Mars Express

Planned achievements: first European Mars orbiter & lander
Launch date: planned for 1 June 2003 (11-day window), Mars arrival 26 December 2003
Mission end: orbiter after 1 martian year (687 Earth days), 1-year extension possible; lander 180 Earth days
Launch vehicle/site: Soyuz-Fregat from Baikonur Cosmodrome, Kazakhstan
Launch mass: 1120 kg (science payload 113 kg, lander 60 kg)
Orbit: heliocentric, followed by 259x11560 km, 86.35°, 7.5 h about Mars for first 440 days, followed by 298x10107 km, 86.35°, 6.7 h
Principal contractors: Astrium SAS (orbiter), Astrium UK (lander), Martin-Baker Aircraft Co (EDLS). Phase-B January-November 1999, Phase-C/D January 2000 - November 2002

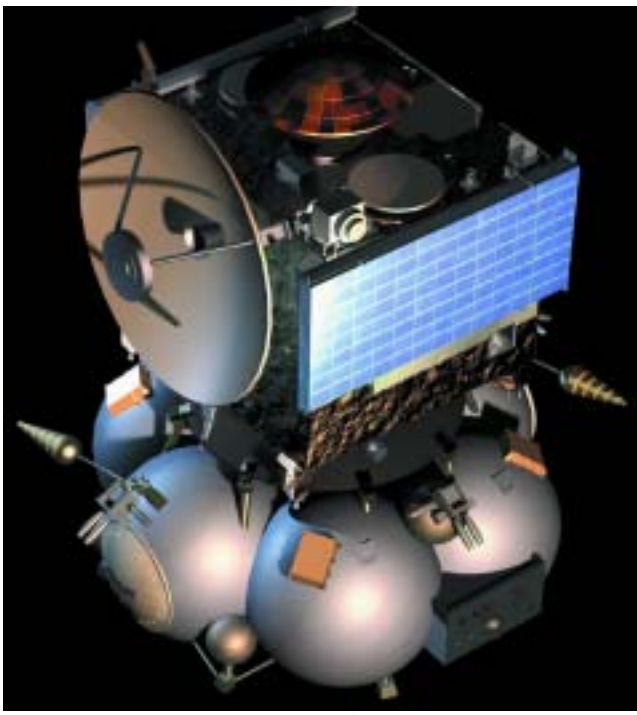
The Mars Express orbiter and Beagle 2 lander have key roles in the international exploration programme planned for the Red Planet over the next two decades.

Some of the orbiter's instruments were originally developed for Russia's ill-fated Mars-96 mission. Now upgraded, they will provide remote sensing of the atmosphere, ground and up to 5 km below the surface. The information will help to answer many outstanding questions about Mars, such as what happened to the water that once flowed freely, and did life ever evolve?

Beagle 2 will be the first lander since NASA's two Viking probes in 1976 to look specifically for evidence of past or present life. No other Mars probe is making exobiology so central to its mission.

Mars Express was conceived in 1997 as the first Flexible low-cost mission in the Horizons 2000 programme. It will cost the Agency no more than €150 million (1996 rates) – only about a third of the cost of similar previous missions. Despite that modest level, however, its future hung in the balance because of the steady erosion of ESA's science budget since 1995. In November 1998, the Science Programme Comittee approved it on the basis that it did not affect missions already selected, particularly Herschel and Planck. Following the Ministerial Council of 11/12 May 1999 approving the funding, the SPC gave the final go-ahead on 19 May 1999.

ESA is funding the orbiter, launch and operations. The science instruments are being provided separately by their home institutes; the lander is a cooperative venture by



The Beagle 2 lander is ejected from the orbiter. Bottom left: Mars Express in launch configuration on the Fregat upper stage.

Mars Express Science Goals

- image the entire surface at high resolution (10 m/pixel) and selected areas at super-high resolution (2 m/pixel)
- map the mineral composition of the surface at 100 m resolution
- map the composition of the atmosphere and determine its global circulation
- determine the structure of the subsurface down to a few kilometres
- determine the effect of the atmosphere on the surface
- determine the interaction of the atmosphere with the solar wind

Beagle 2 lander:

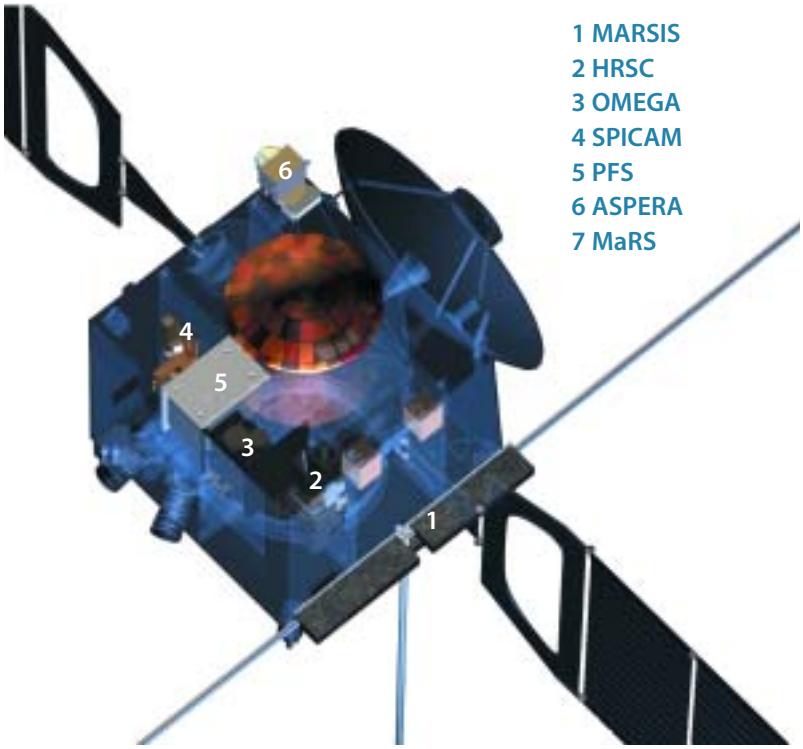
- determine the geology and mineral composition of the landing site
- search for life signatures (exobiology)
- study the weather and climate

ESA and the UK Beagle 2 consortium. The science Announcement of Opportunity was released in December 1997 and 29 proposals were received by the 24 February 1998 deadline, including three for a lander, which was treated as an instrument. The SPC made the selection at the end of May 1998. Beagle 2 cost is €50 million, of which ESA agreed in 2000 to contribute €24 million in return for management oversight and increased return to the European scientific community.

The spacecraft is being built unusually quickly to meet the tight 11-day launch window during the particularly favourable Mars opportunity of 2003. Savings are being made by reusing existing hardware, adopting new management practices, shortening the time from original concept to launch, and procuring the most cost-effective launcher available. Maximum use is being made of off-the-shelf and Rosetta technology – 65% of the hardware is at least partially derived from the Rosetta cometary mission that will also depart in 2003.

ESA is delegating tasks to Astrium SAS in Toulouse (F) that previously would have been performed by the project team at ESTEC. In particular, Astrium is managing the orbiter/payload and orbiter/launcher technical interfaces. The period from concept to awarding the design and development contract was cut from about 5 years to little more than 1 year. Astrium SAS won the €60 million fixed-price prime contract in December 1998 in competition with consortia led by Alenia/Aerospatiale and Dornier. The Phase-B/C/D design and development phase will take less than 4 years, compared with up to 6 years for previous similar missions.

Recent missions have raised many questions about Mars. What forces created the spectacular landscape features? When did they stop – or are they still active? Was early Mars really warm and wet? If so, where did the water and atmosphere go? Did life evolve there? And is primitive life still thriving, perhaps in underground aquifers? Mars Express will help to provide answers by mapping the subsurface, surface, atmosphere and ionosphere from orbit and conducting

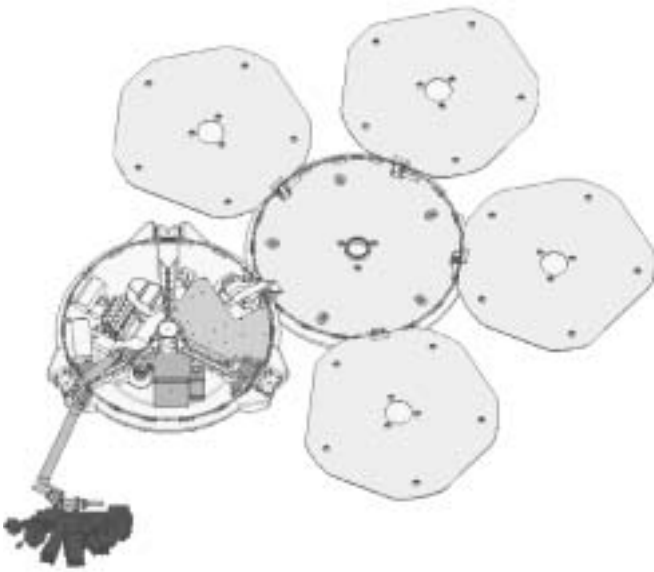


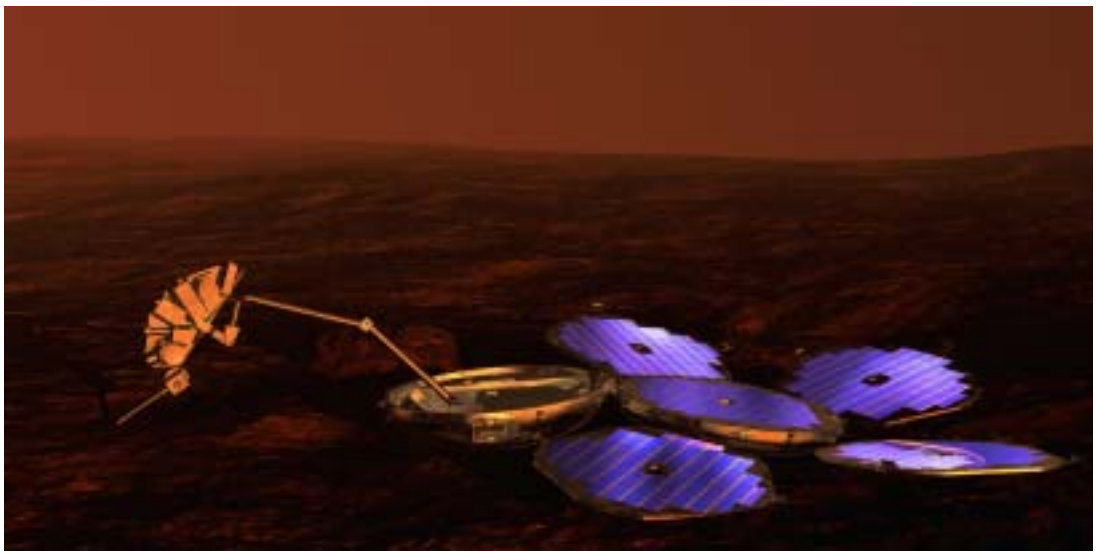
observations and experiments on the surface. Investigations will also provide clues as to why the north is so smooth while the south is so rugged, how the Tharsis and Elysium mounds were raised and whether there are still active volcanoes. Not only does Mars have the largest volcanoes and deepest canyons in the Solar System, it also shows evidence for the most catastrophic floods. Large channels carved by these floods drain into the northern plains, lending support for the existence of an ancient ocean over most of the northern hemisphere. Valley networks that criss-cross the southern highlands were also probably formed by water. And many craters, especially at high latitudes, are surrounded by fluidised ejecta. This suggests there was underground water or ice at the time of impact, and possibly more recently.

If water was largely responsible for these features, however, it has long since disappeared: most of the evidence is more than 3800 million years old. Today, atmospheric pressure at ground level is only about 1% that on Earth. So where did the gases and water go and why? Each of the orbiter's seven instruments will contribute towards the answer.

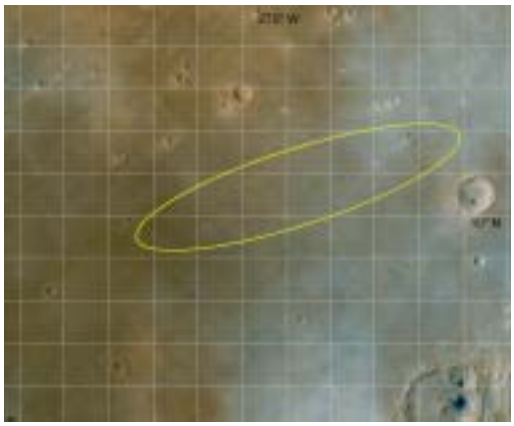
The water could have been lost to space and/or trapped underground. Four orbiter experiments (ASPERA, SPICAM, PFS, MaRS) will observe the atmosphere and reveal processes by which water vapour and other atmospheric gases could have escaped into space. Two (HRSC, OMEGA) will examine the surface and in the process add to knowledge about where water may once have existed and where it could still lie underground. One (MARSIS) will look for underground water and ice. This is the first time that a ground-penetrating radar has been used in space.

Beagle 2 will look for signatures of life on Mars, whether long-dead or still-living, by measuring the $^{12}C/^{13}C$ ratio in the rock. On Earth, many biological processes favour ^{12}C, so a high ratio is taken as evidence of life and has been found in rocks up to 4000 million years old, even where geological processing has occurred. The hope is that the same occurred on Mars.





Most of Beagle 2's instruments are carried on its arm.

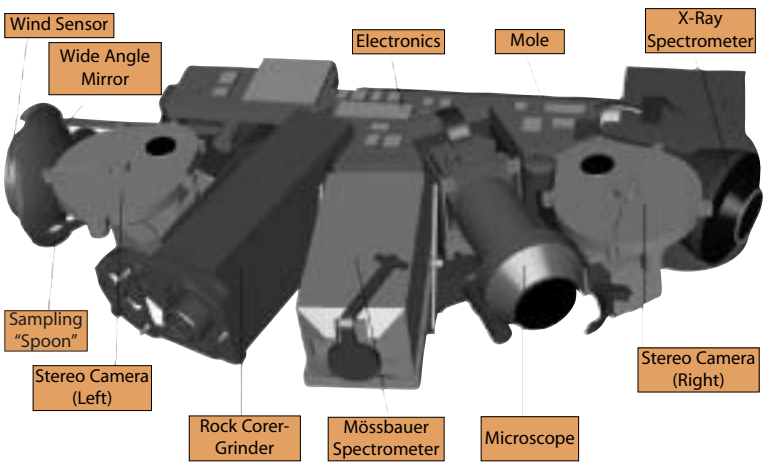


Beagle 2's 95x500 km landing ellipse in the Isidis Planitia. The site was selected in December 2000.

On Earth, life produces another signature: methane. This gas has a very short lifetime on Mars because of the oxidising nature of the atmosphere, so its presence would indicate a replenishing source, which may be life, even if it is buried.

The only previous landers to look directly for evidence of past life were NASA's Vikings in 1976. However, Mars' harsh, oxidising atmosphere would almost certainly have destroyed any such evidence on the surface. Beagle 2 will surmount this problem by using a 'mole' to retrieve soil samples from as deep as 1 m. Its corer and grinder will also expose the interior of rocks for study.

The plan is for Mars Express to release the lander 5 days before its arrival at Mars. Beagle 2 enters the atmosphere at more than 20 000 km/h protected by a heatshield. When its speed has reduced to about 1600 km/h, the heatshield is jettisoned and the parachutes deploy. Finally, large gas bags inflate to protect it as it bounces to a halt, 5 min after entry. Immediately, the bags are ejected, its clamshell outer casing springs open, solar panels unfurl and cameras begin operating. The first few days are spent running pre-programmed sequences, imaging the site and running the environmental sensors, preparing for the very detailed rock and soil analysis.



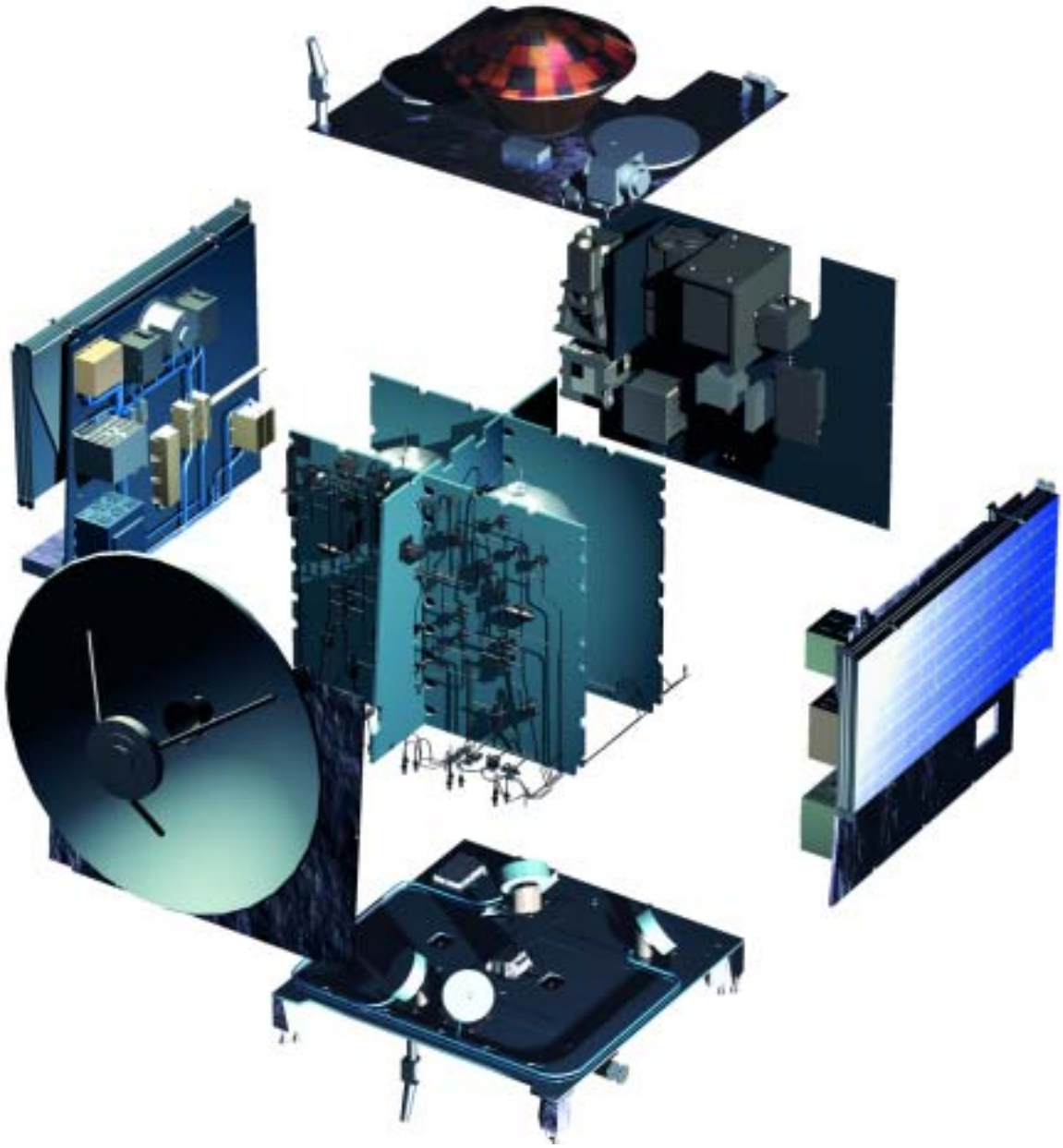
Beagle 2 will land on Isidis Planitia, a large, flat basin straddling the northern plains and ancient highlands. The site (10.6°N, 270°W) is at the maximum latitude for the Sun to provide sufficient warmth and power in early spring. It is not too rocky to threaten a safe landing (but enough to be interesting), has few

