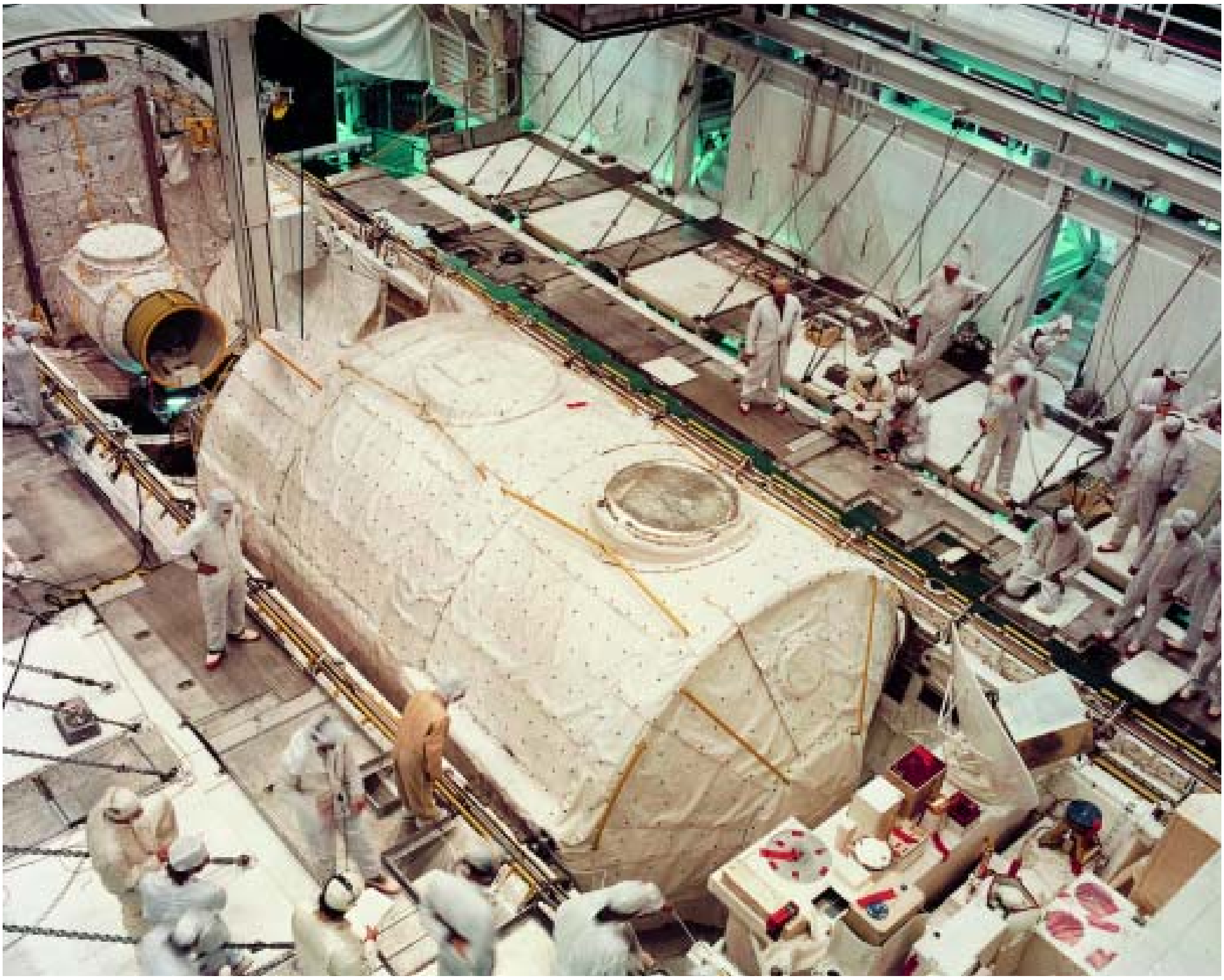
Spacelab

Achievements: principal scientific manned module for US Space Shuttle; major contributions to space sciences research and applications; first European manned space project; 22 missions
Launch dates: see table
Launch vehicle/site: US Space Shuttle, Kennedy Space Center, Florida
Launch mass: typically 10 t (Spacelab-1 totalled 8145 kg Pressure Module and 3386 kg Pallet; including experiments totalling 1392 kg)
Orbits: typically 300 km altitude, inclinations 28-57°
Principal contractors: VFW-Fokker/ERNO (later MBB/ERNO; prime), Aeritalia (PM structure, Igloo, thermal control), Matra (command/data management), Dornier (IPS, ECLSS), British Aerospace (Pallet)

Spacelab was an integral element of NASA's Space Shuttle programme and provided ESA/ESRO with a unique opportunity for developing a manned space capability. The 22 missions made outstanding contributions to astronomy, life sciences, atmospheric physics, Earth observation and materials science under microgravity – advances that stemmed from this crucial European contribution. Spacelab essentially comprised two types of payload carrier: a pressurised manned laboratory module and unpressurised external pallets. Its flexibility allowed it to accommodate both multidisciplinary experiments and complements devoted to a single scientific or applications theme. The Pressure Module (PM) hosted the experiments equipment, data processing and electrical power equipment, an environmental control system and crew control stations. The crew of up to six researchers relied on the Shuttle Orbiter for living quarters, communications and data transmissions.

Europe was invited in 1969 to participate in the post-Apollo programme, ultimately deciding at the Ministerial Meeting of the European Space Conference in Brussels on 20 December 1972 to entrust ESRO with developing a modular, general-purpose laboratory.

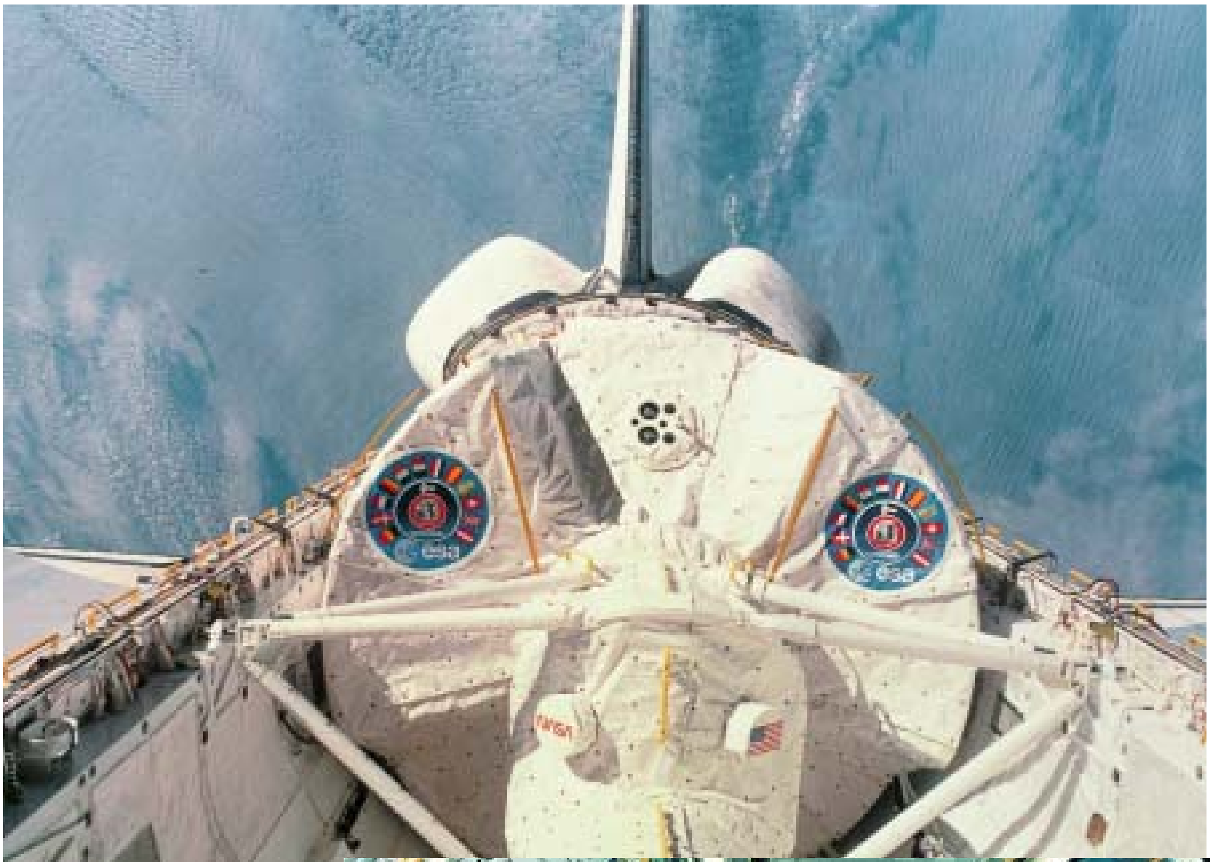
Spacelab was an integral part of the Space Transportation System. Shown is the Spacelab-1 configuration, flown in 1983.



Inserting Spacelab-1 into the Shuttle Orbiter's cargo bay. The tunnel from the Orbiter's cabin has yet to be connected (top left).

The Memorandum of Understanding was signed with NASA on 24 September 1973, giving Europe the responsibility for funding, designing and building Spacelab. Europe agreed to deliver free of charge the Engineering Model and the first Flight Unit, plus ground support equipment, in return for a shared first mission. NASA would purchase any further equipment. The consortium headed by VFW-Fokker/ERNO (later MBB/ERNO) was awarded the 6-year ECU180 million Phase C/D contract in June 1974. Spacelab Flight Unit I, in Spacelab-1 configuration, was formally accepted by NASA in February 1982, comprising a Pressure Module, five Pallets, an Igloo, an Instrument Pointing System, plus support equipment. NASA bought a second set from ESA for about ECU200 million.

The maiden mission was designed to prove Spacelab's capabilities across numerous disciplines. Half the payload was allocated to ESA's First Spacelab Payload (FSLP). The representative configuration was the PM plus one Pallet with a total of 70 experiments. The mission required not only more experiment hardware than any previous ESA flight, but also more experimenters: 100 investigators interested in atmospheric physics, Earth observation, space plasma physics,



Spacelab-1 in orbit: the debut of Europe's manned space laboratory. (NASA)

ESA astronaut Wubbo Ockels at work during the Spacelab-D1 mission.

