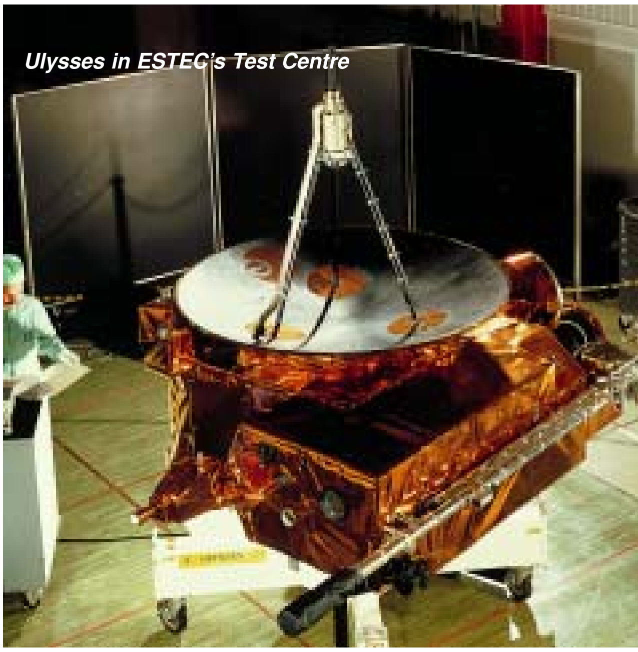
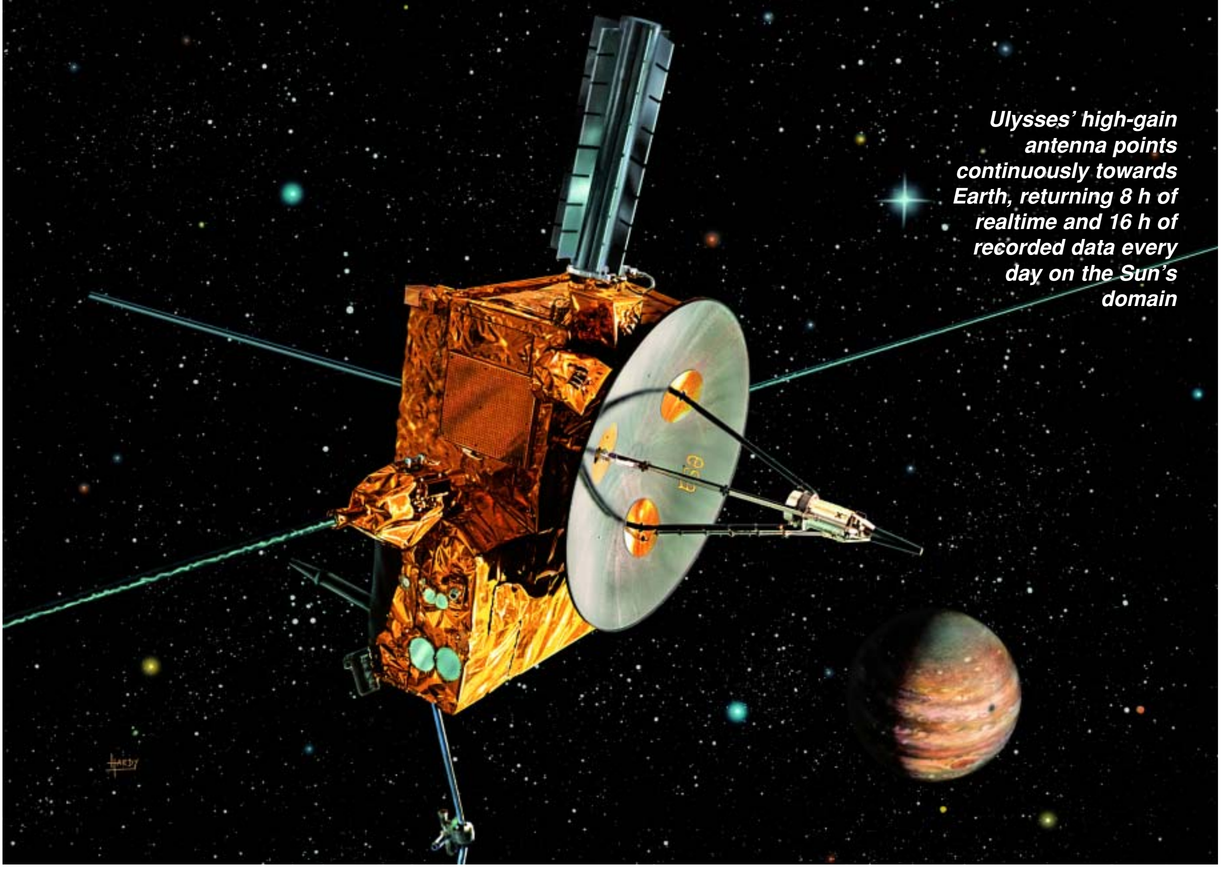
Ulysses

Achievements: first in situ investigation of the inner heliosphere from the solar equator to the poles; first exploration of the dusk sector of Jupiter's magnetosphere; fastest spacecraft at launch (15.4 km/s)
Launch date: 6 October 1990
Mission end: planned September 2004
Launch vehicle/site: NASA Space Shuttle Discovery from Kennedy Space Center, USA
Launch mass: 370 kg (including 55 kg scientific payload)
Orbit: heliocentric, 1.34x5.4 AU, inclined 79.1° to ecliptic, 6.2 year period
Principal contractors: Dornier (prime), British Aerospace (AOCS, HGA), Fokker (thermal, nutation damper), FIAR (power), Officine Galileo (Sun sensors), Laben (data handling), Thomson-CSF (telecommand), MBB (thrusters)]

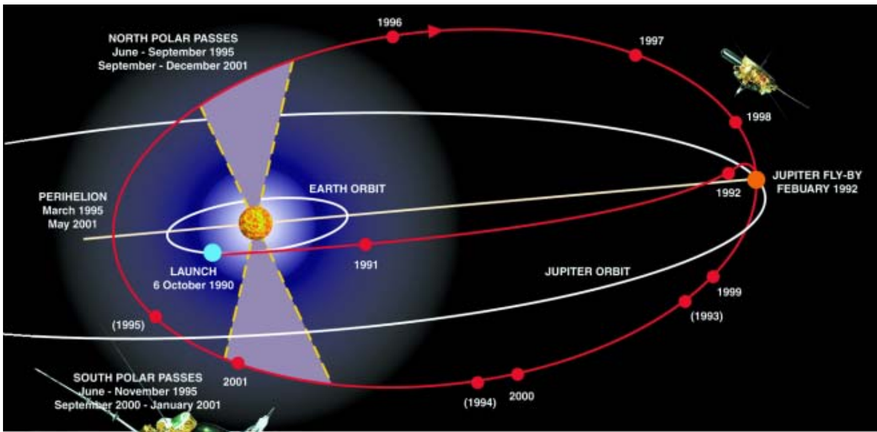
Ulysses is making the first-ever study of the particles and fields in the inner heliosphere at all solar latitudes, including the polar regions. A Jupiter flyby in February 1992 deflected Ulysses out of the ecliptic plane into a high-inclination solar orbit, bringing it over the Sun's south pole for the first time in September 1994 and its north pole 10.5 months later. Ulysses spent a total of 234 days at latitudes >70°, reaching a maximum 80.2° in both hemispheres. The mission was originally to end in September 1995, but Ulysses' excellent health and the prospect of important new science has resulted in operations being extended for a second solar orbit. After crossing the ecliptic in April 1998, Ulysses headed back towards the Sun, passing over the south pole for a second time in November 2000, and the north pole in October 2001. In contrast to the polar passes in 1994/95, which took place near solar activity minimum, the return to high latitudes is under much more active conditions.

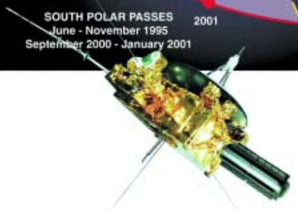
The unique data from Ulysses have added a new dimension to our knowledge of the Sun's environment, the heliosphere. Important accomplishments include the characterisation of two distinctly different solar-wind states (fast wind from the poles filling a large fraction of the heliosphere, and slow wind confined to the equatorial regions), the discovery that high- and low-latitude regions of the heliosphere are connected in a much more systematic way than previously thought, the first-ever direct measurement of interstellar gas (both in neutral and ionised state) and dust particles, and the precise measurement of cosmic-ray isotopes. These, together with numerous other important findings, have resulted in more than 700 publications to date in the scientific literature.


Ulysses in ESTEC's Test Centre



Ulysses' high-gain antenna points continuously towards Earth, returning 8 h of realtime and 16 h of recorded data every day on the Sun's domain





Following the successful completion of its primary mission, Ulysses is now making further passes over the Sun's poles.

ESA and NASA signed the MoU 29 March 1978 for the International Solar Polar Mission (ISPM) as a 2-craft mission launched by a single Shuttle and 3-stage Inertial Upper Stage (IUS) in February 1983. Jupiter gravity assists would have thrown them into opposing solar orbits. NASA awarded TRW the contract for the US spacecraft in July 1979; Dornier was selected in September 1979 as leader of the STAR consortium for ESA's spacecraft. US budget cuts in February 1981 saw NASA unilaterally cancelling its spacecraft to save $250-300 million. NASA would still provide launch, tracking and the RTG. Shuttle and other problems delayed the launch to May 1986 – now using a cryogenic Centaur upper stage – but the *Challenger* accident of January 1986 postponed all flights. Safety concerns prompted the final switch to an all-solid 3-tier IUS/Payload Assist Module (PAM) upper stage.

Ulysses' record 15.4 km/s speed took it across the Moon's orbit in only 8 h. The deployment of the 5.55 m radial boom on 7 October 1990 reduced the spin to 4.7 rpm. Beginning with EPAC, the science instruments were turned on starting 19 October and checked out over several weeks. The 7.5 m axial boom was deployed on 4 November.

After travelling 993 million km and already collecting important information on the interplanetary medium, Ulysses began the Jupiter encounter by detecting the bowshock crossing at 17.33 GMT 2 February 1992, some 113 R_J out, more distant than Pioneer (100 R_J) and Voyager (60 R_J). It approached through the late morning region of the magnetosphere at about 30°N, came within 378 400 km of the cloudtops (5.3 R_J) at 12.02 GMT 8 February 1992, and then exited unscathed on the previously unexplored evening

Ulysses was launched on an IUS topped by a PAM final kick stage. (Boeing)

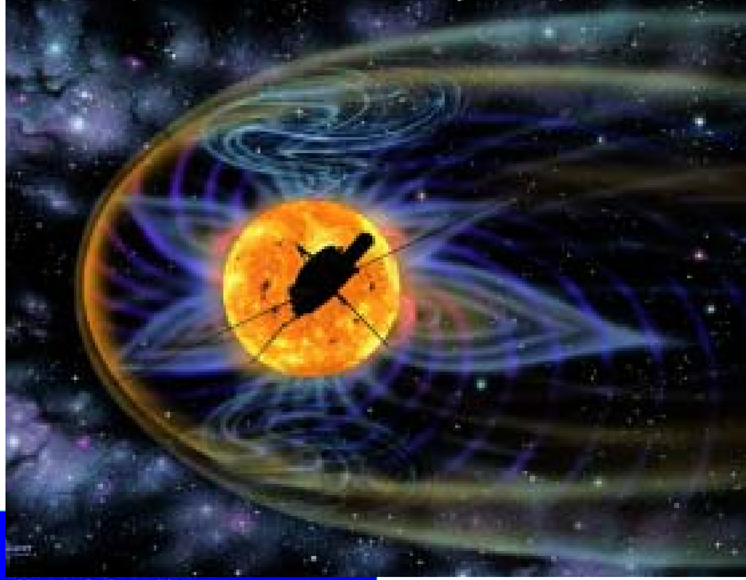
side, at high southern latitudes, having spent more than a week in the magnetosphere. Just before closest approach, Ulysses entered the magnetosphere's polar cap. The close 13.5 km/s flyby produced the high ecliptic inclination – IUS/PAM could have reached only 23° without the assist. A major finding was that the solar wind affects the magnetosphere much more than expected. The magnetic field in the dusk sector is not rotating with the planet and is swept down into the magnetotail. Also, Jupiter's intense radiation belts reach only to 40° latitude, whereas Earth's extend to 70°. Ulysses passed directly through the Io plasma torus (only Voyager 1 preceded it), which plays a key role in refuelling the magnetosphere with plasma.

At the end of February 1992, the Sun, Earth and Ulysses were in direct opposition, the best time to detect gravitational waves by observing an arcmin shift in the craft's position. Although they were not positively identified by this radio science experiment, new upper limits were set with a factor of 20 improvement in sensitivity. Important observations include the first direct detection of ionised O, N and He (and neutral He) atoms arriving from interstellar space, and the measurement of micron-sized dust grains from interstellar space. This first-ever measurement of the interstellar $^{3}He/^{4}He$ ratio sugests that the amount of dark matter created in the Big Bang was greater than previously believed.