Mars Express Scientific Instruments	
HRSC	Super/High-Resolution Stereo Colour Imager. Push-broom scanning camera, 9 CCDs. 10 m global res, 2 m res selected areas. 22 kg, 40 W, 10 Mbit/s. PI: Gerhard Neukum, Institut für Weltraumsensorik und Planetenerkundung (Berlin, D). Participating countries: D, F, RU, US, FIN, I, UK
OMEGA	Visible/IR Mineralogical Mapping Spectrometer. Mineral mapping at 100 m res, Specific surface mineral and molecular phases, mapping photometric units, atmospheric particles. 0.5-5.2 µm. 30 kg, 42 W, 500 kbit/s. PI: Jean-Pierre Bibring, Institut d'Astrophysique Spatiale (Orsay, F). Participating countries: F, I, RU
PFS	Planetary Fourier Spectrometer. Atmospheric composition & circulation, surface mineralogy, surface-atmosphere interactions. 1.2-45 µm. 32 kg, 35 W, 33 kbit/s. PI: Vittorio Formisano, Istituto Fisica Spazio Interplanetario (Frascati, I). Participating countries: I, RU, PL, D, F, E, US
MARSIS	Subsurface Sounding Radar/Altimeter. Subsurface structure from 200 m to few km, distribution of water in upper crust, surface roughness and topography, ionosphere. 40 m-long antenna, 11.3-5.5 MHz RF waves, 17 kg, 60 W, 30 kbit/s. PI: Giovanni Picardi, Universita di Roma La Sapienza (Rome, I). Participating countries: I, US, D, CH, UK, DK
ASPERA	Energetic Neutral Atoms Analyser. Upper atmosphere interaction with interplanetary medium & solar wind (lack of a magnetic field is believed to have allowed the solar wind to sweep away most of Mars' atmosphere); near-Mars plasma and neutral gas environment. 9 kg, 12 W, 6 kbit/s. PI: Rickard Lundin, Swedish Institute of Space Physics (Kiruna, S). Participating countries: S, D, UK, F, FIN, I, US, RU
SPICAM	UV and IR Atmospheric Spectrometer. Water (1.30 µm), ozone (250 nm UV) & dust profiles of atmosphere by stellar occultation. 6 kg, 12 W, 6 kbit/s. PI: Jean-Loup Bertaux, Service d'Aeronomie du CNRS (Verrieres-le-Buisson, F). Participating countries: F, B, RU, US
MaRS	Radio Science Experiment. Atmospheric density, P & T profiles, ionospheric electron density profiles (passage of radio waves through atmosphere), surface dielectric and scattering properties (reflection of radio waves) and gravity anomalies (orbital tracking). PI: Martin Paetzold, Köln University (D). Participating countries: D, F, US, A
Beagle 2	360° panoramic stereo camera & microscope (surface textures, 4 µm res; Mullard Space Science Lab.), X-ray spectrometer (in situ chemical composition; Leicester Univ.), Mössbauer spectrometer (Fe minerals, inc. carbonates, sulphates, nitrates; MPI für Chemie), Gas Analyser Package (GAP; carbon, gas isotopes, trace constituents; Open Univ.), Environmental Sensor Suite (T, P, wind speed/direction, 200-400 nm UV flux, solar protons/cosmic rays, dust impacts; 0.180 kg; Leicester Univ./Open Univ.), mole & corer/grinder (DLR Inst. Space Simulation & Polytechnic Univ. of Hong Kong). Lander surface mass 30 kg (instruments 17 kg, 100 W, 128 Kbit/s). PI: Colin Pillinger, Open Univ. (Milton Keynes, UK). Participating countries: UK, D, F, HK, CH

steep slopes down which the probe may have to bounce, and is not too dusty. Isidis Planitia is low enough to provide sufficient depth of atmosphere to allow the parachutes to brake the descent. Also, the region is a sedimentary basin where traces of life could have been preserved.

Most of Beagle 2's experiments are on its PAW (Position Adjustable Workbench) at the end of a robotic arm. They include stereo cameras, microscope, two spectrometers (Mössbauer and X-ray), the corer/grinder and mole. PAW also has a lamp for illumination, a brush and a sample scoop in case of mole failure.

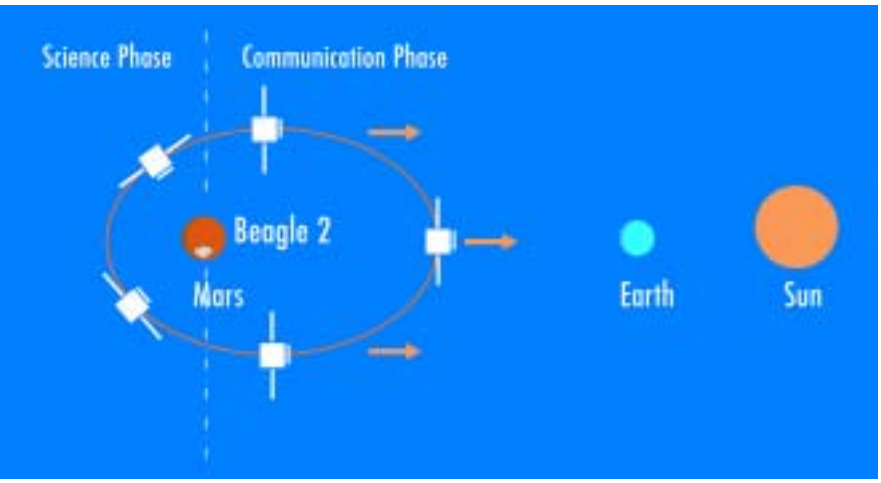
Shortly after landing, the stereo camera will record panoramic shots of the site, followed by close-up images of near-by soil and rocks as candidates for further analysis. When a suitable rock has been chosen, PAW will rotate until the grinder is positioned to remove the weathered



surface. PAW can then position the microscope or spectrometers to analyse the freshly exposed material.

When a rock looks particularly interesting, a sample will be drilled out with the corer and taken to the gas analysis package (GAP) inside the lander by the robotic arm. The mole will collect soil samples and deliver them to the GAP in a similar way. The PAW will rotate until the mole is positioned so that it can burrow underground to collect the samples.

GAP has 12 ovens in which samples can be heated gradually in the presence of oxygen. The carbon dioxide generated at each temperature will be delivered to a mass spectrometer to measure its abundance and the $^{12}C/^{13}C$ ratio. The temperature at which the carbon is generated will reveal its origins, as different carbon-bearing materials combust at different temperatures. The mass spectrometer will also look for methane in atmospheric samples.



A variety of tiny sensors scattered about the lander will measure different aspects of the environment, including: atmospheric pressure, air temperature and wind speed and direction; UV radiation and oxidising gases such as ozone and hydrogen peroxide; dust fall-out and the density and pressure of the upper atmosphere during descent. The stereo camera will help to construct a 3D model of the area within reach of the arm. As PAW cannot be operated in real-time from Earth, this model will be used to guide the instruments into position alongside target rocks and soil. The microscope will pick out features a few 0.001 mm across in rock surfaces exposed by the grinder.

The Mössbauer Spectrometer will investigate the mineral composition of rocks by irradiating exposed rock surfaces and soil with gamma-rays from a ^{57}Co source, and then measuring the spectrum of the gamma-rays reflected back. In particular, the nature of iron oxides in the pristine interior and weathered surface of rocks will help to determine the oxidising nature of the present atmosphere.

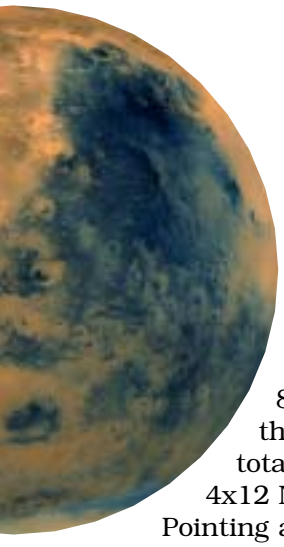
The X-ray spectrometer will measure the elements in rocks by bombarding their exposed surfaces with X-rays from four radioactive sources (two ^{55}Fe and two ^{109}Ca). GAP will estimate rock ages by measuring the ratio of ^{40}K (spectrometer) to ^{40}Ar.

International collaboration, either through participation in instrument hardware or scientific data analysis, is significantly enhancing the mission. NASA's major contribution to MARSIS is an example. Also, arriving at Mars at the very beginning of 2004, Japan's Nozomi spacecraft will follow Mars Express. The missions are highly complementary. From its highly elliptic equatorial orbit, Nozomi will focus on the upper atmosphere as well as the interaction of the solar wind with the ionosphere. Beagle will land at about the same time as NASA's Mars Rover. The agencies are arranging to enable the landers to use each other's orbiter as back-up for relaying data and other communications to Earth. Mars Express is also requesting the use of NASA's Deep Space Network for communications with Earth during parts of the mission. Five of the Mars Express instruments (OMEGA, PFS, ASPERA, HRSC, SPICAM) are descendants of instruments originally built for the Russian Mars-96 mission. Each of the seven orbiter instrument teams has Russian co-investigators.

Orbiter

Configuration: box-shaped bus 1.5x1.8x1.4 m of conventional aluminium construction. Dry mass 680 kg.

Attitude/orbit control: orbit correction & Mars insertion by single 400 N



NTO/MMH thrusters, attitude control by 8x10 N hydrazine thrusters (420 kg in 2 tanks totalling 580 L) and 4x12 Nms reaction wheels. Pointing accuracy 0.15° supported by 2 star trackers, 6 laser gyros, 2 coarse Sun sensors.

Power system: twin 4-panel Si solar wings derived from Globalstar totalling 11.42 m² provide 650 W at Mars (500 W required). Supported by 3x22.5 Ah Li-ion batteries.

Thermal control: aluminium/tin alloy blankets keep interior at 10-20°C.

Communications: via 1.6 m-dia 65 W X-band HGA to 34 m New Norcia, Perth ground station at up to 230 kbit/s from 12 Gbit SSR. UHF antenna receives Beagle 2 data. Processed data will be placed in public archive at ESTEC after 6 months. Controlled from ESOC.

Beagle 2

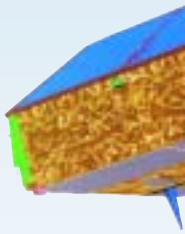
60 kg (30 kg on surface, 17 kg science instruments). Lander 66 cm-dia, 22 cm-high, primary structure carbon-fibre skin on aluminium honeycomb. Powered up shortly before ejection from orbiter, 5 days out from Mars. Comprises lander and Entry, Descent & Landing System (EDLS), drawing heavily on Huygens heritage. EDLS provides a front shield/aeroshell and back cover/bioshield. Mortar fires through patch in back shield to deploy 3.2 m-dia drogue 'chute and then 7.5 m-dia main 'chute; front shield is released pyrotechnically. Three 2 m-dia gas-bags inflated. On contact, 'chute released for lander to bounce away. Coming to rest, a lace is cut for the bags to open. Beagle's clam-shell lid opens to begin the science phase.

Most science instruments mounted on arm with 75 cm reach: stereo camera, microscope, two spectrometers (Mössbauer and X-ray), lamp, mole and corer/grinder.

DLR's Pluto (planetary undersurface tool) mole can crawl 1 cm in 6 s by using spring compression to propel a drive mass. Collects sample in tip cavity, wound back in from up to 3 m by power cable for sample delivery to instruments. Grinder/corer exposes fresh rock surfaces and can drill 1 cm deep for 2 mm-dia 60 mg sample.

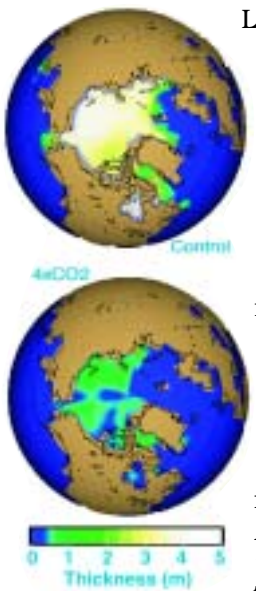
Power provided by GaAs array totalling 1 m² on 5 panels, supported by 200 Wh Li-ion battery. 128 Kbit/s data link by 400 MHz UHF 5 W transmitter via patch antennas to orbiter. Goal for surface operations is 180 Earth days.

CryoSat



Planned achievements: first thickness-change measurements of Arctic ice
Launch date: planned for April 2004
Mission end: after 3.5 years
Launch vehicle/site: to be selected (Rockot/Dnepr-class)
Launch mass: about 737 kg (62 kg SIRAL)
Orbit: planned 717 km circular, 92°, 369-day repeat, 30-day subcycle (validation phase 711 km, 3-day repeat)
Principal contractors: Astrium GmbH (prime, system, platform, AIV)), Alcatel Space Industries (SIRAL); Phase-A Feburary - July 2000; Phase-B July 2000 - January 2001; System Design Review February 2001; Phase-C/D July 2001 - September 2003; Critical Design Review April 2002

Cryosat will monitor changes in the thickness of the polar ice sheets and of floating sea ice. The Announcement of Opportunity for the first Earth Explorer Opportunity mission in ESA's Living Planet programme was released on 30 June 1998; 27 proposals were received by closure on 2 December 1998. On 27 May 1999, ESA approved Cryosat. As an Opportunity mission, it is dedicated to research and headed by a Lead Investigator (LI): Prof. Duncan Wingham of University College London (UK). The LI is responsible for overall mission design, implementation and data processing; ESA has overall mission responsibility

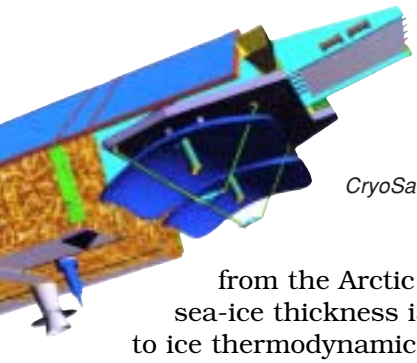


The UK Hadley Centre predicts a thinning of Arctic ice from 5 m to 1 m if the carbon dioxide level quadruples.

Rising temperatures mean that we face the widespread disappearance over the next 80 years of the ice covering the Arctic Ocean. The effects will be profound not only in the Arctic. Warm winter temperatures in Europe result from ocean currents that are affected by fresh water from precipitation and Arctic ice meltwater, and both may increase in a warming climate.

Cryosat will measure variations in the thickness of the Arctic sea ice and the ice sheet, ice caps and glaciers that ring the Arctic Ocean. The team is adapting existing European altimeter flight hardware to use synthetic aperture and interferometric techniques. In the Synthetic Aperture Radar (SAR) mode, Cryosat's radar sweeps across the groundtrack, repeatedly covering any one location as it moves along its orbit. The data from all beams are combined to give a single height measurement for that location. Later measurements will show if there has been a change in height. Of course, this requires that CryoSat's orbit is known accurately. Where higher resolution is required, over the steep edges of ice sheets, the second radar is added to create an interferometer across the track for the 'SARin' (SAR interferometer) mode.

Sea-ice thickness plays a central role in Arctic climate: it limits how much the winter Arctic atmosphere benefits from heat stored in the ocean the previous summer. Heat flux of more than 1.5 kW/m^2 from the open ocean may be reduced by a factor of 10-100 by ice. Secondly, fluctuations in sea-ice mass affect how ocean circulation is modified by fresh water. Presently, half of the fresh water flowing into the Greenland Sea – some 2000 Gt/yr – comes from the wind-driven ice floes



CryoSat Phase-B design.

from the Arctic Ocean. Finally, sea-ice thickness is very sensitive to ice thermodynamics, how ice deforms under stress, and heat from the air and ocean – 10 W/m^2 will melt around 1 m of ice in a year.

It is possible that an irreversible change in Arctic sea-ice mass is already underway. Existing thickness measurements already suggest an important trend in Arctic climate – but it is equally possible that this is merely an unremarkable short-term change. The measurements are still scattered too thinly in space and time to tell. Sea-ice thickness has previously been measured by drilling, by sonar observations of ice draft from submarines operating beneath the pack ice, or in one case, from a moored sonar array across the Fram Strait. Measurements have accumulated over the years, but are rarely of the same locations. Cryosat, by repeatedly sampling 70% of ice floes, will provide an authoritative view of the fluctuations.

Cryosat will do more than observe the floating ice of the Arctic Ocean. Obvious sources for the water causing the 18 cm rise in sea level last century are the ice sheets and glaciers on land. Observations from ERS, Seasat and Geosat indicate that the great central plateaus of the Antarctic and Greenland ice sheets are stable so, if these ice sheets are contributing to the rising sea level, the changes must be happening at their edges. The improvement in resolution from Cryosat's radar, coupled with its interferometric capability, will make continuous measurements of the ice sheet margins and smaller ice caps possible for the first time.

These measurements translate into the need to measure thickness changes in Arctic sea ice of 10^5 km^2 with an accuracy of 3.5 cm/yr (1.6 cm/yr will be achieved); in ice sheets covering 10^4 km^2 of 8.3 cm/yr (3.3 cm/yr will be achieved); and in ice sheets of 13.8x10^6 km^2 of 0.76 cm/yr (equivalent to a loss of 92 Gt of water each year; 0.17 cm/yr will be achieved).

Satellite configuration: total length 4.6 m, width 2.34 m. Box-shaped aluminium bus with extended nose for SIRAL. End/side plates complete main body and support solar array; nadir face as radiator. Controlled by ERC-32 single-chip processor via MIL-1553B bus.

Attitude/orbit control: 3-axis nadir pointing to 0.2/0.2/0.25° roll/pitch/yaw by three 30 Am^2 magnetorquers supported by redundant sets of eight 10 mN cold-gas nitrogen blowdown thrusters (plus four 40 mN for orbit adjust); 32 kg nitrogen in single central sphere. Attitude determination by 3 star trackers, 3 fluxgate magnetometers, and Earth/Sun sensors. Precise orbit determination by DORIS (5 cm radial accuracy; 30 cm realtime), Laser Retroreflectors (cm accuracy) and S-band transponder.

Power system: two GaAs panels totalling 9.4 m^2 on upper bus provide 525 Wh (SIRAL requires 132 W; 99 W in low-res mode). Supported by 60 Ah Li-ion battery.

Communications: controlled from ESOC via Kiruna (S). 320 Gbit downlink each day from 128 Gbit solid-state mass recorder at 100 Mbit/s QSPK 25 W 8.100 GHz. 2 kbit/s TC at 2026.7542 MHz. 4 kbit/s TM at 2201 MHz.

CryoSat Payload
SIRAL
Cassegrain antenna emits 44.8 μs Ku-band pulses, bandwidth 320 MHz. Three operating modes: *Low-Resolution Mode (LRM)* 1 pulse in 44.8 μs burst, 51 kbit/s; *SAR* mode 64 pulses in 3.8 ms burst, 12 Mbit/s, for ice floes & ice sheet interiors at < 1 km res; *SARin* mode 64 pulses in 3.8 ms burst, received by both antennas, 2x12 Mbit/s, for ice sheet edges at 250-300 m res.
DORIS
Doppler Orbitography & Radio-positioning Integrated by Satellite determines the orbit with 5 cm accuracy. It receives 2.03625 GHz & 401.25 MHz signals from ground beacons and measures the Doppler shift every 7-10 s. 91 kg, 16.7 kbit/s, 42 W.
LRR
Cluster of 9 laser reflectors provide orbit determination with cm-accuracy using laser ground stations. Backup to DORIS.

