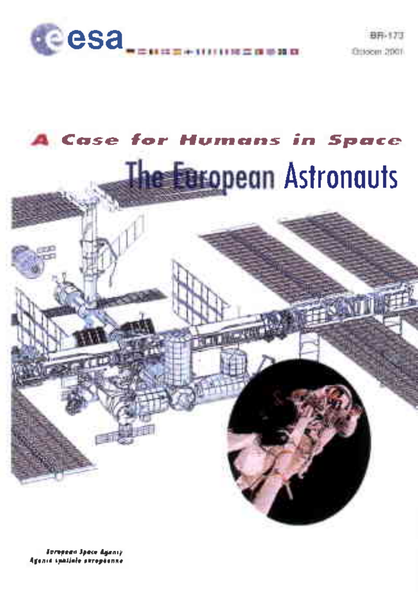

ESA Brochures

ESOC: CENTRE EUROPEEN DE CONTROLE DES SATELLITES (AOUT 2001)
LANDEAU-CONSTANTIN J.
EDS. SCHUERMANN & WARMBEIN B.
ESA BR-110 (UPDATED) // 32 PAGES
PRICE: 10 EURO

THE EUROPEAN ASTRONAUTS – A CASE FOR HUMANS IN SPACE (OCTOBER 2001)
ED. WARMBEIN B.
ESA BR-173 // 38 PAGES
PRICE: 10 EURO

ESA TELECOMMUNICATIONS (NOVEMBER 2001)
- STRATEGIC PLAN
- LONG-TERM PLAN
- IMPLEMENTATION PLAN

ELIA C. (ED. B. BATTRICK)
ESA BR-177 // 69 PAGES + CD-ROM
PRICE: 30 EURO

ROSETTA – EUROPE'S COMET CHASER (SEPTEMBER 2001)
ESA SCIENCE PROGRAMME COMMUNICATION SERVICE
TEXT BY: P. BOND
EDS: BATTRICK B. & TALEVI M.
ESA BR-179 // 21 PAGES
PRICE: 7 EURO

ESA SECTORIAL / CROSS-SECTORIAL STRATEGIES (NOVEMBER 2001)
ESA STRATEGY DEPARTMENT
ED. BATTRICK B.
ESA BR-180 // 40 PAGES
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ESA STRATEGY DEPARTMENT
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ED. BATTRICK B.
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ELIPS: LIFE & PHYSICAL SCIENCES IN SPACE - EXECUTIVE SUMMARY (NOVEMBER 2001)
ED. WILSON A.
ESA BR-183 // 16 PAGES
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A. WILSON
ESA BR-200 // 280 PAGES
PRICE: 30 EURO

ESA Special Publications

ENVIRONMENTAL TESTING FOR SPACE PROGRAMMES – PROCEEDINGS OF THE 4TH INTERNATIONAL SYMPOSIUM, PALAIS DES CONGRÈS, LIÈGE, BELGIUM, 12-15 JUNE 2001 (SEPTEMBER 2001)
ED. SCHÜRMANN B.
ESA SP-467 // 565 PAGES
PRICE: 50 EURO

