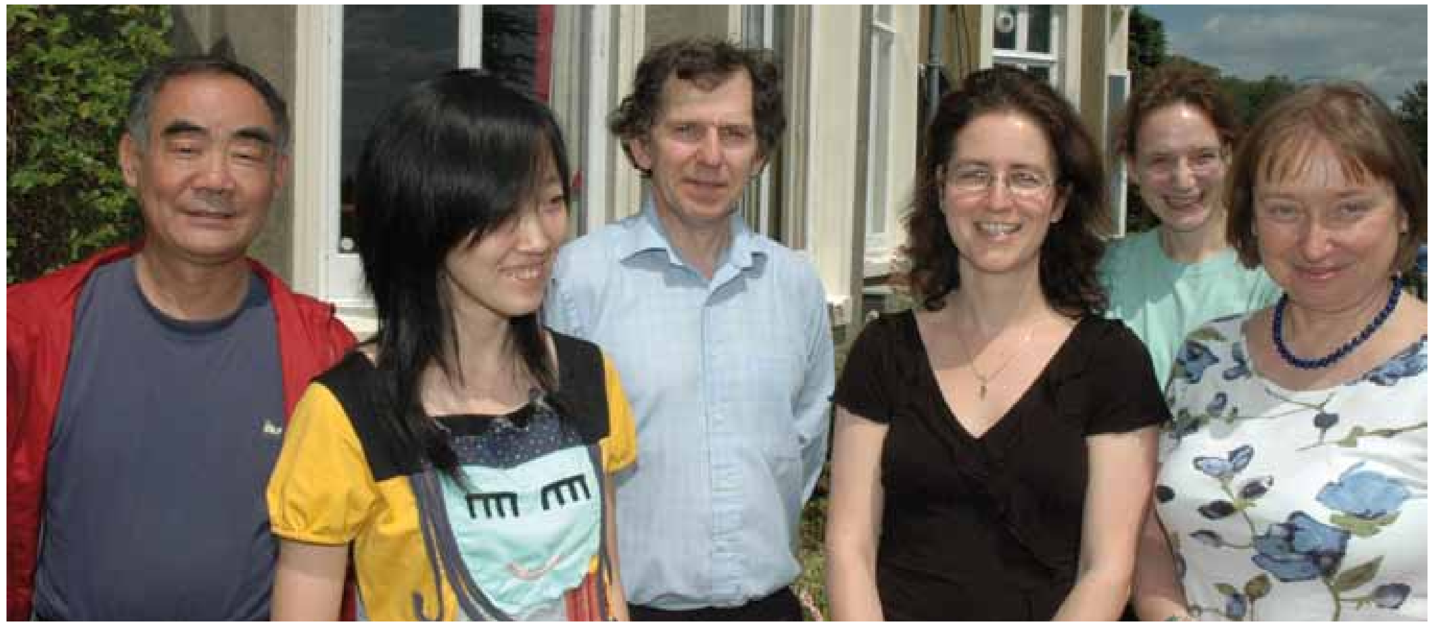
UCL SPACE & CLIMATE PHYSICS

UCL

MSSL

Science
Technology
Innovation

Introduction



MSSL—The Mullard Space Science Laboratory—is the largest university-based space science group in the UK. Since its foundation in 1956 at UCL's Gower Street campus, the group has participated in more than 200 sounding rockets and over 35 satellites and space probes.

We were amongst the first space science groups in the world and had our first rocket launch in the same year that the first man-made satellite, Sputnik 1, went into Earth orbit. From 1967 the space group operated from its own site in Surrey and, as of 2010, hardware built and/or tested there has been used on 16 spacecraft in orbit around the Earth and as far afield as Venus, Mars and Saturn. We have provided instrumentation to all of the major space agencies including the European Space Agency (ESA), NASA, and those of China, Japan and Russia, and we continue to do so. MSSL also provides processing and analysis services for Earth Observation data. In 1993 the laboratory became the Department of Space and Climate Physics, one of the 72 UCL departments.

We deliver a world-leading science programme supported by extensive technology capabilities applicable to space research. Our space science research disciplines include:

- **Astrophysics**
- **Planetary Sciences**
- **Solar Physics**
- **Space Plasma Physics**
- **Climate Extremes**

Our technology programme includes the following disciplines:

- **Cryogenics**
- **Detector physics**
- **Electronic engineering and manufacture**
- **Imaging**
- **Mechanical and thermal engineering and manufacture**
- **Software engineering and computing**
- **Optics**
- **Cleanliness and contamination control**
- **Quality Assurance**
- **Project Management**
- **Systems Engineering**
- **Test and Calibration**

MSSL works closely with industry, both as a customer and as a supplier of specialist hardware with an in-depth knowledge of space projects. It also hosts the UCL Centres for Systems Engineering (UCLse) and Advanced Instrumentation Systems (CAIS), through which we provide professional training, services to industry, and a gateway into UCL's broad expertise.

To deliver our science programme MSSL maintains internationally competitive capabilities in Engineering, Project Management, Systems Engineering, Product Assurance, and Technology Management. Our policy is to be excellent in all that we do and so we research, teach and provide bespoke training in both our science areas and these enabling domains.

Cover image: ESA

Research

MSSL undertakes a broad programme of space related research across five science Themes. These address phenomena on enormously differing scales: from galaxies; to the compact objects at their cores; to an individual star (the Sun); to planetary magnetospheres within that star's outflowing wind; to the surfaces of Solar System bodies. We place a high value on interdisciplinary work, and all of these themes depend on the rich instrumentation and engineering expertise within the laboratory. This close integration of science and instrumentation distinguishes MSSL and makes us a vital contributor to space science and astronomy at an international level.

Astrophysics

MSSL has a large programme of research in astrophysics. Topics encompass both galactic and extragalactic astronomy and employ observations over the full range of the electromagnetic spectrum. These data are obtained from both satellite and ground-based observatories.

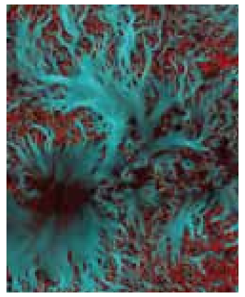
A major focus of the group's work is on objects which emit in the X-ray band. X-rays are emitted either by hot gas (temperatures of millions of degrees) or by fast-moving electrons in a magnetic field. With XMM-Newton we use high-resolution X-ray spectra to probe the ionised winds that are ejected by active galactic nuclei, to study their physical dimensions, mass outflow rates and their effect on the surrounding host galaxy.

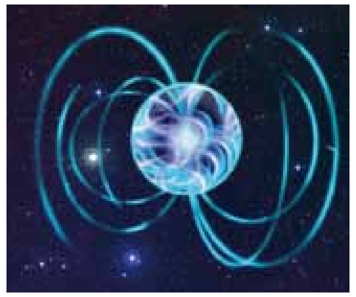
Since the launch of NASA's Swift, Gamma-ray bursts have become a major strand of our research. These spectacular explosions are caused by the deaths of massive stars, and are the most violent events to have occurred since the Big Bang. To fully understand these evens, we are investigating the relationship between the gamma-ray emission and the X-ray/optical afterglows. In addtion, we are using gamma-ray bursts to probe the history of star formation.