ATV

Planned achievements: ISS resupply/reboost
Launch date: first planned for September 2004, then every 15 months
Mission end: nominally after 6 months
Launch vehicle/site: Ariane-5ESV from Kourou, French Guiana
Launch mass: 20 500 kg (7372 kg payload)
Orbit: as ISS (typically 400 km, 51.6°), via 300x300 km
Principal contractors: EADS-Launch Vehicles (development), Astrium GmbH (integration, Propulsion & Reboost Subsystem), Alenia Spazio (Cargo Carrier), Astrium SAS (avionics, software), Oerlikon Contraves (structure), Alcatel Bell Telephon (EGSE)

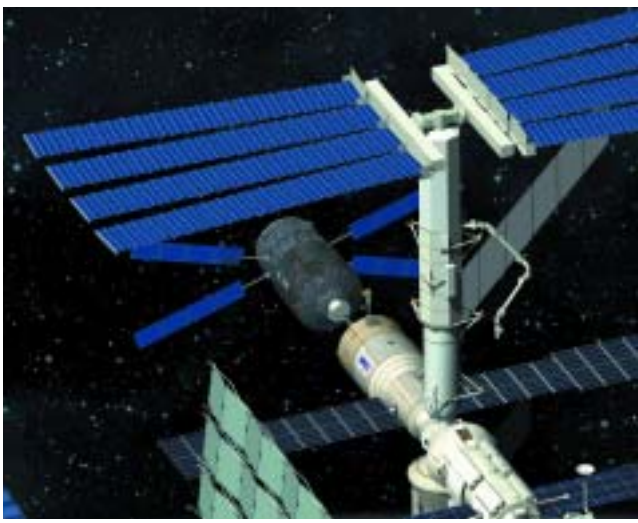
In combination with the Ariane-5 launcher, the Automated Transfer Vehicle (ATV) will enable Europe to transport supplies to the International Space Station. It will dock with Russia's Zvezda module after a 2-day autonomous flight using its own guidance, propulsion and docking systems. Its 7.4 t payload will include scientific equipment, general supplies, water, oxygen and propellant. Up to 4 t can be propellant for ATV's own engines to reboost the Station at regular intervals to combat atmospheric drag. Up to 860 kg of refuelling propellant can be transferred via Zvezda to Zarya for Station attitude and orbit control. Up to 5.5 t of dry cargo can be carried in the pressurised compartment.

ATV offers about four times the payload capability of Russia's Progress ferry. Without ATV, only Progress could reboost the Station. Both technically and politically, it is essential that the Station can call on at least two independent systems.

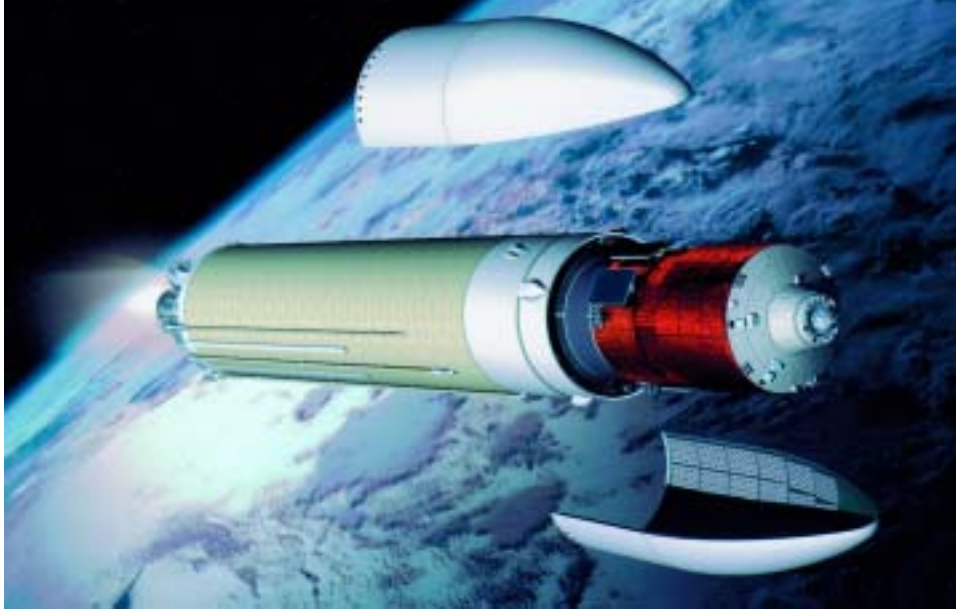
An ATV will be launched on average every 15 months, paying Europe's 8.3% contribution in kind to the Station's common operating costs. It can remain docked for up to 6 months, during which time it will be loaded with Station waste before undocking and flying into Earth's atmosphere to burn up.

Following launch from the Ariane-5 complex in French Guiana, the mission will be controlled from the ATV Control Centre in Toulouse (F). Docking manoeuvres will be coordinated with NASA's Space Station Control Center in Houston and with Russia's control centre near Moscow, which oversees all the Station's Russian modules.

ATV's docking mechanism is being provided by Russia in exchange for ESA's Data Management System (DMS-R) for Zvezda. A similar DMS is being used in Columbus and ATV. The docking system has long been used on Russia's stations and Soyuz and Progress craft. A probe engages the receptacle on Zvezda and is



Right: ATV's launch on an Ariane-5. Bottom left: ATV about to dock with Zvezda. (ESA/D. Ducros)



slowly retracted until the 1.3 m-dia faces and their electrical and hydraulic connectors mate. Eight hooks on each face are closed to complete hard docking. Zvezda's 80 cm-dia hatch is opened by the crew and a long tool is used to unlock ATV's hatch. Finally, 16 clamps are installed for rigidity across the docking collars.

ATV development was confirmed at the October 1995 ESA Ministerial Council meeting in Toulouse. Phase-B2 began in July 1996. The €408.3 million (1997 conditions) Phase-C/D fixed-price contract was signed with EADS-Launch Vehicles on 25 November 1998. PDR was completed in December 2000; CDR is due in 2003. ESA and Arianespace in June 2000 signed a €1 billion contract to launch nine ATVs over a period of 10 years. They will be produced and operated by industry under a single contract (encompassing the launch contract) to be awarded in 2001.

Ariane-5 injects ATV into a 300x300 km, 51.6° transfer path. Orbit circularisation and phasing it with the Station then take about 50 h. At the first apogee, ATV raises perigee to 400 km to stabilise the orbit. All ATV operations are monitored from Toulouse via NASA's Tracking & Data Relay Satellite (TDRS) system. Following the perigee-raising manoeuvre, a series of reconfiguration and check-out operations is performed, notably solar array deployment. Phasing manoeuvres then bring ATV to the Station's altitude. About 90 min before it enters the approach ellipsoid, integrated operations begin and mission authority is transferred to the Mission Control Center in Moscow. Beginning at about 30 km, ATV performs final approach and docking manoeuvres automatically over a period of 5 h, with either automatic or manual capability from the Station crew to trigger a collision avoidance manoeuvre. On first contact, ATV thrusts to ensure capture and to trigger the automatic docking sequence.

After docking, the hatch remains open unless it is closed to minimise the power required from the Station. The crew manually unloads cargo from the pressurised compartment while ATV is dormant. Dry cargo is carried in a shirtsleeve environment.

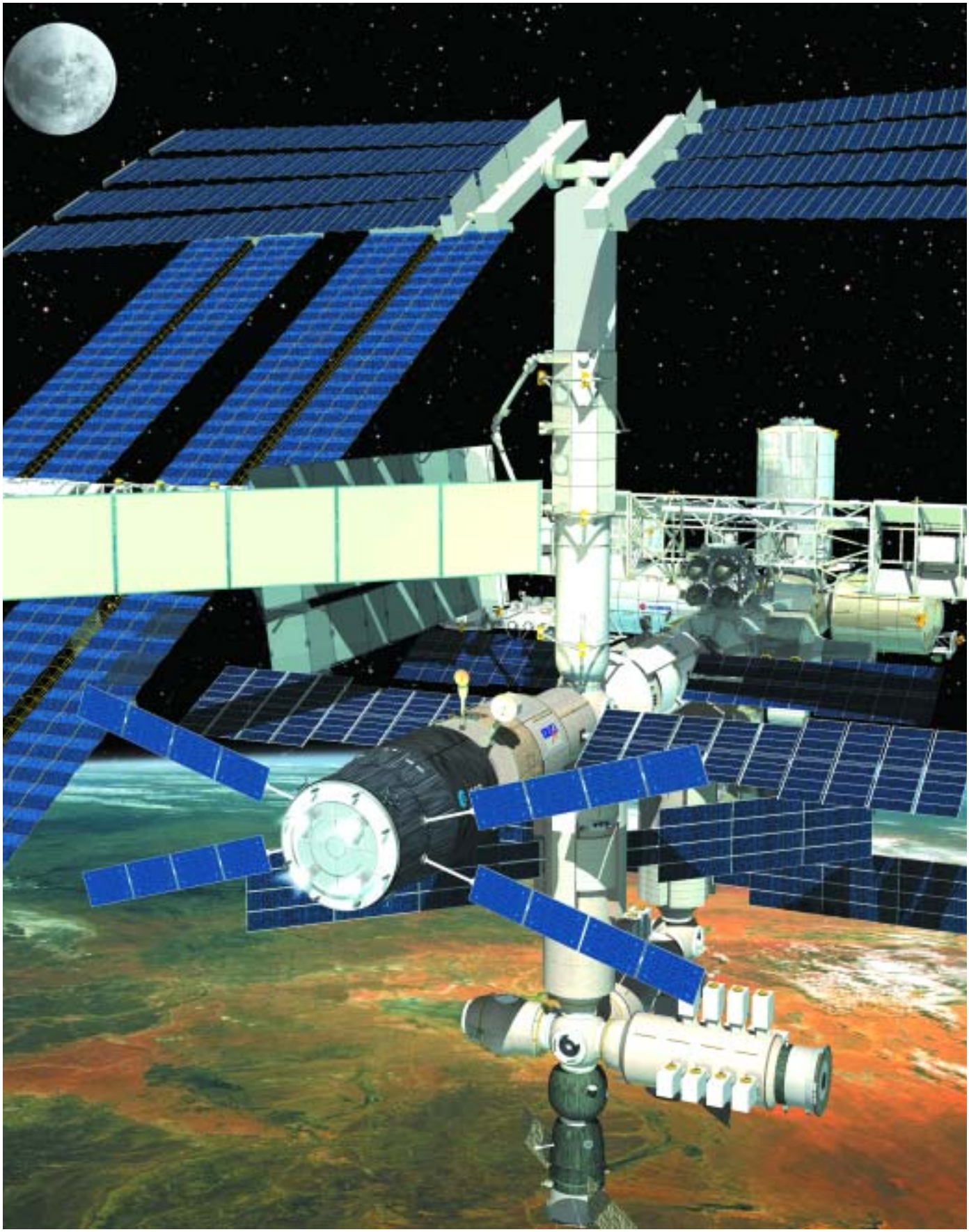
Station refuelling is powered and

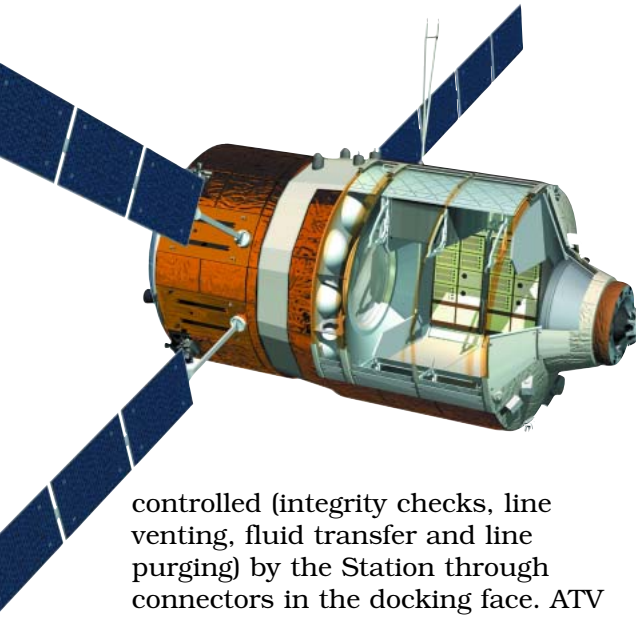
ATV Capacities

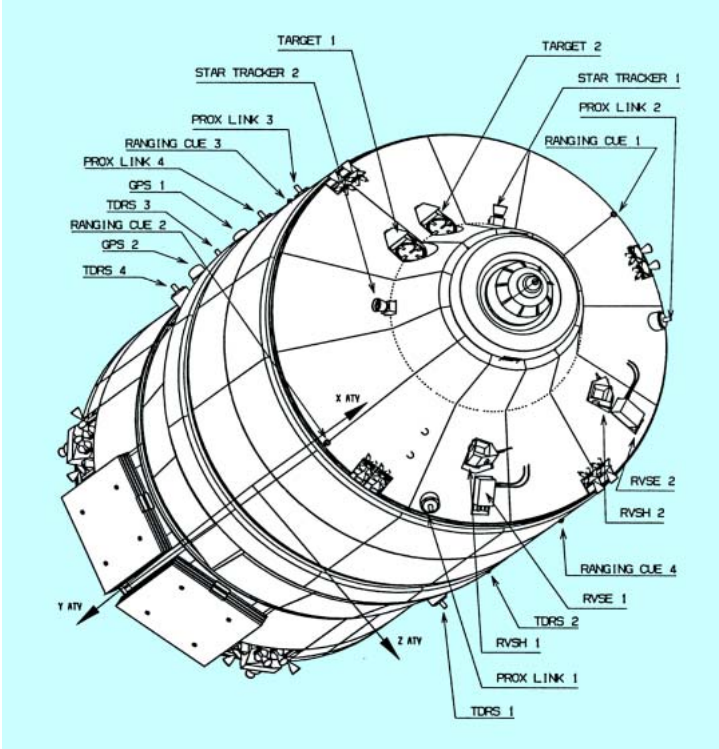
Launch mass: 20500 kg
Cargo: 7372 kg
- dry cargo: 1500-5500 kg
- water: 0-840 kg
- gas (O_2, N_2, air): 0-100 kg
- Refuelling propellant: 0-860 kg (306/554 kg MMH/MON
- Reboost propellant: 0-4000 kg

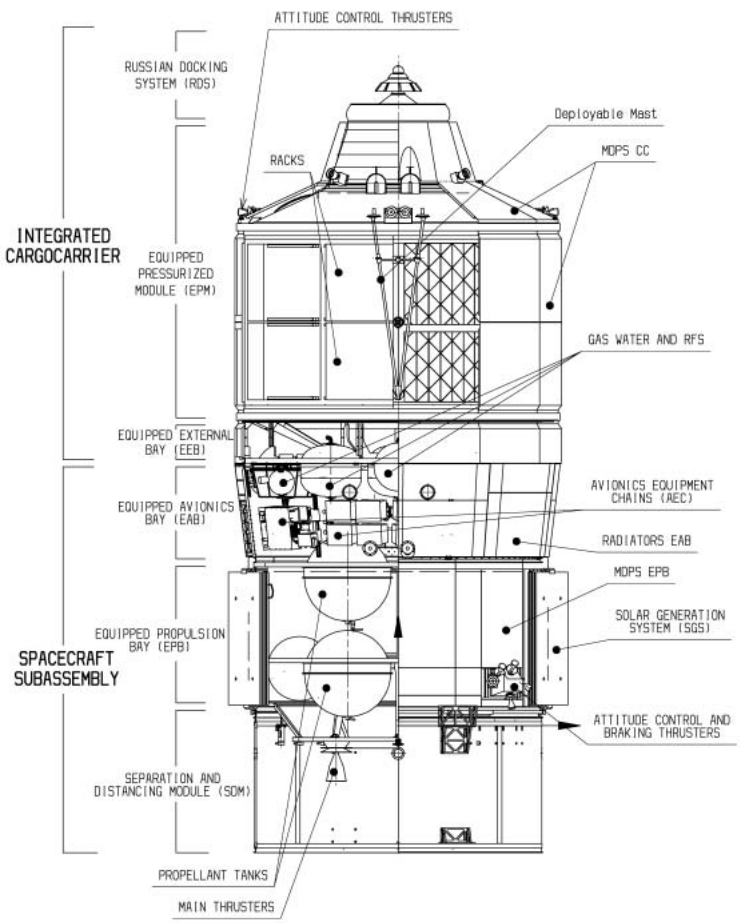
Dry mass: 10720 kg (inc. 7% margin)
Spacecraft dry: 5127 kg
Cargo Carrier dry: 3455 kg (cargo hardware 1437 kg)
Consumables (propellant/He): 2408 kg

ATV's four 490 N main engines fire to boost the Station's altitude. (ESA/D. Ducros)









controlled (integrity checks, line venting, fluid transfer and line purging) by the Station through connectors in the docking face. ATV is reactivated during the attitude control and reboost.

After undocking, ATV automatically manoeuvres for deorbiting and controlled reentry in the Earth's atmosphere. Carrying up to 5.5 t of waste from the Station, ATV will be safely consumed during reentry.

Satellite configuration: flared cylinder, 10.27 m long, max 4.51 m dia, 22.315 m across solar wings. Propulsion Module, Avionics Module and Separation and Distancing Module, all of aluminium alloy, with a Meteoroid and Debris Protection System mounted on the primary structure.

Attitude/orbit control: Propulsion & Reboost Subsystem uses four 490 N main engines (SI >310 s) and 20 220 N attitude thrusters (minimum impulse bit < 5 Ns). Mixed oxides of nitrogen (MON, oxidiser) and monomethyl hydrazine (MMH, fuel) stored in eight identical 1 m-dia titanium tanks, pressurised with helium stored in two high-pressure tanks regulated to 20 bar. Tanks can hold up to 6760 kg of propellant for main navigation and reboost requirements. GNC calculations are based on two GPS receivers for position, four gyros and two Earth sensors for attitude, and two rendezvous sensors for final approach and docking.

Power system: four wings (each of four 1.158x1.820 m panels) in X-configuration, using mix of GaAs and high-efficiency Si cells. 3860 W BOL in Sun-pointing mode; 3800 W EOL. Supported by NiCd batteries during eclipse periods; non-rechargeable batteries are used during some flight phases. Attached to ISS, ATV in dormant mode requires up to about 600 W from the Station.

Communications: via two redundant S-band systems – a TDRS link to ground control and a proximity link to the Station.

Columbus

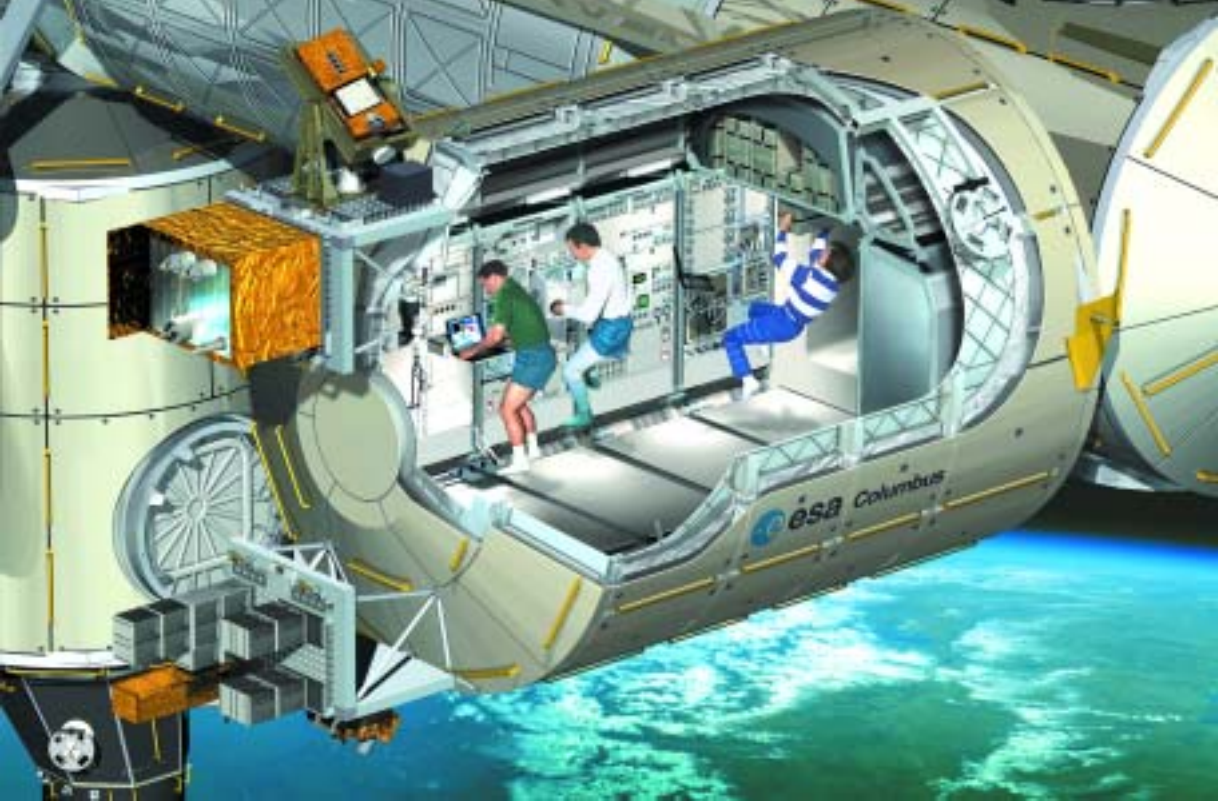
Planned achievements: key Space Station laboratory
Launch date: planned for October 2004
Mission end: nominally after 10 years
Launch vehicle/site: NASA Space Shuttle from Kennedy Space Center, Florida
Launch mass: 12700 kg (including 2500 kg payload)
Orbit: as ISS (about 400 km, 51.6°)
Principal contractors: Astrium GmbH (ex-DASA-RI: prime; ex-Dornier: ECLS), Alenia Spazio (structure, ECLS, thermal control, pre-integration), Astrium SAS (ex-MMS-F, DMS), Aerospatiale (MDPS); Phase-C/D began January 1996; PDR December 1997; CDR October-December 2000

The Columbus laboratory is the cornerstone of Europe's participation in the International Space Station (ISS). Columbus will provide Europe with experience of continuous exploitation of an orbital facility, operated from its own ground control facility in Oberpfaffenhofen, Germany. In this pressurised laboratory, European astronauts and their international counterparts will work in a comfortable shirtsleeve environment. This state-of-the-art workplace will support the most sophisticated research in weightlessness for 10 years or more. Columbus is a general-purpose laboratory, accommodating astronauts and experiments studying life sciences, materials processes, technology development, fluid sciences, fundamental physics and other disciplines.