EUROPEAN ROCKET AND BALLOON PROGRAMMES AND RELATED RESEARCH – PROCEEDINGS OF THE 15TH ESA SYMPOSIUM, BIARRITZ, FRANCE, 28-31 MAY 2001 (AUGUST 2001)
ED. WARMBEIN B.
ESA SP-471 // 691 PAGES
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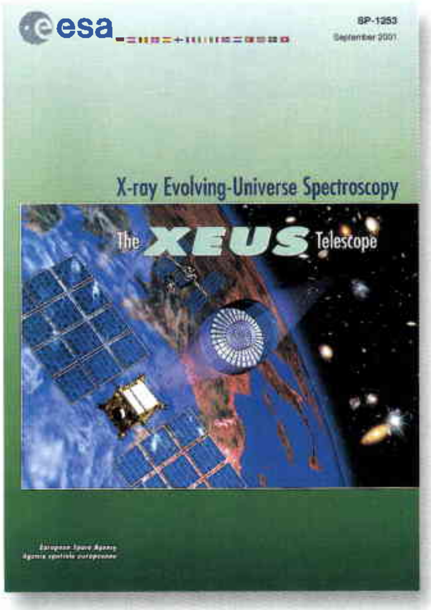
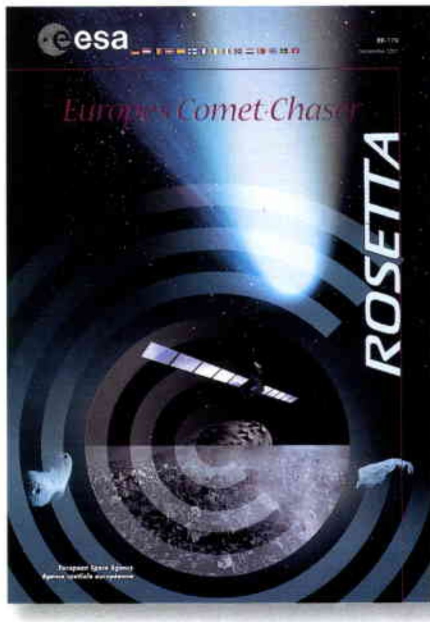
SPACE MECHANISMS AND TRIBOLOGY – PROCEEDINGS OF THE 9TH EUROPEAN SYMPOSIUM, LIÈGE, BELGIUM, 19-21 SEPTEMBER 2001 (SEPTEMBER 2001)
ED. HARRIS R.A.
ESA SP-480 // 359 PAGES + CD-ROM
PRICE: 50 EURO

DASIA 2001: DATA SYSTEMS IN AEROSPACE – PROCEEDINGS OF AN INTERNATIONAL SYMPOSIUM, NICE, FRANCE, 28 MAY – 1 JUNE 2001 (AUGUST 2001)





EDS. SCHÜRMANN B. & SAWAYA-LACOSTE H.
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GREEN PROPELLANTS FOR SPACE PROPULSION – PROCEEDINGS OF THE FIRST INTERNATIONAL CONFERENCE, NOORDWIJK, THE NETHERLANDS, 20-22 JUNE 2001 (OCTOBER 2001)
ED. PERRY M.
ESA SP-484 // CD-ROM
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ESA SP-493 // 476 PAGES
PRICE: 50 EURO

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ED. WARMBEIN B
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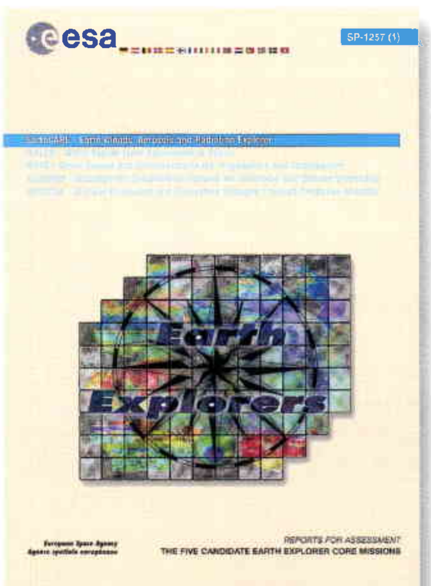