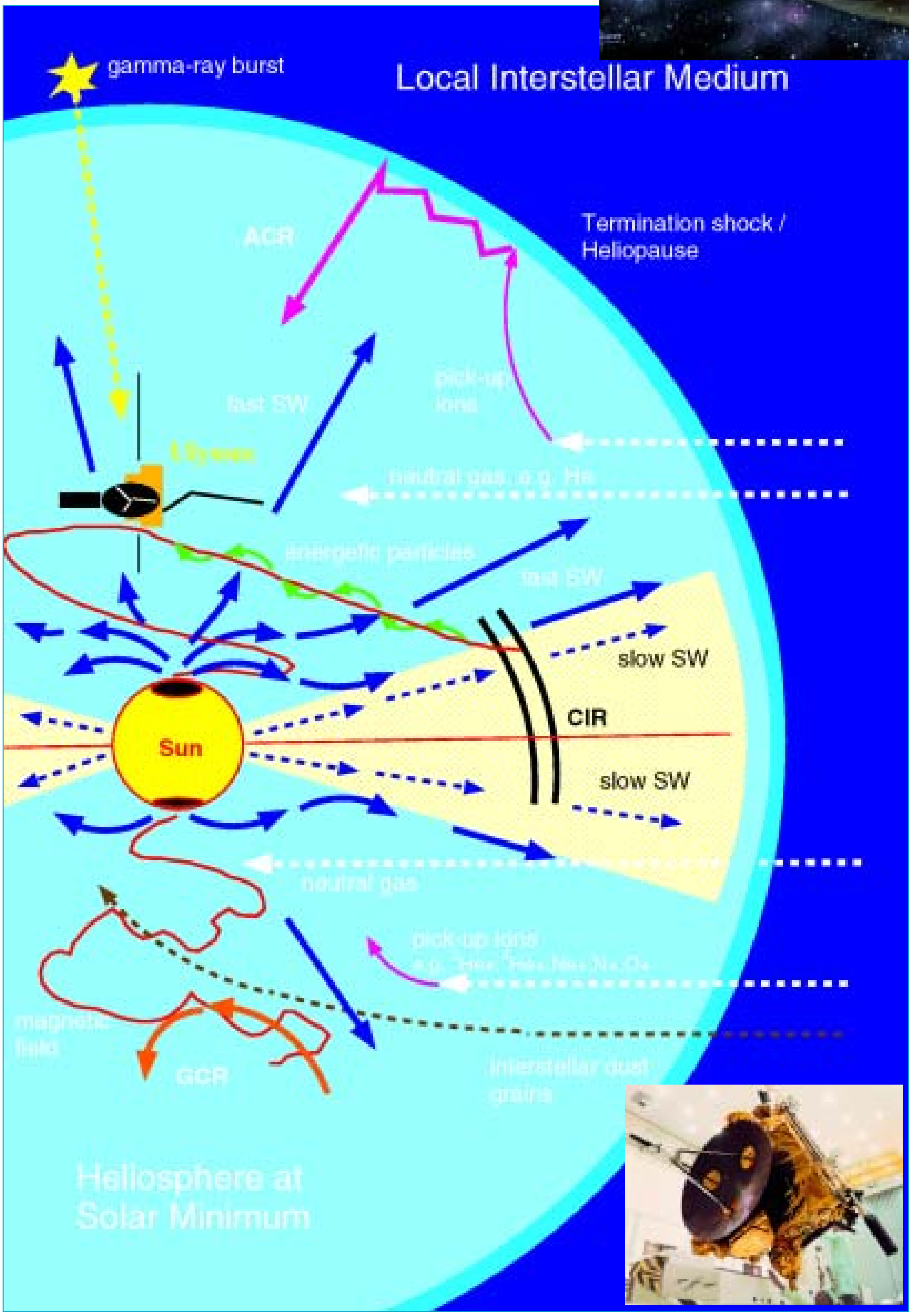
By mid-1993, Ulysses was permanently immersed in the region of space dominated by the Sun's southern pole. This could be seen in the consistently negative polarity measured by the magnetometer from April 1993. Increasing latitude also reduced the intensity of charged particles.

Passage over the Sun's south pole provided the first long-term in situ observations of high-speed solar wind flowing from the large coronal hole that covers that polar cap at solar minimum. Measurements of ionised interstellar neutral gas ('interstellar pickup ions') led to a major advance in understanding the processes affecting this component of the heliospheric particle population.

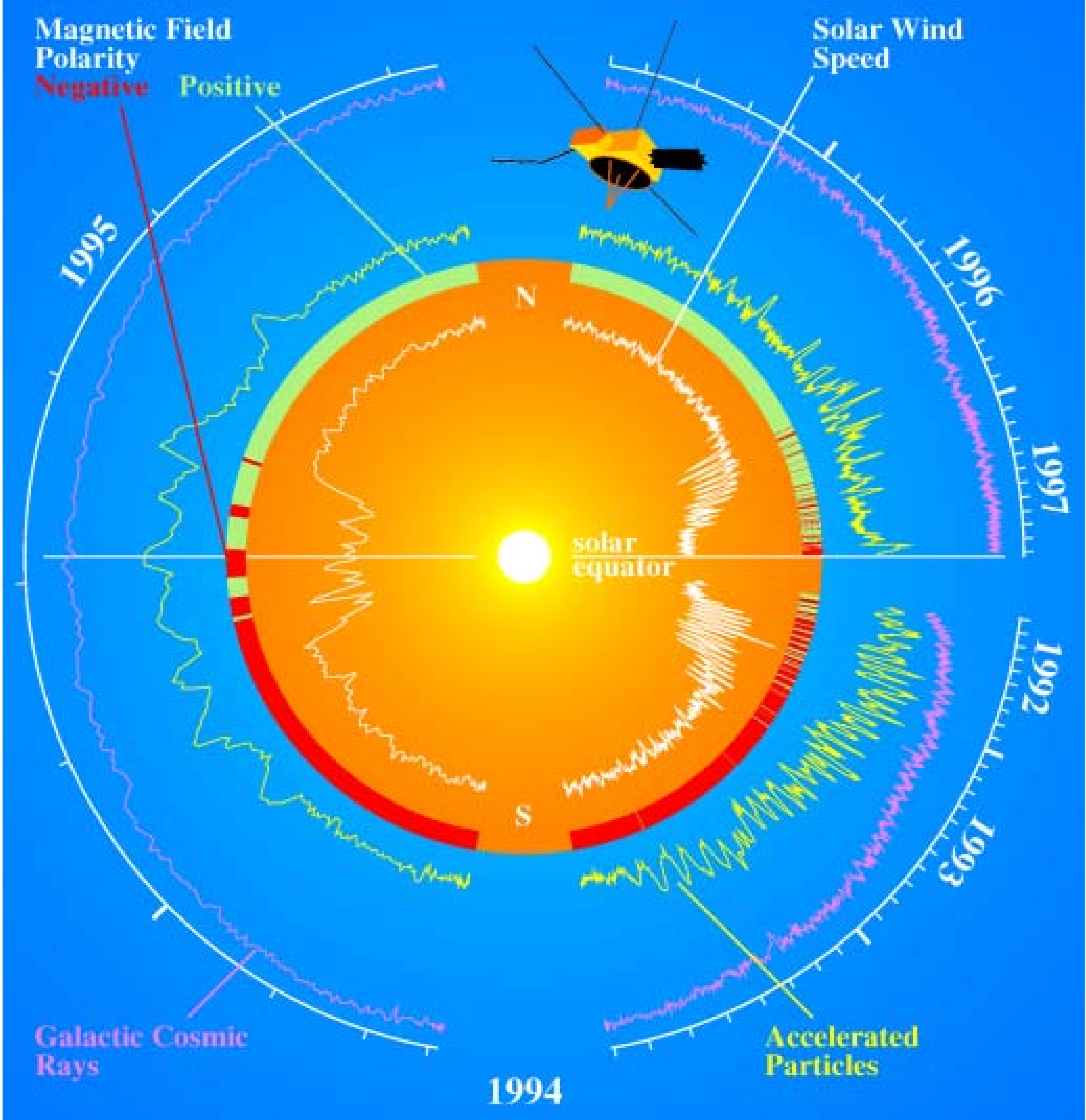
Unexpectedly, the magnetometers detected a wide variety of fluctuations at many spatial scales in the Sun's high-latitude field. They are believed to represent relatively unevolved turbulence originating at the southern polar coronal hole. Another important finding was that the magnetic field radial component varies relatively little with latitude. This is contrary to the expectation that the imprint of the underlying dipole-like magnetic field at the Sun's surface, showing an increase in the radial field at the poles, would be detected at Ulysses' position. Simply, there was no south magnetic pole at high latitudes. Undoubtedly related to the large-scale fluctuations in the polar magnetic field was the detection of an unexpectedly small increase in the influx of cosmic rays over the poles. It was hoped that the much-reduced effects of solar rotation over the pole would result in a smooth near-radial magnetic field, providing easy access to low-energy cosmic rays.



Ulysses is sampling the Sun's sphere of influence in 3-D for the first time.

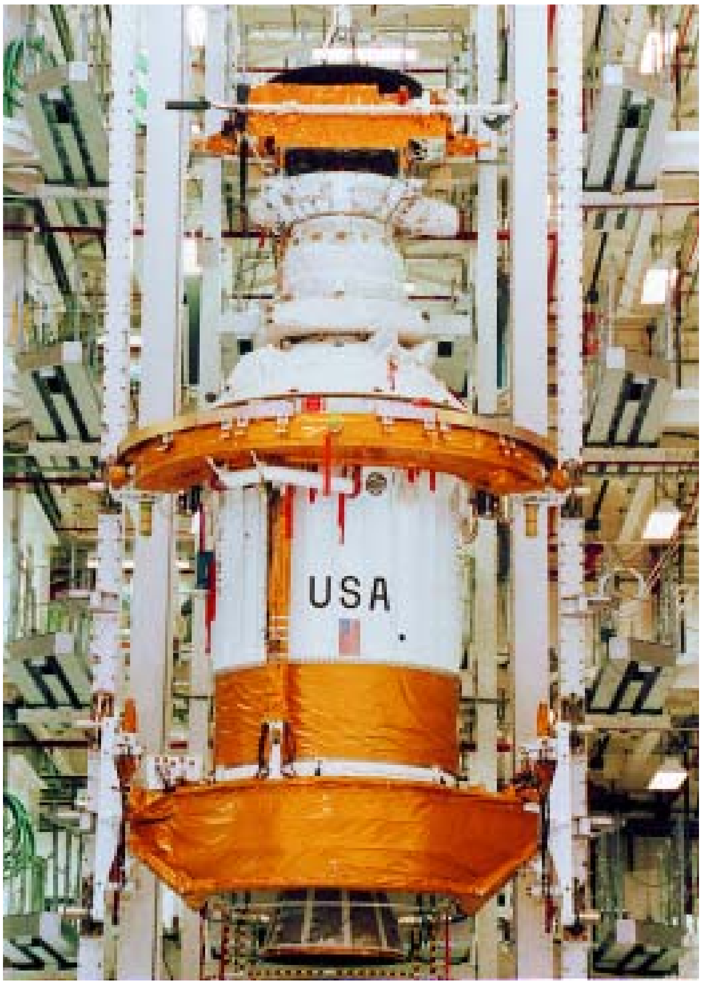


Measurements made by Ulysses during one complete orbit of the Sun, in the form of a polar diagram. The traces show (from the inside moving out) the solar wind speed increasing from 400 km/s near the equator to 750 km/s at latitudes >20-30°, the magnetic field polarity, the intensity of accelerated interplanetary particles, and the intensity of incoming cosmic rays.