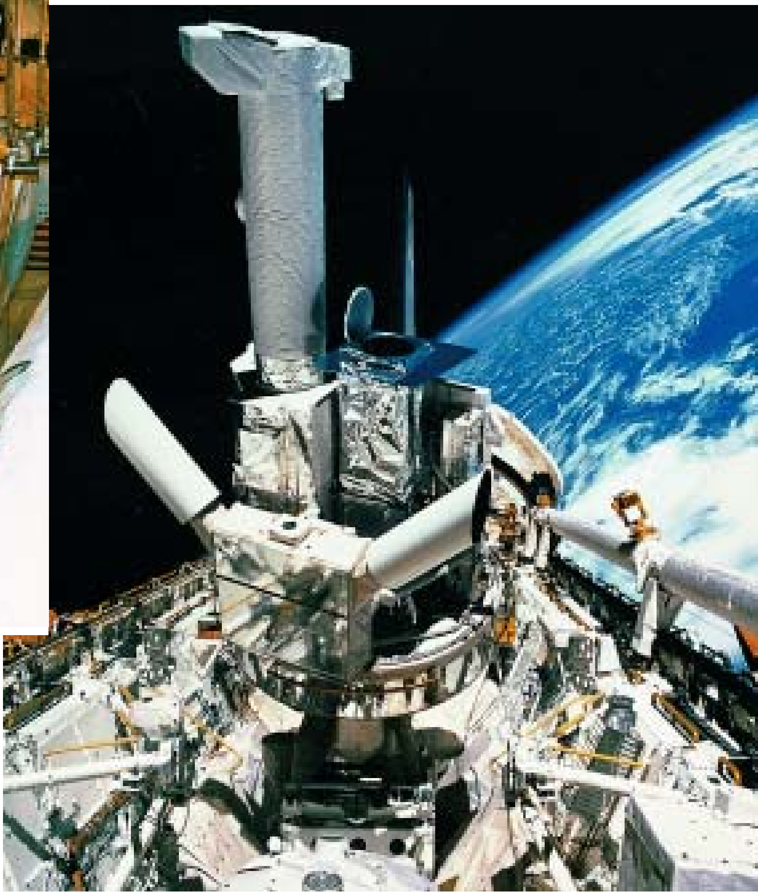
life sciences, materials science, astronomy, solar physics and technology. It also included the first European astronaut, Ulf Merbold, selected by ESA in 1977 along with Wubbo Ockels and Claude Nicollier as the agency's first astronaut corps. The mission was a resounding success, demonstrating Spacelab's far-reaching capabilities. Spacelab went on to prove itself as an unsurpassed asset. In the first eight PM missions alone, 387 experiments involved 323 Principal Investigators from 148 institutes in 26 countries. Spacelab flew its last mission in 1998 – a quarter of a century after Europe began the project – as scientists prepare for the advent of the International Space Station.

Spacelab Missions

STS Orbiter	*Launch Duration*	*Orbit Inc Altitude*	*Mission*	*Configuration*	*Discipline*	*European Astronaut*
STS-9 *Columbia*	28 Nov 83 10 d	57° 250 km	SL-01 FSLP	LM + 1P	Multi-discipline	U. Merbold
STS-51B *Challenger*	29 Apr 85 7 d	57° 360 km	SL-03	LM + MPESS	Materials Science	
STS-51F *Challenger*	29 Jul 85 8 d	50° 320 km	SL-02	IG + 3P + IPS	Solar Astronomy	
STS-61A *Challenger*	30 Oct 85 7 d	57° 330 km	SL-D1	LM + MPESS	Materials/ Life Sciences	W. Ockels E. Messerschmid R. Furrer
STS-35 *Columbia*	2 Dec 90 9 d	28° 350 km	Astro-1	IG + 2P + IPS	Astronomy	
STS-40 *Columbia*	5 Jun 91 9 d	39° 300 km	SLS-01	LM	Life Sciences	
STS-42 *Discovery*	22 Jan 92 8 d	57° 300 km	IML-01	LM	Materials/ Life Sciences	U. Merbold
STS-45 *Atlantis*	24 Mar 92 9 d	57° 300 km	Atlas-1	IG + 2P	Atmos. Physics Solar Astron.	D. Frimout
STS-50 *Columbia*	25 Jun 92 14 d	28° 300 km	USML-01	LM/EDO	Materials Science	
STS-47 *Endeavour*	12 Sep 92 8 d	57° 300 km	SL-J	LM	Materials/ Life Sciences	
STS-56 *Discovery*	8 Apr 93 9 d	57° 300 km	Atlas-2	IG + 1P	Atmospheric Physics	
STS-55 *Columbia*	26 Apr 93 10 d	28° 300 km	SL-D2	LM + USS	Multi-discipline	M. Schlegel U. Walter
STS-58 *Columbia*	18 Oct 93 14 d	39° 280 km	SLS-02	LM/EDO	Life Sciences	
STS-65 *Columbia*	8 Jul 94 15 d	28° 300 km	IML-02	LM/EDO	Materials/ Life Sciences	
STS-66 *Atlantis*	3 Nov 94 11 d	57° 300 km	Atlas-3	IG + 1P	Atmospheric Physics	J-F. Clervoy
STS-67 *Endeavour*	2 Mar 95 17 d	28° 350 km	Astro-2	IG + 2P EDO	Astronomy	
STS-71 *Atlantis*	27 Jun 95 10 d	52° 300 km	SL-Mir	LM		
STS-73 *Columbia*	20 Oct 95 16 d	39° 300 km	USML-02	LM/EDO	Materials Science	
STS-78 *Columbia*	20 Jun 96 17 d	39° 280 km	LMS	LM/EDO	Materials/ Life Sciences	J-J. Favier
STS-83 *Columbia*	4 Apr 97 4 d	28° 300 km	MSL-01	LM/EDO	Materials Science	
STS-94 *Columbia*	1 Jul 97 16 d	28° 300 km	MSL-01R	LM/EDO	Materials Science	
STS-90 *Columbia*	17 Apr 98 16 d	39° 280 km	Neurolab	LM/EDO	Life Sciences	

Atlas: Atmospheric Laboratory for Applications and Science. EDO: Extended Duration Orbiter. IG: Igloo. IML: International Microgravity Laboratory. LM: Long Module. LMS: Life and Microgravity Spacelab. MPESS: Mission Peculiar Experiment Support Structure. MSL: Microgravity Sciences Laboratory. P: Pallet. SL: Spacelab. SLS: Spacelab Life Sciences. USML: US Microgravity Laboratory.

The Atlas Spacelab missions did not include a Pressure Module, but instead housed the avionics in an Igloo (foreground) for controlling the payloads on the two Pallets. (NASA)



The Astro-1 mission was the first to employ the Instrument Pointing System, using the high-precision pointing capabilities for detailed observations of the Sun.

Pressure Module (PM)

The 75 m^3 PM was Spacelab's principal element, providing scientist-astronauts with a comfortable working environment. The 4.1 m-diameter, 7 m-long module was basically a 1.6-3.5 mm-thick aluminium cylinder with conical end pieces. The main segments could be unbolted for ground processing. The experiments racks were integrated outside the PM and then rolled with the floor into place along the PM side support beams. The racks held standard 48.3 cm-wide laboratory trays; the Double Rack had a 1.75 m^3/580 kg capacity. The PM could carry the equivalent of 20 Single Racks, although two DRs were reserved each mission for avionics and equipment storage. The roof and floor offered storage space. The roof included two 1.3 m-diameter apertures: a window in the forward one and a scientific airlock aft for exposing experiments to space.

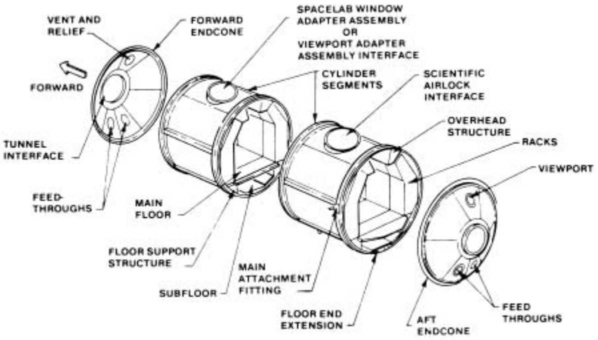
Pallets and Igloo

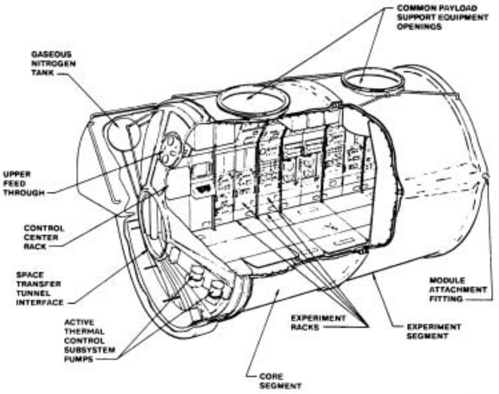
Experiments requiring direct exposure to space were carried on U-shaped Pallets that could be fully integrated before being inserted into the Shuttle's cargo bay. These proved to be so useful that non-Spacelab missions also used the Pallets; indeed, they continue in service for the International Space Station. Each 725 kg, 3 m-long 4 m-wide aluminium Pallet could hold a 3 t payload. Experiments were normally controlled via the PM, but on non-PM missions the pressurised 640 kg, 2.4 m-high 1.1 m-diameter cylindrical Igloo accommodated the avionics.

Instrument Pointing System (IPS)

Three Spacelab missions carried IPS to provide precision control and pointing of astronomical telescopes: the arcsec accuracy for a 2 t payload was 0.4 lateral/11.2 roll under star tracker control, and 0.5/41.0 in Sun mode. The 1.18 t IPS carried all inertial sensors, data and power electronics and the dedicated software for control via the Spacelab computers. It could route 1.25 kW to the payload and provided a 16 Mbit/s data rate.

Transferring the assembled Spacelab-1 to Space Shuttle Columbia. This assembly will be displayed in an annex of the National Air & Space Museum at Dulles International Airport, Washington DC, due to open in December 2003. The second set, flown on the final mission, is at the Space Academy Bremen at Bremen Airport.





Configuration: Spacelab comprised several elements that could be mixed-and-matched according to mission requirements. The Pressure Module (PM) accommodated experiments in a shirtsleeve environment, external experiments were mounted on Pallets, the Instrument Pointing System (IPS) provided precision pointing for large telescopes, and the Igloo housed avionics when the PM was absent (6 out of 22 missions). See the separate sections for descriptions of each.

Attitude/orbit control: provided by Space Shuttle Orbiter.

Life support: a joint effort with the Orbiter to maintain a 1 bar atmosphere at 18-27°C and 30-70% humidity. Orbiter cabin air was drawn in through the linking tunnel, cleaned with lithium hydroxide and charcoal, cooled by heat exchangers and blown into the module through roof diffusers.