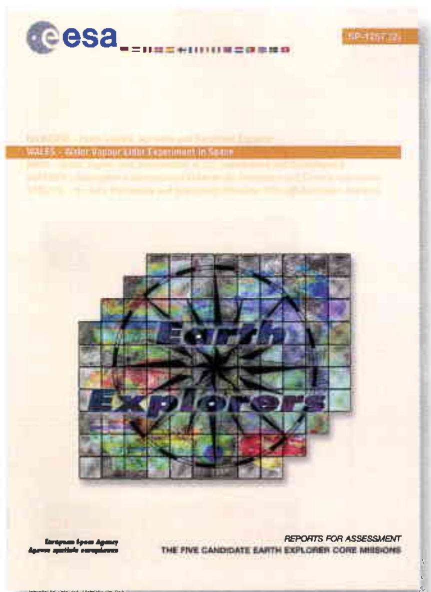

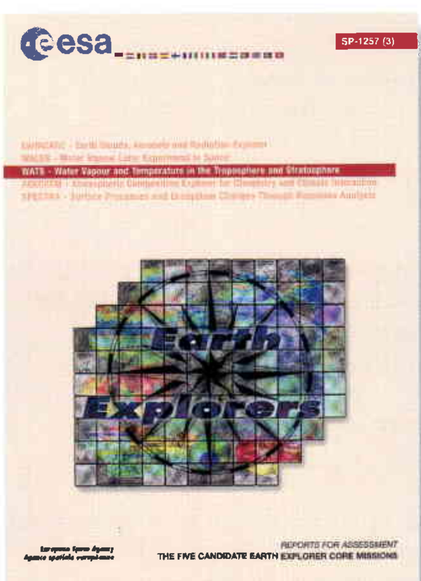

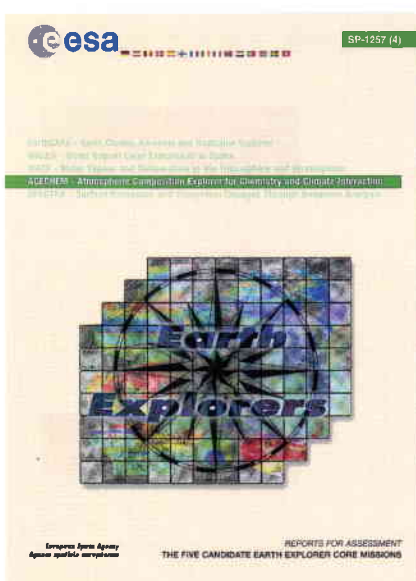

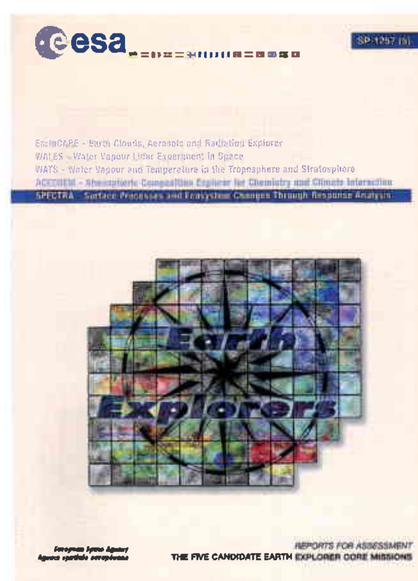

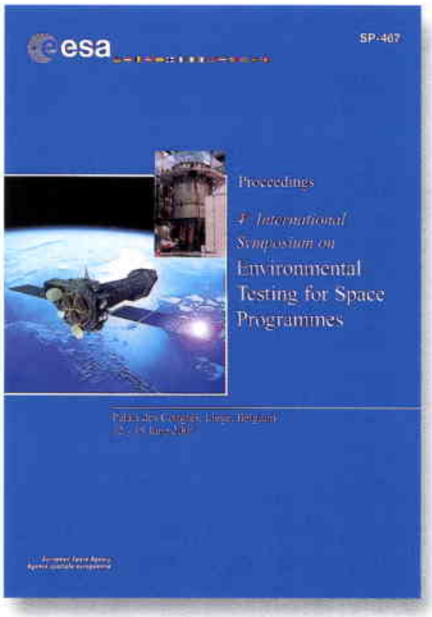

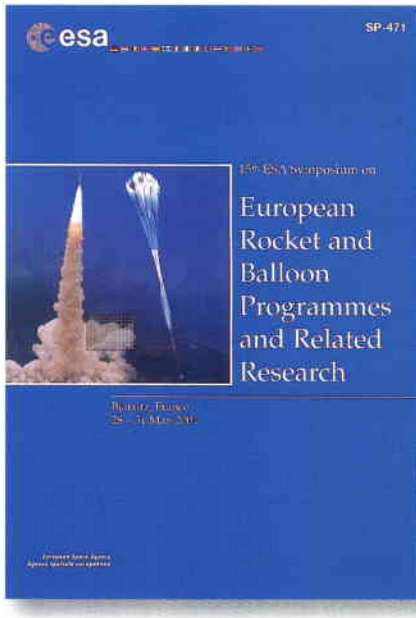