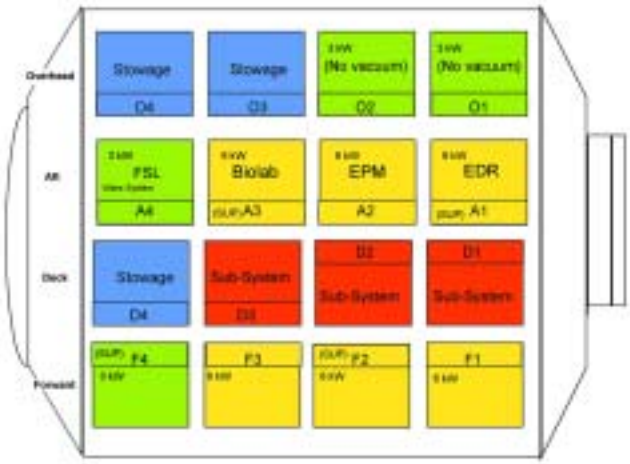
In October 1995, the ESA Ministerial Council meeting in Toulouse approved the programme 'European Participation in the International Space Station Alpha' – 10 years after the authorisation of studies and Phase-B work by the Ministerial Council in Rome in 1985. During that period, a variety of space elements was studied in parallel with the Ariane-5 launcher and Hermes mini-shuttle programmes, which all led to integrated European scenarios that were clearly unaffordable. In late 1994, a series of dramatic cutbacks began, which underwent frequent iterations with ESA Member States and the ISS Partners. The process culminated in a package worth some €2.6 billion being approved in Toulouse, including what was then called the Columbus Orbital Facility (COF).

Soon after that Toulouse conference, a contract was signed with prime contractor Daimler Benz Aerospace (which then became DaimlerChrysler Aerospace or DASA, and now Astrium GmbH), in March 1996, at a fixed price of €658 million, the largest single contract ever awarded by the Agency at the time.

The completed primary structure at Alenia Spazio. The circular holes will carry pressure-relief valves.



Columbus will be attached to Node-2 on the Station's starboard leading edge. (ESA/D. Ducros) Below: Columbus rack positions. The final locations of ESA's multi-user facilities shown in A1-A4 have yet to be finalised.



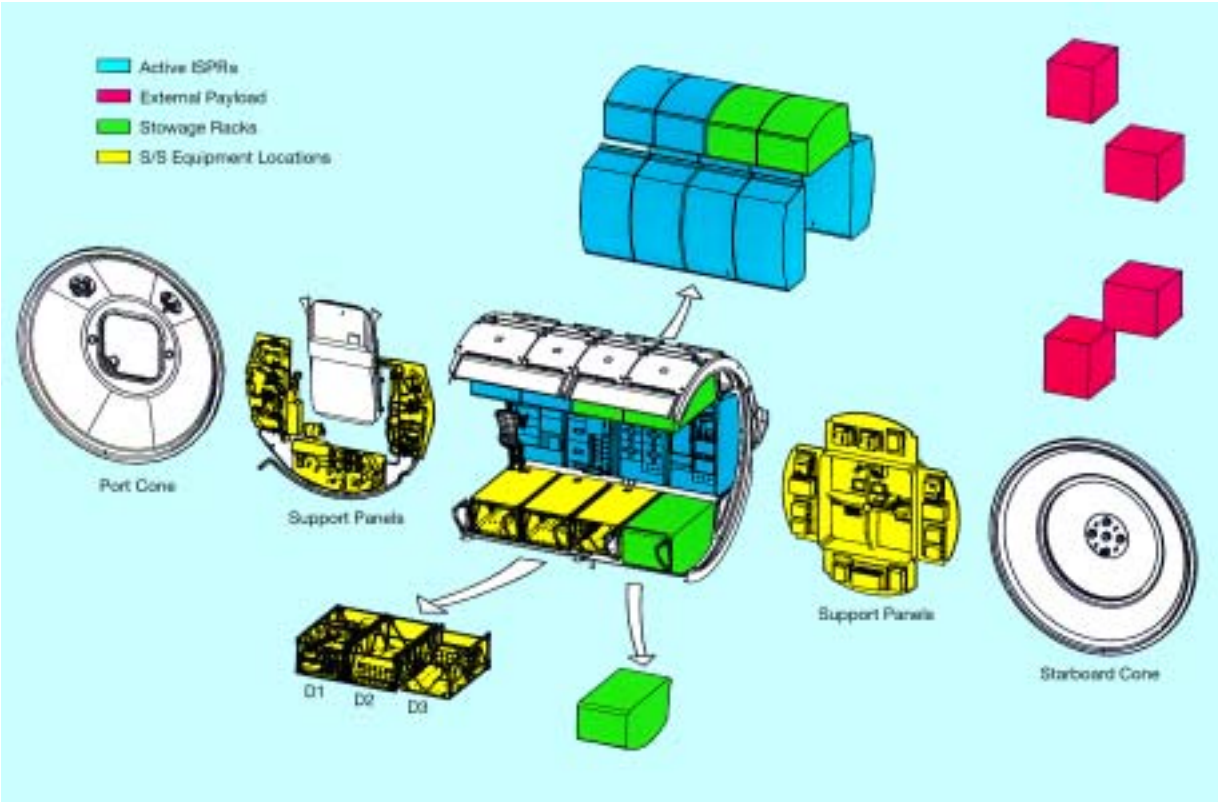
ESA's ISS Exploitation Programme for 2000-2013 was presented at the Ministerial Council in Brussels in May 1999, where the overall programme approach and the initial phase of activities were approved. The programme is being carried out in 5-year phases, each with a 3-year firm commitment and a 2-year provisional commitment. The programme covers the System Operations costs in Europe, the ESA share (8.3%) of the overall Station Common Operations costs and the European Utilisation-related costs. The average yearly cost over the whole period will be about €280 million (1998 rates).

Under an agreement with the Italian Space Agency (ASI), ESA provided the Columbus-derived ECLS for ASI's three Multi-Purpose Logistics Modules (MPLMs, first flown March 2001) in exchange for the Columbus primary structure, derived from that of MPLM. The estimated saving to each partner was €25 million.

Although it is the Station's smallest laboratory module, Columbus offers the same payload volume, power, data retrieval etc. as the others. This is achieved by careful use of the available volume and sometimes by compromising crew access and maintainability in favour of payload accommodation. A significant benefit of this cost-saving design is that Columbus can be launched already outfitted with 2500 kg of payload racks.

Columbus will be delivered to the ISS by the Space Shuttle Orbiter, carried in the spaceplane's cargo bay via its trunnions and keel fitting. A Station-common grapple fixture will allow the Space Station Remote Manipulator System (SSRMS) to lift it out of the Orbiter and transport it to its final destination on Node-2.

In exchange for NASA launching Columbus aboard the Space Shuttle, ESA is providing two of the Station's three Nodes, the Cryogenic Freezer and the Crew Refrigerator/Freezer.



ESA has entrusted responsibility for developing Nodes-2 and -3, which use the same structural concept as Columbus, to ASI. Once Columbus is operational, an ESA astronaut will work on average aboard the Station for 3 months every 8 months.

Inside Columbus, the International Standard Payload Racks (ISPRs) are arranged around the circumference of the cylindrical section, in a 1 *g* configuration, to provide a working environment for up to three astronauts. A total of 16 racks can be carried in four segments of four racks each. Three in the floor contain systems; D1 contains environmental equipment (water pumps, condensing heat exchanger, water separator, sensors); D2/D3 are devoted to avionics. Ten racks are fully outfitted with resources for payloads and three are for stowage. NASA has the rights to five of the payload racks. ISPRs have standardised interfaces that allow operation in any non-Russian ISS module.

Columbus will be launched with an internal payload of up to 2500 kg in five racks: ESA's Biolab, Fluid Science Lab (FSL), European Physiology Modules (EPM), European Drawer Rack (EDR) and a stowage rack. The other five will be delivered by MPLM, the only carrier that can deliver and return whole racks.

European rack payloads are connected to dedicated busses for data to be routed, via the ISS data transfer system, directly to the European Control Centre and thence to the individual users. For NASA rack payloads, interfaces to the NASA Data Management System are provided.

Columbus also offers an External Payload Facility (EPF), added in 1997 when it became clear that leasing US locations would be too expensive and that Japan's sites were full. External payloads will be installed on the four positions on-orbit using the SSRMS. EPF provides the same mechanical interfaces as NASA's standard Express Pallets for external payloads on the ISS Truss.

The External Payload Facility (EPF) on the starboard endcone. (ESA/D. Ducros)

The central area of the starboard cone carries system equipment that requires undisturbed crew viewing and handling access, such as video monitors and cameras, switching panels, audio terminals and fire extinguishers.

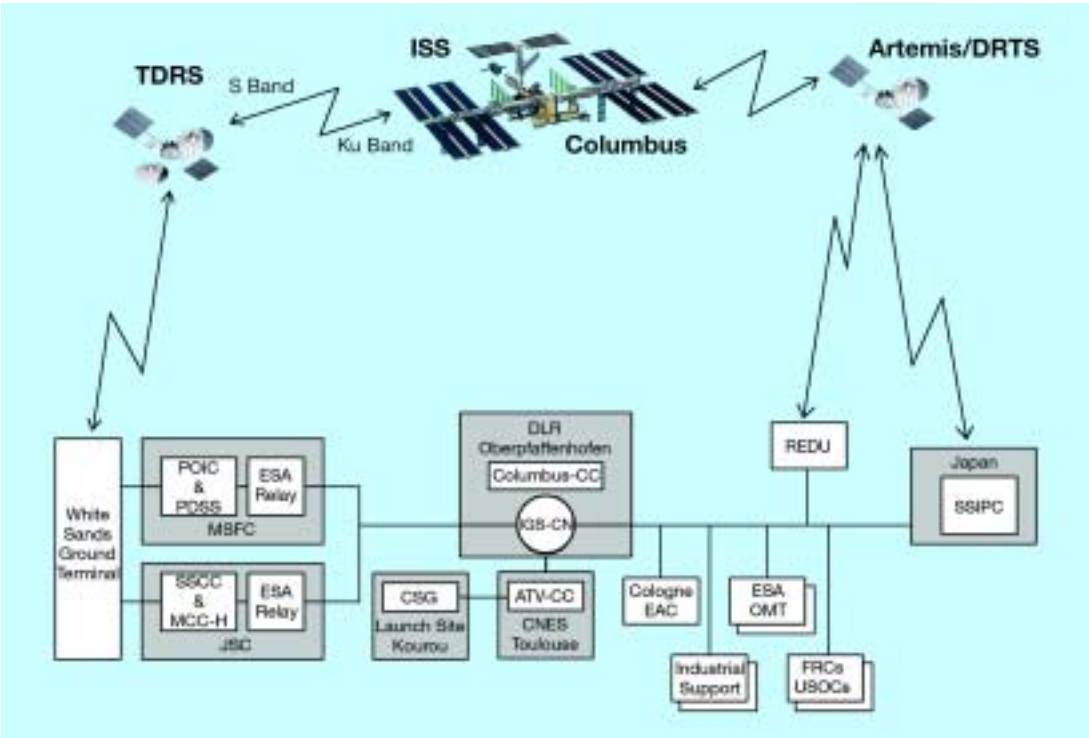
Although Columbus is not autonomous – so it has no power generation or attitude control, for example – it is a manned laboratory and therefore has an Environmental Control and Life Support Subsystem (ECLSS), largely in system rack D1.

Configuration: 10.2 t without research equipment, 12.7 t at launch, 20.1 t fully outfitted. 10.16 t payload (9.0/1.16 t internal/external). 4.2 m-dia cylinder closed with welded endcones. 3004 kg primary structure is 2219-aluminium alloy, 3.8 mm thick, increasing to 7 mm for the endcones. Length 6.2 m. Total volume 75 m^3, reducing to 50 m^3 with full rack load. Passive NASA-provided Common Berthing Mechanism (CBM) attaches it to active CBM of Node-2. Other endcone has 2.5 m-dia hole used on ground to install large items such as system racks. On completion, the hole is permanently closed off by a bolted plate.

Power: Columbus is sized to receive 20 kW total (13.5 kW for payloads). The Station's 120 Vdc system goes through the Columbus Power Distribution Unit and then, as 120 Vdc or 28 Vdc, to all payload racks, EPF locations, centre aisle standard utility panels and subsystems.

Thermal control: active control via a water loop serving all payload rack locations. Connected to the ISS centralised heat rejection system via interloop heat exchangers. In addition, there is an air/water heat exchanger to remove condensation from cabin air. The module is wrapped in goldised Kapton Multi Layer Insulation to minimise overall heat leaks. A system of electrical heaters combats the extreme cold possible at some Station attitudes. These heaters will be activated during launch and the transfer from the Shuttle bay, drawing on the SSRMS power supply.

Atmosphere: the cabin is ventilated by a continuous airflow entering via adjustable air diffusers on the upper stand-offs, sucked in from Node-2 by a fan centred below the hatch in the port cone. The air returns to the Node for refreshing and carbon dioxide



The communications infrastructure for Columbus. ATV-CC: Automated Transfer Vehicle Control Centre (Toulouse, F), EAC: European Astronaut Centre (ESA), FRC: Facility-Responsible Centre, IGS-CN: Interconnected Ground Subnet, JSC: Johnson Space Center (NASA), MCC-H: Mission Control Center-Houston, MSFC: Marshall Space Flight Center (NASA), PDSS: Payload Data Service System, POIC: Payload Operations Integration Center (NASA), SSCC: Space Station Control Center, SSIPC: Space Station Inter-Process Communication, USOC: User Support Operations Centre.

removal. The crew can control temperature (16-30°C) and humidity, and air content is monitored for contamination.

Communications: data rate up to 43 Mbit/s available (ESA has access right of 8.3%) through NASA Ku-band TDRS/White Sands system; also possible via Japan's JEM to Artemis to Redu ground station. System/payload control by Data Management System (DMS) using MIL-STD-1553 bus and Ethernet LAN; crew access via laptops. Columbus Control Centre is at DLR Oberpfaffenhofen (D).

MDPS: Columbus is protected by the 2 t Meteoroid and Debris Protection System of bumper panels. There are two general panel types: single (1.6 mm-thick Al 6061-T6), double (2.5 mm-thick Al 6061-T6 with a separate internal bumper of Nextel & Kevlar). The cylinder carries 48 panels: double on the side along the velocity vector (+Y), and single on the anti-velocity face (–Y). The port cone has 16 singles; the starboard cone has 16 doubles plus a single on the central disc.

Columbus internal payload accommodation: payloads carried in 10 ISPRs supplied with services via Columbus. ISPR (2013 mm ht, 1046 mm width, 858 mm max depth, empty mass 99 kg) supports 704 kg in 1.2 m^3. 3 kW & 6 kW versions, located in six 6 kW & four 3 kW slots, with water cooling loop sized to match. 13.5 kW total to

Columbus will be launched with four multi-user units installed (from left): EPM, FSL, Biolab and EDR. (ESA/D. Ducros)

Columbus will be launched with four ESA research facilities, and a fifth (MSL) will be added later.

Biolab: biological experiments on micro-organisms, animal cells, tissue cultures, small plants and small invertebrates in zero gravity. This is an extension – as for so many other payloads – of pioneering work conducted on the Spacelab missions.

European Physiology Modules (EPM): body functions such as bone loss, circulation, respiration, organ and immune system behaviour, and their comparison with 1 *g* performance to determine how the results can be applied to Earth-bound atrophy and age-related problems.

Fluid Science Laboratory (FSL): the complex behaviour of fluids, the coupling between heat and mass transfer in fluids, along with research into combustion phenomena that should lead to improvements in energy production, propulsion efficiency and environmental issues.

Material Science Laboratory (MSL, to be delivered later): solidification physics, crystal growth with semiconductors, measurement of thermophysical properties and the physics of liquid states. For example, crystal growth processes aimed at improving ground-based production methods can be studied. In metal physics, the influences of magnetic fields on microstructure can be determined. Microstructure control during solidification could lead to new materials with industrial applications.

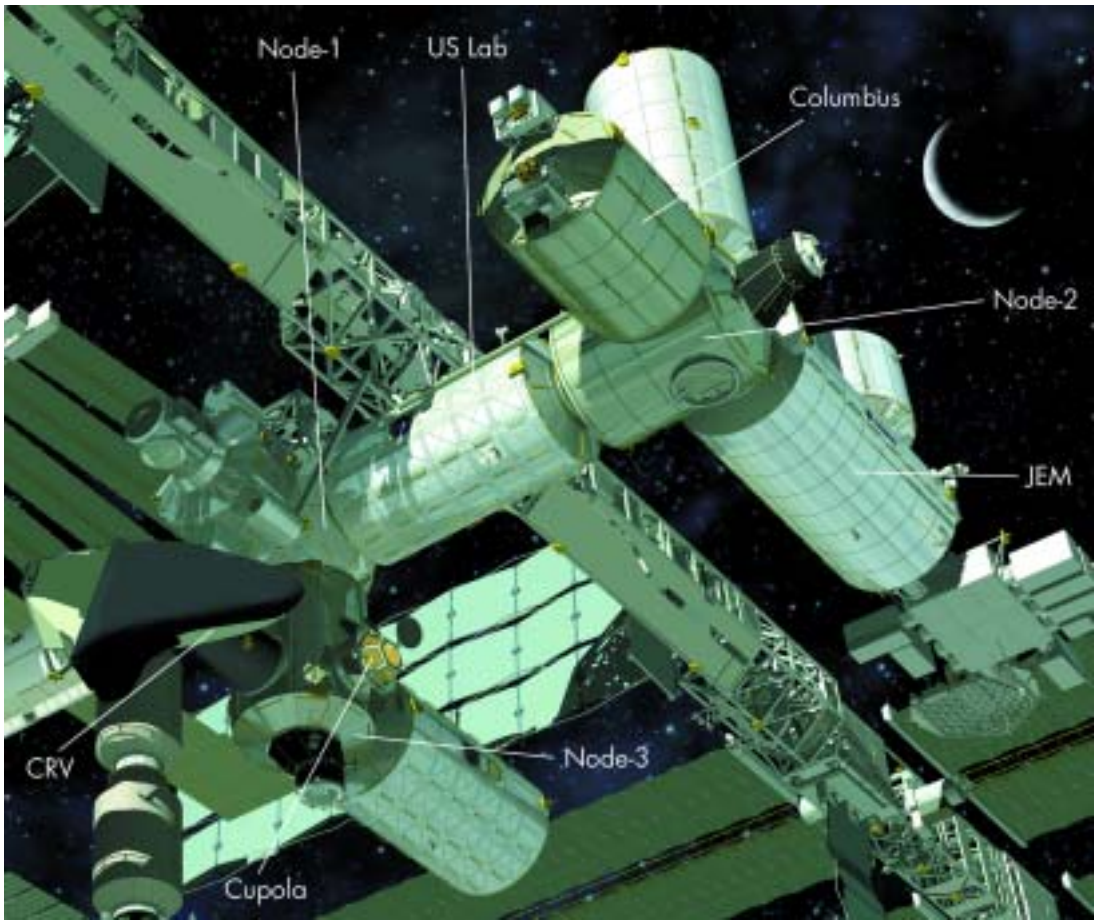
The first set of external payloads is: *Atomic Clock Ensemble in Space* (ACES), providing an ultra-accurate global time-scale, supporting precise evaluations of relativity; *Expose*, mounted on the Coarse Pointing Device (CPD), for long-term studies of microbes in artificial meteorites and different ecosystems; *Sport*, to measure polarisation of sky diffuse background at 20-90 GHz; *Solar* (also CPD), to measure the Sun's total and spectral irradiance; *European Technology Exposure Facility* (EuTEF), a wide range of on-orbit technology investigations.

payloads. GN2 supply, vacuum (except rack positions O2/O1), 32 Mbit/s (Columbus max 43 Mbit/s), video system (A4 only), MIL-STD-1553 Columbus & Destiny payload bus & LAN. Payloads also carried in centre aisle, which provides only data & power (500 W) links.