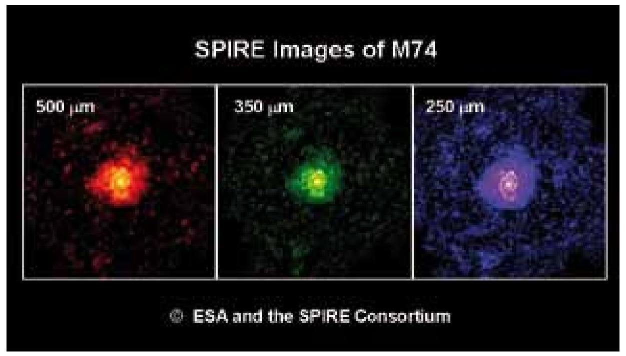
Our study of Gamma-ray bursts naturally complements a broader interest in compact objects. Such objects create extreme environments that cannot be reproduced on Earth – intense gravitational and magnetic fields for instance. Understanding the behaviour of such objects allows us to test our physical laws more thoroughly.

Another thrust of our present research is the study of X-ray and infrared source populations in the early universe. We also make systematic studies of X-ray and ultraviolet sources in nearby galaxies, and more recently in the far infrared using data from ESA's Herschel Space Observatory. Herschel opens up parts of the electromagnetic spectrum that were previously inaccessible to astronomers, allowing us to probe the dust-obscured Universe during the main epoch of galaxy formation.

Through the research strengths of MSSL in the field of galactic dynamics, we have secured key hardware development contracts on ESA's Gaia mission – mapping a billion stars in our galaxy with exquisite precision. In turn this has enabled an expansion of our research base in this area and a now thriving galactic dynamics sub-group.







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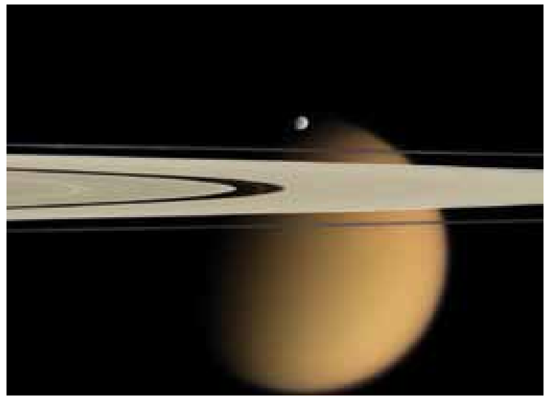
Planetary Sciences



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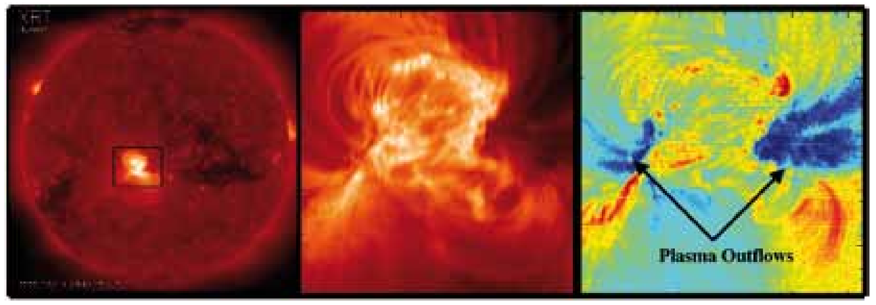
The Planetary Science group is engaged in the exploration of the solar system. We primarily study the interaction of the solar wind with bodies within the solar system and are also developing a programme of planetary surface studies.

The NASA/ESA Cassini-Huygens mission at Saturn has yielded spectacular science returns. We lead the team which provided the electron spectrometer, part of the Cassini Plasma Spectrometer which also includes ion instrumentation. Since 1 July 2004, Cassini-Huygens has been giving us excellent data on Saturn's magnetosphere, the plasma near Saturn's rings and plasma interactions with the largest moon, Titan. We have discovered heavy negative hydrocarbon and nitrile ions high in Titan's atmosphere (evidence of complex chemistry), water cluster ions and charged ice grains coming from Saturn's ring atmosphere and from its the highly active moon, Enceladus. Cassini's orbital tour of Saturn has been extended to 2017 owing to the outstanding success of this mission, and to study seasonal effects during Saturn's 30-year orbit.

With the ASPERA-3 instrument on ESA's Mars Express mission, we are also analyzing the solar wind interaction with Mars, studying the process of water loss from the Martian atmosphere via solar wind erosion. For comparison, we use data from ASPERA-4 on ESA's Venus Express to study plasma processes at Earth's twin, including some common to all these objects.

Solar Physics

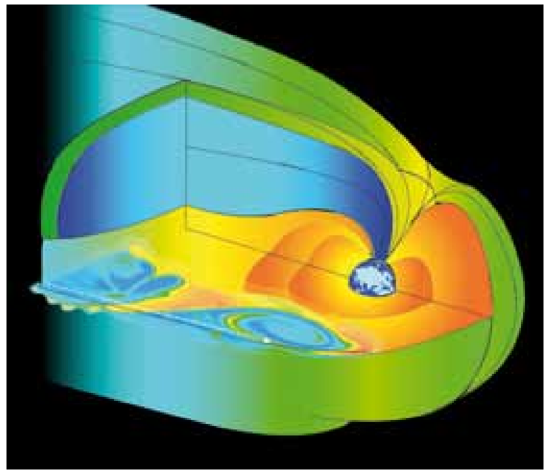
Our research within the solar physics group at MSSL focuses on understanding the origins of solar activity and the subsequent impact on the near-Earth environment. We use space instrumentation to observe the hot and dynamic atmosphere of the Sun in UV, EUV and X-ray wavelengths, measuring key parameters of the plasma using state-of-the-art imaging and spectroscopy.



The current research programme is fusing together new observations from the Japanese Hinode and NASA STEREO missions with data from other spacecraft (SDO, SOHO, TRACE, RHESSI) to study a vast range of eruptive phenomena, including flares and coronal mass ejections. A major focus of our research is to understand the relationship between magnetic fields in the solar atmosphere and these eruptive events. We study how the magnetic fields emerge into the solar atmosphere and how they change over time due to plasma motions and physical processes such as reconnection. In particular we are studying how the magnetic fields provide the energy source to drive coronal mass ejections into the solar system. We are then able to track eruptions as they head towards the Earth and determine the characteristics that make them most likely to disturb the near-Earth space environment to produce the so-called 'Space Weather'. We study the drivers of the solar wind, the continual outflow of plasma and magnetic field that fills the heliosphere, and the potential impacts of short-term solar activity on weather and climate.

The group has had a substantial involvement in all of the major solar space missions in the past four decades and is actively involved in the definition and planning of future ones.