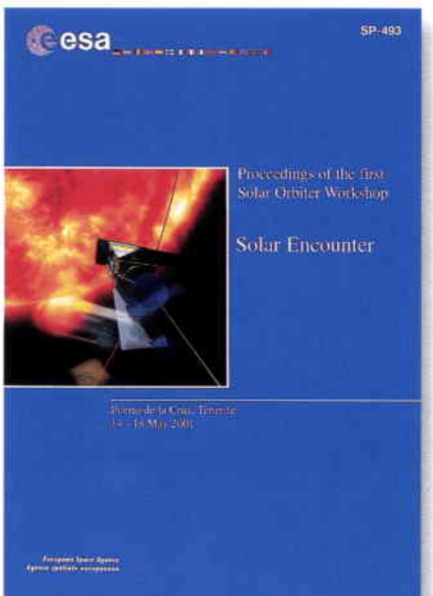

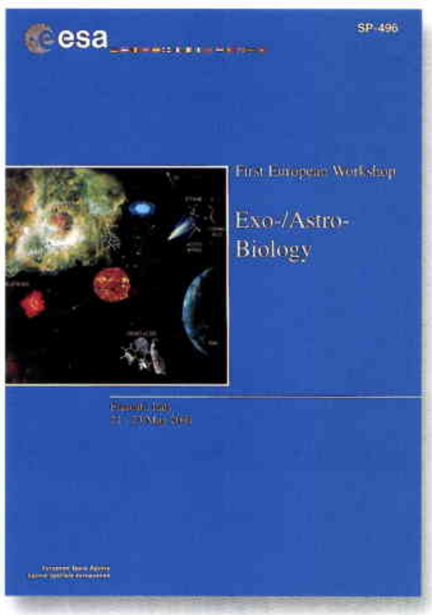

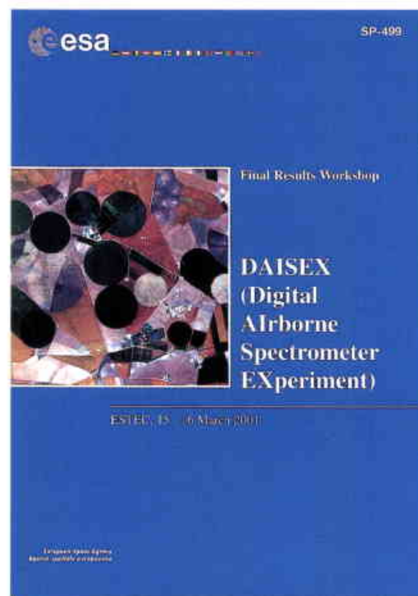

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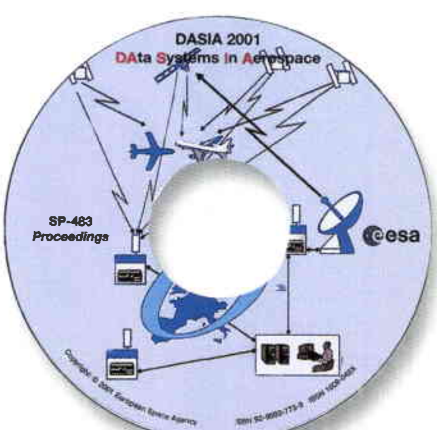