Further information on the Ulysses mission can be found at http://sci.esa.int/ulysses/
The Ulysses Qualification Model is displayed at the Noordwijk Space Expo at ESTEC

Installed on its kick stages at Cape Canaveral, Ulysses is ready for installation aboard the Space Shuttle. (NASA)

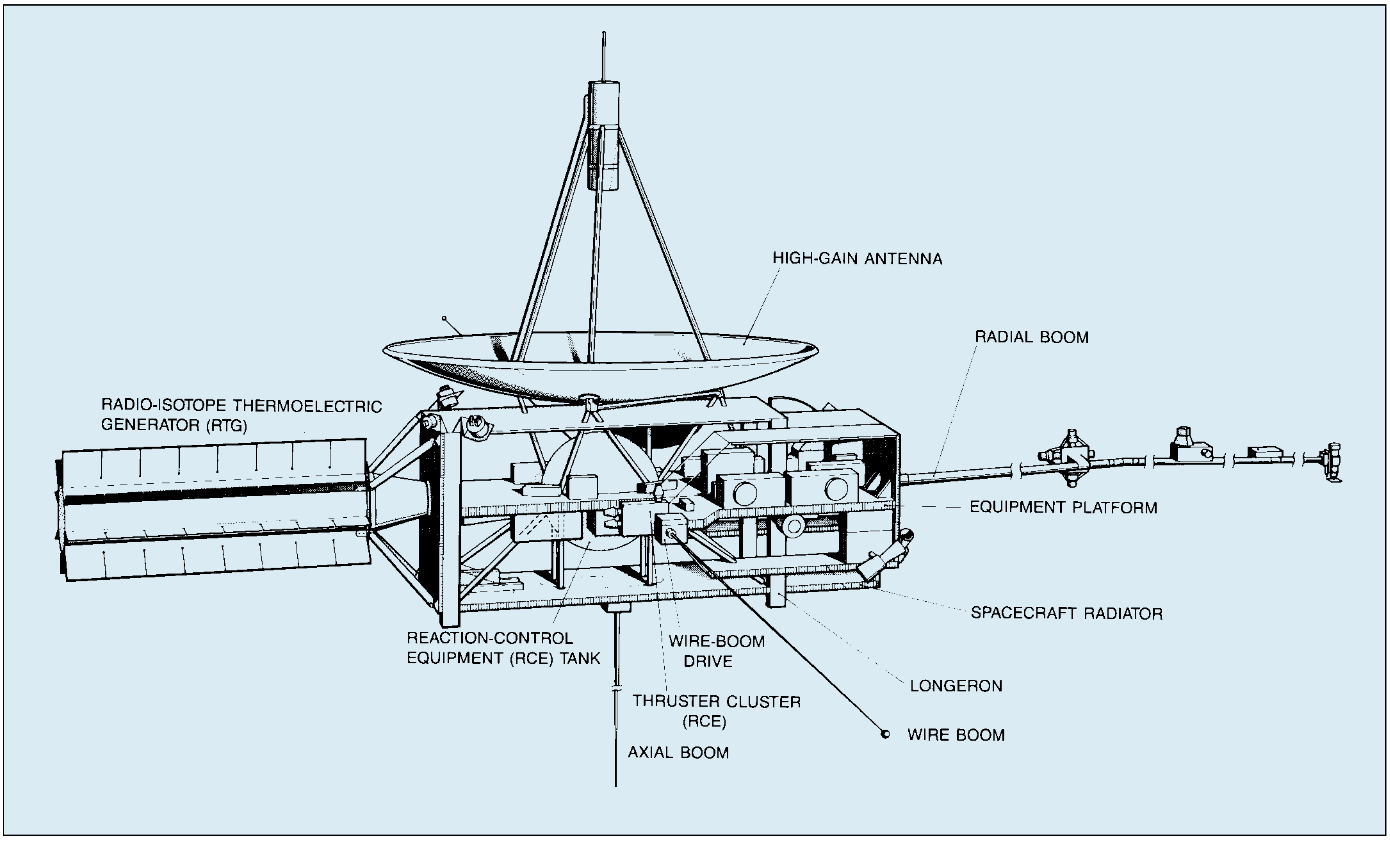


Moving back towards the equator, Ulysses left the fast solar wind (750 km/s) in which it had been immersed for more than 18 months, crossed briefly into the equatorial region dominated by slow wind (400 km/s) and once again became immersed in the fast wind, this time from the north pole. The boundaries were strikingly symmetric: 22°S/21°N. The magnetic field changed from negative (directed inwards) to positive (outwards), reflecting the configuration of the Sun's dipole-like surface field. The radial component's strength continued to show no change with latitude. With the exception of the N-S solar wind asymmetry and cosmic-ray intensity, the north pass was generally similar to the south pass.

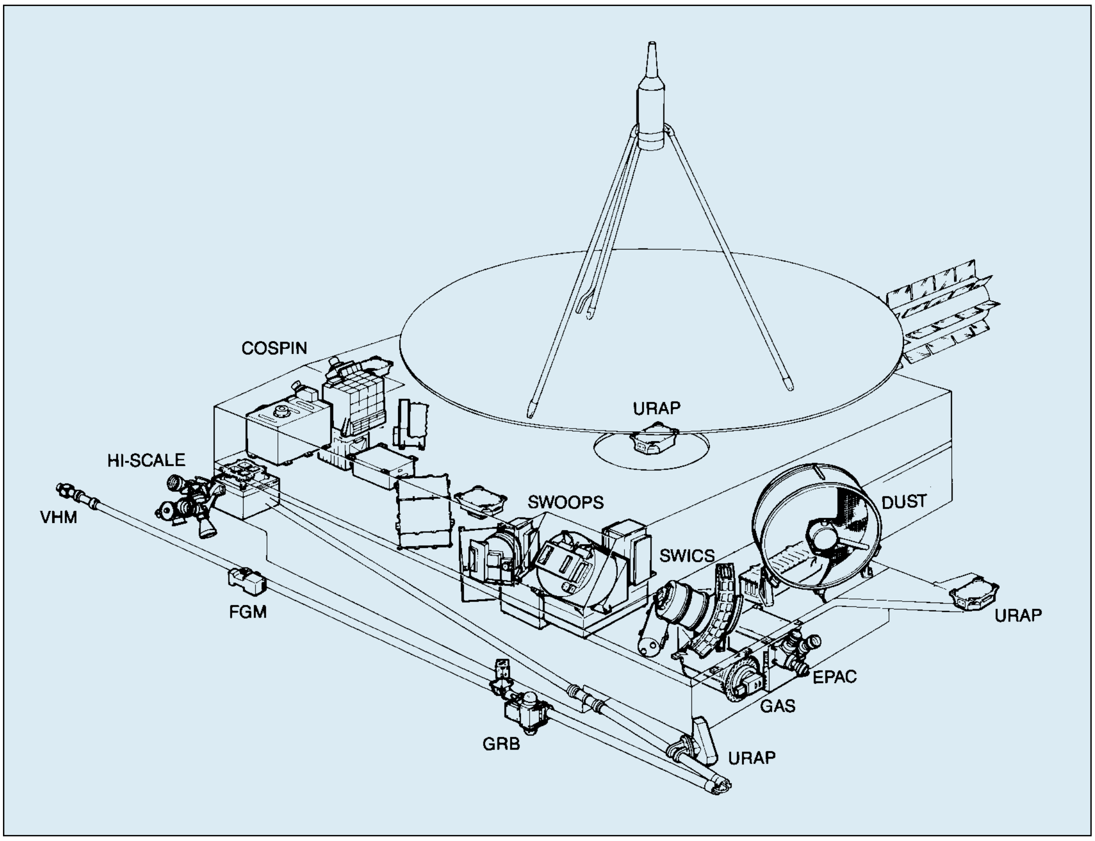
An unexpected result was the finding that Ulysses crossed the distant tail of Comet Hyakutake in 1996. Not well understood at the time, the signature in the magnetic field, solar wind and low-energy ion data was recognised in 1999 to be cometary in origin. With this result. Ulysses set a record for the observation of the longest (3.8 AU) comet tail.

In June 2000, ESA's Science Programme Committee approved additional funding to continue operations until September 2004. A key argument for the extension was to observe the effects of the Sun's magnetic polarity reversal on the heliosphere's structure. From 2002, however, the RTG will not be able to power the full payload. The power-sharing strategy guarantees a set of core measurements covering fundamental solar wind and magnetic field parameters, as well as a number of energetic particle and cosmic ray channels.

After crossing the ecliptic at a distance of 5.4 AU in April 1998 (thus completing the first out-of-the-ecliptic orbit), Ulysses headed back towards the increasingly active Sun, passing over the south pole for a second time in November 2000, and the north pole in October 2001. The solar wind structure is fundamentally different; the speed measured during 1998-2000 is persistently variable. There are no signs of the stable stream structure seen earlier, and the wind speed rarely exceeds 600 km/s. Although magnetic field compressions related to stream interactions are seen, these show no persistent recurrence and extend to the highest latitudes covered to date.



Ulysses principal features.



Locations of Ulysses' scientific instruments. See the table for explanation of the acronyms.

ESA named the project after Homer's mythological hero and in reference to Dante's description in the *Inferno* of Ulysses' urge to explore 'an uninhabited world behind the Sun'.

Ulysses Scientific Instruments

Instrument		*Measurements*	*Instrumentation*	*Mass (kg)*	*Power (W)*	*Data (bit/s)*
SWOOPS	Solar Wind Plasma	ions 0.257-35 keV/Q; electrons 1-903 eV	2 electrostatic analysers + channel electron multipliers	6.7	5.5	160
SWICS	Solar Wind Ion Composition	elemental & ion charge composition, T & speed of 145 km/s (H^+)-1352 km/s (Fe^{+8}) solar wind ions	electrostatic analyser time-of-flight/ energy measurement	5.6	4.0	88
DUST	Cosmic Dust	2×10^{-9}-2×10^{-15}g	multi-coincidence impact detector with channeltron	3.8	2.2	8
MAG	Magnetic Field	±0.01-44 000 nT	triaxial vector helium and fluxgate magnetometers	4.8	5.1	80
GRB	Solar X-rays/ Cosmic Gamma Bursts	5-150 keV	2 Si solid-state + 2 CsI scintillation detectors	2.0	2.6	40
EPAC/ GAS	Energetic Particle Composition	0.080-15 MeV/nucleon composition Interstellar Neutral Helium	4 solid-state detectors LiF-coated conversion plates with channel electron multipliers	4.3	4.0	160
HISCALE	Low-Energy Ions & Electrons	0.050-5 MeV ions; 30-300 keV electrons	2 sensor heads with 5 solid-state detectors	5.8	4.0	160
COSPIN	Cosmic Rays/ Solar Particles	0.3-600 MeV/nucleon; 4-2000 MeV electrons	5 solid-state detectors + double Cerenkov and semiconductor telescope for electrons	14.8	14.8	160
URAP	Radio & Plasma Waves	0-60 kHz plasma waves 1-940 kHz 10-500 Hz magnetic fields	72.5 m radial dipole antenna 7.5 m axial monopole antenna 2-axis search coil	7.4	10.0	232

Radio Science investigations (Coronal Sounding and Gravitational Wave Experiments) were conducted during the primary mission phase.

Satellite configuration: box-shaped aluminium bus supports body-mounted aluminium/CFRP HGA, RTG boom and several science booms: 5.55 m radial boom carries four sensors for HED, STO and HUS experiments (see table), 7.5 m axial boom acts as monopole for STO and two wire booms 72.5 m tip-to-tip as dipole for STO.

Attitude/orbit control: spin-stabilised at 5 rpm, with fixed HGA pointing continuously at Earth. Two sets of 4x2 N hydrazine thrusters (33 kg supply stored at 22 bar) provide spin control and trajectory corrections. Attitude determined by Sun sensors and HGA X-band signal angle.

Power system: RTG provided 284 W initially, decreasing to 221 W by 2001.

Communications/data: Ulysses is tracked 8 h/day by the 34 m antennas of NASA's Deep Space Network. Operations are controlled by a joint ESA/NASA team at NASA's Jet Propulsion Lab in California. 1.65 m-diameter HGA downlinks realtime data at 1024 kbit/s interleaved with playback of stored data at 20 W 8.4 GHz X-band. 5 W S-band 2112/2293 MHz up/down is used for dual-frequency radio science investigations. Two redundant tape recorders each store 45.8 Mbit at 128/256/512 bit/s.

ERS

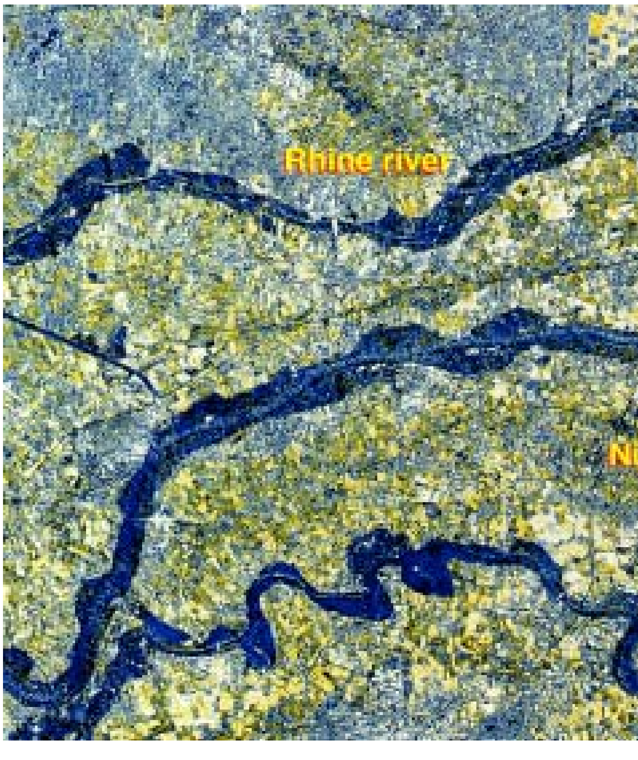
Achievements: first European radar satellites, first long-duration civil radar satellites
Launch dates: ERS-1 17 July1991; ERS-2 21 April 1995
Mission end: ERS-1 10 March 2000; ERS-2 continues full operations. 3-year projected lives
Launch vehicle/site: Ariane-4 from Kourou, French Guiana
Launch mass: ERS-1 2384 kg on-station BOL (888 kg payload, 318 kg hydrazine); ERS-2 2516 kg on-station BOL
Orbit: ERS-1 782x785 km, 98.5° Sun-synchronous with 35-day repeat cycle during most of operational phase; ERS-2 784x785 km, 98.6° Sun-synchronous, phased with ERS-1 for 1-day revisits
Principal contractors: Dornier (prime), Matra (bus), Marconi Space Systems (AMI), Alenia Spazio (RA), British Aerospace (ATSR); ERS-2 added Officine Galileo (GOME)

The European Remote Sensing (ERS) satellite is the forerunner of a new generation of environmental monitoring satellites, employing advanced microwave techniques to acquire measurements and images regardless of cloud and lighting conditions. Such techniques had been used previously only by NASA's short-lived Seasat mission in 1978, and during brief Space Shuttle experiments.