Space Plasma Physics



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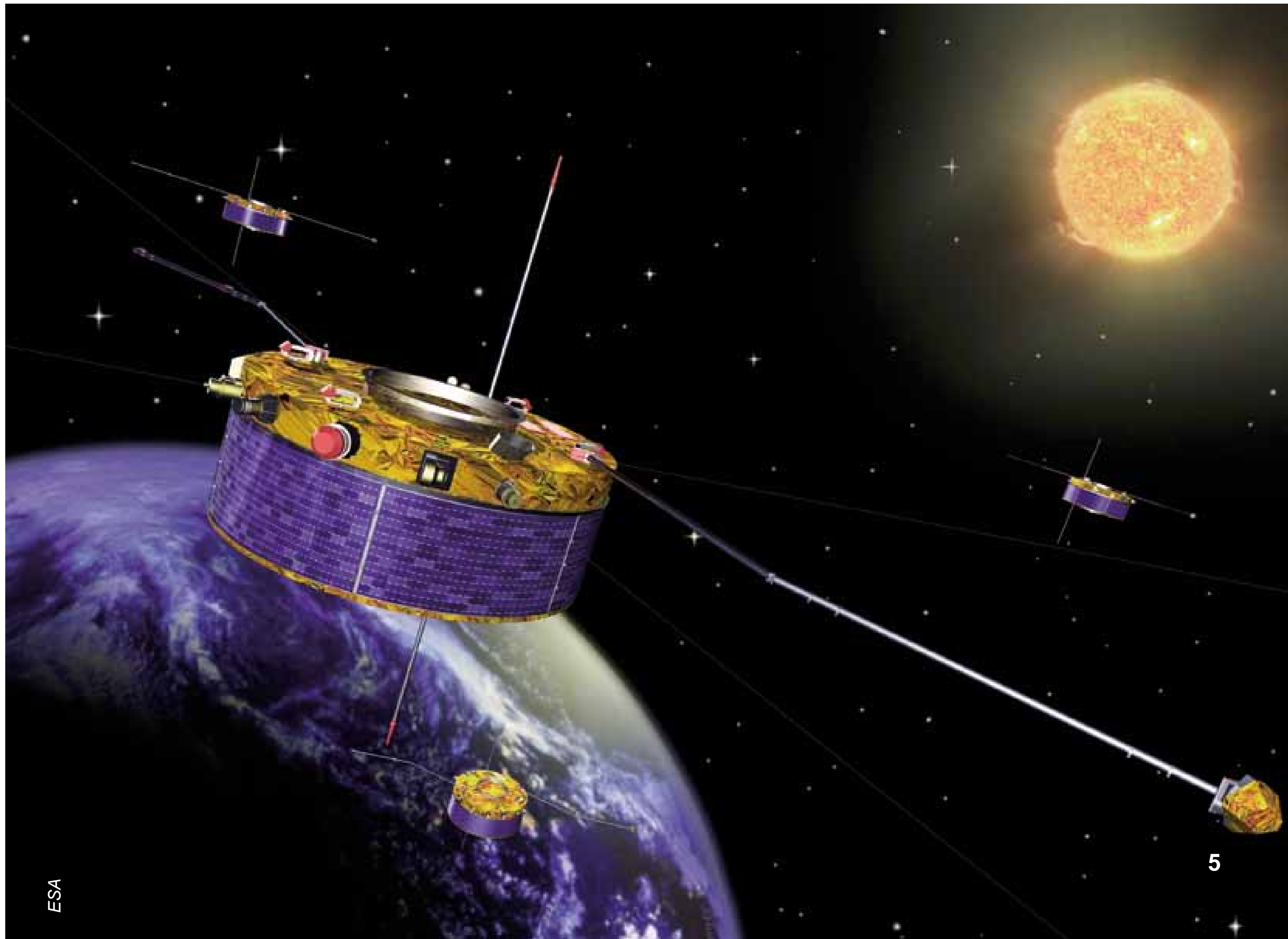
The Space Plasma Physics group studies the Earth's magnetosphere – the region of space directly influenced by the Earth's magnetic field, and its surrounding regions. We measure and interpret the dynamic interactions of the charged particle flow from the Sun, the 'solar wind', and its interaction with the Earth's magnetic field. We fly to the heart of regions where fundamental plasma processes occur such as magnetic reconnection, and where collisionless shocks and plasma turbulence can be studied. Our experimental expertise is in the design and construction of plasma analysers, which measure the characteristics of electron and ion populations in these regions.

For more than a decade, ESA's four-spacecraft Cluster mission has been returning data from our instruments in the magnetosphere. MSSL has also contributed to a number of other magnetospheric missions, including leading an instrument team on the pair of Chinese Double Star spacecraft.

We study the processes coupling energy and momentum from the solar wind, across the Earth's magnetopause ultimately driving internal magnetospheric dynamics. We follow plasma transport through the funnel-like cusp regions in the Earth's magnetic field and down to the polar ionosphere. We directly measure the electrons which are accelerated to form the aurora. We measure the processes determining the intensity of the Earth's outer electron radiation belts. We also study how energy from the solar wind can be stored and then explosively released during magnetospheric substorms.

In addition, we collaborate with the MSSL Solar group to study the connection between events on the solar surface and disturbances subsequently arriving at the Earth.



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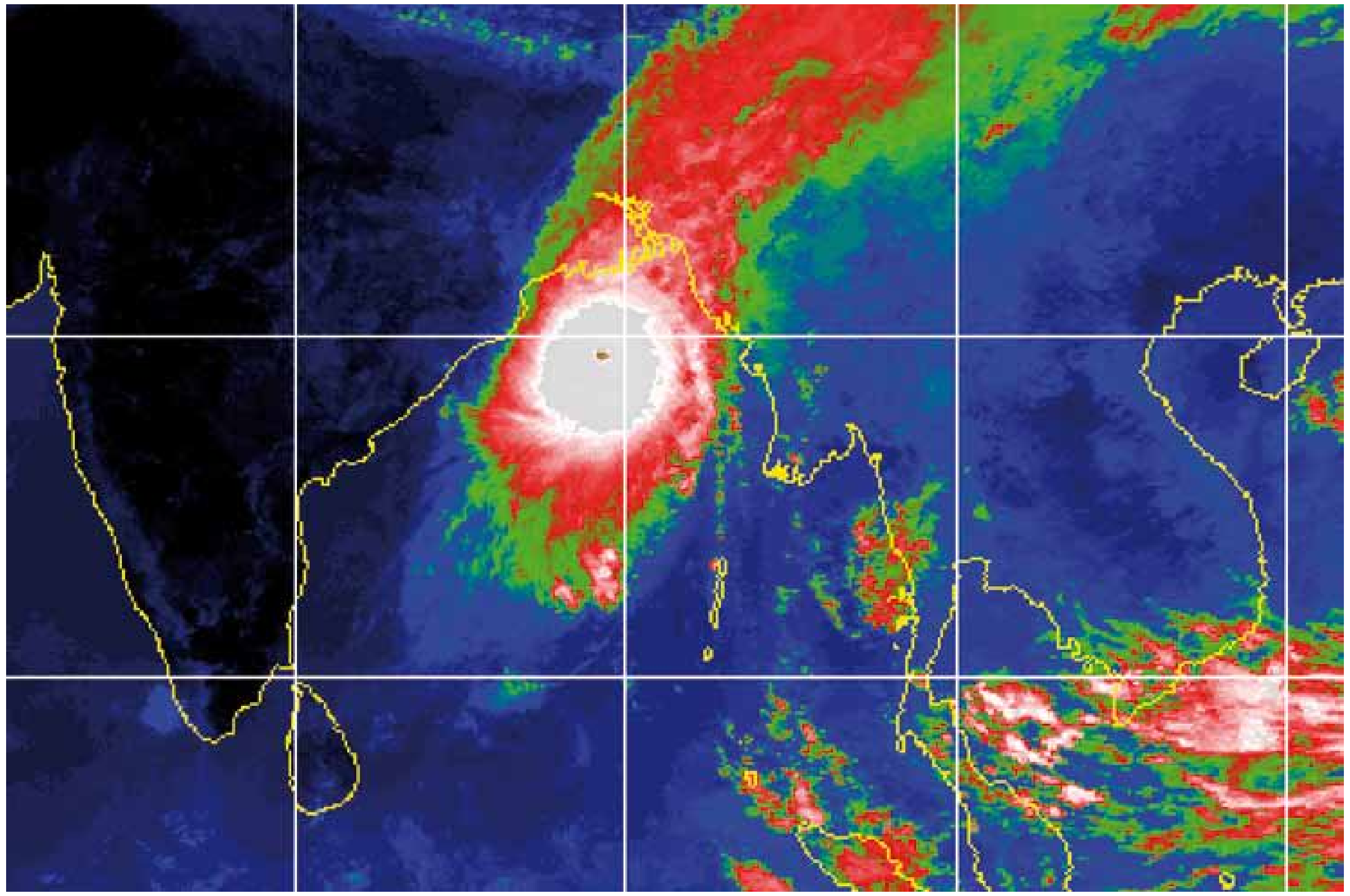
Climate Extremes

The Climate Extremes group monitors, models and predicts weather and climate extremes worldwide. The group has developed a range of innovative and successful prediction models and real-time monitoring products for many of the world's most damaging climate events and phenomena including hurricanes, cyclones, El Niño and La Niña, the North Atlantic and Arctic Oscillations, winter storms and droughts.