EPF Accommodation: 4 positions each offer payload envelope of 981x1194 mm, 1393 mm ht, 227 kg, 2x1.25 kW @ 120 Vdc, 32 Mbit/s, interface to Columbus/Destiny payload bus & LAN. No thermal control GN2, venting. Payload carries integrated standard Express Pallet Adapter (EPA) on active Flight Releasable Attachment Mechanism (FRAM). SSRMS positions payload on EPF's passive FRAM.

Nodes-2 & -3

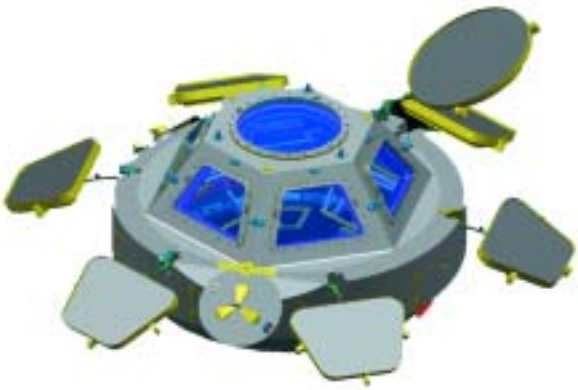
Nodes-2 & 3 will provide important on-orbit resources for operating other ISS elements. In particular, Node-3 will provide water processing and oxygen generation for the US segment, avoiding sole dependence on the Russian segment. Node-2 will be delivered to the Kennedy Space Center in September 2002, and launched in November 2003. Node-3 delivery is scheduled for July 2003, and its launch July 2005. The Nodes have the same basic geometry of a



Node-2 internal configuration. (Alenia Spazio)

Node-3 internal configuration.(Alenia Spazio)

Cupola will provide a clear view of robot arm operations.



Node-2's welded primary structure at Alenia Spazio, Turin.

cylindrical pressure shell capped by two end-cones with axial ports. The cylinder is a 2-bay section for housing eight racks plus a section with four radial ports.

The initial NASA concept design for Nodes-2/3 was the same as that of Node-1. However, NASA wanted longer Nodes from Europe. Stretching provided additional locations for stowage. Node-3 was a Node-2 copy for future Station use. NASA then decided to make the stowage area configurable for Crew Quarters, so that Node-2 could provide early Station habitation, and most of the former US Habitation module functions such as air revitalisation and water processing were moved into Node-3. Eventually, Node-3 was configured with resources for other attached elements: Cupola, CRV and a future Habitation module, in addition to providing redundant ports with growth utilities for docking of MPLMs, Shuttle or another laboratory module.

Node-2 Major Capabilities

- regulation and distribution of power to elements and Node equipment (sized for 56 kW);
- active thermal control of coolant water for heat rejection from internal Node equipment and from attached elements;
- temperature, humidity and revitalisation control of cabin air and air exchanged with attached elements;
- distribution lines for cabin air sampling, oxygen, nitrogen, waste water and fuel cell water;
- data acquisition and processing to support power distribution, thermal control and environmental control functions inside the Node, as well as data exchange between the US Lab and Node-attached elements;
- audio and video links.

Node-3 Major Capabilities

Featuring the same basic Node-2 capabilities, Node-3 manages less power but adds:

- on-orbit air pressure and composition control, including carbon dioxide removal;
- oxygen generation, a dedicated rack also scarred for future water generation;
- waste and hygiene compartment;
- urine and water processing;
- controlled venting of byproducts from environmental control;
- drinking water distribution;
- audio and video recording;
- on-orbit reconfiguration of utilities provided to Cupola, MPLM and TransHab.

Each Node is 7.19 m long overall and 4.48 m in diameter. Node-2 carries four avionics racks and four rack locations for either stowage or crew quarters. Node-3 has two avionics racks, four for environmental control and one Waste & Hygiene Compartment packaged in two rack locations. Externally, the layout includes almost 100 MDPS panels with thermal blankets underneath, to minimise heat flux across the shell and to protect against meteoroids and debris. Heat exchangers between the external panels and the pressure shell reject heat from Node internal equipment and attached modules.

Node-2 will be attached in front of the US Lab, with its longitudinal axis along the Station's velocity vector. The forward port supports Shuttle docking, via a Pressurized Mating Adapter (PMA). The starboard side provides resources for Columbus, and the port side for JEM. At the zenith position, Node-2 will initially accommodate Japan's Experimental Logistics Module-Pressurized Section (ELM-PS), before JEM appears, and later the Centrifuge Accommodation Module (CAM). Finally, the nadir port will allow temporary docking of MPLM or Japan's HII Transfer Vehicle (HTV).

When Node-2 is delivered to the Station, its aft port will be docked first to Node-1's port side so that Shuttles can continue docking with the US Lab's forward port. The Station's arm will then move it to the final position.

Node-3 will be attached to Node-1's nadir, with its radial ports closer to Earth. To starboard, Node-3 accommodates the CRV, while the port side is reserved for a future Habitation module. The forward position includes utilities for berthing the Cupola and is also a backup location for the MPLM. The aft port can be used for temporary parking of Cupola. Nadir offers a redundant location for Shuttle docking, via a PMA.

Galileo

Planned achievements: first European global navigation satellite system; civil position accuracy to 5 m
Launch date: first planned for 2004
Mission end: each satellite will have a nominal lifetime of 15 years
Launch vehicle/site: operationally in clusters of 8 on Ariane-5ECB from Kourou, French Guiana, replacements by vehicles such as Soyuz-Fregat
Launch mass: about 650 kg
Orbit: 24 000 km circular, 56°, in 3 orbital planes
Principal contractors: to be selected (expected early 2002). Development & Validation Phase 2001-2005 (Preliminary System Design Review March 2002; Validation Review late 2005); Deployment Phase 2006-2007; Operations Phase beginning 2008

For the first time, the Agency has taken a lead role in the navigation segment. ESA and the European Commission have joined forces to design and develop Europe's own satellite navigation system, Galileo. Whereas the US GPS and Russian Glonass systems were developed for military purposes, the civil Galileo will offer a guaranteed service, allowing Europe to develop its own integrated transport system. It will also allow the European economy to benefit from the enormous growth expected in value-added services and equipment for navigation systems.

Europe's first venture into satellite navigation is EGNOS (European Geostationary Navigation Overlay Service), a system to improve the reliability of GPS and Glonass to the point where they can be used for safety-critical applications, such as landing aircraft and navigating ships through narrow channels. ESA engineers first developed plans for a GPS and Glonass augmentation system in the late 1980s. Working in close cooperation with the EC and the European Organisation for the Safety of Air Navigation (Eurocontrol), the Agency later adopted the plans as the EGNOS programme. When EGNOS becomes operational in early 2004 using payloads on Artemis and the Inmarsat-3 satellites, it will be Europe's contribution to the first stage of the Global Navigation Satellite System (GNSS-1), complementing similar enhancements in the US and Japan.

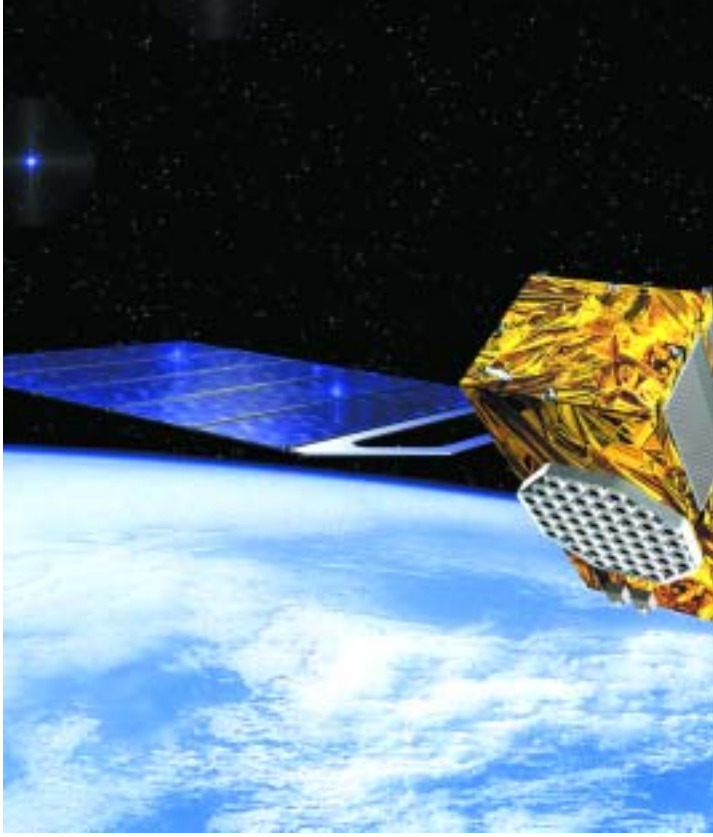
In addition, the European Union recognised the need for its own independent global satellite navigation system. Consultations began in 1994 and 4 years later plans for a fully European system were

drawn up. Early in 1999, the EC announced Galileo. It will be interoperable with GPS and Glonass, so that a user can take a position with the same receiver from any of the satellites in any system. By offering dual frequencies as standard, however, Galileo will deliver positioning accuracy down to 5 m, which is unprecedented for a public system. It will also guarantee availability of the service under all but the most extreme circumstances and will inform users within 6 s of a failure of any satellite. This will make it suitable for safety-critical applications.

The fully-fledged service will be operating by 2008 when 30 Galileo satellites are in position in circular orbits 24 000 km above the Earth. The first will be launched in 2004 and by 2006 sufficient should be in place to begin an initial service. The orbits will be inclined at 56° to the equator, giving good coverage at all latitudes. 27 satellites will be operational and three will be active spares, ensuring that the loss of one has no discernible effect on the user. Ground stations spread around the globe will monitor the satellites' positions and the accuracies of their onboard clocks. The stations will be connected to central control facilities in Europe via a dedicated network. The control facilities will monitor and control the constellation and compute navigation messages to transmit to the satellites via the ground stations. The control facilities will also keep service providers, such as providers of traffic management services, informed about the operating status of the satellites.

ESA approved the initial studies in May 1999 at its Ministerial Council Meeting in Brussels; the EC decided on its own go-ahead in June 1999. The EC is responsible for the political dimension: it is undertaking studies into the overall system architecture, the economic benefits and the needs of users. ESA defined the Galileo space and ground segments under its GalileoSat programme. ESA placed contracts with European industry to develop critical technologies, such as navigation signal generators, power amplifiers, antennas and highly accurate atomic clocks, and to provide tools to simulate the performance of the whole constellation. The studies supported by the EC are feeding into the design of the Galileo constellation and ground segment as well as the political decision-making process.

Europe's traditional space industry undertook Galileo definition studies from November 1999 to February



2001 under two contracts financed separately by the EC and ESA. Industries not usually associated with space, such as mobile phone manufacturers and service providers, are, in addition to their involvement in the EC-funded definition study, undertaking their own studies of services and applications.

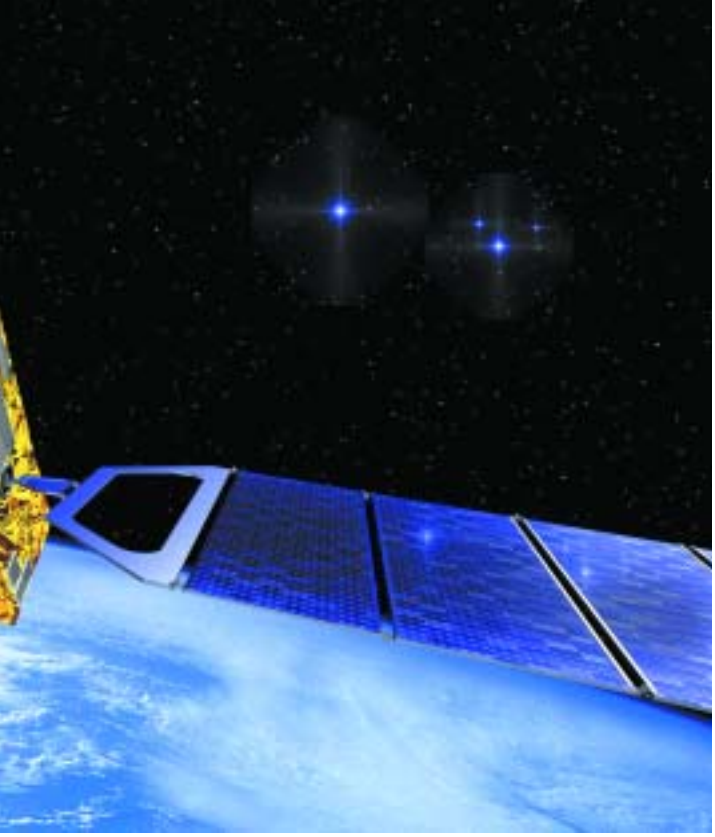
The EC, ESA and private industry are expected to meet the €3250 million estimated cost of Galileo through a public/private partnership (PPP). The nature of the PPP has yet to be worked out and will depend partly on the outcome of studies and trials to determine the nature and size of the revenue stream that Galileo is expected to deliver to industry.

Early studies suggest that Galileo will repay its initial investment handsomely, estimating that equipment sales and value-added services will earn an extra €90 billion over 20 years. More recent studies yielded higher estimates by considering potential earnings from value-added services that combine Galileo positioning with other services provided by the new generation of mobile phones, such as internet services. So far, the EC and ESA have agreed a common action plan, but have financed the industrial definition studies and critical technology developments separately. Funding on the EC side has come from the European Union's 5th Framework programme of research and development and on the ESA side from the Agency's GalileoSat definition programme (November 1999 to February 2001, costing €40 million, including technology development). Different arrangements, however, will be in place for the development phase when it begins at the end of 2001.

The development phase can be divided into three, each of which could operate under different financial arrangements. The first stage (development and in-orbit validation) will cost about €1.1 billion, financed equally by ESA and the EU from public money. It aims to have in orbit by the end of 2005 a handful of satellites for validating the Galileo system.

At its meeting on 30 January 2001, ESA's Navigation Programme Board approved the release of funding for the Galileo Phase-B2 study, the mission consolidation studies and the support studies on the Galileo services and PPP consolidation to begin. ESA plans to release the second tranche (€497 million) before the end of 2001.

On the EU side, the Transport Ministers on 5 April 2001 approved the release of €100 million to start development. The ministers will decide on the release of a further €450 million in December 2001, when they will also approve the setting up



of an entity to manage the programme. Moreover, they agreed to take the formal decision by the end of 2003 on the deployment of the full constellation.

The €2.1 billion cost of the second (deployment) phase will be met from a mixture of public and private sources. ESA and the EU are expected to share the public slice equally. During this phase, which will end in 2007 when all the satellites are launched, industry and service providers will be able to develop commercial opportunities.

The third (operations) phase, starting after 2007, will be financed by the private sector. By this time, the system will be fully operational and available for a wide variety of commercial and public service users.

The total cost for the design, development, in-orbit validation and deployment of the first full constellation, including the ground segment, EGNOS integration and application developments is €3250 million. The annual operating costs for EGNOS and Galileo are estimated at €25 million and €220 million, respectively.

Navigation payload: the navigation signals are modulated with 500-1000 bit/s data messages received from ground stations through the TT&C subsystem and stored, formatted and encoded onboard. Galileo will use up to four L-band carriers. A highly stable onboard reference frequency of 10.23 MHz is generated from rubidium atomic frequency standards and passive hydrogen masers operating in hot redundant, parallel configuration. Solid-state amplifiers generate some 50 W output per signal carrier. The navigation antenna uses twin beam-forming networks (one for each band) and an array of radiating elements to provide global coverage with a single beam. High data rates maximise the potential for value-added services such as weather alerts, accident warnings, traffic information and map updates. The use of 'pilot' signals (ranging codes with no data messages) is being studied for improving navigation signal acquisition under adverse receiving conditions.

Search & Rescue (SAR) payload: the SAR payload, being defined in cooperation with COSPAS-SARSAT, receives signals from standard 406 MHz distress beacons through a dedicated antenna. The signals are amplified and transmitted at 1544 MHz to SAR Control Centres using the navigation antenna. Acknowledgement messages are relayed back to the beacon by integrating them in the navigation data stream.

ERA

Planned achievements: first European robot arm in space
Launch date: no earlier than 2005
Mission end: 10 years
Launch vehicle/site: Space Shuttle from Kennedy Space Center, Florida, US
Launch mass: 630 kg
Orbit: attached to International Space Station (altitude about 400 km)
Principal contractors: Fokker Space (prime), SABCA (joint subsystem), Netherlands National Aerospace Laboratory (MPTE)

ESA's European Robotic Arm (ERA) will play an important role in assembling and servicing the International Space Station (ISS). It is a cooperative venture between ESA and Rosaviakosmos, the Russian space agency. The project began as the Hermes Robot Arm (HERA) for the Hermes mini-shuttle. When Hermes was discontinued, studies for the arm to fly on Russia's proposed Mir-2 second generation space station were conducted between Fokker and RSC-Energia. These studies highlighted the value of a robotic manipulator in reducing the time needed for expensive manned activities in a hazardous environment.

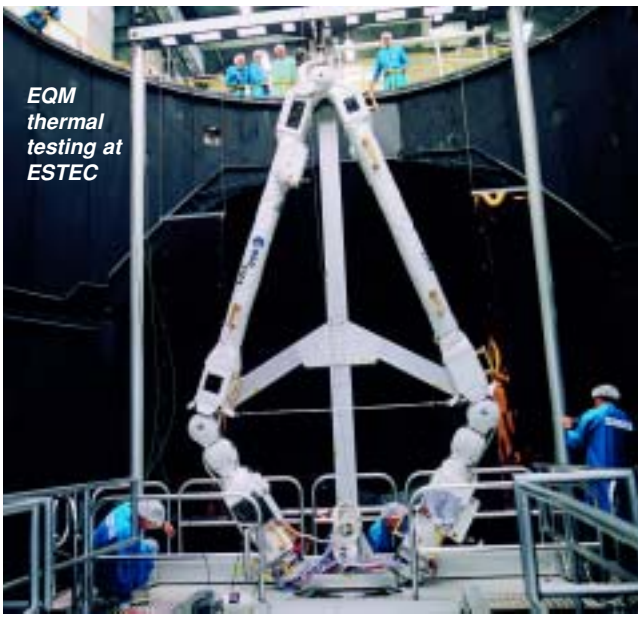
Following Russia joining the ISS programme in 1993, the arm was formally incorporated into the station's Russian Segment in July 1996. It will be mounted on Russia's Science and Power Platform (SPP), launched together on the US Shuttle. Among its first tasks is installing the SPP's solar arrays. ESA will be ready to deliver the arm in 2002, but launch will not be before 2005 because Russian funding problems have postponed work on the SPP.