ERS is unique in its systematic and repetitive global coverage of the Earth's oceans, coastal zones and polar ice caps, monitoring wave heights and wavelengths, wind speeds and directions, precise altitude, ice parameters, sea-surface temperatures, cloud-top temperatures, cloud cover and atmospheric water vapour content. Until ERS appeared, such information was sparse over the polar regions and the southern oceans, for example.

ERS is both an experimental and a pre-operational system, since it has had to demonstrate that the concept and the technology have matured sufficiently for successors such as ESA's Envisat, and that the system could routinely deliver to end users some data products such as sea-ice distribution charts within a few hours of the satellite observations.

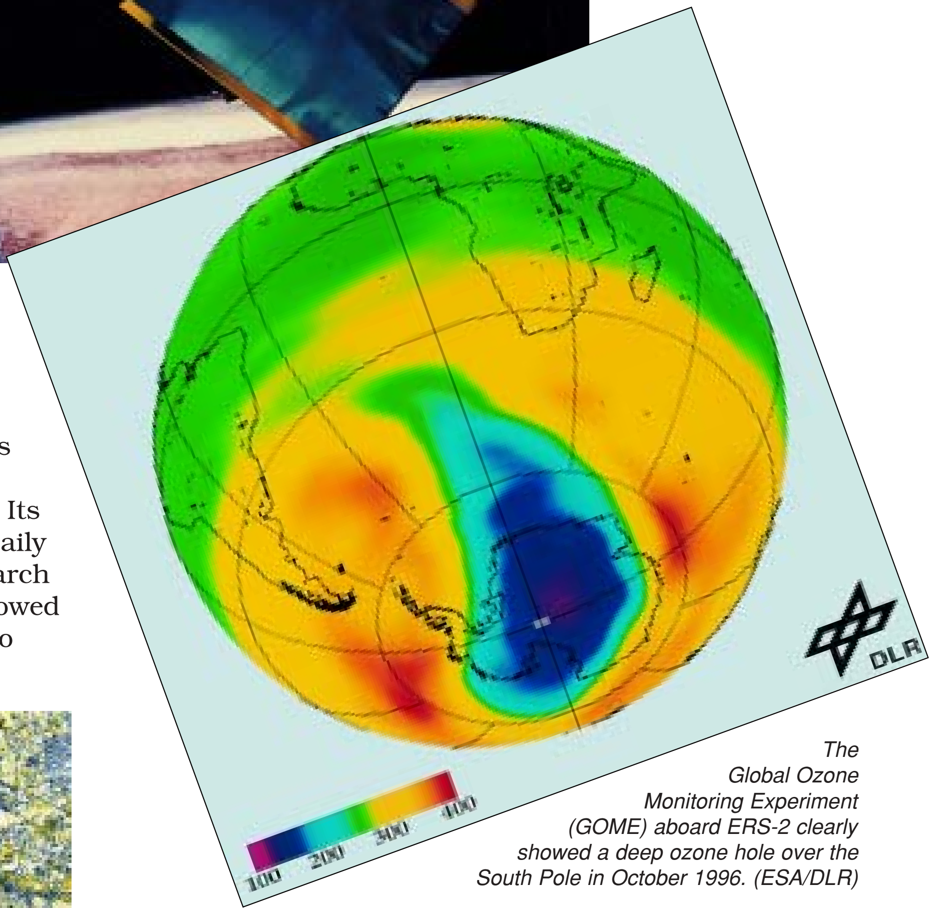
ESA launched ERS-2 to ensure continuity of service until Envisat's appearance in 2001, and the pairing with ERS-1 made new demonstrations possible. The two satellites operated simultaneously from August 1995 to May 1996 – the first time that two identical civil Synthetic Aperture Radars (SARs) had worked in tandem. The orbits were carefully phased for 1-day revisits, allowing the collection of



ERS in orbital configuration. During its remarkable career, ERS-1 generated about 1.5 million SAR scenes. More than 3500 scientists have published more than 30 000 scientific papers based on ERS data. (Dornier)

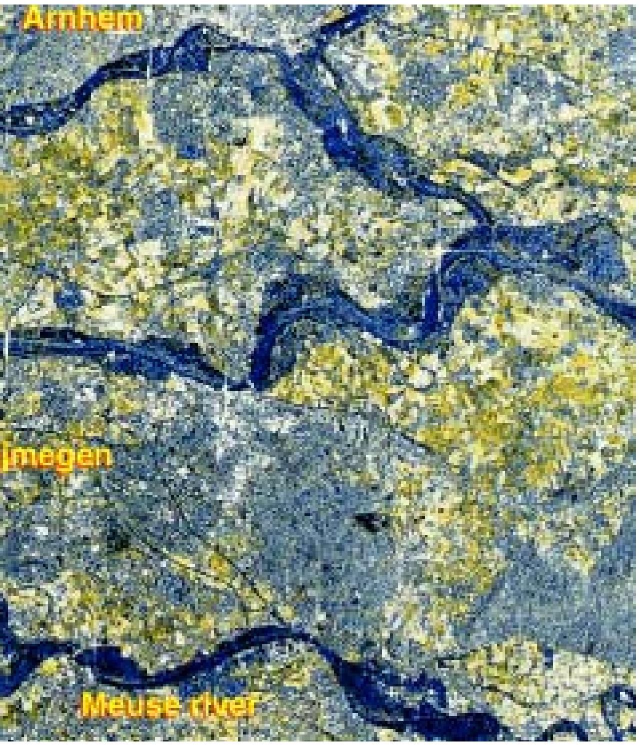
'interferometric' image pairs revealing minute changes.

ERS-1 was held in hibernation as a backup from June 1996, while ERS-2 continued full operations. Its SAR Image mode was activated daily for battery conditioning. On 8 March 2000 a computer failure was followed the next day by an unrelated gryo

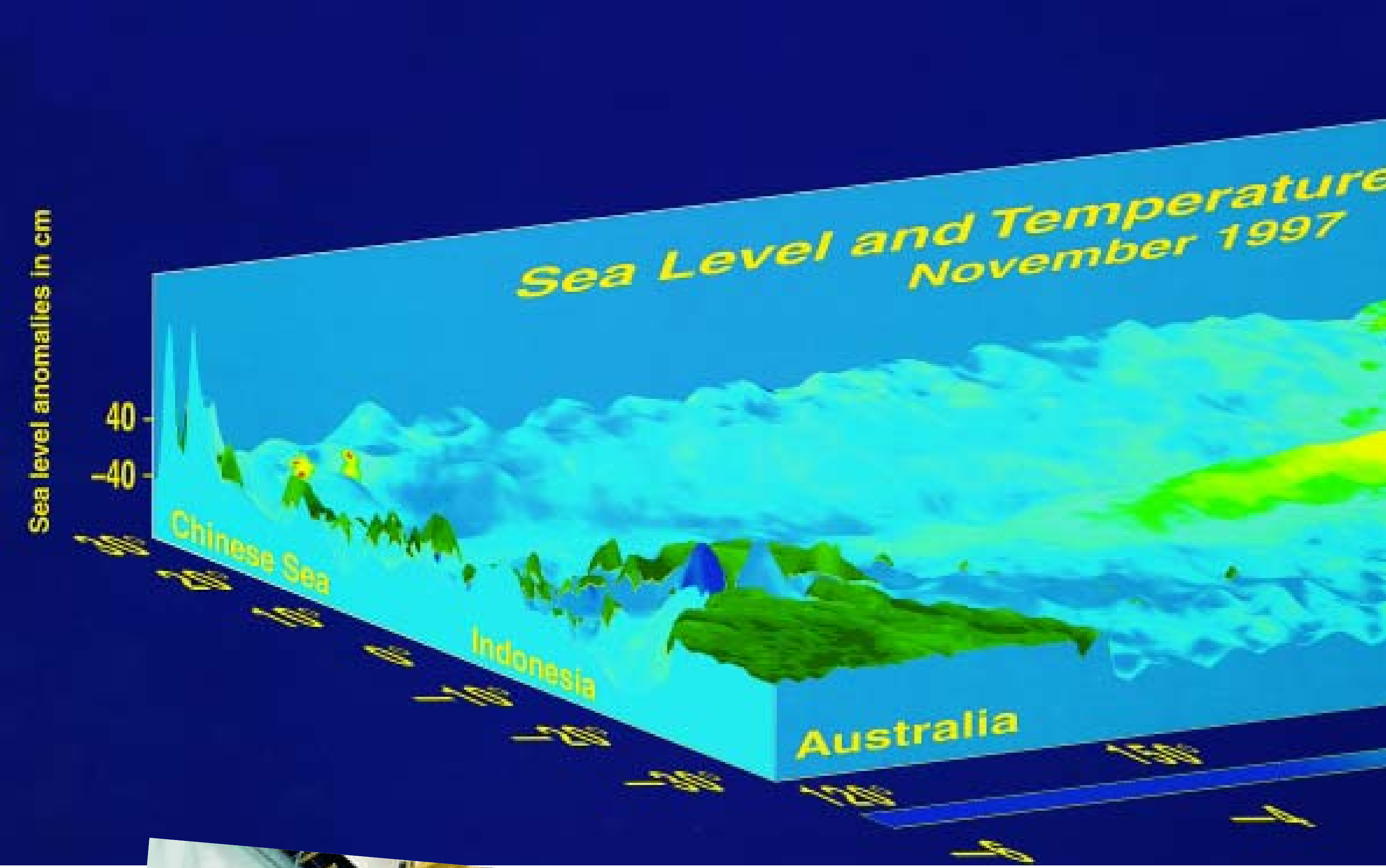


The Global Ozone Monitoring Experiment (GOME) aboard ERS-2 clearly showed a deep ozone hole over the South Pole in October 1996. (ESA/DLR)

control failure, leading to battery depletion on 10 March. During its remarkable career, major progress was made in environmental and geophysical applications such as disaster monitoring and risk management. It is hoped that ERS-2 will continue operations until at least Metop-1 is commissioned in 2006.

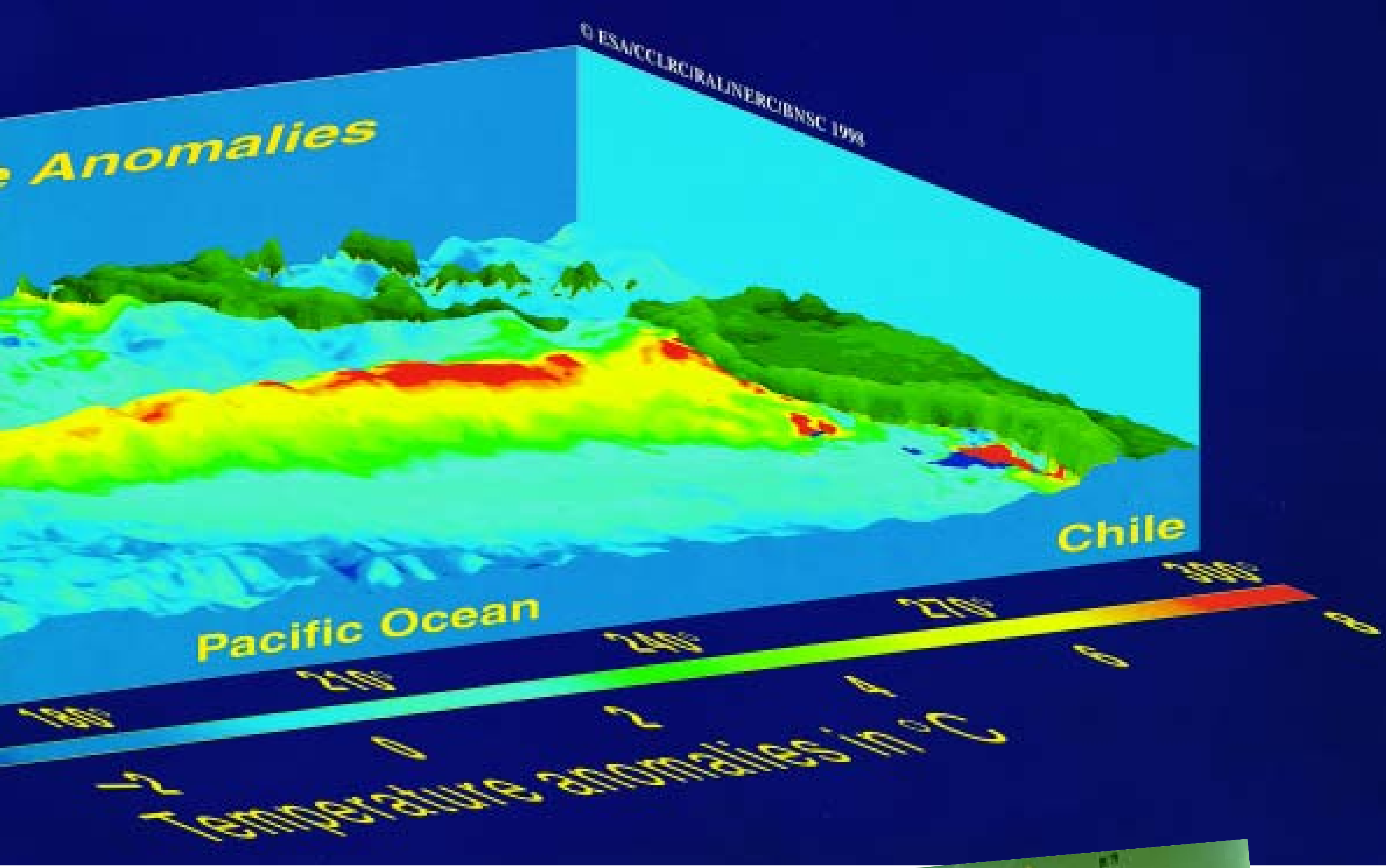


ERS view of flooding in Northern Europe in January 1995. This image was created by superimposing two Synthetic Aperture Radar images and assigning different colours to each. The first image was acquired on 21 September 1994 and the second on 30 January 1995. Flooded areas appear in blue.