Our projects include the award winning Tropical Storm Risk (TSR) which provides real-time feeds of forecasts of tropical storm activity to humanitarian relief agencies worldwide. Its warnings prior to cyclone Sidr's strike on Bangladesh (November 2007) helped to save thousands of lives and its forecasts for the record-breaking 2005 Atlantic hurricane season outperformed those from all leading U.S. groups. The commercial arm of TSR offers real-time products for mapping and predicting the windfields of active tropical cyclones worldwide and has several leading insurance companies as customers.

Other projects include EuroTempest, which provides a range of innovative and quantitative weather risk warning products for the UK, and the Global Drought Monitor, which is the first of its kind to provide global coverage, providing quantitative monitoring of the severity and impact on effected population of droughts.

Associated Press



Infrared satellite image of Cyclone Sidr, Bay of Bengal, 15 November 2007. Image courtesy of Univ. Wisconsin-Madison, Cooperative Institute for Meteorological Satellite Studies.

Earth Observation

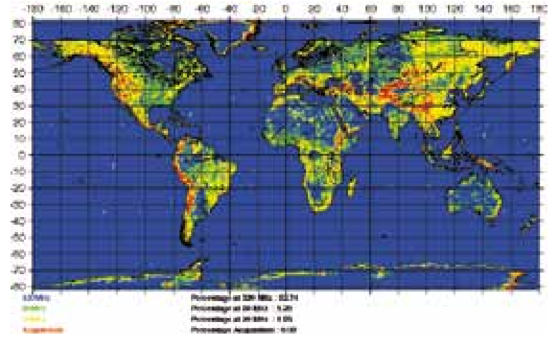
Since 1981 MSSL has been providing expert support to European Earth Observation satellite missions, particularly those carrying Radar Altimeter instruments.

The MSSL group has led or participated in numerous ESA-funded studies into the technical design and applications of satellite radar altimeters, including those on ERS-1/2, on ENVISAT, the SIRAL on CRYOSAT, and Sentinel-3. In particular, these have centred on the use of altimetry over land ice and sea ice surfaces, and pioneering work on the use of altimeter data over land and inland water. We are internationally recognised as leaders in this field and are an ESA-designated Expert Support Laboratory for these missions.

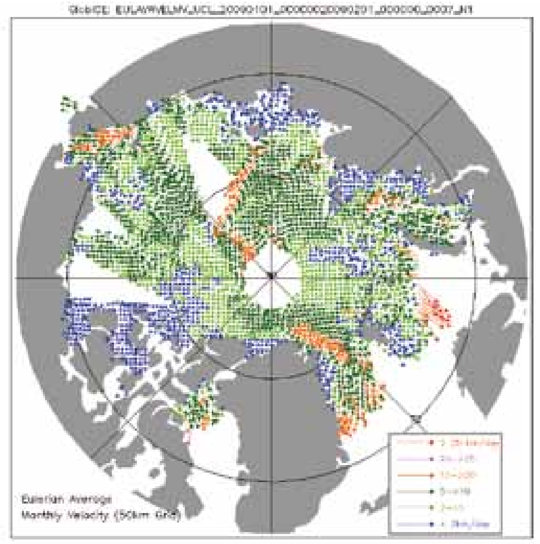
Our involvement covers the full mission lifecycle from concept through to operations. We develop software simulators to support mission concepts and design of the on-board instrument control. We perform the design and specification of data processing algorithms and their resultant data products; we then build reference processors or the operational processing pipelines themselves. After launch we are actively involved in the instrument commissioning and tuning of the ground segment. Throughout the operational phase we provide performance monitoring of the instrument and QA of the data products.

We are also engaged in processing of Earth Observation data to produce higher-level geophysical datasets in support of climate change research. We work closely with our colleagues in UCL's Earth Science Department who are undertaking programmes of EO research.

We developed the software simulator for an advanced high resolution radar altimeter to support a proof-of-concept study. This led on to a successful UCL-led proposal for an ESA Earth Explorer mission, resulting in the launch of CryoSat2 in April 2010.



Monitoring of RA2 operating mode on Envisat during September 2010.



Monthly maps of Arctic Ice drift are produced by UCL's "GlobIce" system

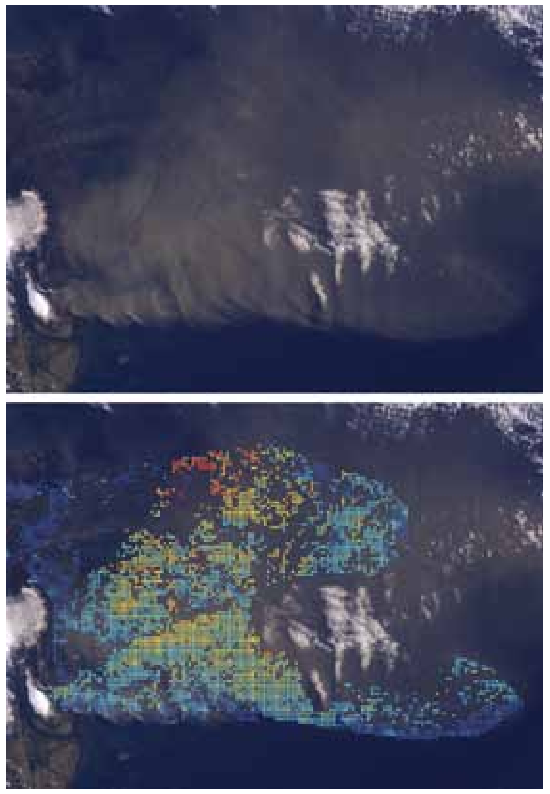
ESA

Imaging

Imaging is a cross-cutting technology of increasingly wide application in all areas of space science and climate physics. It includes the development of new sensors able to measure heights and winds of cloud-tops, smoke and dust plumes of the Earth and other planets, from multiple angles in the thermal IR (in day and night), to new sensors to detect Hospital Acquired Infections using fluorescent imaging from tiny laser diodes.

The deluge of image data – of the Sun, of stars within our galaxy, of galaxy shapes in the Universe and of the 3D surface of Mars from orbit – requires that automated machine vision systems be developed, and the data processed, in a way that is verifiable, giving scientists confidence in their hypotheses. In order to study the Earth's climate system, measurements of radiation need to be sufficiently accurate so that effects due to changes in the Sun from coronal mass ejections or long-term changes due to changes in land use, or the distribution of sea-ice or changes in Carbon Dioxide and Methane, can be reliably understood. This requires the development of extremely precise measurements of the Earth's radiation field and better characterization of the effects of landscape features, such as trees.