ERA is functionally symmetrical, with each end sporting an 'End-Effector' that works either as a hand or as a base from which the arm can operate. There are seven joints (in order: roll, yaw, pitch, pitch, pitch, yaw, roll), of which six can operate at any one time. This configuration allows ERA to relocate itself on to different basepoints on the SPP, using a camera on the End-Effector to locate a basepoint accurately.

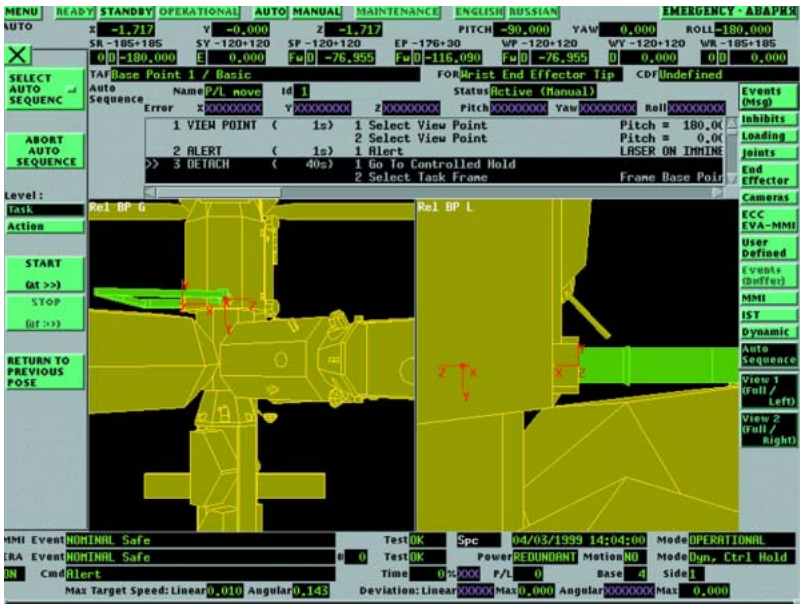
Each End-Effector includes a special fixture to grapple and carry payloads of up to 8 t. Through this fixture, the arm can supply power and exchange

ERA Characteristics

Total length:	11.4 m
Reach:	10 m
Mass:	630kg
Payload positioning accuracy:	5 mm
Payload capability:	8000 kg
Maximum tip speed:	20 cm/s
Stiffness (fully stretched):	>0.4 N/mm
Operating power:	475 W avg
Arm booms:	carbon fibre, 25 cm dia



EQM thermal testing at ESTEC



Cosmonauts will control ERA via IMMI's computer-generated views.

data and video signals. In addition, it features a built-in Integrated Service Tool that can activate small mechanisms in the grappled payload. Equipped with a foot restraint, ERA can carry spacewalking cosmonauts, providing them with a platform as they work in weightlessness.

Unusually, ERA's main computer is mounted on the arm itself, providing a simpler control interface. It can be controlled from inside the Station, using the Internal Man-Machine Interface (IMMI) at the Zvezda module's central control post. IMMI's synoptic display provides computer-generated detailed and overview pictures of ERA and its surroundings. In addition, monitors display video images from ERA and the Station's external cameras. ERA can also be operated by a spacewalker via the External Man-Machine Interface (EMMI) control panel. Commands are entered via toggle switches, while LEDs display arm status and operations progress. Both approaches offer an automatic mode (using prepared mission plans), semi-automatic mode (standard autosequences) and manual mode (controlling the individual joints).

Cosmonauts will train on the Mission Planning and Training Equipment (MPTE), a realistic simulator of the arm and its environment. At its core is a fully flight-representative ERA onboard computer using the full flight software. The MPTE, including mock-ups of IMMI and EMMI and using their flight software, will be located in Russia at RSC Energia and the Gagarin Cosmonaut Training Centre, and at ESTEC in the ERA Support Centre. The Russian MPTEs will be used to train ERA's cosmonaut operators and generate ERA flight procedures for transmission to the Space Station. The MPTE can also provide on-line support during ERA operations, and play back and analyse actual operations. ESTEC's MPTE will support these activities.

Crews aboard the Station will maintain their expertise via a special 'Refresher Trainer'. This is a reduced ERA simulation built into a standalone laptop. They can practise an entire ERA operation before it is done for real.

There are two main development models. The Engineering/Qualification Model (EQM) was tested in November 1999 in the Large Space Simulator at ESTEC to check its thermal balance. The Flight Model underwent EMC and vibration testing at ESTEC at the end of 2000. The final acceptance review is planned for 1Q 2002. Under the July 1996 agreement, Russia takes ownership of the flight hardware once it is launched, in exchange for which ESA will participate in robotics activities aboard the Station and Agency astronauts will be trained at the Gagarin centre.

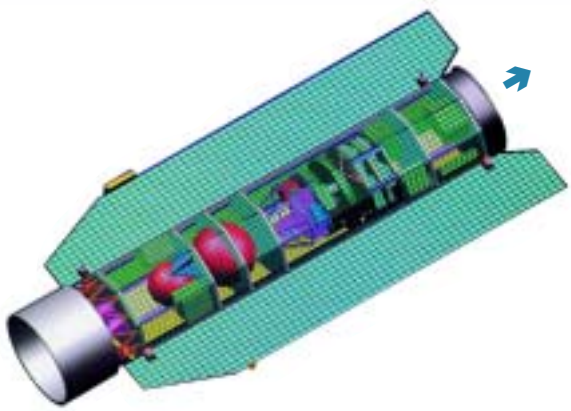
GOCE

Planned achievements: major improvement in measurement of Earth's gravity field and geoid; first use of gradiometry in space
Launch date: planned for October 2005
Mission end: nominal 20 months, extended 30 months
Launch vehicle/site: to be selected
Launch mass: 980 kg (194 kg payload)
Orbit: planned 250 km circular, 96.5° Sun-synchronous
Principal contractors: Alenia Spazio (prime), Astrium GmbH (bus), Alcatel Space Industries (gradiometer), ONERA (gradiometer accelerometers); Phase-A June 1998 - June 1999; Phase-B December 2000 - December 2001; Phase-C/D January 2002 - July 2005

The Gravity Field and Steady-State Ocean Circulation Mission (GOCE) will measure the Earth's gravity field and geoid with unprecedented accuracy and resolution using a 3-axis gradiometer. This will improve our understanding of the Earth's internal structure and provide a much better reference for ocean and climate studies, including sea-level changes and ice-sheet dynamics.

GOCE was selected in 1999 as the first Earth Explorer Core mission in the Living Planet programme. Four candidate Core missions were selected in November 1996 for 12-month Phase-A studies, completed in June 1999. GOCE and ADM were selected in November 1999 in order of priority. Alenia Spazio was selected as GOCE prime contractor in January 2001.

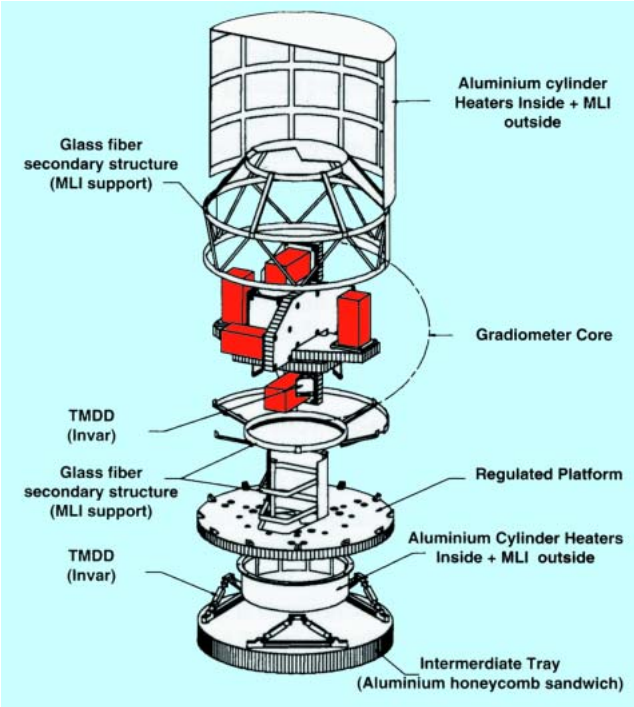
The Earth's gravity field is the fundamental physical force for every dynamic process on the surface and below. Since the beginning of the space age, mapping the global gravity field has been seen as a high-priority task. The first era lasted for about 40 years, with Europe playing a leading role. The research was characterised by a combination of satellite geodetic (optical, laser, Doppler) and terrestrial gravity methods. It produced significantly improved measurements at the scale of several thousand km. The new era will see dedicated satellite missions determining the global gravity field with consistent accuracy and higher resolution. GOCE puts European science and technology in a leading position. The GOCE-derived gravity field and associated geoid will be the dominant reference for the following decades of geophysical research.



GOCE will map Earth's gravity field with unprecedented accuracy. The gradiometer package is in the centre. GOCE flies along the line of the main axis, towards top right. The paired ion thrusters for combating air drag are at bottom left (purple). The red spheres are propellant tanks.

GOCE's gradiometer will for the first time measure gravity gradients in all directions. It is specifically designed for the stationary gravity field – measuring the geoid and gravity anomalies with high accuracy (1 cm and 1 mgal, respectively) and high spatial resolution (100 km). In particular, it will provide:

GOCE's gradiometer uses six paired proof masses (red) to measure variations in the gravitational field. MLI: Multi-Layer Insulation. TMDD: Thermal and Mechanical Decoupling Devices.



Why Measure the Gravity Field?

The gravity field plays a dual role in Earth sciences. Gravity anomalies reflect mass variations inside the Earth, offering a rare window on the interior. The geoid is the shape of an ideal global ocean at rest, and it is used as the reference surface for mapping all topographic features, whether they are on land, ice or ocean. The geoid's shape depends solely on Earth's gravity field, so its accuracy benefits from improved gravity mapping. Measuring sea-level changes, ocean circulation and ice movements, for example, need an accurate geoid as a starting point. Heat and mass transport by oceans are important elements of climate change, but they are still poorly known and await measurement of ocean surface circulation.

- new understanding of the physics of the Earth's interior such as geodynamics associated with the lithosphere, mantle composition and flow, uplifting and subduction processes,
- a precise estimate of the marine geoid for the first time, which is needed in combination with satellite altimetry for measuring ocean circulation and transport of mass,
- estimates of the thickness of the polar ice sheets through the combination of bedrock topography derived from space gravity and ice surface height measured by altimeter satellites.
- a high-accuracy global height reference system for datum point linking, which can serve as a reference surface for studying topographic processes, including the evolution of ice sheets and land topography.

Space gradiometry is the measurement of acceleration differences, ideally in all three dimensions, between separated proof masses inside a satellite. The differences reflect the various attracting masses of the Earth, ranging from mountains and valleys, via ocean ridges, subduction zones and mantle inhomogeneities down to the topography of the core-mantle-boundary. The technique can resolve all these features imprinted in the gravity field. Non-gravitational forces on the satellite, such as air drag, affect all the accelerometers in the same manner and so are cancelled out by looking at the *differences* in accelerations. The satellite's rotation does affect the measured differences, but can be separated from the gravitational signal in the analysis. The gravitational signal is stronger closer to Earth, so an orbit as low as possible is chosen, although that then requires thrusters to combat the air drag. GOCE's cross-section is as small as possible in order to minimise that drag.

The gradiometer measurements are supplemented by a GPS/Glonass receiver that can 'see' up to 12 satellites simultaneously. The gravity

The Benefits from GOCE

Geodesy

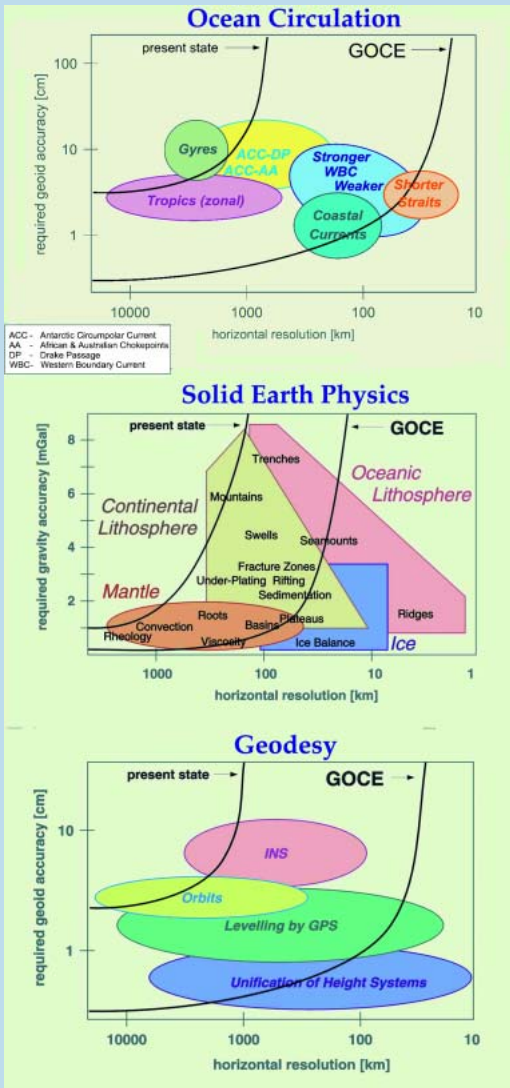
Geodesy is concerned with mapping the Earth's shape, to the benefit of all branches of the Earth sciences. Whereas positions on the Earth's surface can be measured purely geometrically, height determination requires knowledge of the gravity field. Geodetic levelling provides mm-precision over short distances, but has systematic distortions on a continental scale that severely limit the comparison and linking of height systems used in neighbouring countries or, for example, of tide gauges on distant coasts. Separation of land areas by sea inevitably leads to large discontinuities between height systems. GOCE data will serve to control or even replace traditional levelling methods, making feasible levelling with a global spaceborne reference system such as GPS and Galileo. This will help us towards worldwide unification of height systems, allowing, for example, comparison of the sea-level and its changes in the North Sea with those in the Mediterranean.

Absolute Ocean Circulation

With ocean topography measured by altimeter satellites using GOCE's geoid as the reference surface, almost all ocean current systems from the strongest (Gulf Stream, Kuroshio, Antarctic Circumpolar Current) through to weaker deep-ocean and coastal current systems will be determined in terms of location and amplitude. Uncertainties in mass and heat transport will be halved in the upper layers, with significant reductions throughout the ocean depths. Clear benefits are expected in high-resolution ocean forecasting.

Solid Earth

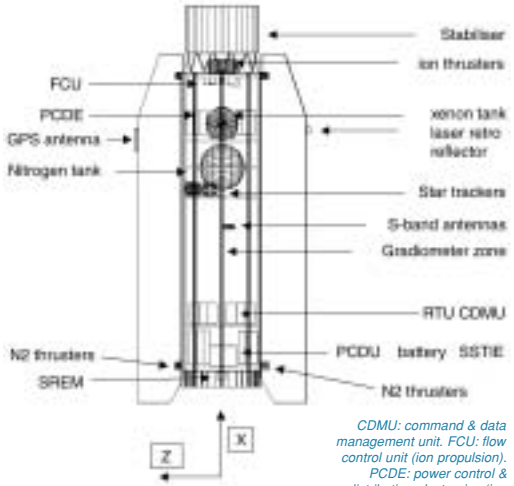
Detailed 3-D mapping of density variations in the lithosphere and upper mantle, derived from a combination of gravity, seismic tomography, lithospheric magnetic-anomaly information and topographic models, will allow accurate modelling of sedimentary basins, rifts, tectonic movement and sea/land vertical changes. It will contribute significantly to understanding sub-crustal earthquakes – a long-standing objective.



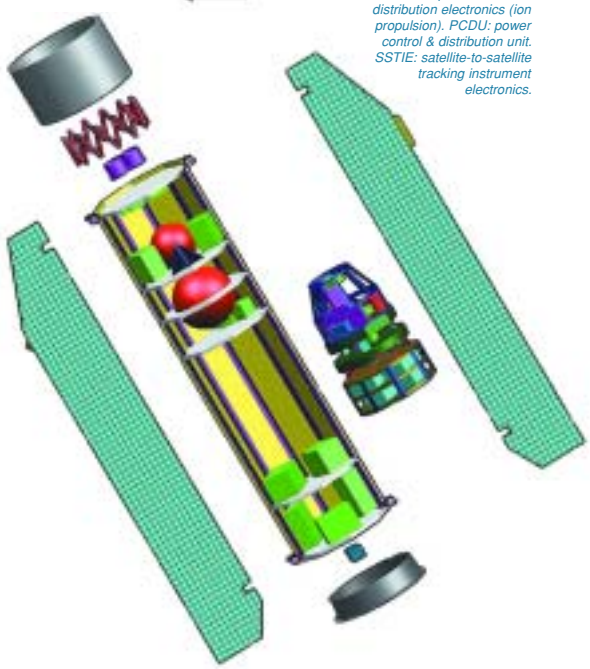
The accuracies necessary to resolve the noted phenomena and processes. The curves show current accuracies and what can be expected from GOCE. (INS: Inertial Navigation System – uncertainties in the geoid introduce errors in inertial navigation.)

Ice Sheets

GOCE will improve our knowledge of the bedrock landscape under the Greenland and Antarctic ice sheets, especially undulations at scales of 50-100 km. A precise geoid will be a major benefit to modern geodetic surveys of the ice sheets, while improved gravity maps in polar regions will help satellites to measure their orbits using altimeters.



CDMU: command & data management unit. FCU: flow control unit (ion propulsion). PCDE: power control & distribution electronics (ion propulsion). PCDU: power control & distribution unit. SSTIE: satellite-to-satellite tracking instrument electronics.



GOCE Payload
Gradiometer
The Electrostatic Gravity Gradiometer (EGG) is a set of six 3-axis capacitive accelerometers mounted in a diamond configuration in an ultra-stable carbon/carbon structure. Each accelerometer pair forms a 'gradiometer arm' 50 cm long, with the difference in gravitational pull measured between the two ends. Each accelerometer measures the voltage needed to hold the proof mass centred between electrodes, controlled by monitoring the capacitance between the mass and the cage. Three arms are mounted orthogonally: along-track, cross-track and vertically.
Laser Retroreflector (LRR)
As used on ERS and Envisat: 9 corner cubes in hemispherical configuration, Earth-facing for orbit determination by laser ranging.
SREM
ESA Standard Radiation Environment Monitor for the ionising radiation environment in the EGG's sensitivity range.
Satellite-to-Satellite Tracking (SST)
Position, speed and time data using GPS C/A signal and, optionally, Glonass.

field's long-wavelength effects on the orbit will be detected by this technique. Laser-ranging will independently monitor GOCE's orbit to cm-precision to validate the GPS/Glonass-based orbit.

Satellite configuration: bus is an octagonal prism 4 m long, 90 cm dia, of sandwich side panels connected by CFRP longerons. Total length 5.02 m; span 2.20 m across fixed solar wings. Small cross-section of 0.8 m² and symmetry minimises atmospheric perturbations. Six transverse platforms.

Attitude/orbit control: paired Xe ion thrusters operate continuously along the main axis to counteract atmospheric drag and torques. Thrust controllable 1-22 mN; 22 kg Xe. Attitude control proportional cold-gas or electric thrusters; thrust selectable 0-1 mN. GPS/Glonass receiver, gradiometer and star trackers provide attitude/orbit data.