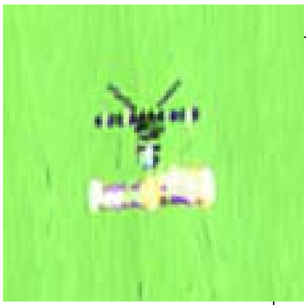
El Niño is a disruption of the ocean-atmosphere in the tropical Pacific that affects weather around the globe. The 1997-98 El Niño is one of the strongest this century, with increased rainfall causing destructive flooding in the US and Peru, and drought in the western Pacific, also associated with devastating fires. The phenomenon is characterised by a rise of up to 40 cm in sea level and up to 8°C in sea-surface temperature in the eastern equatorial Pacific and falls of up to 40 cm/6°C in the western equatorial Pacific. They are closely monitored by the ERS Radar Altimeter and Along-Track Scanning Radiometer. The image above shows the state of the Pacific Ocean in November 1997. The height of this 3D image represents sea-level anomalies, ranging from -40 cm to +40 cm; the colours indicate sea-surface temperature anomalies ranging from -6°C (blue) to 8°C (red).

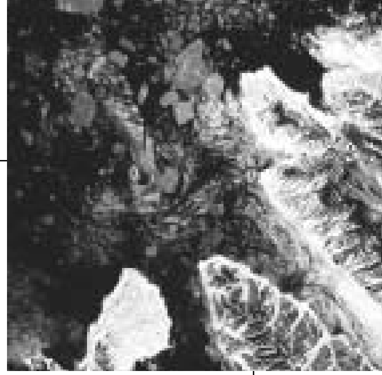
ERS-2 undergoing final launch preparations at Kourou, French Guiana. (ESA/CSG/Arianespace)

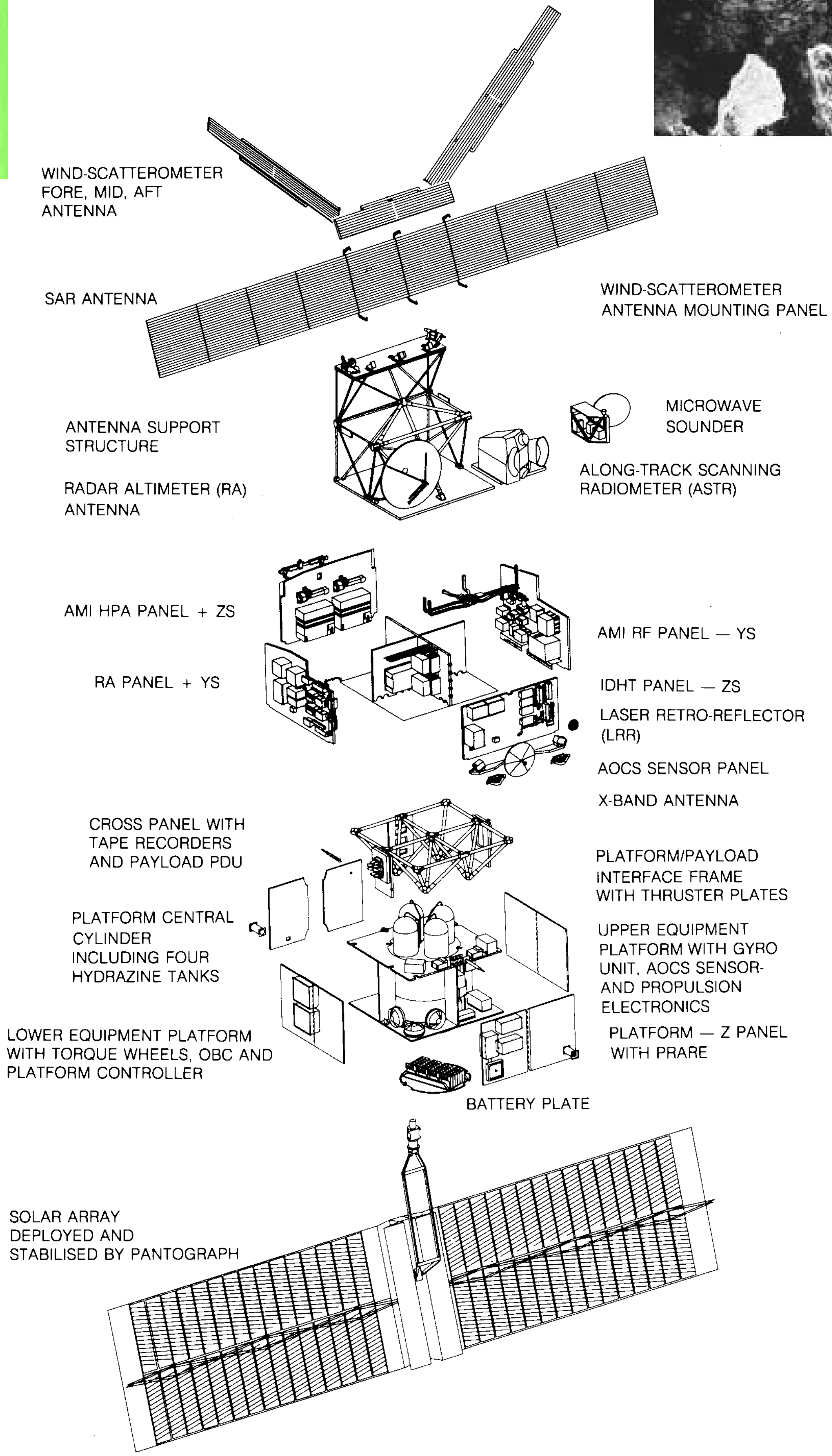


The 'normal' state of the ocean is such that the sea level on the western side is higher than on the eastern side. This difference is due to the Trade Winds blowing constantly from east to west, causing the waters to pile up at the western side. Also due to the Trade Winds, the surface water on the eastern side is constantly transported westward, and replaced by cold, nutritious water rising from deeper layers. So generally along the South American coast, cold and nutritious waters prevail, while on the western side there is warm surface water. During an El Niño event the Trade Winds relax, and become very weak (and may even reverse). This causes the warm surface waters to flow back eastward, and stops the upwelling on the eastern side. No more upwelling means that the sea-surface temperatures rise, implying a sea level rise.

ERS-2 in the Large European Acoustic Facility at ESTEC.






WIND-SCATTEROMETER
FORE, MID, AFT
ANTENNA
SAR ANTENNA
WIND-SCATTEROMETER
ANTENNA MOUNTING PANEL
ANTENNA SUPPORT
STRUCTURE
MICROWAVE
SOUNDER
RADAR ALTIMETER (RA)
ANTENNA
ALONG-TRACK SCANNING
RADIOMETER (ASTR)
AMI HPA PANEL + ZS
AMI RF PANEL — YS
RA PANEL + YS
IDHT PANEL — ZS
LASER RETRO-REFLECTOR
(LRR)
AOCS SENSOR PANEL
X-BAND ANTENNA
CROSS PANEL WITH
TAPE RECORDERS
AND PAYLOAD PDU
PLATFORM/PAYLOAD
INTERFACE FRAME
WITH THRUSTER PLATES
PLATFORM CENTRAL
CYLINDER
INCLUDING FOUR
HYDRAZINE TANKS
UPPER EQUIPMENT
PLATFORM WITH GYRO
UNIT, AOCS SENSOR-
AND PROPULSION
ELECTRONICS
LOWER EQUIPMENT PLATFORM
WITH TORQUE WHEELS, OBC AND
PLATFORM CONTROLLER
PLATFORM — Z PANEL
WITH PRARE
BATTERY PLATE
SOLAR ARRAY
DEPLOYED AND
STABILISED BY PANTOGRAPH

ERS principal features (ESA). Inset left: ERS-1 imaged from 41 km above by France's Spot-4 Earth observation satellite on 6 May 1998 over the Tenere Desert of Niger, Africa (CNES). Inset right: the first recorded SAR image (at Kiruna) from ERS-1, taken at 11:50:32 UT 27 July 1991 and centred on 79.99°N/15.01°E (ESA).

Satellite configuration: payload support module, 2x2 m, 3 m high, above a platform derived from Matra's 3-axis Spot platform providing power, AOCS and overall operational management. Total 11.8 m high, 11.7 m deployed span.

Attitude/orbit control: primary attitude control by reaction wheels, unloaded by magnetorquers. Hydrazine thrusters provide orbit adjust and further attitude control. Pitch/roll information from Digital Earth Sensor, yaw reference from Sun sensor; supported by 6 gyros. ERS-2 began 1-gyro control in Feb 2000, and switched to gyroless control (using DES and X-axis RW) in Feb 2001 to preserve remaining good gyro for critical operations.

Power system: twin 2.4x5.8 m Si-cell solar wings sized for 2.2 kW after 2 years, supported by four 24 Ah nickel cadmium batteries.

Communications: controlled from ESOC at Darmstadt, Germany with ESA ground receiving stations at Salmijärvi, near Kiruna (Sweden, primary station, also for TT&C), Fucino (I), Gatineau (CDN), Maspalomas (E), Prince Albert (CDN), plus national & foreign stations e.g. at Fairbanks (Alaska, US), Neustrelitz (D), West Freugh (UK), Alice Springs (Australia). SAR's 105 Mbit/s image data returned in realtime only, available only when the wave/wind modes are inactive (other data recorded onboard, thus providing global coverage). ESA's ESRIN ERS Central Facility (EECF) facility at Frascati (I) is the user service and data management centre and prepares the mission operation plan for ESOC, with processing/archiving facilities at Brest (F), Farnborough (UK), DLR Oberpfaffenhofen (D) and Matera (I). Some products, such as from the wind scatterometer, are available within 3 h of observation.

ERS Earth Observation Payload

Active Microwave Instrument *(AMI)*

Incorporates two separate 5.3 GHz C-band 4.8 kW-peak power radars: a Synthetic Aperture Radar using a 1x10 m antenna for the image and wave modes; a 3-beam scatterometer for the wind mode. *SAR imaging:* 30 m resolution, linear-vertical polarisation, 37.1 µs transmit pulse width, 105 Mbit/s data rate, 100 km swath width, with 23° incident angle at mid-swath (up to 35° using experimental roll-tilt attitude control system mode). *SAR wave mode:* operates at 200 km intervals along-track for 5x5 km images to provide ocean wave speed and directions. *AMI Wind Scatterometer:* three antennas (fore/aft 360x25 cm, mid 230x35 cm) providing fore/mid/aft beams sweep 500 km swath in 50 km cells for surface wind vectors: 4-24 m/s, 0-360±20°.

Radar Altimeter *(RA)*

The 120 cm-diameter nadir-viewing, 13.8 GHz, 1.3°-beamwidth altimeter measures, in Ocean Mode, wind speed (2 m/s accuracy), 1-20 m wave heights (50 cm accuracy, 2 km footprint), and altitude to 5 cm. Ice Mode operates with a coarser resolution to determine ice sheet topography, ice type and sea/ice boundaries.