Power/thermal system: Spacelab was powered by the Space Shuttle's fuel cells at 28 Vdc, limited to 8 kW by the thermal control system. Experiments and avionics were mounted on cold plates linked to the Orbiter's cooling system. Cooling air was also forced up inside the experiment racks and drawn off. The whole module carried an external jacket of 39 layers of Dacron and goldised Kapton completed by an outer layer of Teflon-coated beta cloth.

Communications/data: data were usually transmitted in realtime through NASA's relay satellite system at up to 50 Mbit/s via the Orbiter's Ku-band system. When the realtime link was unavailable, a High Data Rate Recorder provided 32 Mbit/s storage. Spacelab's systems and experiments were controlled by three IBM AP-101SL computers (originally Matra 125/MS 64 kbit).

Giotto

Achievements: first cometary close flyby; first dual-comet mission; first European deep space mission; first European gravity-assist mission; first reactivation of an ESA spacecraft
Launch date: 2 July 1985
Mission end: 2 April 1986 (Halley flyby); 23 July 1992 Giotto Extended Mission
Launch vehicle/site: Ariane-1 from Kourou, French Guiana
Launch mass: 960 kg (574 kg at time of Halley flyby)
Orbit: injected into 199x36 000 km, 7° GTO; Mage boosted Giotto on 3 July 1985 into heliocentric orbit with 120 000 km Halley miss-distance
Principal contractors: British Aerospace (prime), Alcatel Thomson Espace (telecommunications), SEP (antenna despin, kick motor), FIAR (power), Fokker (thermal), TPD (starmapper), Dornier (structure)

Giotto's flyby of Comet Halley in March 1986 was the culmination of the international effort to investigate the most famous of all comets. Halley was selected because, of all the >1000 comets then known, it was unique in being young, active and with a well-defined path – essential for an intercept mission. ESA's probe was also unique: of all the worldwide scientific instrumentation focused on the comet, Giotto was the only platform that could take a payload close in to the nucleus. It was the first – and remains the only – spacecraft to do this.

Observations from the two Soviet Vega probes were crucial for pin-pointing Halley's nucleus, reducing the Earth-based error from 1500 km to 75 km. At 21:00 UT on 12 March 1986, the JPA instrument signalled the beginning of the encounter, detecting the first Halley hydrogen ions 7.8 million km from the nucleus. At 19:40 UT on 13 March, and still 1 064 000 km out, Giotto crossed the bowshock in the solar wind. The formal 4 h encounter began 35 min later. The first of 12 000 dust impacts came 122 min before closest approach. At 23:58 UT, at a distance of 20 100 km, Giotto passed through the contact surface where the solar wind was turned away by cometary material. The closest approach of 596 km occurred at 00:03:02 UT on 14 March over the sunlit hemisphere.

The best of Giotto's 2112 images, from 18 270 km, showed a lumpy nucleus 15 km long and 7-10 km wide, the full width being obscured by two large jets of dust and gas on the active sunward side. The dark

Giotto during the solar simulation test at Intespace in Toulouse, France. Visible are the Halley Multicolour Camera (white baffle, two horns for balancing during camera rotation) and the starmapper (red cover).

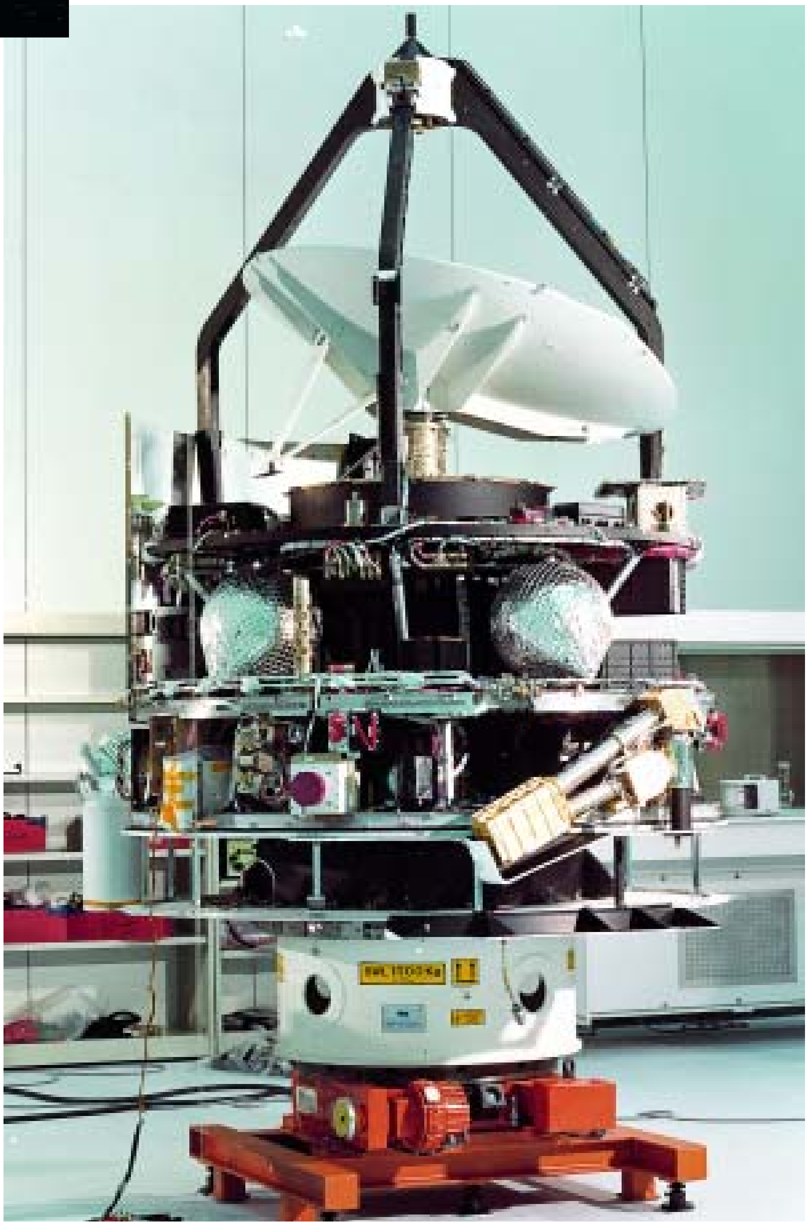
Giotto depicted a few days before closest approach to Halley's Comet. The diameter of Halley's visible dust coma at the time of encounter was about 100 000 km.

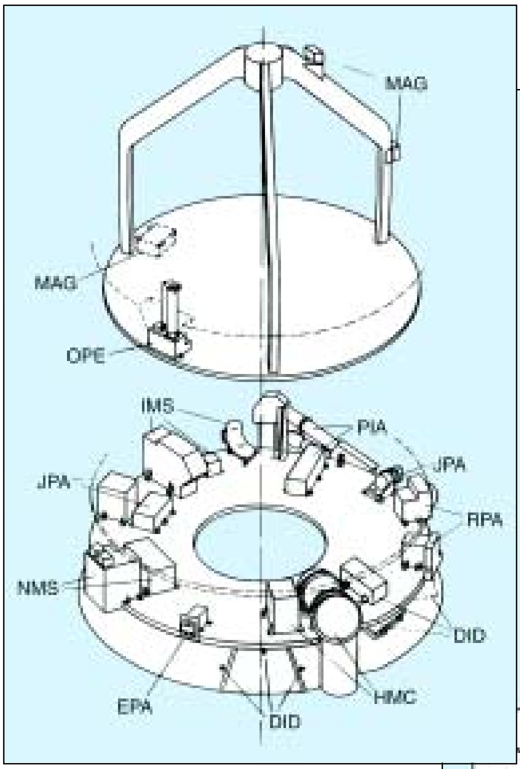
side, with an unexpectedly low albedo of 2-4%, was quiescent but image enhancement revealed circular structures, valleys and hills over the entire surface. The jets broke through the dark crust that insulated the underlying ice from solar radiation.

Images continued to within 1372 km, 18 s before closest approach. The rate of dust impacts rose sharply in the final few minutes, and in the last seconds there were 230 strikes as Giotto apparently penetrated one of the jets. Only 7.6 s before closest approach, it was hit by a particle large enough to break Earth lock, although data for the following 30 min were later recovered from the degraded signal.

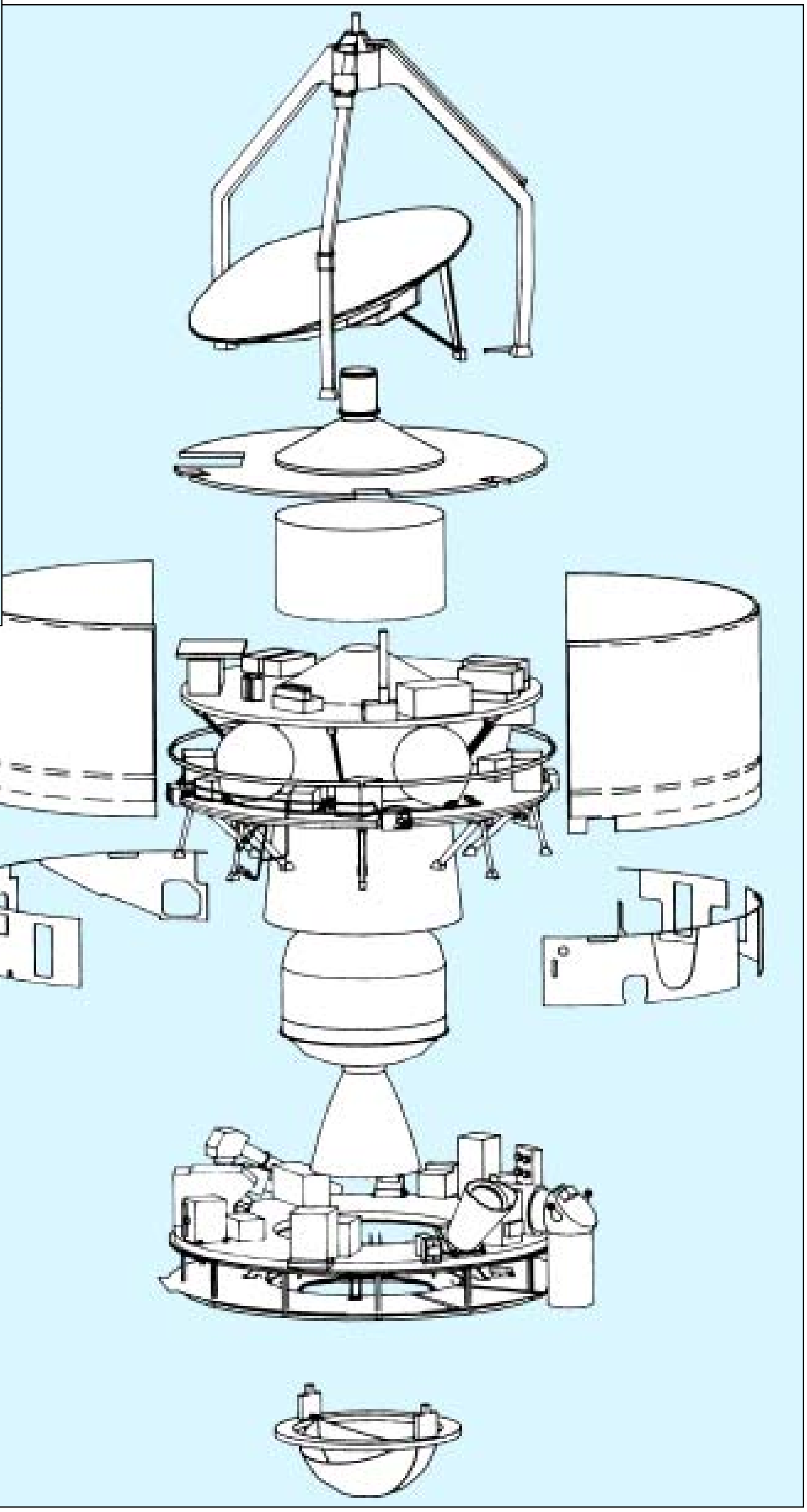
Giotto confirmed that Halley had formed 4500 million years ago from ices condensing onto grains of interstellar dust, and had then remained almost unaltered in the cold, outer regions of the Solar System. Analysis of the dust particles provided some surprises. Comets are not dirty snowballs, as previously believed, but largely dust with embedded ice. Tiny grains the size of smoke particles were much more abundant than expected, and – unlike most space dust – they were