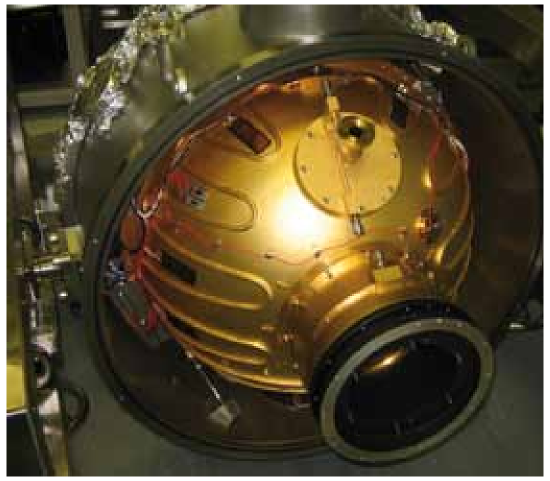
The MSSL Imaging group supports the development of new sensors and 3D display techniques for planetary exploration through ESA's Aurora programme, the automated reduction of orbital images into 3D maps and the better mapping of surface composition through correction of atmospheric scattering effects from dust particles, with applications both to the Earth and Mars. Novel techniques are being developed for mapping land surface albedo and for a more definitive understanding of the variability of cloud systems and their impact on the Earth's radiation field. Imaging is involved in developing techniques and automated processing systems for generating both verifiable geophysical parameters and in interfacing these measurements to numerical atmospheric circulation climate models through data assimilation. Imaging also includes generating datasets to determine the optimum landing sites and in the development of web-enabled Geographical Information Systems (GIS) for the display and distribution of geophysical datasets to space and climate physicists.



April 2010, Icelandic Eyjafjallajökull volcanic ash top heights, derived from NASA MISR instrument data. Results such as these could aid predictions of volcanic ash dispersal, reducing the need for drastic air traffic control restrictions.

Instrumentation for space

Space provides an ideal observing point to study the universe without the distortions and absorptions caused by the Earth's atmosphere. For Earth Observation space-borne instruments provide global data which address important issues such as climate change. Spacecraft fly through our magnetosphere and around/onto distant planets and so provide a platform for direct measurement of these environments. Much of the electromagnetic spectrum (e.g. infrared and X-rays) are completely absorbed by our atmosphere, so that space instrumentation is essential to observe the Universe at these wavelengths.



In the ultraviolet and X-ray wavelengths we observe the most energetic, violent and hot parts of our Universe as well as seeing a different perspective of our local star, the Sun. In the infrared we see the coolest stuff – quite literally. MSSL has ultraviolet telescopes surveying the Sun with the Japanese Aerospace Exploration Agency and the more distant Universe from NASA's Swift observatory and ESA's XMM-Newton observatory. We were responsible for the cryogenic thermo-mechanical engineering of the SPIRE instrument on ESA's Herschel mission, currently surveying the sky at the longest infrared wavelengths, and detecting galaxies so far away we see them at the time of their birth.

With instruments in-situ we can measure the direction and speed of the charged particles in the space between the planets, to find out how the solar wind interacts with them. Our instruments have been sent to Venus, Earth (orbit), Mars and Saturn.

ESA's global space astrometry mission, Gaia, is equipped with the largest CCD camera ever made. MSSL has partnered with EADS Astrium in the calibration and characterisation of that camera, as well as working with ESA for nearly a decade in the mission definition. Two years after Gaia goes into space will see the launch of NASA's James Webb Space Telescope, the huge successor to the Hubble Space Telescope: MSSL has built the in-flight and on-ground calibration systems for the near-infrared spectrograph, again working with EADS Astrium.

Engineering

The stresses of launch and the space environment place significant demands upon the scientific equipment that we fly. This equipment is often a novel, complex integration of sensors, microprocessors, electronics, power converters, mechanical structures, mechanisms, optics, and thermal control elements. MSSL hosts specialist space engineering groups that design, build and test flight and ground systems, and we have significant on-site capability for electronic, mechanical, thermal and software engineering. While much of our manufacturing is contracted to UK industry, specialist manufacturing, assembly and integration is performed on site, where we have a range of state-of-the-art tools and facilities.

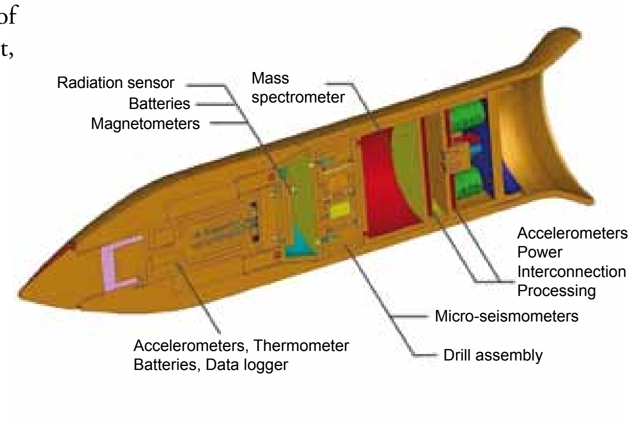
Future instrument designs are driven by the need for miniaturisation, high performance, high reliability, radiation tolerance and low power consumption. Other drivers may include the need for extreme optical stability and the requirement for stiffness and delicate thermal control whilst meeting a tight mass budget. The sensors in our instruments typically need analogue signal conditioning, digitisation, data processing and power conditioning tasks to be carried out.

Systems

Scientific instruments can be viewed as complex systems that integrate a variety of functions including sensing, data acquisition and processing, power management, communications, thermal control, operations and autonomy.

Systems development demands 'Systems Thinking' in which the complexity is managed through simple architectures and robust sub-system interfaces. It is essential that individual sub-systems can be developed and tested in parallel, so that when they come together, they work first time. This way, potential problem areas are minimised and are more easily remedied.

One such system, for example, is the planetary penetrator currently being developed by MSSL as part of a nation-wide consortium. These small, extremely rugged probes are designed to withstand a high-speed impact into the surfaces of icy worlds such as Jupiter's moon, Europa. They need to then be able to search for astro-biological signatures, as well undertake chemical, geophysical and environmental investigations.



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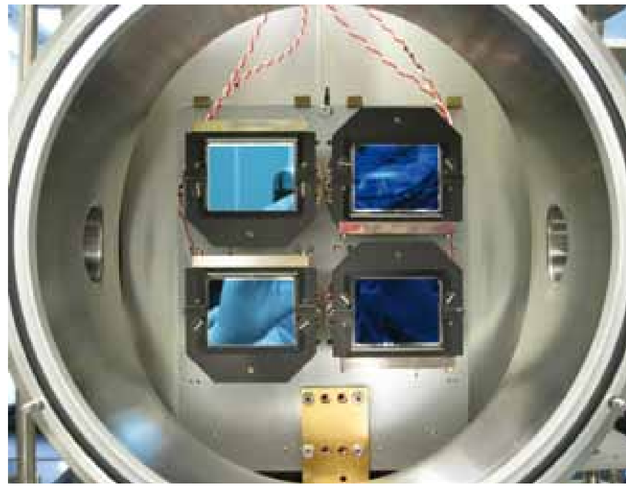
Technology Research and Development

MSSL is concerned with the development of various forms of sensor devices deployed in space. Such sensors tend to be at the forefront of technology and a full understanding of their behaviour is essential when seeking to extract the maximum information from the downstream raw science data. This knowledge comes from both a profound study of detector physics and also the development and calibration of the hardware. MSSL continues to innovate and excel in this area. Four key areas of development are outlined below:

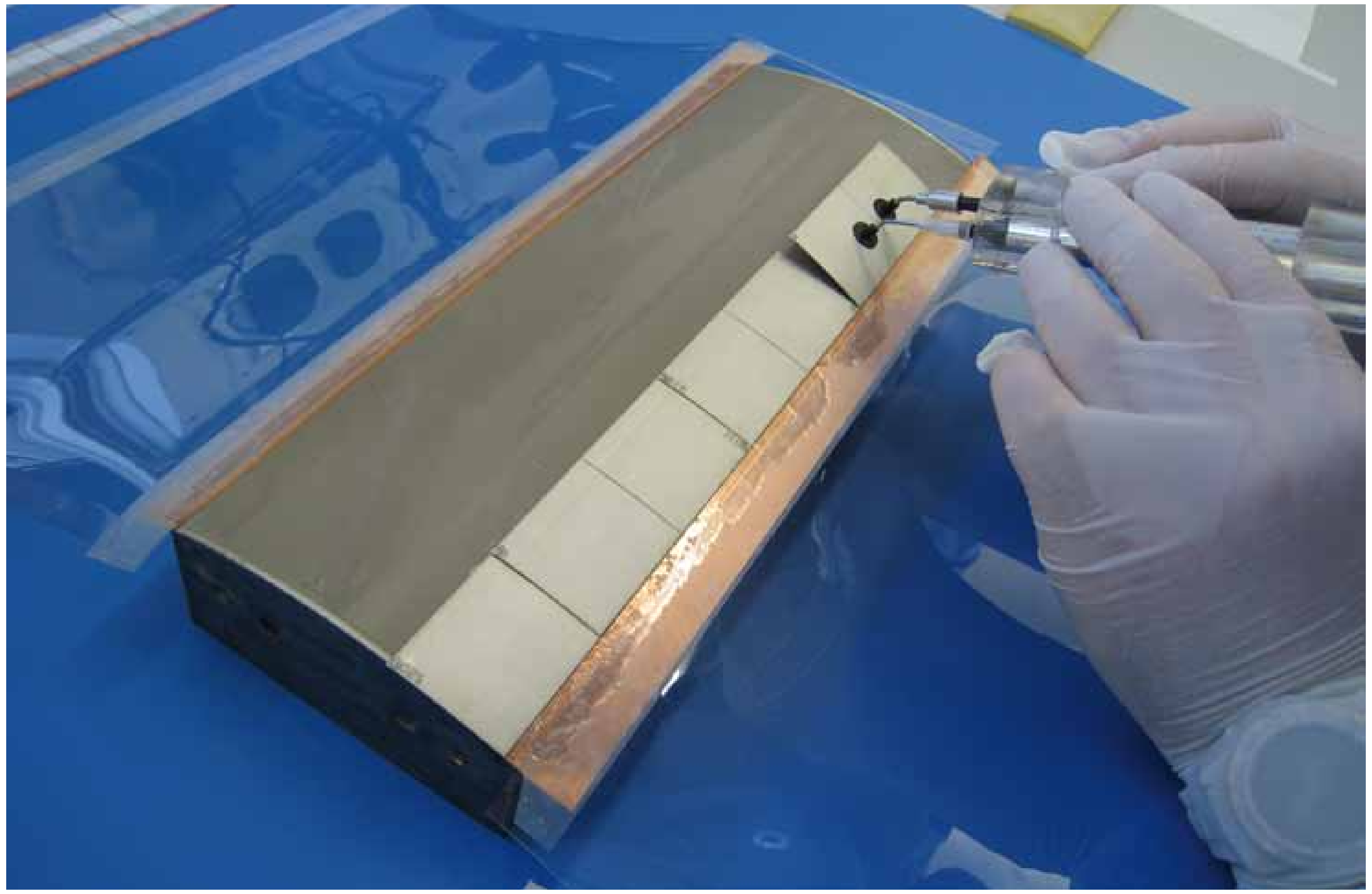
CCD-based cameras

Charge Coupled Devices (CCDs) are extensively used in astronomical detectors and the MSSL CCD Group has a broad programme of CCD camera development and research for both current and future space projects. Working closely with manufacturers, MSSL scientists provide valuable insight into the operation of novel CCDs and are key in enabling these devices to reach the technology readiness levels needed for flight operations.



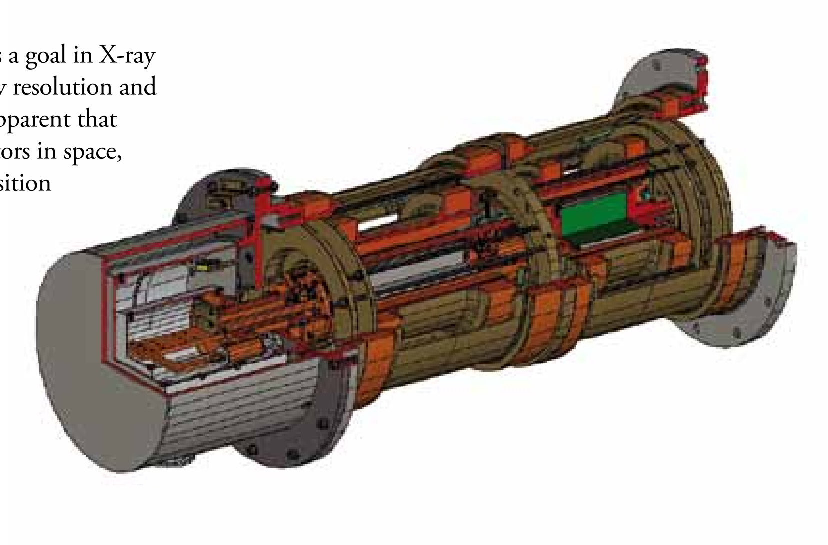
Smart X-ray Optics

MSSL is playing a key role in the Smart X-ray Optics basic technology programme, developing the technologies necessary for the production of thin actively controlled grazing incident optics, suitable for the next generation of X-ray space telescopes, and improving the resolution of X-ray optics on the micro-scale using microstructured optical arrays. The latter, in conjunction with a bench top micro-focus source, also developed within the programme, will provide a valuable diagnostic tool in the field of radiobiological research.