Along-Track Scanning Radiometer and Microwave Sounder *(ATSR-M)*

An experimental 4-channel IR radiometer for temperature measurements and a 2-channel nadir-viewing microwave sounder for water vapour measurements. *IR Radiometer:* scanning at 1.6/3.7/10.8/12 µm, 0.5 K resolution over 50x50 km, 1 km spatial resolution; 500 km swath. ERS-2 added 0.55/0.67/0.78 µm visible channels to improve monitoring of land applications, such as vegetation moisture. *Microwave Sounder:* 23.8/36.5 GHz channels measuring the vertical column water vapour content within a 20 km footprint, providing corrective data for ATSR sea-surface temperature and RA measurements.

Global Ozone Monitoring Experiment *(GOME, ERS-2 only)*

Near-UV/visible scanning spectrometer measuring backscattered Earth radiance in 3584 pixels over four channels, 240-316/311-405/405-611/595-793 nm, to determine ozone and trace gases in troposphere and stratosphere.

Precise Range/Range Rate Experiment *(PRARE)*

For precise orbit determination with ranging accuracy of 3-7 cm using 8.5 GHz signals transmitted to a network of mobile ground transponders. ERS-1 PRARE failed within 3 weeks because of radiation damage, but ERS-2's improved design remains operational.

Laser Retroreflector

Also permits precise range/orbit determination, but less frequently than PRARE, and RA calibration.

Further information on ERS and other ESA Earth observation projects can be found at http://earth.esa.int

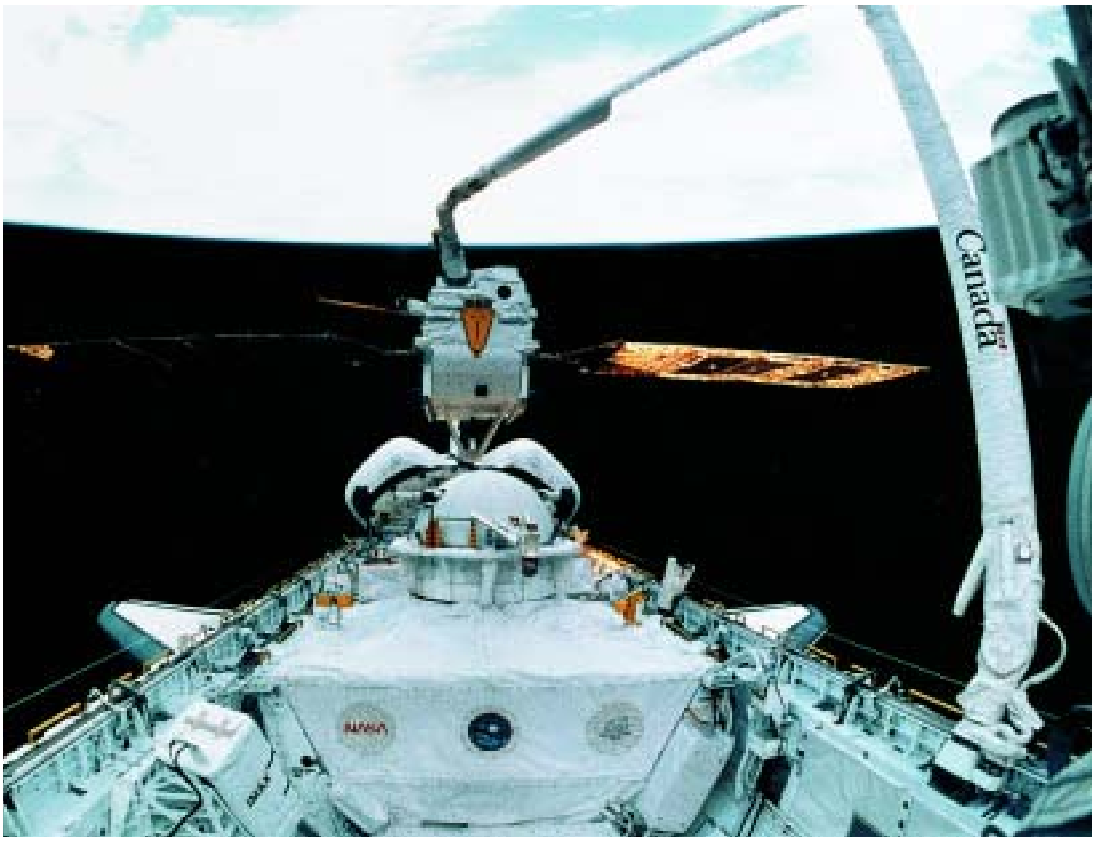
Eureca

Achievements: world's first dedicated microgravity free-flyer; Europe's first reusable satellite
Launch date: 31 July 1992
Mission end: 24 June 1993
Launch vehicle/site: NASA Space Shuttle from Kennedy Space Center, Florida
Launch mass: 4490 kg (payload capacity up to 1000 kg)
Orbit: released from Shuttle into 425 km, 28.5°, raised to 508 km for experiment operations, lowered to 476 km for retrieval by Shuttle
Principal contractors: MBB-ERNO (prime)

ESA began studying the European Retreivable Carrier (Eureca) in 1978 as a follow-on to the manned Spacelab programme; the ESA Council approved it in December 1981. Eureca was designed to carry a mix of experiments totalling up to 1 t for 6-9 months in orbit, released and retrieved by NASA's Space Shuttle. It was the world's first free-flyer designed specifically to satisfy microgravity experiments, providing 10^{-5} g conditions for long periods. Although Eureca was controlled from ESOC in Germany, it could operate autonomously for up to 48 h. An important feature was reusability: Eureca was capable of making five flights over a 10-year period.

Eureca-1 and its 15 experiments (see separate box) were launched aboard Shuttle mission STS-46 in July 1992 and released from the Shuttle's robot arm by ESA Mission Specialist Claude Nicollier on 2 August. Eureca's thrusters raised its orbit by 83 km within a week and the 6 months of operations began on 18 August. Most of the microgravity experiments were completed by January 1993, but others continued even as it Eureca waited for recovery during Shuttle mission STS-57 in June 1993. By that time, its orbit had decayed through atmospheric drag to 490 km and its thrusters lowered it further to 476 km for NASA astronaut George Low to capture it during 24 June.

The Eureca-1 mission was rated as highly successful, and a 1995 Eureca-2 mission was planned but ESA Ministerial meetings rejected further funding. The carrier was stored at DASA (ex-MBB/ERNO) in Bremen, where it was hoped that a DASA-led consortium could provide commercial flights.



Eureca's solar wings were safely deployed before the free-flyer was released. (NASA)

Integration of Eureca at DASA in Bremen. (DASA)

Eureca-1 Payload

ESA's five microgravity core multi-user facilities:

- Automatic Mono-ellipsoid Mirror Furnace (AMF)
- Solution Growth Facility (SGF)
- Protein Crystallisation Facility (PCF)
- Multi Furnace Assembly (MFA)
- Exobiological Radiation Assembly (ERA).

Two further microgravity elements were:

- High Precision Thermostat (HPT, Germany)
- Surface Forces Adhesion Experiment (SFA, Italy).

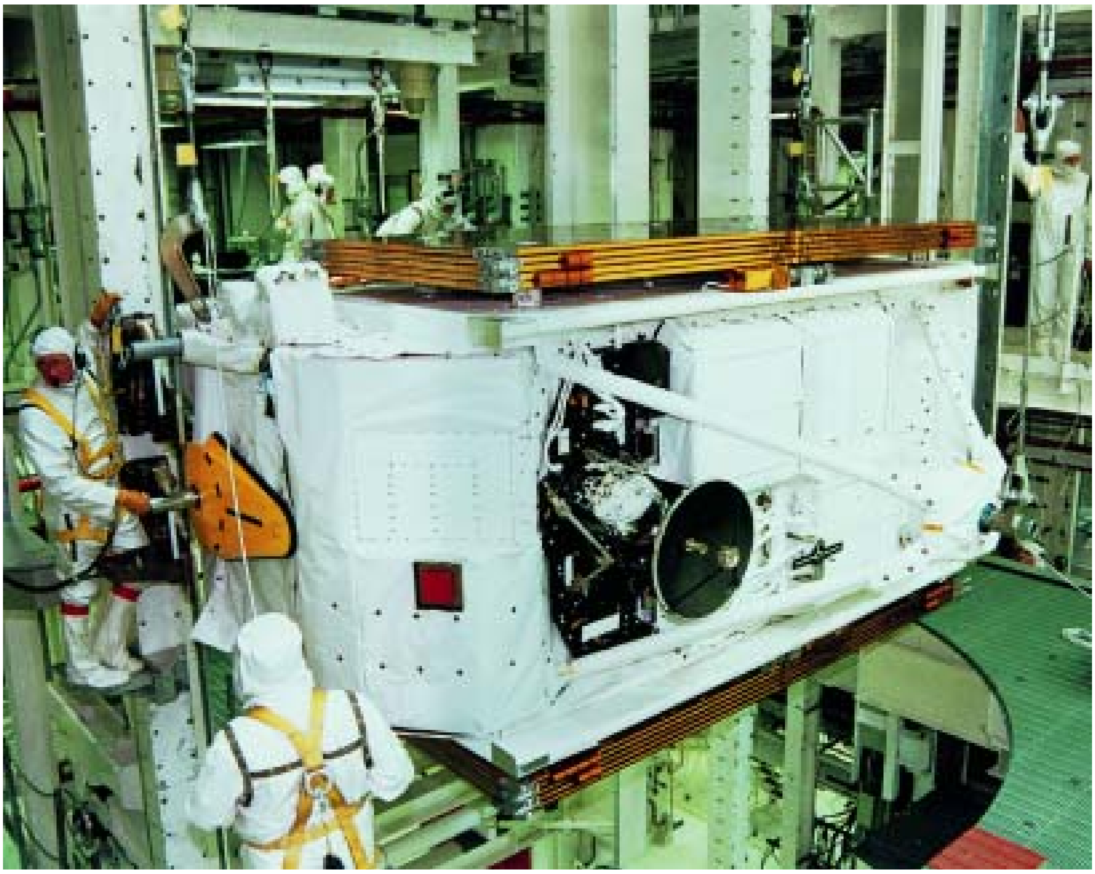
The five space science experiments were:

- Solar Spectrum Experiment (SOSP)
- Solar Variation Experiment (SOVA)
- Occultation Radiometer (ORA)
- Wide Angle Telescope for Cosmic and X-ray Transients (WATCH)
- Timeband Capture Cell Experiment (TICC).

The three technology demonstrations were:

- Radio Frequency Ionization Thruster Assembly (RITA)
- Advanced Solar Gallium Arsenide Array (ASGA)
- Inter Orbit Communication Experiment (IOC, working with Olympus).

Eureca – with its solar wings already folded against its sides – was recaptured in June 1993 after almost a year in orbit. (NASA)



Processing Eureca at the Kennedy Space Center for insertion into the Space Shuttle cargo bay. (NASA)

Satellite configuration: total width 4.6 m, total height about 2.6 m. Bus structure consisted of carbon fibre struts connected by titanium nodal joints. The nodes carried larger hardware loads, while smaller assemblies were fastened to standard Equipment Support Panels. Supported in Shuttle cargo bay by two longeron and one keel fitting. Grapple fixture allowed deployment/retrieval by Shuttle Remote Manipulator System.

Attitude/orbit control: 3-axis control (normally Sun-pointing) by magnetorquers, supported by Reaction Control Assembly of 6x21 mN nitrogen thrusters. Orbit transfers between about 400-500 km by Orbit Transfer Assembly of redundant 4x21 N hydrazine thrusters (supply sized for two transfers plus 9-month on-orbit stay). Attitude/rate determination by accelerometer package, gyros and IR Earth and Sun sensors.

Power system: twin deployable/ retractable 5-panel Si-cell wings generated 5 kW at 28 Vdc, providing 1 kW average for payload operations (1.5 kW peak). Supported by 4x40 Ah nickel cadmium batteries.

Eureca has been displayed since November 2000 at the Swiss Museum of Transport and Communication in Lucerne. (Courtesy of the Museum)

Communications: controlled from ESOC in Darmstadt, Germany. S-band link provided up to 256 kbit/s downlink for payloads, with 128 Mbit onboard memory.

ISO

Achievements: world's first space infrared observatory; fundamental discoveries on the nature of the Universe; far-exceeded design life
Launch date: 19 November 1995 (routine science operations began 4 February 1996)
Mission end: deactivated 12:00 UT 16 May 1998; last science observation 10 May 1998; cryogen exhausted 8 April 1998
Launch vehicle/site: Ariane-4 from Kourou, French Guiana
Launch mass: 2498 kg (2418 kg BOL)
Orbit: initially 500x71 850 km, 5.25°; raised to operational 1038x70 578 km, 5.2°, 24 h
Principal contractors: Aerospatiale (prime), DASA (cryostat payload module)

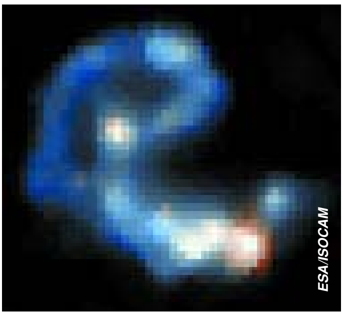
The spectacular success of the Infrared Space Observatory (ISO) as the world's first spaceborne observatory working in the cool light of the infrared has provided an entirely fresh perspective on the Universe. It has proved a major boost to most areas of astrophysics, reaching from the nearby planets to the most distant quasars, taking in star formation, dark matter and superluminous galaxies.