Giotto with the cylindrical solar cell array removed. Shown on the payload platform are (from left to right) the Halley Multicolour Camera (HMC), the electronics box of the Dust Impact Detection System (DIDS), the Rème Plasma Analyser (RPA) with its red cover on, and the dust mass spectrometer (PIA). Seen on the upper platform are two of the four hydrazine fuel tanks for attitude and orbit control.





Locations of Giotto's scientific instruments. The abbreviations are explained in the table.



Giotto's principal elements. Most of the experiments were housed on the bottom section, behind the dual bumper shield. At the very bottom is the closure mechanism that sealed the shield after the firing of the solid-propellant motor.

not stony but organic. Giotto discovered particles rich in carbon, hydrogen, oxygen and nitrogen – elements essential for life. Dust from comets could have fertilised Earth, supplying the raw materials for nucleic acids and proteins to form.

Giotto's encounter with Halley proved to be a magnificent success, providing unprecedented information on the solar system's most active but least known class of object. Although its primary mission was successfully completed, Giotto was placed in

The Giotto mission begins. (CSG/CNES/Arianespace)

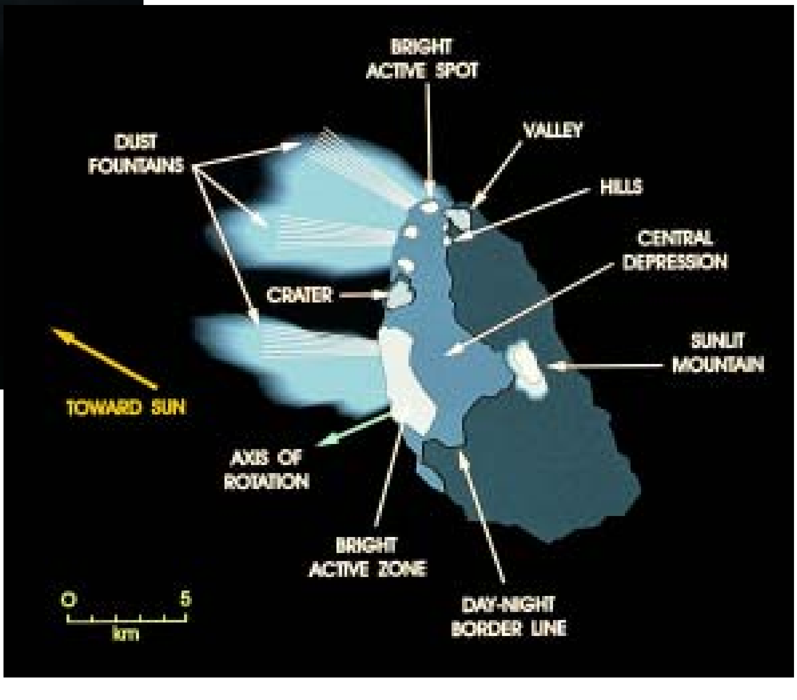
Installation of Giotto on its Ariane launcher at Kourou. The dome cover of the third stage liquid hydrogen tank can be seen protruding through the centre of the Vehicle Equipment Bay. (CSG/CNES/Arianespace)

hibernation on 2 April 1986 in the hope that another mission could be attempted.

ESOC reactivated Giotto in 1990 after 1419 days in hibernation to assess its condition for the Giotto Extended Mission (GEM). This time, a flyby of Comet Grigg-Skjellerup complemented the Halley observations by studying a far less active comet. The camera proved to be unusable because it was blocked by its Halley-damaged baffle, but

Giotto returned more than 2000 images during its close flyby of Comet Halley. The six shown here range from #3416 375 s before closest approach to #3496 only 55 s before closest approach. (MPAE, courtesy Dr. H.U. Keller)

This composite of seven Halley images highlights details on the nucleus and the dust jets emanating from the sunlit side. (MPAE, courtesy Dr. H.U. Keller)



Principal features identified on Giotto's images of Comet Halley.

eight scientific instruments were still active. JPA detected the first cometary ions 440 000 km from the nucleus, and MAG found exciting wave phenomena not previously seen in a natural plasma. EPA saw surprising differences in the structures compared with Halley. OPE provided the first indication of entering the dust coma at 17 000 km; combined with MAG data, it showed that Giotto passed by on the dark tail side. Closest approach was about 100 km at 15:30:43 UT on 10 July 1992.

Spacecraft configuration: 1.867 m diameter, 2.848 m high, cylindrical bus (derived from Geos design). Central aluminium thrust tube supported three aluminium sandwich platforms: the top one carried the despun antenna and telecommunications equipment; the central one housed the four propellant tanks; the bottom one carried most of the experiments behind the bumper shield. Because of the 68 km/s Halley encounter speed, Giotto ventured into the coma protected by dual bumper shield capable of stopping of a 1 g particle: a 1 mm-thick aluminium alloy outer shield 23 cm in front of a 13.5 mm-thick Kevlar sandwich.

Attitude/orbit control: spin-stabilised at 15 rpm about main axis. Redundant sets of four 2 N thrusters (69 kg hydrazine loaded) provided spin control and orbit adjust. Mage 1SB solid-propellant motor provided 1.4 km/s boost from GTO into Halley intercept orbit. Mage was housed in the thrust tube, firing through a central hole in the bumper shield, which was then closed by two quadrispherical aluminium shells. Attitude reference by Earth and Sun sensors for near-Earth, then Sun and star mapper.

Power system: 5032 Si cells on the cylindrical body were sized to provide 190 W at Halley encounter, supported by four 16 Ah silver cadmium batteries for peak demands.

Communications: the 1.47 m-diameter 20 W S/X-band antenna was canted 44.3° to the spin axis to point at Earth during the Halley flyby. The 8.4 GHz X-band provided 40 kbit/s realtime data to ESOC – there was no onboard storage as Giotto might not have survived encounter. Two low-gain antennas were used for near-Earth operations.

Giotto Science Instruments

Halley Multicolour Camera (HMC)

CCD camera with f/7.68 Ritchey-Chretien telescope, 22 m resolution from 1000 km.13.5 kg, 11.5 W.
PI: H.U. Keller, MPI für Aeronomie (D)

Neutral Mass Spectrometer (NMS)

Energy/mass of neutral atomic particles: 1-36 amu, 20-2110 eV. 12.7 kg, 11.3 W.
PI: D. Krankowsky, MPI für Kernphysik (D)

Ion Mass Spectrometer (IMS)

Energy/mass of ions. 9.0 kg, 6.3 W.
PI: H. Balsiger, Univ. of Bern (CH)

Dust Mass Spectrometer (PIA)

Mass ($3x10^{-16}$-$5x10^{-10}$ g) and composition (1-110 amu) of dust particles. 9.9 kg, 9.1 W.
PI: J. Kissel, MPI für Kernphysik (D)

Dust Impact Detector (DID)

Mass spectrum of dust particles: 10^{-17}-10^{-3} g. 2.3 kg, 1.9 W.
PI: J.A.M. McDonnell, Univ of Kent (UK)

Johnstone Plasma Analyser (JPA)

Solar wind and cometary ions 10 eV-20 keV, cometary ions 100 eV-70 keV/1-40 amu. 4.7 kg, 4.4 W. PI: A. Johnstone, Mullard Space Science Laboratory (UK)

Rème Plasma Analyser (RPA)

Solar wind and cometary ions 10 eV-30 keV, cometary ions 1-200 amu. 3.2 kg, 3.4 W.
PI: H. Rème, Centre d'Etude Spatiale des Rayonnements (F)

Energetic Particles Analyser (EPA)

3-D measurements of protons (15 keV-20 MeV), electrons (15-140 keV), α-particles (140 keV-12.5 MeV). 1.0 kg, 0.7 W. PI: S. McKenna-Lawlor, St Patrick's College (IRL)

Magnetometer (MAG)

0.004-65 536 nT. 1.4 kg, 0.8 W.
PI: F.M. Neubauer, Institut für Geophysik und Meteorolgie (D)

Optical Probe Experiment (OPE)

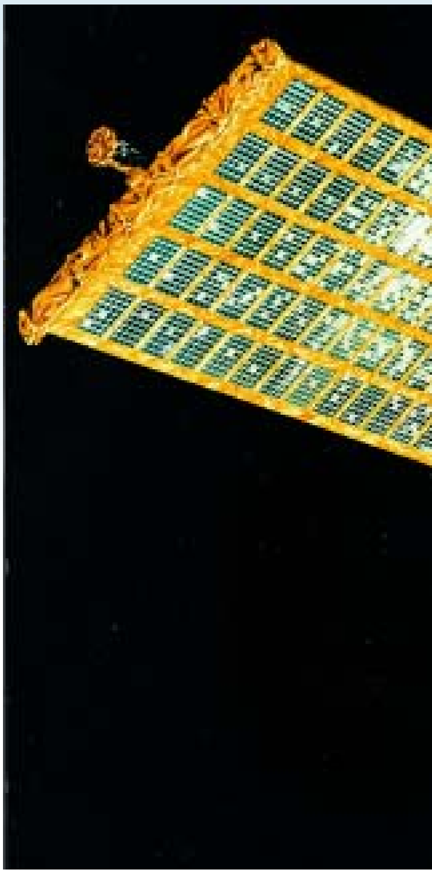
Coma brightness in dust and gas bands.
PI: A.C. Levasseur-Regourd, Service d'Aeronomie du CNRS (F)