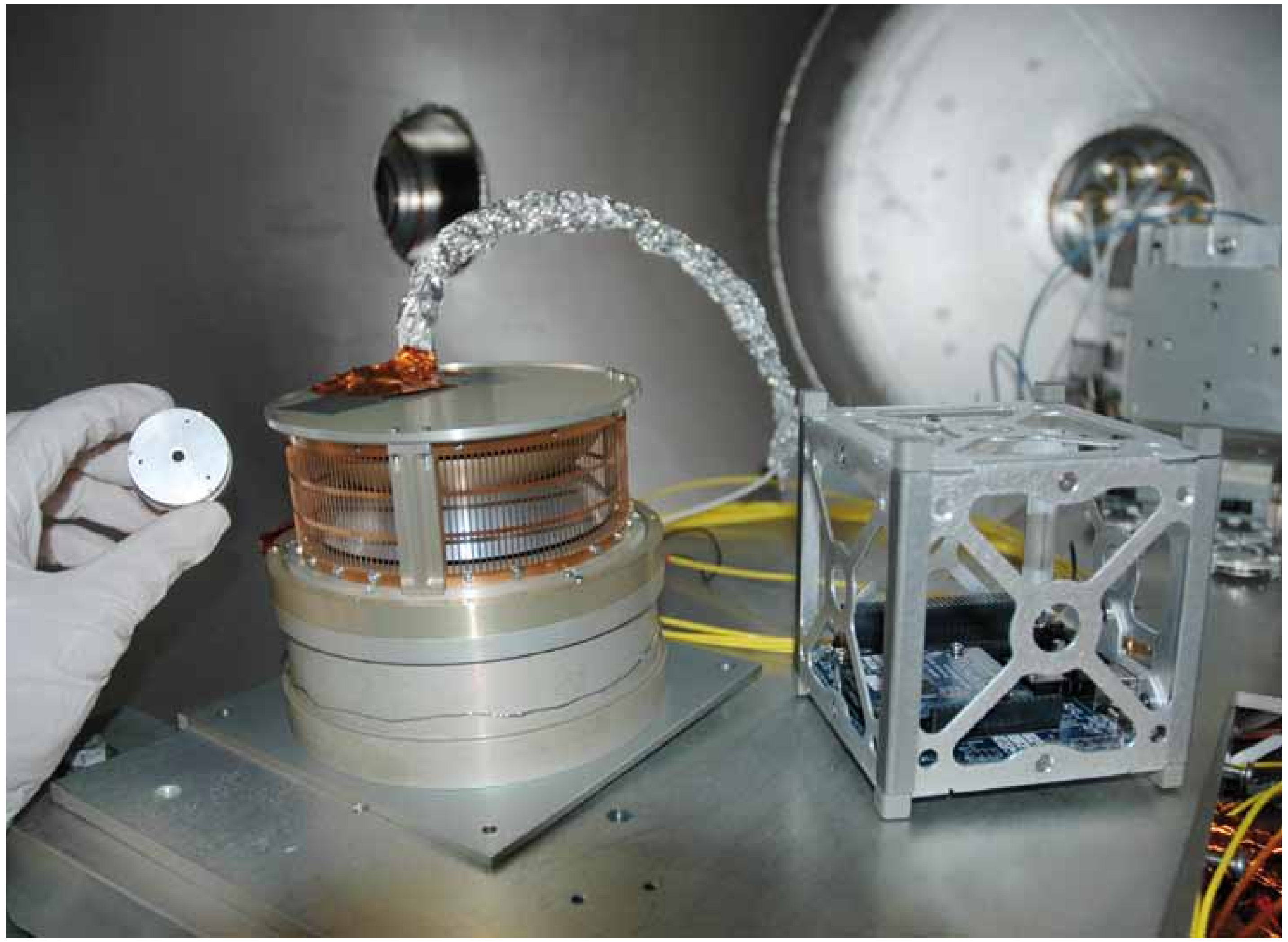
Cooling Systems for space

MSSL has a research programme in space coolers. For many years a goal in X-ray detector development has been the realisation of both high energy resolution and high quantum efficiency within the same device. It has become apparent that to achieve this aim it will be necessary to operate cryogenic detectors in space, including superconducting tunnel junction (STJ) arrays and transition edge sensors, at temperatures below 0.1 K (i.e. less than -273 °C). Therefore one of the main aims is to develop future refrigerators (cryogen-based and cryogen-free) so that these detectors can be flown. MSSL's Adiabatic Demagnetization Refrigerator (ADR) technology is a key part of this programme.



Miniaturised plasma instruments

Current development activities in instrument miniaturisation involve using novel instrument geometries and micro-fabrication techniques typical of Micro-Electro-Mechanical Systems (MEMS). The technologies being developed on the programme will provide a generic solution framework for a wide range of mission needs, from the monitoring of plasma environment and radiation on commercial satellites to the detailed scientific investigations of low energy plasmas from scientific satellites. Such instruments will provide a technology leap with considerable saving in resource, making it especially attractive for future multi-satellite, nano-satellite or planetary missions. These miniaturisation activities are well aligned with MSSL's CubeSat development programme, providing powerful enabling technologies for a range of CubeSat based applications e.g. networks of low-cost space weather satellites.



Test facilities

MSSL has a wide range of test facilities available to space instrument builders in industry and academia.

Our recently refurbished ISO 6 Class Cleanroom is home for two major new facilities:

The magnetically screened plasma calibration vacuum chamber is a world-class resource, boasting both a wide-beam, tunable, mono-energetic electron source and an ion source.

The optical vacuum chamber, 2m in diameter, can accommodate large payloads, and as well as calibration of telescopes and cameras via externally connected light sources, can provide temperature environments between -180°C and +150°C.

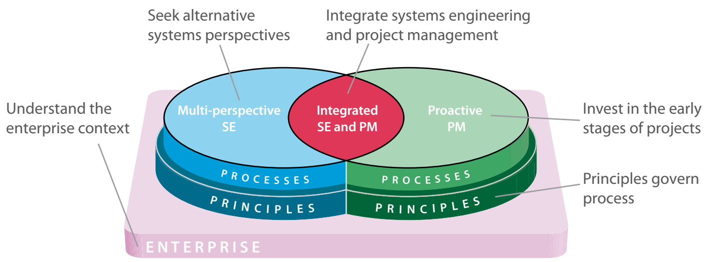
A further two cleanrooms provide facilities for assembly, integration and test of space flight hardware: an ISO 5 Class Cleanroom with horizontal laminar flow and an ISO 8 Class Cleanroom, including a 6m tall section for integration of large payloads and other scientific instruments, such as the SuperNEMO detector modules. Other resources include a vibration test facility capable of force-controlled testing, a thermal vacuum system, a laser cutter, a sputter coater and vacuum cryostats for characterisation of CCDs and associated electronics.

Technology Management and Systems Engineering

UCL Centre for Systems Engineering (UCLse) is a university-wide initiative to develop systems engineering research, teaching and technology transfer. Hosted by the Technology Management Group in MSSL, UCLse brings together expertise from across UCL's departments to tackle difficult and industrially relevant systems engineering problems. UCLse is a centre of excellence for research, education and training in systems engineering, technical project management, risk management and strategic technology management.

Principles

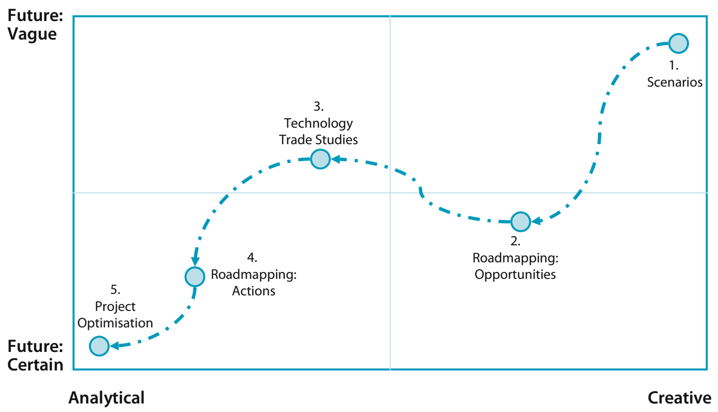
Our systems engineering teaching and research is based on five principles as shown in the figure below:



Research

Specific areas of research interest are:

Technology Planning



A novel approach for planning the introduction of new technologies was conceived during a three-year research project sponsored by EPSRC, the DTI, GlaxoSmithKline, and Syngenta, and refined in consultancy projects with GlaxoSmithKline and the Photonics Knowledge Transfer Network. Research in this area was awarded the prize for the most novel use of systems engineering in the 2006 European Systems Engineering Conference.