The cryogenically-cooled ISO studied the Universe's 2.5-240 µm IR radiation as a follow-up to the all-sky survey undertaken by IRAS (8-120 µm) in 1983. However, ISO's sensitivity at 12 µm was about 1000 times greater and spatial resolution 100 times higher, and it was operated from ESA's station in Villafranca, Spain as an *observatory*, studying specific targets for up to 10 h at a time, with more than half of its observing time available to the general astronomical community.

Very deep camera and photometer images were recorded to study the early evolution of galaxies and to help determine the history of star formation. All the instruments observed many star-forming regions to study how clouds of dust and gas collapse to form young stars. Many observations looked at stars with discs of matter to unravel the mysteries of planet formation. The spectrometers found abundant water in many different places: Comet Hale-Bopp, Mars, Titan and the giant planets in our own solar system, around young and old stars and even in external galaxies. ISO looked hard at the mysterious 'ULIRGs' (ultra-luminous IR galaxies) and shed new light on whether their prodigious power comes mainly from bursts of star formation (the 'baby' theory) or

New-born stars in the Rho Ophiuchi cloud. The bright fuzzy object at top is a new massive star – much heavier than the Sun – still wrapped in the placental cloud from which it formed. (ESA/ISO, CEA Saclay, ISOCAM Consortium)

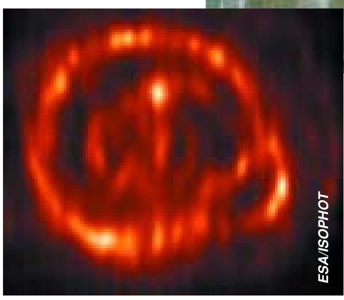
The Antennae: the collision of two galaxies has triggered star formation within dense IR-bright dust clouds.



from stars being swallowed by black holes (the 'monster' theory). ISO found the characteristic chemical signatures of starbursts.

ISO's payload module was supported by the service module below. (Aerospatiale)

ISO found clear links between stars, comets and Earth's origin. It found the spectral signature of the mineral olivine – a major constituent of Earth's interior – in Comet Hale-Bopp and in dusty discs encircling young stars where planetary systems are forming. Many molecular species were detected in interstellar space for the first time, including carbon-bearing molecules such as the methyl radical and benzene, providing insight into the complex organic chemistry necessary to produce the molecules of life.

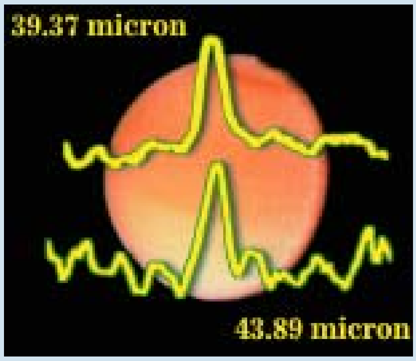


Seen in the far-IR, the Andromeda Galaxy (M31) sports multiple rings rather than the classical spiral form seen in visible light.

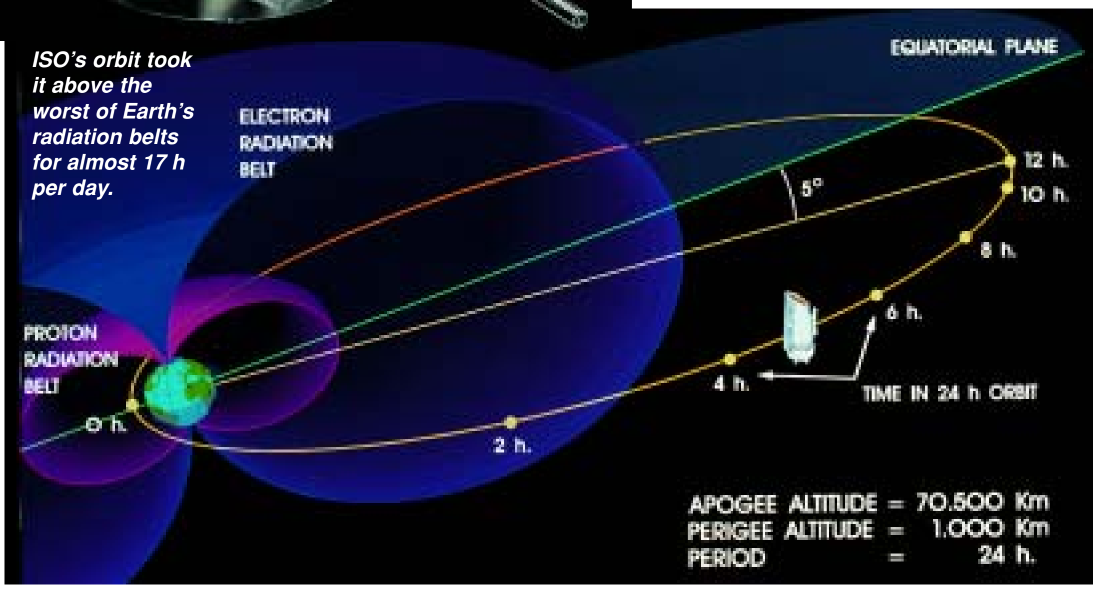
ISO made more than 26 000 separate observations and, by the time orbital operations ended, the work of detailed analysis was only just starting. The flood of results shows no sign of abating: almost 700 refereed papers were published between late 1996 and May 2001, and about 100 astronomers every month retrieve data from the ISO archive in Villafranca (E).

Working at these thermal wavelengths meant that ISO's telescope and detectors had to be encased in a cryostat filled with >2100 litres of superfluid helium chilled to only 1.8 K above absolute zero. A pre-mission life of about 18 months was required before the helium completely boiled away, leaving the instruments to warm up, but the supply lasted for 10 months longer, until 8 April 1998. This allowed, for example, two series of observations of the Taurus-Orion region, an important cradle of star birth. Even after the cryogen was exhausted, a few of the short-wavelength detectors in a spectrometer could be used for a special scientific programme interleaved with final calibrations and technology tests. Some extra 150 h were used to measure almost 300 stars at 2.4-4 µm. ISO's 'last light' observation, late on 10 May 1998, was of the Canis Majoris hot supergiant star. The remaining propellant was then used to lower the perigee in order to speed up the orbit's decay: ISO is expected to reenter within 20-30 years.

ISO's telescope and detectors were encased in a cryostat filled with superfluid helium at 1.8 K. Incoming infrared radiation was fed to the four science instruments below the main mirror. (DASA)

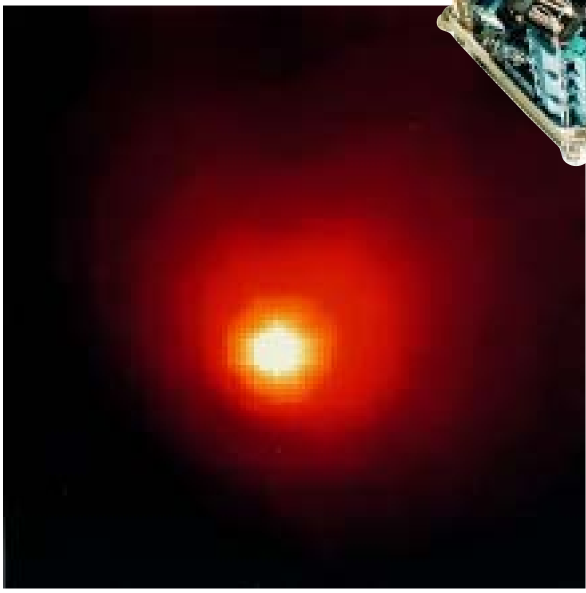


ISO saw water throughout the Universe, increasing expectations of life beyond Earth. Particularly exciting was finding water on Titan – Saturn's largest moon and the target of ESA's Huygens probe. Titan will help us to understand the organic chemistry of the young Earth, with its mix of elaborate organic molecules resembling the chemical soup out of which life emerged. Thanks to ISO, the cosmic history of water was traced for the first time. During the violent early stages of starbirth, a young star spews out high-speed gas, generating a shock wave that heats and compresses the surrounding hydrogen and oxygen, creating the right conditions for water to form. ISO saw the process at work in the Orion and Sagittarius nebulae. ISO also unexpectedly found large amounts of water in the higher atmospheres of the Solar System's giant planets. The water must be coming from cometary grains. (ESA/ISO SWS)



ISO's orbit took it above the worst of Earth's radiation belts for almost 17 h per day.

ISOCAM image of Comet Hale-Bopp in October 1996, revealing the comet's dust coma 100 000 km across. Inset: ISOCAM.



The Whirlpool Galaxy was ISO's 'first light' target on 28 November 1995, when the telescope was opened to the sky. The ISOCAM image shows regions of star formations along the spiral arms and on either side of the nucleus.

Satellite configuration: cylindrical payload module with conical sunshade and two star trackers, supported by service module providing basic spacecraft functions. Overall size: 5.3 m high, 2.3 m wide. The payload module was a cryostat enveloping the telescope and detectors, cooled by a toroidal tank holding 2250 litres of 1.8 K superfluid helium for at least 18 months' observations. Some detectors were cooled to 2 K by copper links to the tank; other elements were cooled to 3-4 K by the boiloff gas. A toroidal tank with 60 litres of normal liquid helium provided cooling on the pad for the last 100 h before launch.

Attitude/orbit control: 3-axis arcsec-control for stable observations of up to 10 h incorporated Earth/Sun sensors, star trackers, four rate integrating gyros, four skewed reaction wheels and redundant sets of 8x2 N hydrazine thrusters.

Power system: 600 W provided from two fixed Si-cell body panels (which also acted as thermal shields).

Communications: realtime downlink (no onboard recorders) at 33 kbit/s (24 kbit/s for science data) to ISO Control Centre at Villafranca, Spain, allowing about 13 h of contact daily. NASA's Goldstone station in California extended coverage to almost 24 h daily. ISO was used scientifically while outside the radiation belts, i.e. about 16.75 h per day.

ISO Scientific Instruments

The 60 cm-diameter Ritchey-Chrétien telescope fed four focal-plane instruments behind the main mirror for photometry and imaging at 2.5-240 μm and medium/high-resolution spectroscopy at 2.5-196 μm.

ISOCAM

2.5-17 μm camera/polarimeter, 1.5/3/6/12 arcsec resolutions, two channels each with 32x32-element arrays.
PI: Catherine Cesarsky, CEN-Saclay, France.

ISOPHOT

2.5-240 μm imaging photopolarimeter, operating in three separate modes as 30-240 μm far-IR camera, 2.5-12 μm spectro-photometer, and 3-110 μm multi-band multi-aperture photopolarimeter.
PI: Dietrich Lemke, MPI für Astronomie, Germany.

SWS

2.5-45 μm Short Wavelength Spectrometer (two gratings and two Fabry-Perot interferometers), 7.5x20 and 12x30 arcsec resolutions, 1000 and 20 000 spectral resolution.
PI: Thijs de Graauw, SRON, Netherlands.

LWS

45-196 μm Long Wavelength Spectrometer (grating and two Fabry-Perot interferometers), 1.65 arcmin resolution, 200 & 10 000 spectral resolution.
PI: Peter Clegg, Queen Mary & Westfield College, UK.

Soho

Achievements: unique studies of helioseismology, the heating and dynamics of the corona and transition region, the acceleration and composition of the solar wind and coronal mass ejections, comets, the heliosphere and the interstellar wind
Launch date: 2 December 1995
Mission end: operations approved to 2003 (2-year design life); further extensions possible
Launch vehicle/site: Atlas 2AS from Complex 36, Cape Canaveral Air Station
Launch mass: 1864 kg (655 kg payload, 240 kg hydrazine)
Orbit: halo orbit around Sun-Earth L1 libration point (1.5 million km from Earth); arrived 14 February 1996
Principal contractors: Matra Marconi Space (prime, payload module, propulsion subsystem), British Aerospace (AOCS), Alenia (structure, harness), CASA (thermal control), Saab Ericsson (communications, data handling)

The Solar and Heliospheric Observatory (Soho) is a cooperative project between ESA and NASA studying the Sun, from its deep core, through its outer atmosphere and the solar wind, into the heliosphere.