Radio Science (GRE)

Cometary electron content and mass fluence.
PI: P. Edenhofer, Institut für Hoch- und Höchstfrequenztechnik (D)

Olympus

Achievements: demonstrated new communications services; largest civil telecommunications satellite
Launch date: 12 July 1989
Mission end: 30 August 1993 (5-year target)
Launch vehicle/site: Ariane from Kourou, French Guiana
Launch mass: 2612 kg (359 kg communications payload; 1328 kg propellant)
Orbit: geostationary, at 19°W
Principal contractors: British Aerospace (prime), Alenia Spazio, Marconi Space and Alcatel-Bell (payloads)



ESA's Olympus telecommunications project was aimed at demonstrating new market applications using state-of-the-art payloads and a new-generation satellite platform. It also helped to establish the requirements for future Data Relay Satellites. The demonstrations covered TV and radio broadcasting direct to users' dishes, inter-city telephone routing, business communications and ground-breaking mm-wave links. For example, the In-Orbit Communications (IOC) experiment tested the first Ka-band data relay between two spacecraft, working with ESA's Eureca satellite during August 1992 to June 1993. Users of the direct-broadcast beam included Eurostep, an association of institutions interested in exploiting satellites for education, training and distance-learning projects. More than 100 organisations in 12 countries employed the facility. Technical institutes across Europe took measurements of the Ku/Ka-band propagation beacons and coordinated their results on how these frequencies behaved under different conditions to help plan for future satellite systems.

Olympus achieved most of its objectives but control was lost in 1991 and it drifted from its operational position at 19°W. A complex recovery programme that in itself broke new ground brought it back after 77 days, on 13 August 1991. The rescue drew heavily on the propellant reserves, but it was still hoped that Olympus would complete its nominal 5-year mission. However, control was lost again 2 years later and the remaining propellant was almost exhausted; Olympus was thus lowered from GEO and deactivated.

Satellite configuration: 257 cm-high, 210x175 cm cross-section box-shaped bus centred on cylindrical propulsion unit, with base service module.

Attitude/orbit control: 3-axis control in GTO/GEO by reaction wheels and 16x22 N N_2O_4/MMH thrusters (first ESA satellite under 3-axis control in GTO). GEO insertion by Marquardt R-4D 490 N liquid apogee engine.

Power system: two solar wings spanning 27.5 m delivered 3.6 kW (payload required 2.3 kW). Batteries: 24 Ah nickel cadmium + 35 Ah nickel hydrogen.

Olympus deployed in its orbital configuration.

Olympus launch preparations at Kourou.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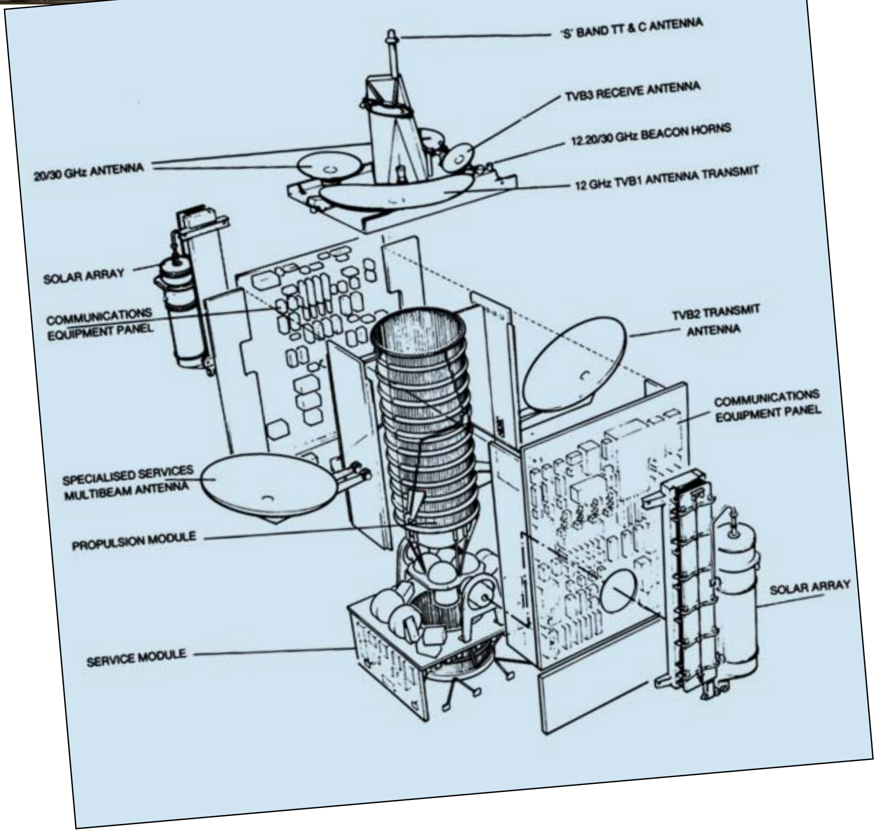
Integration of Olympus with its Ariane carrier at the Kourou launch site. (CSG/Arianespace)

Olympus undergoing electromagnetic compatibility testing at the David Florida Laboratory in Canada.

Communications payload:

- two 230 W 12.2 GHz TWTAs for delivering TV/radio direct to users with 45 cm and 90 cm dishes: one for Italy (1.0x2.4° elliptical beam), one Europe-wide (1.5° circular beam). Both antennas fully steerable.
- four 30 W 12.5 GHz TWTAs Specialised Services Payload working through steerable beams for high-speed data transmission, video conferencing and TV delivery.
- two 30 W 19 GHz TWTAs providing two steerable 0.6°-diameter spot beams for experimental video conferencing, business applications, VSAT and SNG.
- 20 GHz and 30 GHz beacons for propagation research.