Systems Modelling and Optimisation

ADL

We are experts in systems modelling, and with BAE Systems and Alexander Dennis Buses have recently been awarded a £4m grant over three years to develop hybrid electric/diesel technology for passenger transit vehicles. Our role is to develop a model to optimise the energy storage and power management throughout the vehicle, and to predict the challenges of integrating the technology into the existing system and its environs.

Our MSc programme involves significant research projects undertaken in industry and at any one time ~20 such projects are in progress. This has allowed the Systems Engineering group to develop a broad portfolio of highly relevant research.

Training

In our experience, the successful delivery of large, complex projects is a combination of good systems engineering practice, strategic planning, project management and systems thinking. Sharing this experience, we provide a range of courses to industry in all these areas of technology management as well as providing expert trainers for UCL's APM-accredited Project Management training courses.

Working closely with client organisations, we identify skills gaps and deliver courses to fill those gaps, instilling a multi-level, long-term view of systems developments. These organisations can then be proactive in dealing with the dynamics of the modern business environment. We offer focused short courses, a Masters in Systems Engineering Management, and bespoke training courses relevant to a wide range of industries including transport, aerospace, defence, communications and energy.

We host courses at UCL's central London campus, or elsewhere (such as at customers' sites), and provide web-based training that can be integrated with taught material, or used alone. We can also combine training with consultancy or research relevant to the needs of the organisation.

Our training clients include:

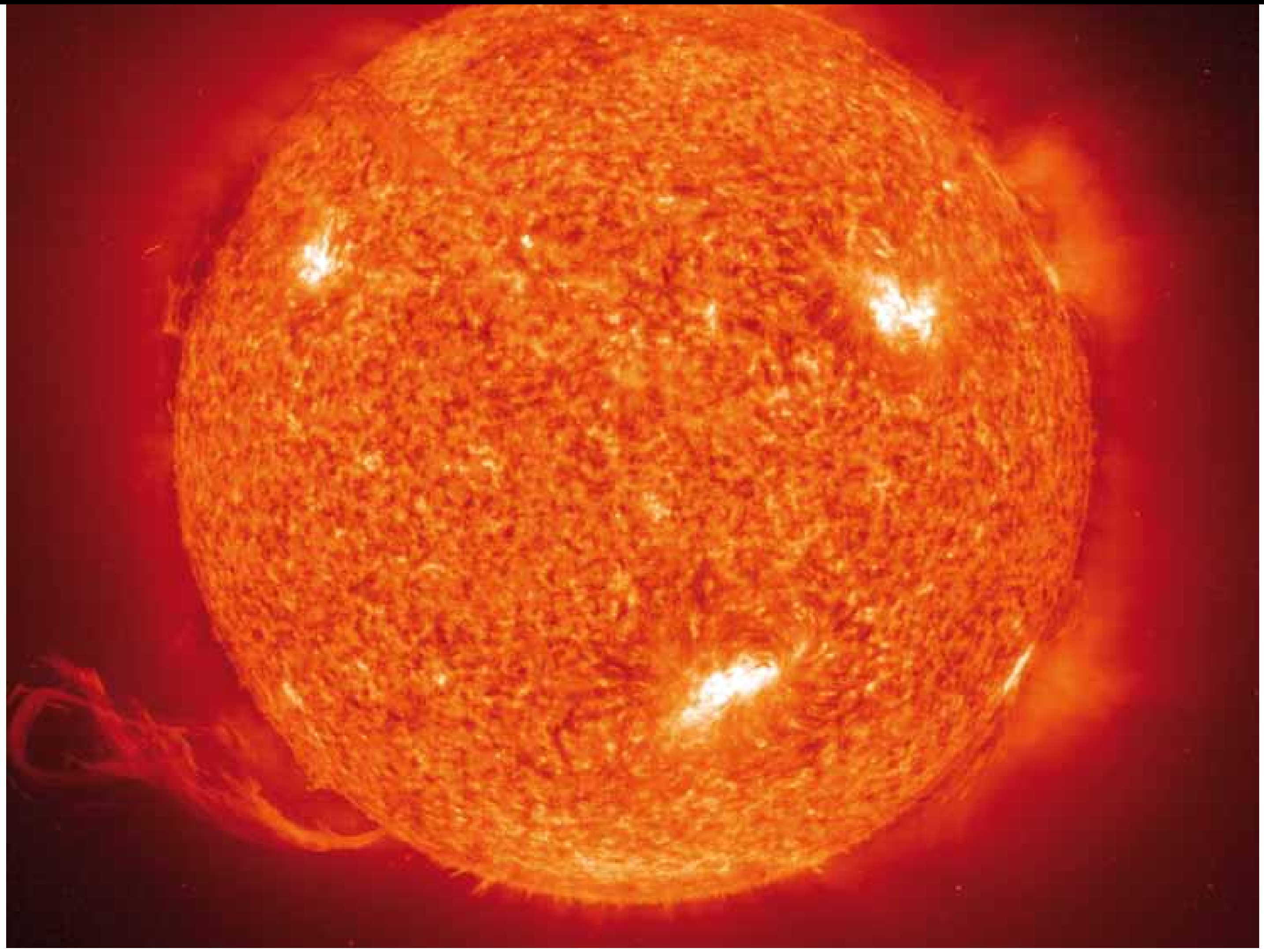
- **Ultra Electronics**
- **General Dynamics UK**
- **EADS Astrium**
- **Marshall SV**
- **GE Aviation**
- **QinetiQ**
- **BP**

Teaching

A key part of MSSL's mission is high quality teaching and research supervision, which develops the core skills of space scientists and engineers of the future. This builds on MSSL's world-class science and technology foundation combined with the outstanding expertise in communications technology offered by the UCL Department of Electronic and Electrical Engineering.

The MSc Programme in 'Space Science and Engineering' is run jointly by these two Departments. It is delivered by internationally respected scientists, who base their lectures on state-of-the-art science and technology. A large part of the programme is project-based, in which students work alongside top engineers building and testing instruments for space. There are two pathways: 'Spacecraft Technology and Satellite Communications', focussing on the application of space technology in industrial settings and careers in space technology, satellite communications and related fields; 'Space Science', is centred on scientific research applications of space technology, aiming to equip participants with knowledge of the physical principles essential for careers in space research.

Our close contact with space agencies such as ESA and NASA, and with industry, encourages the development of transferable, desirable skills, such as project management. Successful graduates progress to further degrees, academic research, engineering roles in the international aerospace industry, or to analytical positions in other domains.



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Public Engagement with science

MSSL has an active award-winning public engagement programme which aims to promote a dialogue with groups of all ages. This programme builds on the audience's natural interest in space science and astronomy and delivers inspirational events which engage with over three thousand children and adults every year.

Our primary school programme aims to provide teachers with information, materials and resources to be able to teach space science and astronomy in the classroom with confidence. We also provide in-school workshops and talks aligned to the national curriculum with a focus on investigative science activities. The secondary school programme provides workshops and talks which link into the National Curriculum science and mathematics content, but also go beyond to discuss the very latest in research and technology.

Demonstrating the applications of science in the area of space and giving information on the broad spectrum of careers available is also an important part of our programme. This aspect is delivered through dedicated careers events and by providing work placements for secondary school and university level students. This provides students with the opportunity to become deeply involved in a current research or engineering project, working alongside MSSL scientists and engineers. Other highlights of the public engagement programme include activities for gifted and talented students, our annual community open day and working with arts organizations to reach a broad audience in a truly open and engaging way.

UCL

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