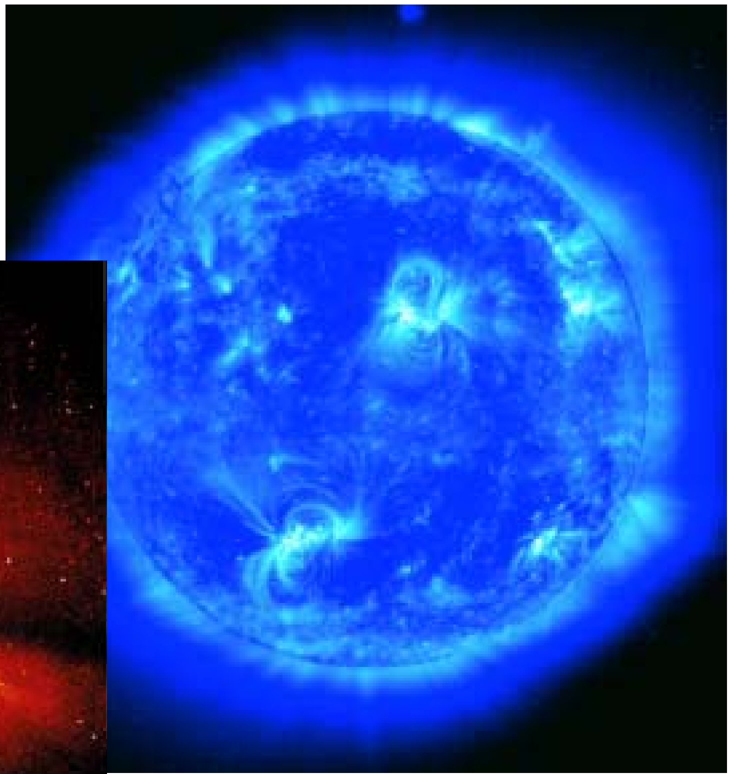
Three helioseismology instruments are providing unique data – cleaner by at least an order of magnitude compared to ground observations – on the structure and dynamics of the Sun's interior, from the very deep core to the outermost layers of the convection zone. Five complementary imagers, spectrographs and coronagraphs observing in EUV, UV and visible-light are providing our first comprehensive view of the outer solar atmosphere and corona, helping to solve some of the Sun's most perplexing riddles, including the heating of the corona and the acceleration of the solar wind.

Three particle instruments explore the detailed composition, state and variability of the Earth's space environment in space, as influenced by the solar wind, coronal mass ejections and extragalactic sources. The outward-looking SWAN scans the sky for clues to the changing large-scale structure of the solar wind and its interaction with the intergalactic medium, as well as giving unique measurements of comet properties.

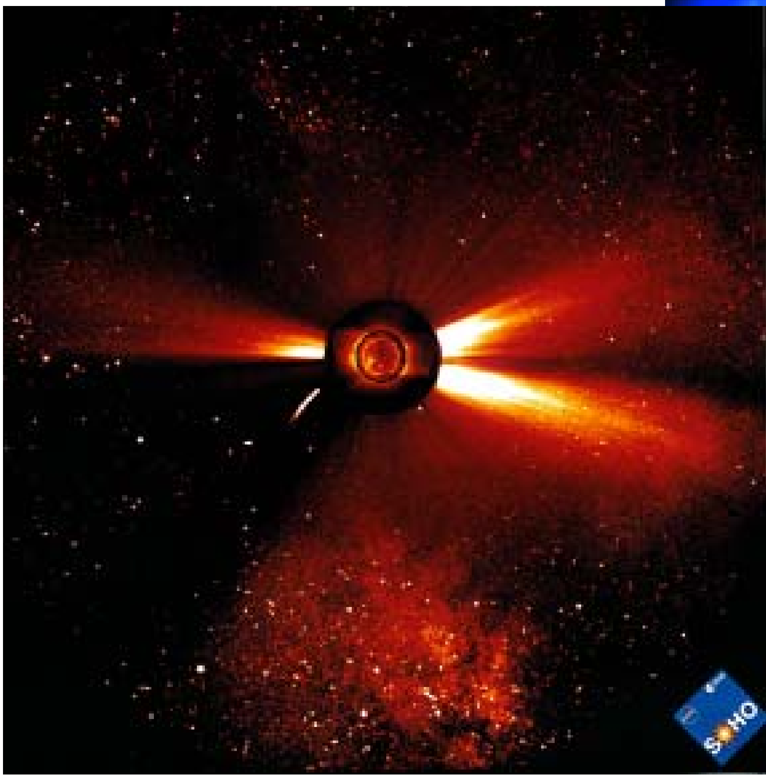
Soho is providing solar physicists with their first long-term, uninterrupted view of the Sun, helping us to understand the interactions between the Sun and the Earth's environment with unprecedented clarity.

Soho recorded its first solar image on 19 December 1995, en route to its orbit around the L1 Lagrangian point. Halo-orbit insertion occurred on 14 February 1996, 6 weeks ahead of schedule following a launch so


Soho's Payload Module at Matra Marconi Space



Right: EIT image in resonance lines of 8- and 9-times ionised iron (Fe IX/X) at 171 Å in the extreme ultraviolet showing the solar corona at a temperature of about 1 million K. This image was recorded on 11 September 1997. It is dominated by two large active region systems, composed of numerous magnetic loops. (EIT/ESA/NASA)



Left: Soho's LASCO coronagraph masks the Sun's bright disc or order to reveal the much fainter corona. LASCO's unprecedented sensitivity enables it to see the thin ionised gas of the solar wind out to the edges of the picture, 22 million km from the Sun's surface. A doomed comet evaporates in the Sun's atmosphere. The disc image is EIT 284 Å, surrounded by UVCS O VI. (LASCO/UVCS/EIT/ESA/NASA)

precise it retained enough hydrazine for 50 years of operations. Routine science operations began after commissioning was formally completed on 16 April 1996. Since then, Soho has generated a torrent of data that place it centre stage in solar physics. Scientific highlights include:

- unprecedented accuracy in modelling the solar interior, and in measuring solar irradiance variations;
- detecting plasma rivers beneath the surface;
- discovering a quasi-periodic oscillation in the rotational shear near the base of the solar convection zone;
- discovering a magnetic surface 'carpet', subducted and replaced every 1.5-3 days, that may be the energy source for coronal heating;
- the first detection of a flare-induced 'sun-quake';
- holographic imaging of the Sun's far side – the Sun made transparent;
- identifying the source regions of the fast solar wind;
- revealing the highly dynamic nature of the transition region even in 'quiet Sun' areas;
- detecting polar plume oscillations of 11-25 min indicative of compressive waves;
- discovering 'EIT waves' and their relation to CMEs, dramatically improving space weather forecasting reliability;
- possibly the first direct observations of a post-CME current sheet;
- providing invaluable statistics on, and spectacular images and movies of coronal mass ejections;
- measuring ion temperatures in coronal holes up to 200 million K;
- significantly contributing to understanding the acceleration of the solar wind;
- discovering large differences between the heating and acceleration mechanisms at play in polar versus equatorial coronal holes;
- discovering falling coronal structures;

Soho's Payload Module at Matra Marconi Space.

– initial acceleration of >10 MeV particles seem to occur when an 'EIT wave' propagates to the Earth-connected field lines;
– measuring ion freeze-in temperatures and their variations with element and time;
– discovering >300 Sun-grazing comets (more than a quarter of all comet discoveries since 1761!);
– uniquely measuring cometary outgassing rates and nucleus sizes;
– detecting active regions on the Sun's far side through their 'lighthouse' effect.

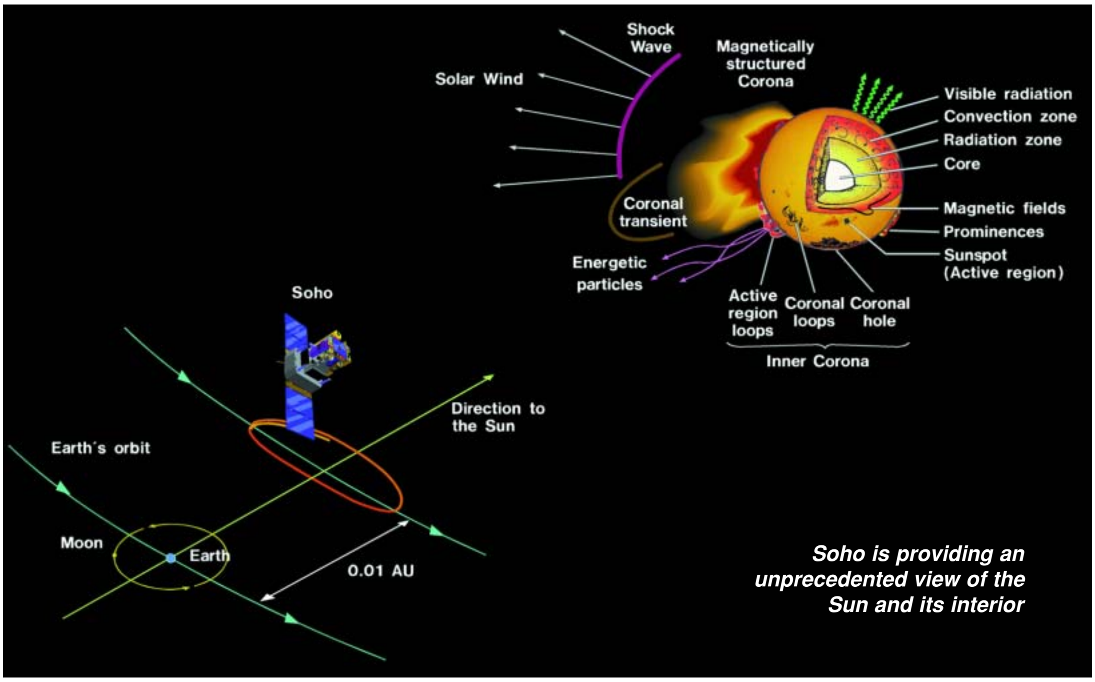
Soho had returned about 2 million images when, on 25 June 1998, control was lost during routine maintenance operations. Contact was re-established on 3 August, allowing the batteries to be charged, and the propulsion system and its hydrazine to be thawed. Sun-pointing was restored on 16 September and Soho was finally returned to normal mode on 25 September. The first instrument (SUMER) was switched on 5 October and all 12 science instruments were back to normal on 4 November. Soho's mission continued.

Although the freezing had not seriously affected the instruments, two of Soho's three gyros were damaged by the cold. Then, on 21 December 1998, the surviving gyro failed and Soho began firing its thrusters to maintain Sun-pointing. To halt the rapid depletion of hydrazine, engineers devised software to ignore faulty gyro data, making Soho the first 3-axis stabilised spacecraft to operate without gyros. Science operations resumed 2 February 1999.

In order to fulfil its high promise, Soho observations were planned to continue at least through the period of maximum sunspot activity in 2000. The two agencies then agreed to extend the mission to 2003, operating Soho as the flagship of a multi-national fleet of solar spacecraft that includes Ulysses and Cluster. Further extension is likely.

Satellite configuration: 2.5x2.9 m, total height 3.9 m, 9.5 m span across solar array. Instruments accommodated in Payload Module, highly decoupled from Service Module, which forms the lower portion of the spacecraft and provides power, thermal control, AOCS, pointing and telecommunications for the whole spacecraft and support for the solar panels.

Attitude/orbit control: 3-axis stabilisation, Sun-pointing with 10 arcsec accuracy, pointing stability 1 arcsec per 15 min (10 arcsec per 6 months), using 4 reaction wheels



Soho Scientific Instruments		
Instrument		*Principal Investigator*
GOLF	Global Oscillations at Low Frequencies	A. Gabriel, IAS, F
VIRGO	Variability of Solar Irradiance and Gravity Oscillations	C. Fröhlich, PMOD Davos, CH
MDI	Michelson Doppler Imager	P. Scherrer, Stanford Univ, US
SUMER	Solar Ultraviolet Measurements of Emitted Radiation	K. Wilhelm, MPAe Lindau, D
CDS	Coronal Diagnostic Spectrometer	R. Harrison, RAL, UK
EIT	Extreme UV Imaging Telescope	J.-P. Delaboudinière, IAS, F
UVCS	UV Coronagraph Spectrometer	J. Kohl, SAO, US
LASCO	Large Angle Spectroscopic Coronagraph	R. Howard, NRL, US
SWAN	Solar Wind Anisotropies	J.-L. Bertaux, SA, F
CELIAS	Charge, Element and Isotope Analysis System	P. Boschler, Univ Bern, CH
COSTEP	Comprehensive Supra Thermal and Energetic Particle Analyser	H. Kunow, Univ Kiel, G
ERNE	Energetic and Relativistic Nuclei and Electron Expt	J. Torsti, Univ Turku, SF

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

and two sets (redundant) of eight thrusters. Attitude data from two fine-pointing Sun sensors, two star trackers and three gyros (no-gyro operations since February 1999).

Power system: 1400 W from twin 2.3x3.66 m Si-cell solar wings (payload requires 440 W), supported by two 20 Ah nickel cadmium batteries.

Communications: science instruments normally return 40 kbit/s (+160 kbit/s when MDI in high-rate mode) at 2.245 GHz S-band to NASA's Deep Space Network for 12 h daily; supported by 1 Gbit tape recorder and 2 Gbit solid-state recorder. Instrument operations are controlled from the Experiment Operations Facility at NASA's Goddard Space Flight Center.