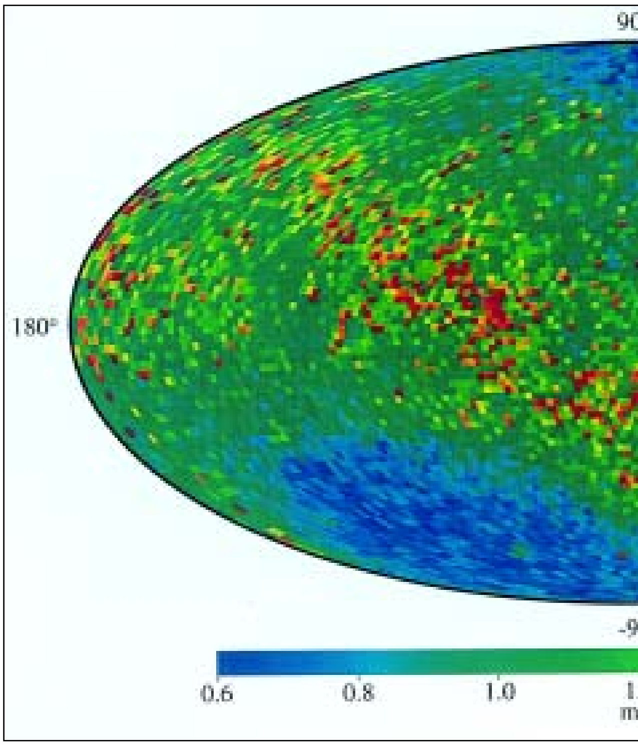


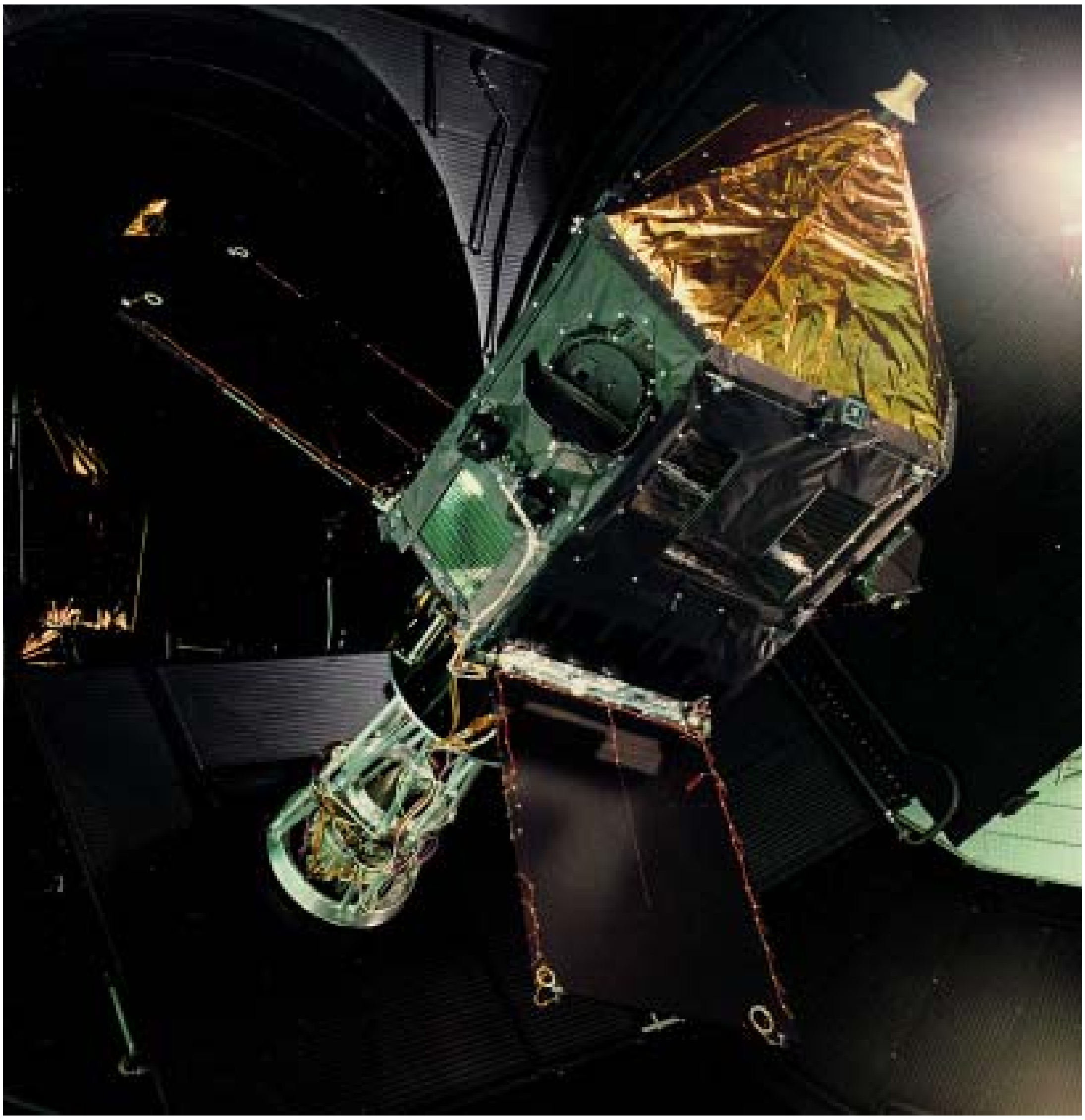
Hipparcos

Achievements: first space-based astrometric survey
Launch date: 8 August 1989 (design life 30 months)
Science operations began/ended: November 1989/March 1993. Communications ended 15 August 1993
Launch vehicle/site: Ariane-44LP from CSG/Kourou, French Guiana
Launch mass: 1140 kg (including 215 kg science payload)
Orbit: boost motor failure left Hipparcos in 200x35 896 km, 6.9° instead of placing it in geostationary orbit at 12°W. Thrusters raised it to 526x35 900 km for revised science operations
Principal contractors: Matra Marconi Space (satellite prime, payload development), Alenia Spazio (co-prime: spacecraft procurement & AIT)

Hipparcos ('High Precision Parallax Collecting Satellite') had the single goal of producing the most accurate positional survey of more than 100 000 stars, in the process determining their distances, their motions and other characteristics such as their variability and binary nature. Improving on ground-based accuracies by a factor of 10-100, Hipparcos is fundamentally affecting every branch of astronomy, from the Solar System to the history of the Universe, and especially on theories of stars and their evolution.

The mission was a major technical challenge for European industry in building the satellite and the European astronomical community in generating the resulting star catalogues. The satellite design required extreme thermal stability to maintain optical precision, smooth jitter-free motion, realtime attitude determination to within 1 arcsec, and fast realtime data downlinking to handle the information generated by the scanning. 1000 Gbit were returned during the 4 years of operations, making the production of the catalogues the largest data analysis problem ever undertaken in astronomy. The approach was simple: measure the angles between selected pairs of stars as Hipparcos' rotation scanned its telescope across the sky. Covering the whole celestial sphere allowed these 118 000 target stars to be precisely located to within about 0.001 arcsec. Simultaneously, redundant star mappers of the satellite's attitude determination system performed the less accurate 'Tycho' survey of 1 million stars. The Hipparcos Catalogue (118 218 entries) and the Tycho Catalogue (1 058 332 entries) were both declared final on 8 August 1996, and the 17-volume set was published by ESA in 1997.

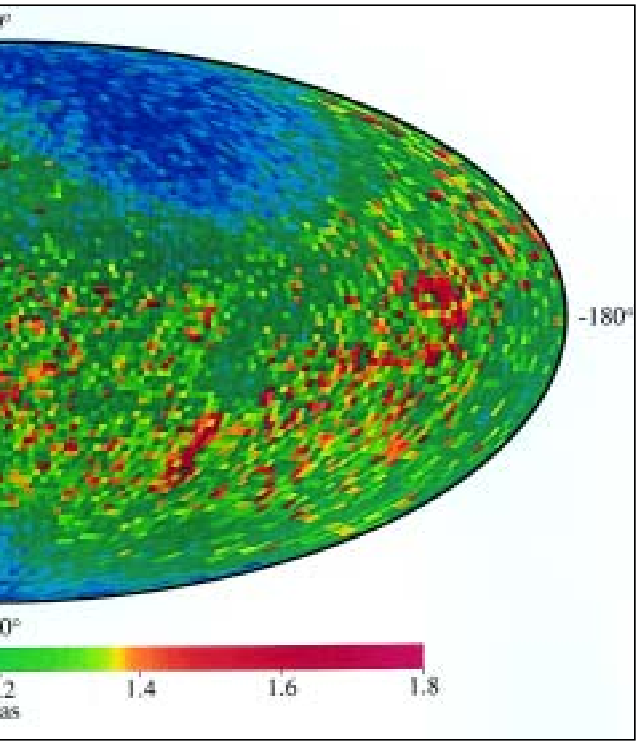




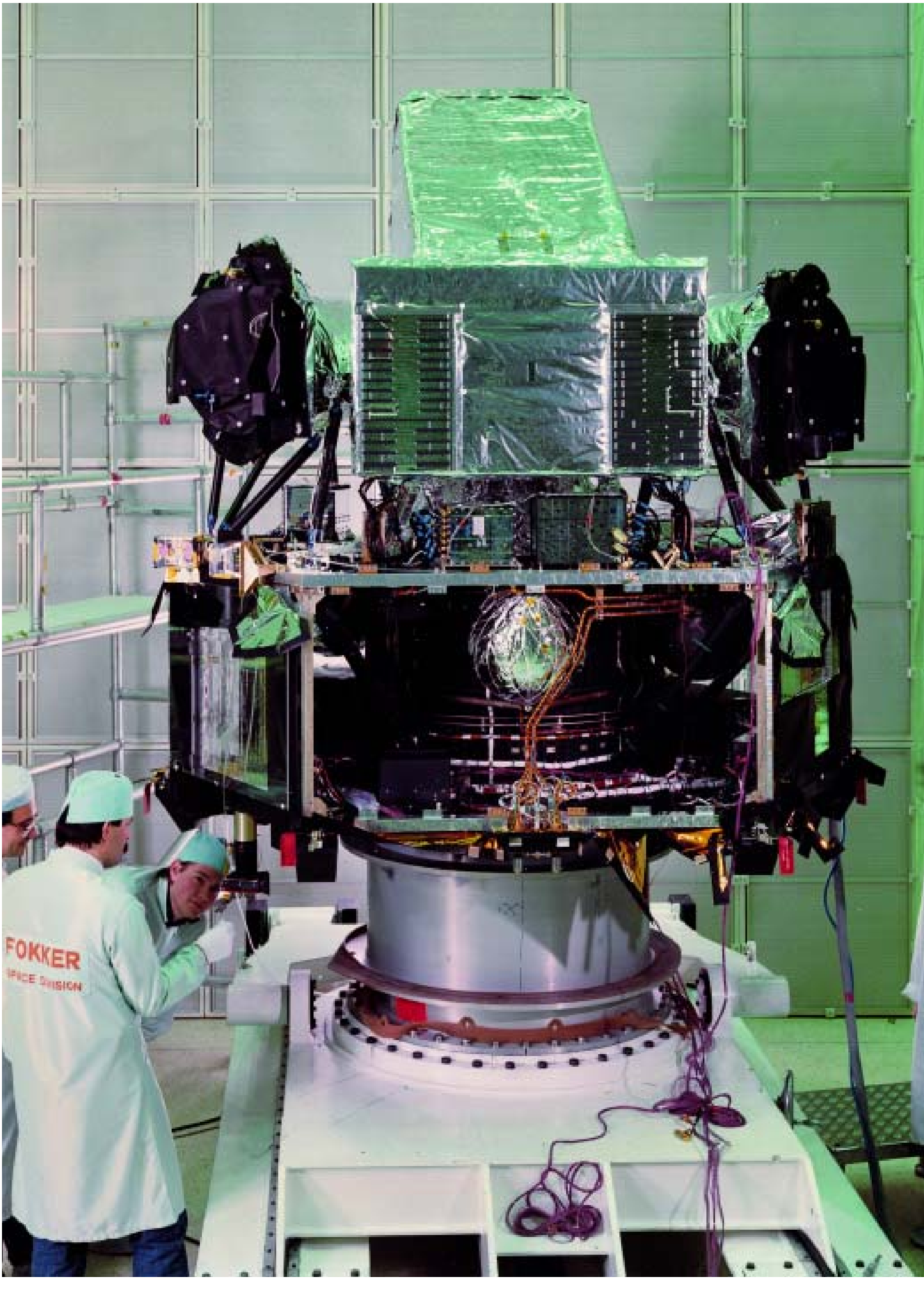
Hipparcos final qualification testing in the Large Space Simulator at ESTEC. One of the telescope's two semi-circular apertures is seen closed; the other is side-on at far right.

Astronomers continue to analyse the data: the Tycho-2 catalogue covering 2 539 913 stars (99% of all stars down to 11th magnitude) was issued in 2000. Hipparcos pioneered techniques that will be used by ESA's GAIA mission (see separate entry) to analyse the composition, formation and evolution of our Galaxy by mapping 1000 million stars.

The resounding success of Hipparcos is even more remarkable considering its dramatic problems soon after

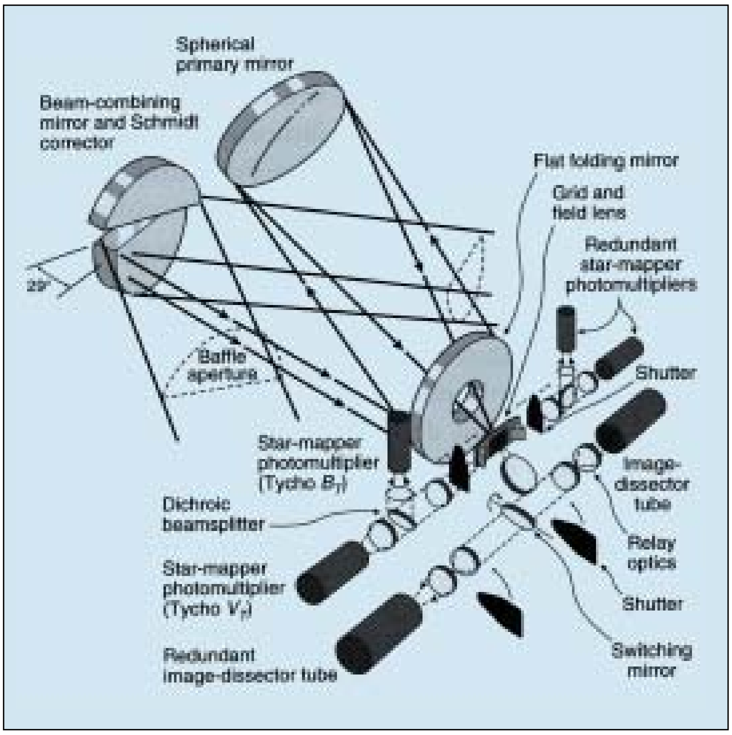


Accuracy of Hipparcos stellar distances. The data obtained by Hipparcos is of unprecendented accuracy and is being used to tackle many issues in astronomy, such as the structure of the Galaxy, the evolution of stars, and the age the Universe. The map is in equatorial coordinates; mas = milliarcsecond. (From the Hipparcos and Tycho Catalogues, ESA SP-1200 - Volume 1.)