Thermal: MLI, paint pattern, OSRs, heaters, thermistors. GOCE flies in Sun-synchronous orbit with one side always facing the Sun. High-dissipation units such as the battery and transponders are mounted on the 'cold' side.

Power system: >1.3 kW EOL from fixed 3-panel GaAs wings, supported by 19 Ah NiCd battery.

Communications: controlled from ESOC via Kiruna. 5 kbit/s data stored on 1 Gbit SSR for S-band downlinking to Kiruna at maximum 1 Mbit/s.

Vega

Achievements: cost-effective small launcher
Launch dates: planned debut December 2005
Launch site: Kourou, French Guiana
Launch mass: 132 t
Performance: optimised for LEO. 1500 kg into 700 km 90° polar, 800-1200 kg into 1200 km Sun-synchronous
Principal contractors: Vega: FiatAvio, CASA, Fokker, TNO-StorkContraves, CRISA, SABCA, Saab; P80: FiatAvio, Europropulsion, Snecma, TNO-Stork, Sabca

Vega's primary role is to fill a gap in Europe's line of launchers. While the market segment initially targeted was science satellites of 1000-1200 kg into LEO, new forecasts prompted a focus on polar-orbiting Earth observation satellites of 400-2500 kg. The launch service price will be below $20 million (15% lower than equivalent US vehicles), assisted by synergy with Ariane-5 production and operations and based on only 2-4 government and 1-2 commercial missions annually.

Vega began as a national Italian concept in the 1980s. BPD Difesa e Spazio in 1988 proposed a vehicle to the Italian space agency (ASI) to replace the retired US Scout launcher based around the Zefiro (Zephyr) motor developed from the company's Ariane expertise. The design was significantly reworked in 1994 towards the current configuration. Over the same period, CNES was studying a European Small Launcher drawing on Ariane-5 technology and facilities. Spain was also studying its own smaller Capricornio to operate from the Canary Islands.

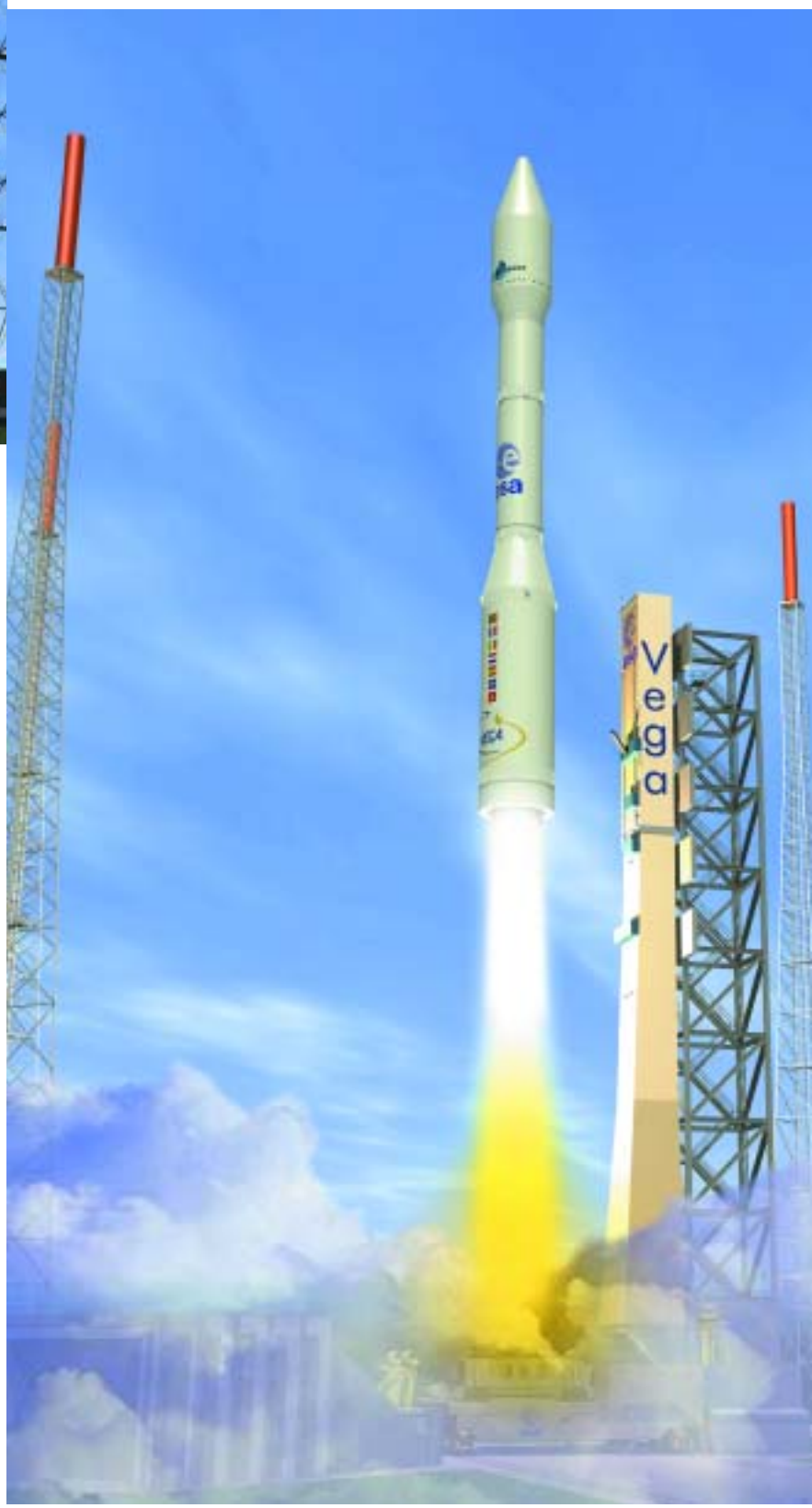
In February 1998, ASI proposed Vega as a European project. In April 1998, ESA's Council approved a Resolution authorising programme start in June; but this was only a limited declaration, approving the first step of pre-development activities, notably on solid-booster design. Step-1, running from June 1998 to September 1999, studied a Vega using a P85 first stage derived from Ariane-5's existing strap-on. At the October 1999 Council, France declined to support that approach. In November 2000, after a further trade-off between different vehicle configurations and options for the first and third stages, it was agreed to proceed with two strands: an advanced booster that could serve as both an improved Ariane-5 strap-on and as Vega's first stage, and the Vega programme itself.

The Vega Programme was approved by ESA's Ariane Programme Board on 27-28 November 2000, and the project officially started on 15 December 2000 when seven countries subscribed to the Declaration.

The separate P80 Solid Propulsion Stage Demonstrator programme will cost a total of €123 million (2000

What's in a Name?

Vega is the brightest star in the constellation of Lyra, and one of brightest in the northern sky. The name has never been used for a launch vehicle before - but it has come close. It was suggested in 1973 for the L3S design, but at the time it evoked a brand of beer. L3S, of course, instead took the name Ariane. Even further back, NASA planned the Atlas-Vega launcher for deep-space missions but the upper stage was cancelled in 1959.

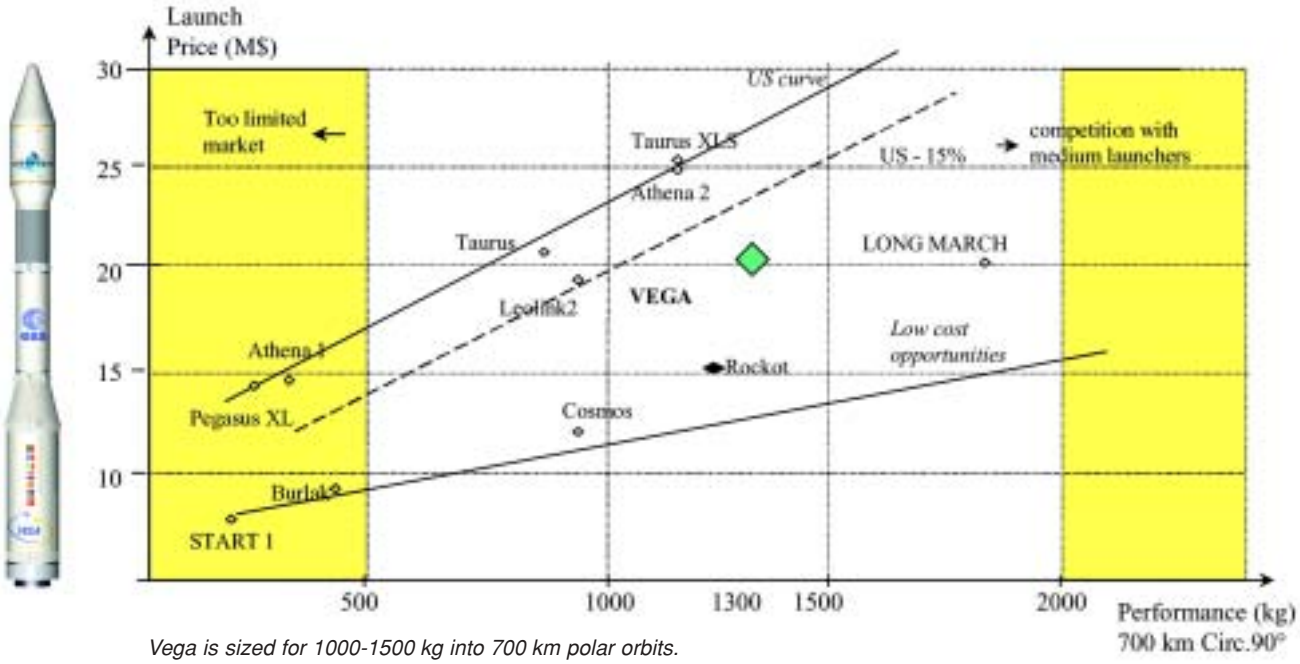


conditions), with €54 million from ESA, €63 million from Italy via the prime contractor and €6.6 million from Belgium via ESA's General Support & Technology Programme. The overall contributions are therefore (€ million): Belgium 6.6, France 45.1, Italy 68.6, Netherlands 2.7, Spain t.b.d.

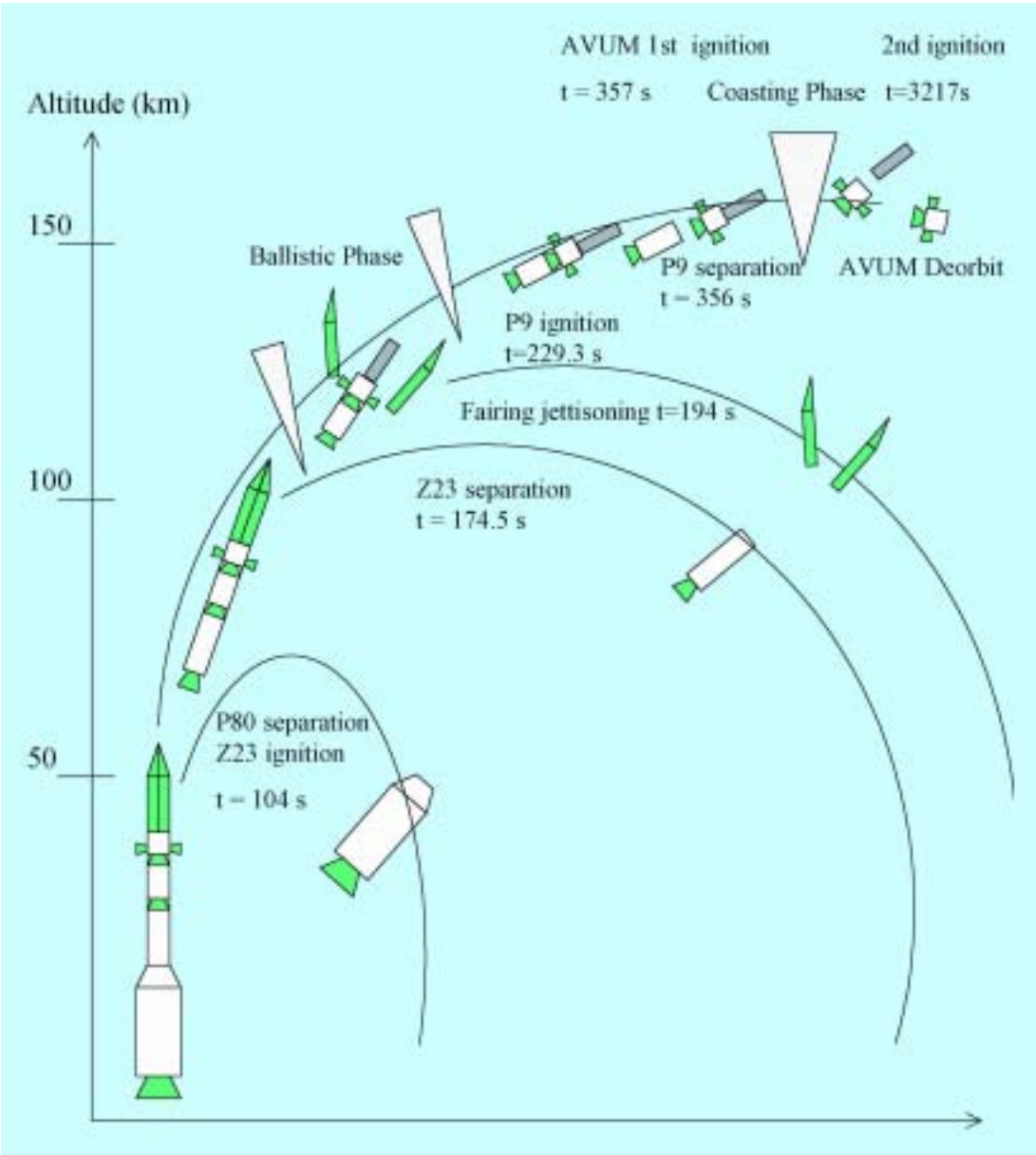
The ESA cost-to-completion for Vega is €335 million (1997 conditions), including the €44 million of Step-1. The national contributions (€ million) are: Belgium 5.63%, France 1.5% (Step 1 contribution), Italy 65%, Netherlands 2.75%, Spain 5%, Sweden 0.8%, Switzerland 1%.

Vega's PDR was held in June-July 2001, with the CDR planned for mid-2003. The qualification flight in December 1995 will be offered to customers at a reduced price. P80's PDR is planned for end-2001, the development firing test end-2004, CDR end-2004, Qualification Motor-1 firing early 2005 and QM-2 mid-2005.

Vega will be integrated in a new Bâtiment d'Intégration Vega (BIV) at Kourou; the final configuration of the ground installations is under study.



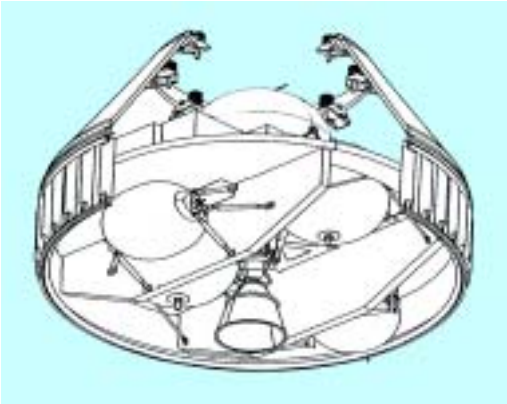
Vega is sized for 1000-1500 kg into 700 km polar orbits.



Vega Characteristics
Total length: 30.22 m
Principal diameter: 3.005 m
Launch mass: 132 t
Launch thrust: 2700 kN sea level
Capability: reference mission is 1500 kg into 700 km 90° orbit from Kourou. Injection accuracy: ±10 km altitude, ±0.1° inclination
Reliability goal: 0.98
Guidance: avionics mounted on AVUM, most derived from Ar-5. Stages-1/2 use Ar-5 guidance approach, stage-3/AVUM Ar-4.

Stage-1
Principal contractor: FiatAvio
Length: 12.18 m
Principal diameter: 3.005 m
Motor: P80, filament-wound graphite-epoxy casing, 84 t high-aluminium/low binder content, SI 280 s vac, 100 bar operating pressure, length 11.0 m, mass fraction 0.92
Thrust: 2500 kN avg vacuum
Burn time: 100 s
Steering: TVC by ±8° deflection of flexible nozzle joint by electromechanical actuators provides vehicle pitch/yaw control

Stage-2
Principal contractor: FiatAvio
Length: 7.5 m
Principal diameter: 1.90 m
Motor: Zefiro 23, filament-wound carbon-epoxy casing, 23 t HTPB 1614 16% aluminium, finocyl grain, SI 287 s vac, 95 bar maximum operating pressure, mass fraction 0.92, EPDM insulation. Scaled up from Zefiro 16 (length 7.3 m) tested 18 Jun 1998, 17 Jun 1999, 15 Dec 2000 (QM1), 2 more planned
Thrust: 900 kN avg vacuum
Burn time: 70 s
Steering: TVC by ±6.5° deflection of submerged flexible nozzle joint by electromechanical actuators provides vehicle pitch/yaw control, 3D carbon-carbon throat



AVUM carries Vega's control system and provides the final injection.