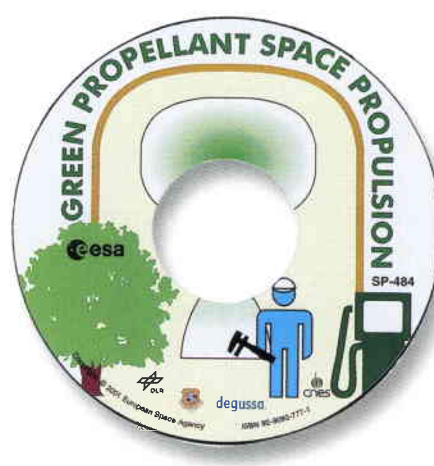

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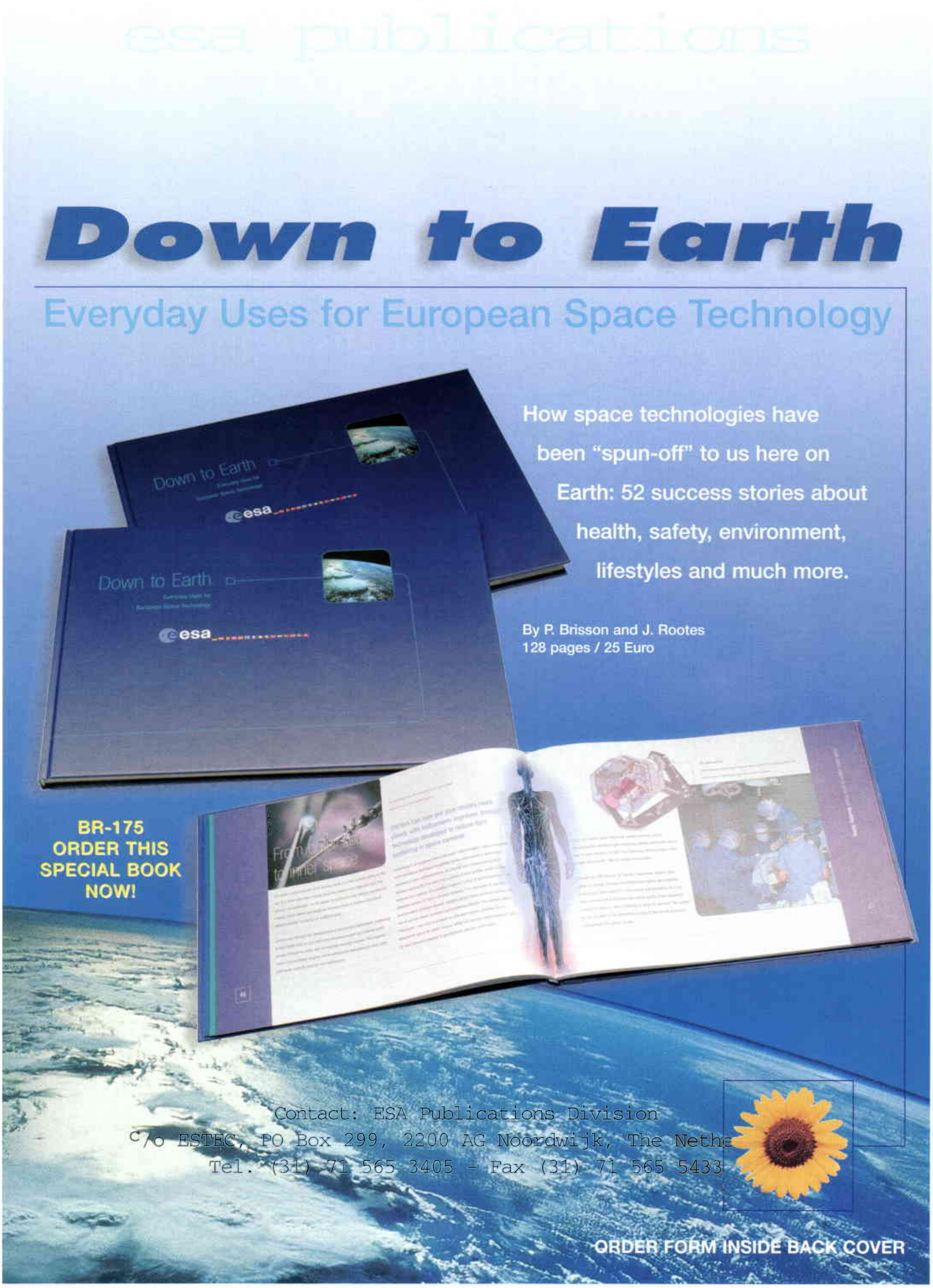
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