The Hipparcos Engineering Model is displayed at the Noordwijk Space Expo at ESTEC.

The Hipparcos flight model being prepared for testing in the Large Space Simulator at ESTEC, April 1988. The payload module is mounted on the bus before installation of the Sunshield. The two telescope aperatures are covered at top.



Hipparcos' optical system measured the angular separations of stars by timing their passages over a modulating grid, combining fields of view 58° apart on the sky. Processing the voluminous data required a very accurate knowledge of the satellite's orientation at all times. These data, along with data for the million-star Tycho Catalogue, came from separate detectors and a star-mapper grid on one side of the main grating.

launch. The satellite was destined for geostationary orbit, but it was stranded in the transfer orbit when its solid-propellant boost motor failed to fire. Using 26 kg of its 32 kg hydrazine supply allowed its small thrusters to lift the 200 km perigee away from atmospheric drag, but that still left severe operational problems. The solar panels and spacecraft electronics were not designed for repeated passage through the harsh Van Allen radiation belts, and unexpected periods in Earth's shadow threatened battery breakdown. Also, the torrent of realtime data could no longer be collected by the single Odenwald station in Germany as Hipparcos swung around the Earth – stations in Kourou, Perth and Goldstone had to be added, increasing costs. Despite these problems, the goal of 30 months' observations was comfortably achieved before the electronics succumbed to the bombarding radiation in 1993.

The mission's scientific aspects were conducted by four consortia, altogether comprising some 200 scientists, responsible for constructing, documenting and publishing the final catalogues.

Satellite configuration: bus was an irregular hexagonal prism of conventional aluminium design with central thrust tube. Payload module mounted on top; CFRP structure required for thermal stability. Topped by Sunshade. Total height 3 m; body diameter 1.8 m.

Attitude/orbit control: 6x20 mN nitrogen thrusters (9.3 kg supply in two tanks, 285 bar) maintained smooth spin stabilisation at 11.25 revolutions daily for scanning. Supported by 4x5 N hydrazine thrusters (32 kg supply in two tanks, 22-5.5 bar blowdown). Mage-2 Apogee Boost Motor to circularise GTO into GEO (failed).

Power system: three 119x169 cm deployed Si solar panels generated 380 W at 50 Vdc (payload requirement 110 W); 2x10 Ah nickel cadmium batteries.

Communications/data: 2.5 W 2.24 GHz S-band omni transmitter provided 24 kbit/s realtime science data downlink.

Hipparcos Scientific Payload

1.400 m-focal length 29.0 cm-diameter Schmidt telescope simultaneously observed two 0.9° star fields separated by 58°. Combining mirror focused the two fields on a 2.5x2.5 cm detector carrying 2688 3.2 mm-wide parallel slits 8.2 mm apart for the modulated light over a 38 arcsec field to be sampled by a redundant image dissector tube at 1200 Hz. As Hipparcos' spin axis changed by 4.415° daily, the whole sky was scanned several times. An average star crossed the detector in 20 s and was observed 80 times during the mission. This allowed the positions, proper motions and parallaxes of 118 000 programmed stars to be measured with 0.001 arcsec accuracy. Also, two star mappers used primarily for attitude determination produced the Tycho catalogue of position (0.015 arcsec) and photometric (0.01m) data on 1 million other stars.

Hubble Space Telescope
Faint Object Camera

Achievements: first photon-counting high-resolution camera for Hubble Space Telescope
Launch date: 24 April 1990
Mission end: planned for 2002 (return to Earth by Space Shuttle)
Launch vehicle/site: NASA Space Shuttle mission STS-31, Kennedy Space Center, Florida
Launch mass: 320 kg (Hubble Space Telescope 10 843 kg)
Orbit: about 600 km, 28.5°
Principal contractors: Dornier/Matra Espace (co-contractors), British Aerospace (photon-counting assembly)

The objective of the Hubble Space Telescope (HST) mission is to operate a 2 m-class astronomical telescope in orbit for at least 15 years as an international observatory. HST's advantages over a ground-based observatory include the diffraction-limited angular resolution and access to the UV and near-IR ranges. ESA's 15% contribution consists of three main elements:

- the Faint Object Camera (FOC), a prime focal plane instruments;
- two pairs of solar wings (the original pair was replaced by the second, improved, pair during the first Servicing Mission in December 1993);
- scientific and technical personnel seconded to the Space Telescope Science Institute (STScI) in Baltimore, Maryland, US.

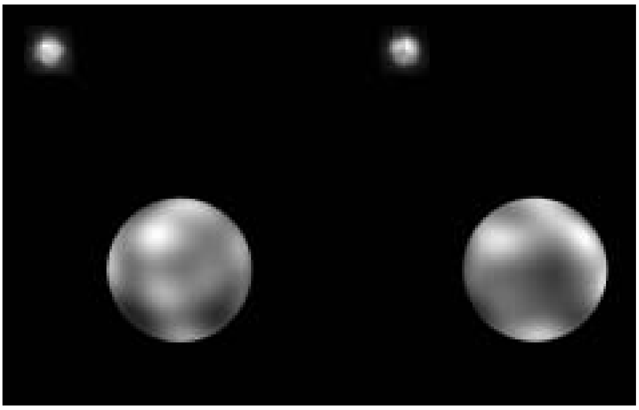
In return, European astronomers from ESA Member States are guaranteed a minimum of 15% of HST observing time. However, in open competition, Europe averages about 20%. European astronomers are also supported by the ESA/ESO Space Telescope - European Coordinating Facility (ST-ECF), located within the European Southern Observatory at Garching (D). ST-ECF's main functions are to provide a regional source of information on instrument status, analysis software and access to the HST data archives.

The most important change in HST's status after SM1 was correction of the spherical aberration discovered in the primary mirror after launch. That mission substituted the least-used High Speed Photometer with the COSTAR device to deploy pairs of corrective mirrors in front of the remaining axial instruments. The FOC optics have performed flawlessly, showing text-book diffraction-limited images of stars.

Almost 7000 images were recorded with the FOC and archived, providing

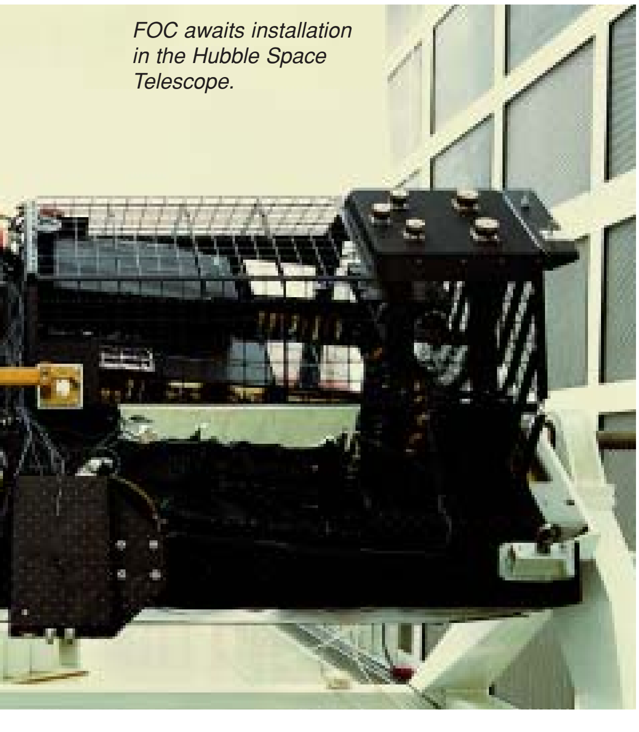
ESA provided HST's solar array and one of the five original scientific instruments. The Faint Object Camera is one of the four box-like units in the base section.

The first surface maps of Pluto constructed from a long series of FOC images taken in 1994. The two smaller inset pictures give samples of the actual raw FOC images. Pluto is only two-thirds the size of the Moon and is 12000 times farther away.



unique close-up views of almost every type of astronomical object known – from the asteroids and planets of our solar system to the most remote quasars and galaxies. FOC was last used scientifically 3 July 1999 to image quasar Q1157+317, but it will continue to be operated for calibration purposes until it is removed. FOC's major achievements include:

- first direct image of the surface of the red giant star Betelgeuse;
- first high-resolution image of the circumstellar ring and ejecta of Supernova 1987A;
- first detection of white dwarfs and stellar mass segregation in a globular cluster;
- first detection of intergalactic helium in the early Universe.

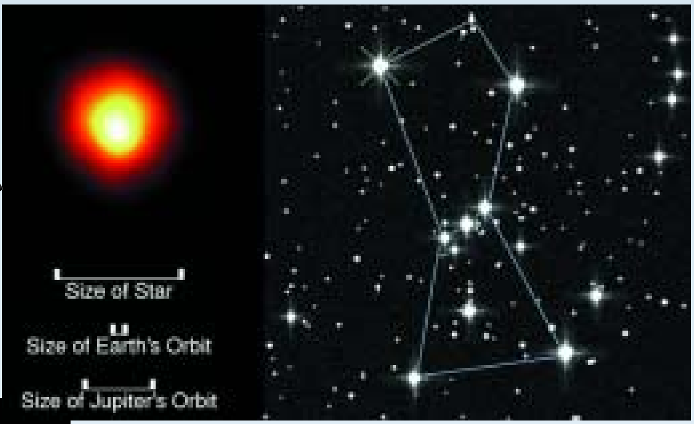


FOC awaits installation in the Hubble Space Telescope.