Stage-3
Principal contractor: FiatAvio
Length: 3.2 m (including 3.6 m interstage)
Principal diameter: 1.915 m
Motor: P9 derived from Zefiro 16, filament-wound carbon-epoxy casing, 9 t HTPB 1614 16% aluminium, finocyl grain, SI 294 s vac, 67 bar maximum operating pressure. mass fraction 0.925, EPDM insulation
Thrust: 220 kN avg vacuum
Burn time: 116 s
Steering: as stage-2

AVUM Attitude & Vernier Upper Module
AVUM provides the final injection accuracy, orbit circularisation, deorbit, roll control during stage-3 burn and 3-axis control during all coasts. Lower section is APM (AVUM Propulsion Module), upper is AAM (AVUM Avionics Module).
Principal contractor: FiatAvio
Length: 1.6 m
Principal diameter: 1.90 m
Propulsion: single 2000-2400 N NTO/UDMH (370 kg propellant) engine for delta-V, SI 315 s; 50 N GN2 thrusters for attitude control
Burn time: typically 200 s #1 + 170 s #2

Payload Fairing and Accommodation
Payloads are protected by a 2-piece fairing until it is jettisoned after about 200 s during the coast after stage-2 burn. Carbon skin on aluminium honeycomb. Total length 7.5 m, diameter 3.5 m; payload envelope 4.5 m high, 2.3 m diameter. Prime contractor Contraves.
Acceleration load (static): 5.5 *g* max longitudinal, 1 *g* lateral
Acoustic: max 140 dB overal

Metop

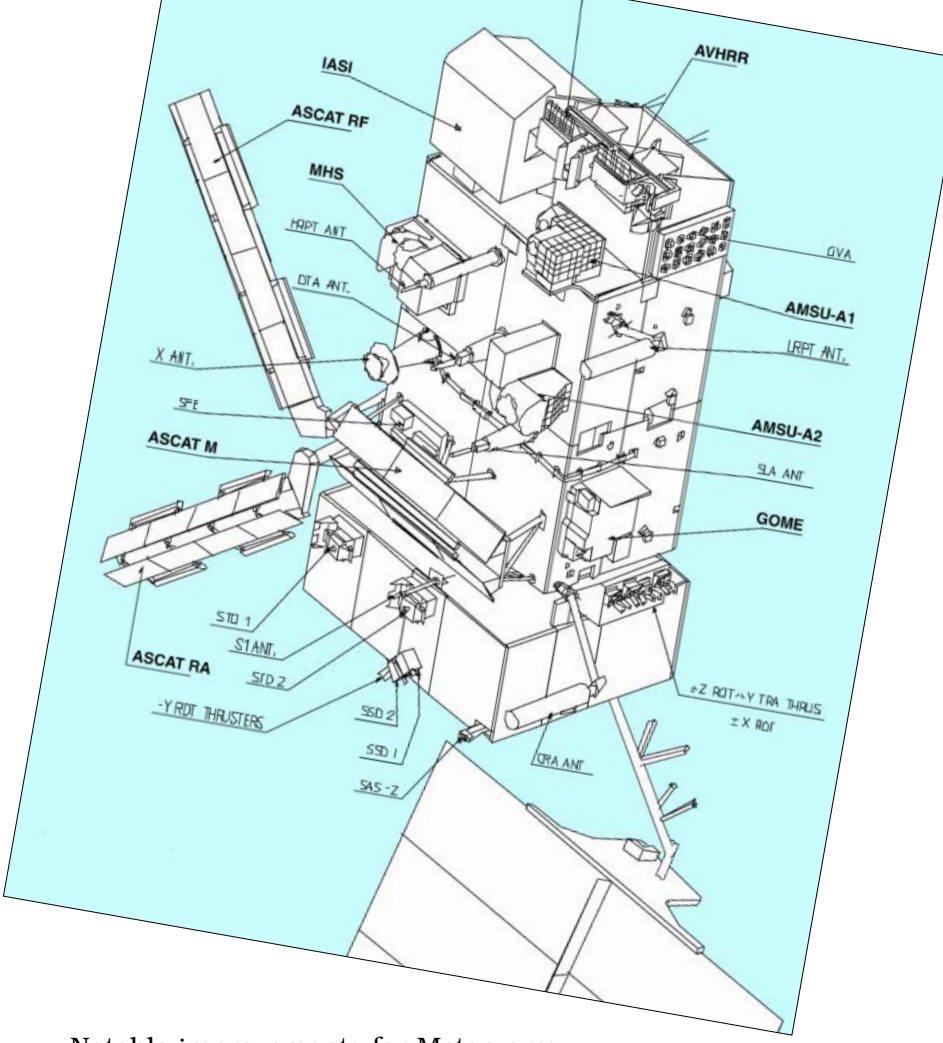
Planned achievements: first European meteorological satellite in polar orbit
Launch dates: Metop-1 planned for December 2005, Metop-2 2009, Metop-3 2013
Mission end: nominally after 5 years
Launch vehicle/site: Soyuz-ST from Baikonur Cosmodrome, Kazakhstan
Launch mass: 4175 kg
Orbit: planned 825 km circular, 98.7° Sun-synchronous (09:30 local time descending node), 5-day/71-rev repeat cycle
Principal contractors: Astrium SAS (prime, service module), Astrium GmbH (payload module, ASCAT, GRAS), Officine Galileo/Alenia Difesa (GOME-2), Fokker (solar generator); all other instruments are customer-provided

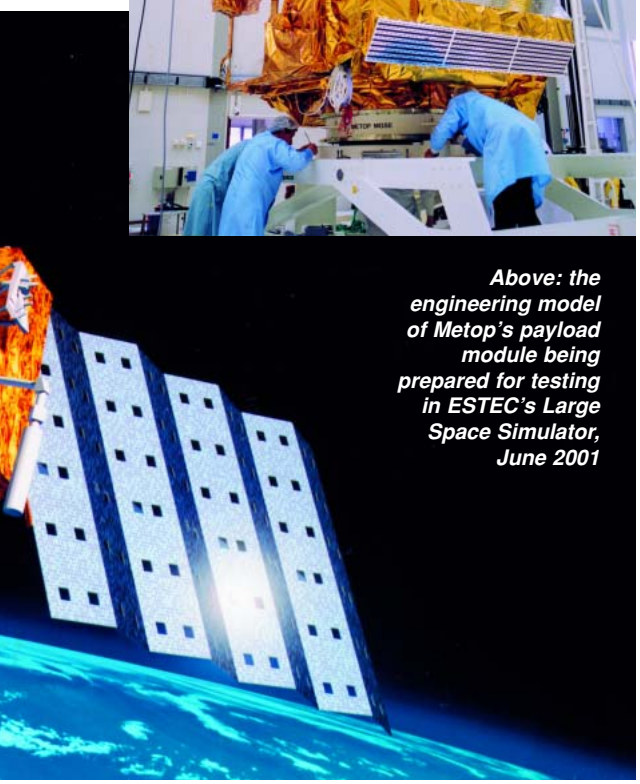
Metop will provide Europe's first meteorological satellites in polar orbit. They were originally part of a much larger satellite concept, called POEM, which was to have been the successor to ERS, based on the Columbus Polar Platform. This very large satellite would have carried the payloads of both Envisat and Metop and would have been serviceable in-orbit. At the ESA Ministerial Council in Granada, Spain in 1992, this approach was abandoned and Envisat and Metop were born. Metop is a joint undertaking by ESA and Eumetsat as part of the Eumetsat Polar System (EPS). In addition to the satellites, EPS comprises the ground segment, the launches and various infrastructure elements. ESA is funding 64% of Metop-1, while Eumetsat covers the rest and all of the follow-on satellites. The Metop-1 agreement between the two agencies was signed on 9 December 1999, at the same time as the industrial contract with Matra Marconi Space (now Astrium). EPS will provide an operational service for 14 years, which requires three satellites with nominal lifetimes of 5 years.

The US currently operates polar meteorological satellites in four Sun-synchronous planes, for two services: an early morning and afternoon pair of DMSP military satellites and a mid-morning and afternoon NOAA civil pair. In future, the joint US/European system will maintain three orbital planes: early morning, mid-morning and afternoon; EPS/Metop will provide the mid-morning service. During the transitional phase, the older generation of instruments will continue to fly as the newer instruments are introduced; Metop-1/2/3 will carry older instruments from NOAA as well as more advanced, European, ones.

Metop stores its data for downlinking each orbit, but it also provides continuous direct data-broadcast services to users. The channels can be selectively encrypted for decoding by

commercial customers. The High-Resolution Picture Transmission (HRPT) broadcasts the full data set at L-band for regional meteorological organisations to receive relevant data in realtime. The Low-Resolution Picture Transmission (LRPT) service at VHF provides a subset of the HRPT data. It is comparable to the existing NOAA automatic picture transmission (APT) service, with the objective of providing inexpensive access to low-resolution AVHRR images by local users.





Above: the engineering model of Metop's payload module being prepared for testing in ESTEC's Large Space Simulator, June 2001

Notable improvements for Metop are:

- new instruments: ASCAT, IASI, GOME-2 and GRAS;
- an innovative onboard compression scheme that is a considerable improvement over the existing APT service and provides LRPT user access to three channels of AVHRR data at full instrument spatial and radiometric resolution;
- continuous onboard recording of the global data set for dumping every orbit to a high-latitude ground station, with the global processed data available to users within 2.25 h of the measurements;
- high pointing and orbital stability to ensure that data may be geo-located without reference to ground-control points in imagery;
- a selective encryption system to ensure the commercial and data-denial needs of Eumetsat and the US Government, respectively.

The first three Metops will carry transition instruments from the current NOAA satellites:

- Advanced Very High Resolution Radiometer (AVHRR), an optical/infrared imager for global

Metop payload	
Advanced Very High Resolution Radiometer (AVHRR/3)	*NOAA*
6-channel visible/IR (0.6-12µm) imager, 2000 km swath, 1x1 km resolution. Global imagery of clouds, ocean and land. 35 kg, 622/39.9 kbit/s (high/low rate), 27 W.	
High-resolution Infra-Red Sounder (HIRS/4)	*NOAA*
20-channel optical/IR filter-wheel radiometer, 2000 km swath, IFOV 17.4 km (nadir). 35 kg, 2.9 kbit/s, 21 W. Replaced on Metop-3 by IASI.	
Advanced Microwave Sounding Unit (AMSU-A1/A2)	*NOAA*
Step-scan 15-channel microwave radiometers for 50 GHz oxygen absorption line, 2000 km swath, IFOV 30 km (nadir). A1/A2: 55/50 kg, 2.1/1.1 kbit/s, 78/30 W.	
Microwave Humidity Sounder (MHS)	*Eumetsat*
5-channel quasi-optical heterodyne radiometer, 190 GHz (water vapour absorption line), 89 GHz (surface emissivity), 2000 km swath, IFOV 30 km (nadir). 66 kg, 3.9 kbit/s, 89 W.	
Infrared Atmospheric Sounding Interferometer (IASI)	*CNES/Eumetsat*
Fourier-transform spectrometer, 3.62-15.5 µm in 3 bands. 4 IFOVs of 20 km at nadir in a square 50x50 km, step-scanned across track (30 steps), synchronised with AMSU-A. 2000 km swath. Resolution 0.35 cm^{-1}. Radiometric accuracy 0.25-0.58 K. Integrated near-IR imager for cloud discrimination. Water vapour sounding, NO_2 & CO_2, temperature sounding, surface & cloud properties. 251 kg, 1.5 Mbit/s, 240 W.	
Advanced Scatterometer (ASCAT)	*ESA*
5.255 GHz C-band radar scatterometer with 3 dual-swath (2x500 km width, offset 384 km left/right of groundtrack) antennas (fore/mid/aft) for measurement of radar backscatter at three azimuth angles to provide surface wind vectors of 4-24 m/s with accuracy ±2 m/s & ±20°, spatial resolution 50 km (25 km experimental), 0.57 dB radiometric accuracy. Incidence angle range 25-65°, 10 ms pulses of 120 W peak power. Additional products such as sea-ice cover, snow cover and vegetation density. 270 kg, 60 kbit/s, 251 W.	
Global Ozone Monitoring Experiment (GOME-2)	*ESA/Eumetsat*
Scanning spectrometer, 250-790 nm, resolution 0.2-0.4 nm, 960 km or 1920 km swath, resolution 80x40 km or 160x40 km. Double monochromator design: first stage of quartz prism with physical separation of 4 channels (240-315, 311-403, 401-600, 590-790 nm); second stage of blazed grating in each channel. Detector: 1024-pixel random-access Si-diode arrays. Ozone total column & profiles in stratosphere & troposphere; NO_2 BrO OClO ClO. Albedo and aerosol; cloud fraction, cloud-top altitude, cloud phase. 73 kg, 40 kbit/s, 45 W.	
GNSS Receiver for Atmospheric Sounding (GRAS)	*ESA/Eumetsat*
GPS satellite occultation (up to 500/day) receiver for bending angle measurement better than 1 µrad, fitting data to stratospheric model for temperature profile (vertical sounding of ±1 K with vertical resolution of 150 m in troposphere (5-30 km altitude) and 1.5 km in stratosphere), retrieval of refractive index vs. altitude profile. 30 kg, 60 kbit/s, 42 W.	
Advanced Data Collection System (ADCS)	*CNES*
Collection of oceanographic, atmospheric and/or meteorological 400 bit/s or 4800 bit/s data on 401.65 MHz from platform transmitters (PTT) on buoys, ships, land sites and balloons worlwide for later relay to ground via X-band and HRPT. Determines PTT location by Doppler. Can transmit to PTTs on 466 MHz at 200 bit/s or 400 bit/s. 24 kg, 7.5 kbit/s, 64 W.	
Space Environment Monitor (SEM-2)	*NOAA*
Multi-channel charged particle spectrometer as part of NOAA's 'Space Weather' activities. Total energy of electron & proton fluxes 0.05-1 keV and 1-20 keV; directional & omni measurements in 6 bands 30-6900 keV for protons and three bands 30-300 keV for electrons. 18 kg, 166 bit/s, 6 W.	
Search & Rescue (S&R)	*CNES/NOAA*
Relay of distress beacon signals; 121.5/243.0/406.05 MHz uplink from EPIRB (Emergency Position Indicating Rescue Beacon), 1544.5 GHz 2.4 kbit/s downlink. 35 kg, 77 W.	

coverage of clouds, ocean and land;
- High-resolution Infra-Red Sounder (HIRS), a spectrometer with a relatively coarse spatial resolution and a mechanical scan over a wide swath, from which height profiles of atmospheric pressure and temperature may be derived (replaced on Metop-3 by IASI);
- Advanced Microwave Sounding Unit-A (AMSU-A), a mechanically scanned multi-channel microwave radiometer for pressure and temperature profiles;
- Microwave Humidity Sounder (MHS), a new instrument on the last of the NOAA satellites: global sounding, cloud and Earth radiation budget, sea ice;
- Space Environment Monitor (SEM), to measure the charged-particle radiation environment;
- Data Collection System (DCS/Argos), which receives brief telemetry signals from a large global network of remote stations. As well as delivering these messages to a central processing site, this new version can also send messages *to* the terminals;
- Search & Rescue (S&R), immediately rebroadcasts signals from emergency transmitters typically carried on ships and aircraft.

The new generation of instruments offers improved sensing capabilities:

- Infrared Atmospheric Sounding Interferometer (IASI), an important development providing a significant improvement in determining the vertical temperature and humidity profiles in the atmosphere;
- Advanced Scatterometer (ASCAT), developed within the Metop-1 contract, uses multiple radar beams to measure the small-scale roughness of the ocean surface from three directions, over a wide swath on each side of the satellite, enabling the speed and direction of the wind to be determined;
- Global Ozone Measurement Experiment-2 (GOME-2), an improved successor to the ERS-2 GOME-1, is a high-resolution visible/UV spectrometer for measurements over a wide swath and wide spectral range to determine ozone profiles and total column amounts of many other trace gases;
- GNSS Receiver for Atmospheric Sounding (GRAS), developed within the Metop-1 contract, is a geodetic-quality GPS receiver equipped with three antennas to measure the signals from GPS satellites in occultation by Earth's atmosphere, revealing temperature and pressure profiles.

Satellite configuration: payload module supported by box-shaped service module derived from Envisat (mechanical design) and Spot-5 (electrical design) service modules. Launch configuration 3.4x3.4x16.5 m; in-orbit 5x5.2x17.6 m.

Attitude/orbit control: 3-axis by 3 0.45 Nm/40 Nms (at max 2400 rpm) reaction wheels; orbit adjust by redundant 8x22.7 N thrusters in blowdown mode (22 bar BOL), max. 316 kg hydrazine in 4 tanks.

Power system: single 8-panel flatpack solar array provides 2210 W orbit average EOL (1700 W for payload). Each panel 1x5 m. Total area 40 m^2 carrying 32.4x73.7 mm Si BSR cells, supported by five 40 Ah batteries.

Communications: data downlinked at 70 Mbit/s 7750-7900 MHz X-band from 24 Gbit solid-state recorder to 2 ground stations within one orbit of recording. Realtime broadcasting of data for HRPT (3.5 Mbit/s 1701.3 MHz L-band) and LRPT (72 kbit/s 137.1 MHz VHF). Spacecraft controlled by Eumetsat via Kiruna (S) S-band 2053/2230 MHz up/down ground station at 2.0/4.096 kbit/s up/down. Metop autonomy for 36 h without ground contact.

SMOS

Planned achievements: the first global measurements of soil moisture and ocean salinity; first passive L-band interferometer in space
Launch date: planned for early 2006
Mission end: after minimum 3 years (2-year extension expected)
Launch vehicle/site: to be selected from Rockot, Dnepr and PSLV
Launch mass: about 600 kg (300 kg payload)
Orbit: planned 755 km circular, Sun-synchronous (06:00 local time ascending node), revisit time 3 days at the equator for ascending passes
Principal contractors (Phase-A): Alcatel Space Industries platform prime, EADS-CASA payload prime; Extended Phase-A September 2000 - November 2001; Phase-B/C/D to follow

The Soil Moisture and Ocean Salinity (SMOS) mission will use an L-band (1.4 GHz) passive interferometer to measure two crucial elements of Earth's climate: soil moisture and ocean salinity. It will also monitor the vegetation water content, snow cover and ice structure. SMOS was selected as the second Earth Explorer Opportunity mission in ESA's Living Planet programme. The AO was released on 30 June 1998 and 27 proposals were received by closure on 2 December 1998. On 27 May 1999, ESA approved Cryosat as the first for Phase-A/B, with an extended Phase-A for SMOS as the second.

Human activities appear to be influencing our climate. The most pressing questions are: is the climate actually changing and, if so, how fast and what are the consequences, particularly for the frequency of extreme events? Answering these questions requires reliable models to predict the climate's evolution and to forecast extreme events. Significant progress has been made in weather forecasting, climate monitoring and extreme event forecasting in recent years, using sophisticated models fed with data from operational satellites such as Meteosat. However, further improvements now depend to a large extent on the global observation of a number of key variables, including soil moisture and sea-surface salinity. No such long-duration space mission has yet been attempted.

The RAMSES mission (Radiométrie Appliquée à la Mesure de la Salinité et de l'Eau dans le Sol) was proposed in 1997 to CNES as a French national mission and studied to Phase-A. Further work produced the SMOS proposal to ESA by a team of scientists from 10 European countries and the USA, bringing together most of the available expertise in the related fields. As an Explorer Opportunity mission, it is dedicated to research and headed by Lead Investigators (LIs): Yann H. Kerr of the Centre d'Etudes Spatiales de la Biosphère (CESBIO, F); and Jordi Font, Institut de Ciències del Mar (E). The LIs are responsible for overall mission design, implementation and data processing. ESA has overall mission responsibility, CNES is managing the satellite bus, and Spain will manage the Payload Mission and Data Centre at Villafranca. A joint team will be in charge of technical definition and development of the mission components.

The microwave emission of soil depends on its moisture content to a depth of a few cm. At 1.4 GHz, the signal is strong and has minimal contributions from vegetation and the atmosphere. Water and energy exchange between land and the

atmosphere strongly depend on soil moisture. Evaporation, infiltration and runoff are driven by it. It regulates the rate of water uptake by vegetation in the unsaturated zone above the water table. Soil moisture is thus critical for understanding the water cycle, weather, climate and vegetation.

At sea, the 1.4 GHz microwave emission depends on salinity, but is affected by temperature and sea-state. Those factors must be accounted for.

The global distribution of salt in the oceans and its variability are crucial factors in the oceans' role in the climate system. Ocean circulation is driven mainly by the momentum and heat exchanges with the atmosphere, which can be traced by observing sea-surface salinity. In high-latitude ocean regions such as the Arctic, salinity is the most important variable because it controls processes such as deep water formation by controlling the density. This is a key process in the ocean thermohaline circulation 'conveyor belt'. Salinity is also important for the carbon cycle in oceans, as it determines ocean circulation and plays a part in establishing the chemical equilibrium that, in turn, regulates the carbon dioxide uptake and release – important for global warming.

Monitoring sea-surface salinity could also improve the quality of the El Niño-Southern Oscillation prediction by computer models. The lack of salinity measurements creates major discrepancies with the observed near-surface currents.

Satellite configuration: CNES Proteus platform, 1 m cube, hardware on four side walls. Flight software in MA3-1750 microprocessor; dual redundant MIL-STD-1553B bus.

Attitude/orbit control: 3-axis control to 32±3° in pitch by reaction wheels and magnetotorquers, measured to 0.05° using star tracker, Sun sensors, 3 gyros and 2 magnetometers. Orbit control by four 1 N hydrazine thrusters (30 kg propellant, including safe mode and SMOS disposal EOL). GPS provides 100 m position accuracy.

Power system: 619 W EOL orbit average from two solar wings of four 80x150 cm Si panels each; 220/300 W required for payload/bus. Supported by Spot-4 NiCd battery.

Communications: controlled from Spacecraft Operations Control Centre at Toulouse (F), commands uplinked typically weekly at 4 kbit/s S-band. Science data downlink under study: either generic Proteus S-band to Kiruna (plus possibly second station), or by X-band, both with onboard storage. Payload Mission and Data Centre, Villafranca (E).

SMOS Payload

The accuracies required are: soil moisture 4% every 3 days at 50x50 km resolution; *salinity* 0.1 psu every 10-30 days at 200x200 km resolution (psu = practical salinity unit, equates to 0.1% mass; oceans typically 32-37 psu); *vegetation moisture* 0.3 kg/m² every 7 days at 50x50 km resolution.

L-band Interferometric Radiometer

A passive interferometer using three CFRP arms in Y-shaped configuration. 72 receiver elements, including 21 on each arm, 19 cm-dia. 1.4 GHz L-band, H/V polarisation. Records emission within FOV instantaneously and then at several incidences (0-55°) as SMOS moves along orbit. Swath width ~1000 km, spatial resolution < 35 km in centre FOV, radiometric resolution 0.8-2.2 K.