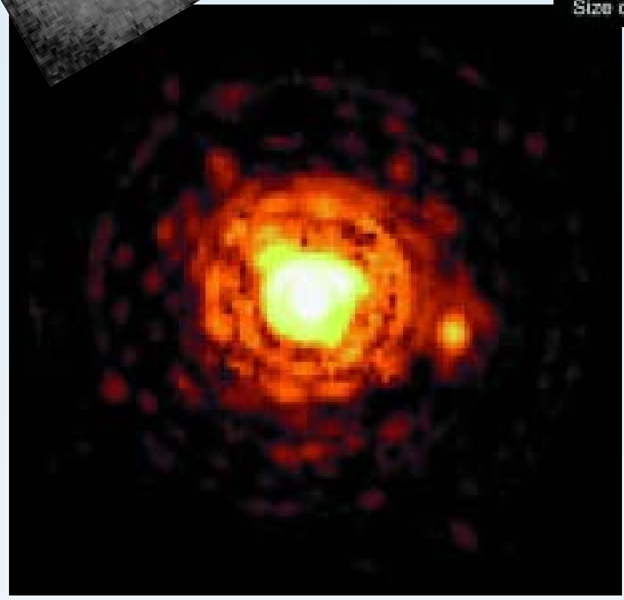
SM3A in December 1999 renewed Hubble's gyros. SM3B in 2002 will replace FOC with NASA's own Advanced Camera for Surveys (ACS), and ESA's flexible solar wings with rigid US versions. FOC will be returned to ESA for inspection and possibly museum display.

A fifth servicing mission in 2003/04 will replace COSTAR with the Cosmic Origins Spectrograph (COS) and WFPC2 by Wide Field Camera 3 (WFC3). After that, HST will continue operations on a reduced-cost basis, possibly beyond 2009 when its Next Generation Space Telescope (NGST) successor begins to build on the Hubble legacy. The ESA/NASA HST MoU expired in April 2001 but a concept agreement for continuing the collaboration, including possible NGST participation, is expected to be signed in 2001.

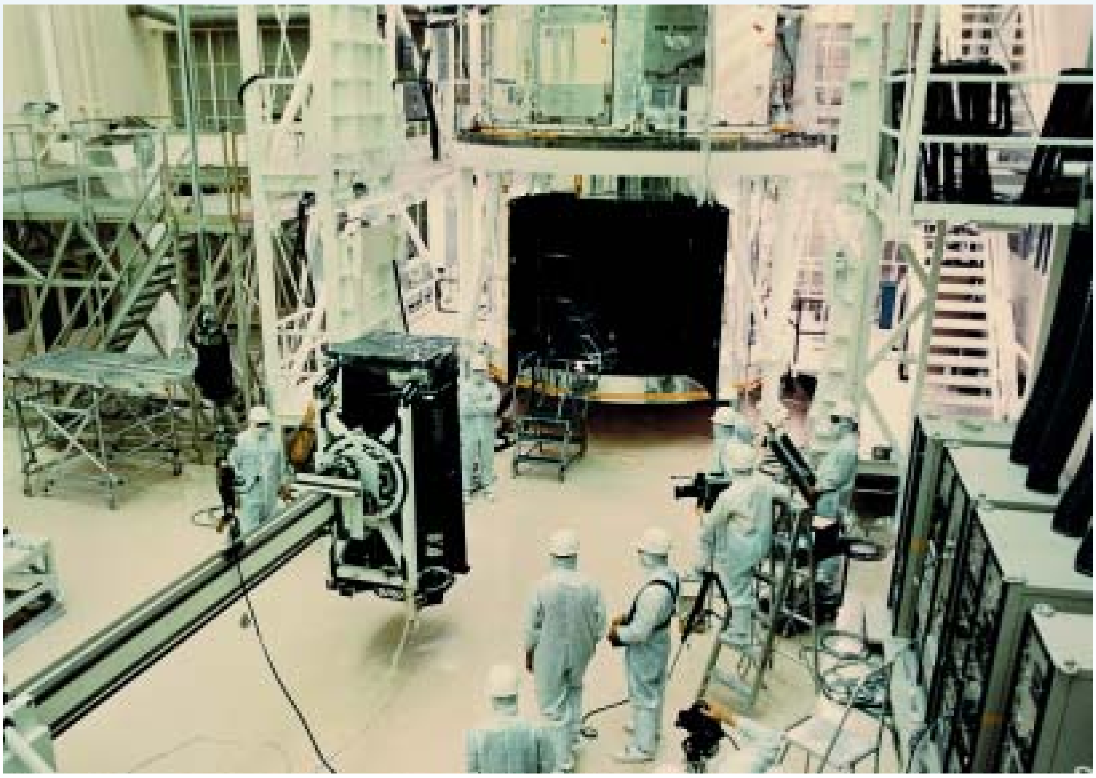
FOC images of a single star taken before (left) and after (right) the 1993 servicing mission. The 'halo' of improperly focused light seen in the left image is completely rectified in the COSTAR-corrected image.



This FOC image of the red giant star Betelgeuse in ultraviolet light is the first direct image ever taken of a star other than the Sun. It reveals a huge tenuous atmosphere with a mysterious hot spot on its surface.

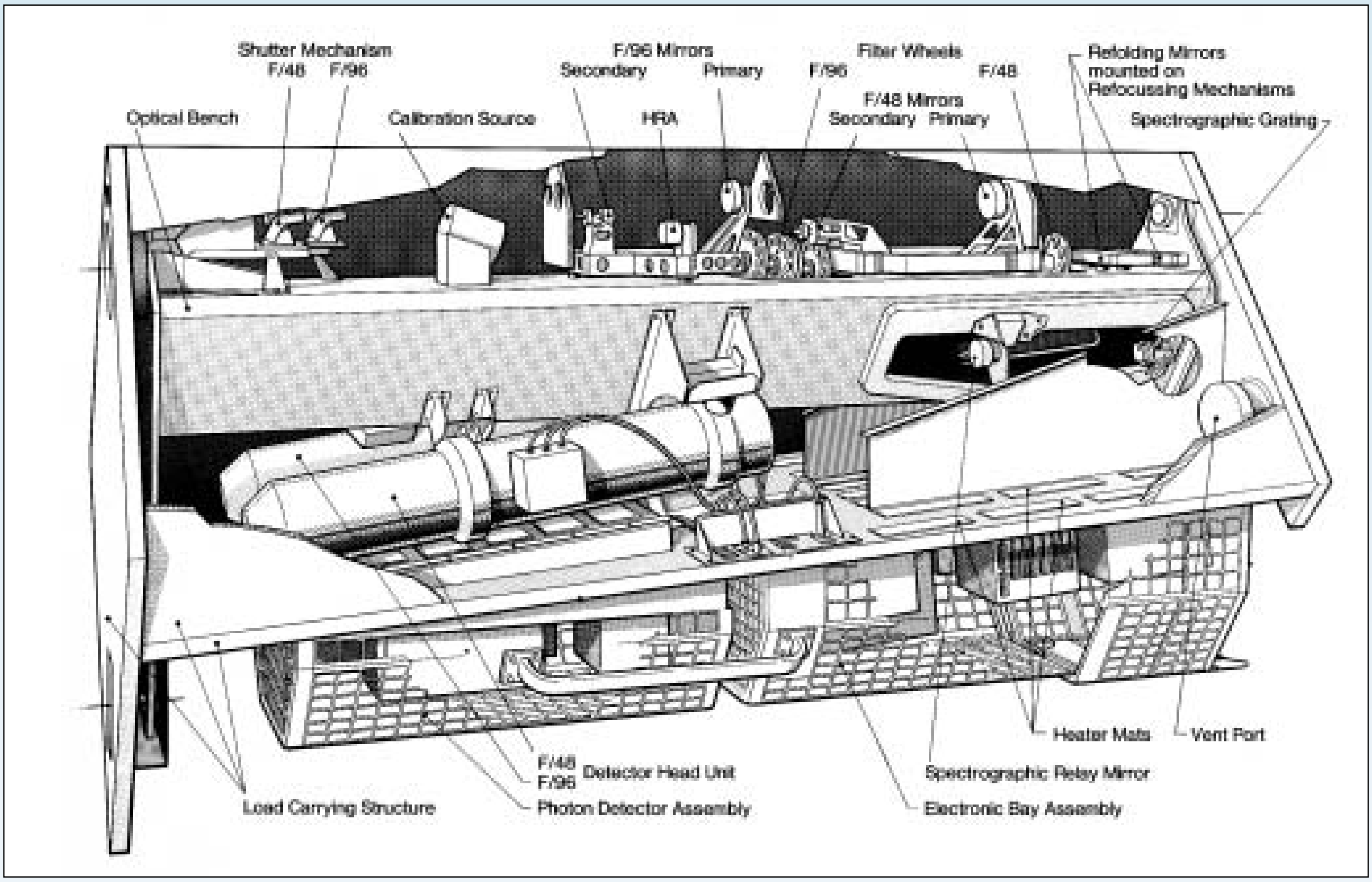


This FOC image reveals one of the smallest stars in our Galaxy, Gliese 623b. The diminutive star is ten times less massive and 60 000 times fainter than the Sun, and appears as the smaller component (right of centre) of a double star system in which the separation between the two members is only twice the distance between the Earth and the Sun.



The Faint Object Camera is installed in the base of Hubble, behind the main mirror. The camera will be returned to Earth aboard the Space Shuttle in 2002.

Further information on HST and Europe's involvement can be found at http://hubble.esa.int



Principal features of the Faint Object Camera.

HST configuration: HST,13.1 m long and 4.27-4.7 m diameter, employs a 2.40 m-diameter primary mirror and optical relaying light to five (four after SM1) aft-mounted focal plane instruments. The f/24 Ritchey-Chrétien Cassegrain optical system comprises an 830 kg primary mirror of ultra-low expansion titanium silicate glass and a 30 cm-diameter Zerodur secondary. Effective focal length is 57.6 m. The 5 m-distant secondary directs the light cone through the primary's 60 cm-diameter central aperture to a focus 1.5 m behind the face plate for dispersion to the scientific instruments.

Power system: FOC requires 150 W when operating, 75 W in standby. HST is powered (until SM3B in 2002) by twin ESA/British Aerospace solar wings providing 5.0 kW BOL and 4.3 kW after 5-year design life. Each 150 kg, 2.83x11.8 m wing carries 24 380 Si cells.

FOC: 2 m long, 1x1 m cross section, optimised to exploit HST's full resolution capabilities for faint objects of magnitude +24 to +29 using long exposures. Covering 1150-6500 Å, it operated in four principal modes: direct imaging at f/48 (22x22 arcsec FOV, 2x magnification), f/96 (11x11 arcsec, 4x) and f/288 (4x4 arcsec, 12x), and as a 20x0.1 arcsec R=1000 long-slit spectrograph. Four wheels provided banks of filters, polarisers and objective prisms. Two photon-counting intensified cameras acted as detectors. Following SM1, FOC's optical chains were fed corrected but magnified images: f/96 became f/150 (7 arcsec FOV), f/48 became f/75 (14 arcsec) and f/288 became f/450.