ESA's Mars Express Mission – Europe on Its Way to Mars

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ESA's exciting and fast-track Mars Express mission is the first of the new flexible (F) missions, which are based on a new implementation scenario to maintain overall mission cost below a very stringent cost cap. The key features of an F-mission are streamlined management, up-front definition of the payload, and the transfer of more responsibility to industry. The cost ceiling is 175 M€ for future F-missions, but only 150 M€ for Mars Express. The scientific objectives of the mission include the remote and in-situ study of the surface, subsurface, atmosphere and environment of the planet Mars. ESA's Science Programme Committee preliminarily approved Mars Express in November 1998, provided sufficient funding would be available, and gave its full approval on 19 May 1999.

The selection of the scientific payload for Mars Express was completed in early May 1998 whilst the spacecraft design was still undergoing competitive feasibility studies. Towards the end of 1998, Matra Marconi Space (MMS) was chosen as Prime Contractor for the entire spacecraft procurement programme. The payload is composed of seven instruments and a lander, Beagle 2, to search for traces of life on Mars. Beagle 2 is currently only confirmed until the end of this year and its continuation is subject to the agreement of a financial and technical plan by the end of 1999.

ESA's aim is the implementation of a top-class mission at a much lower cost than hitherto achieved. Significant savings will be made by purchasing recurrent systems from ESA's Rosetta mission. A compressed implementation schedule, a new relationship between ESA, industry and the scientific community, and the exploitation of synergies between the ground operation systems of Rosetta and Mars Express will help the latter to stay within the allocated budget.

The launch by a Soyuz/Fregat must take place within an eleven-day launch window opening on 1 June 2003.

Introduction

In the broad context of planetary science, Mars represents an important transition between the outer volatile-rich, more oxidised regions of the accretion zone of the terrestrial bodies (asteroid belt) and the inner, more refractory and less oxidised regions from which Earth, Venus and Mercury accreted. Its size, the degree of internal activity, the age of its surface features, and the density of its atmosphere are manifestations of Mars' special position and its transitional character. Its parameters are intermediate between those of the large terrestrial planets (Earth, Venus) and the smaller planetary bodies (Mercury, Moon, and asteroids). Although geologically less evolved, the Martian surface is more Earth-like than that of any other terrestrial planet. Consequently, the exploration of Mars is crucial for a better understanding of the Earth from the comparative-planetology perspective.

Spacecraft exploration of Mars started in the 1960s. The first global survey was conducted by Mariner-9 in 1971, but the most significant and scientifically rewarding mission was Viking in 1976, consisting of two orbiters and two landers. Most of the existing environmental models of Mars have been derived from Viking data. More recently, the United States, Russia and Japan have launched new missions to Mars, including Mars Pathfinder, Mars Global Surveyor and the failed Mars-96 mission in 1996, Planet-B and other Mars Surveyor missions in 1998.

A new series of extremely challenging missions will be launched in 2003 and thereafter. They include ESA's Mars Express, NASA's telecommunications orbiters for high-speed Internet access to assets on and near Mars, and an aeroplane flying in the atmosphere of Mars on 17 December 2003, exactly a century after the Wright Brothers' first human flight on Earth. Starting in 2003, NASA also intends to send sample-return missions to Mars. Tiny return capsules, about 14 cm in diameter and holding a treasure of Martian soil and rocks, would lift off from Mars in March 2004 and in the autumn of 2006. Mars Express would aid in tracking the capsules as they orbit around Mars, in order to help another spacecraft to grab them for return to Earth.

The spacecraft parameters, launcher capability and the celestial constellation of Mars and Earth lead to a launch window for Mars Express opening on 1 June 2003 and closing eleven days later. The launch will be provided by a Soyuz/Fregat launcher from Baikonur in Kazakhstan. ESOC will conduct the operations using their new 35m-ground station near Perth, in Australia. The mission is optimised for observations of the Martian surface from a near-polar orbit with pericentre and apocentre altitudes of 250 and 11 490 km, respectively (Fig. 1). 440 days into the mission, the apocentre will be lowered to 10 050 km.

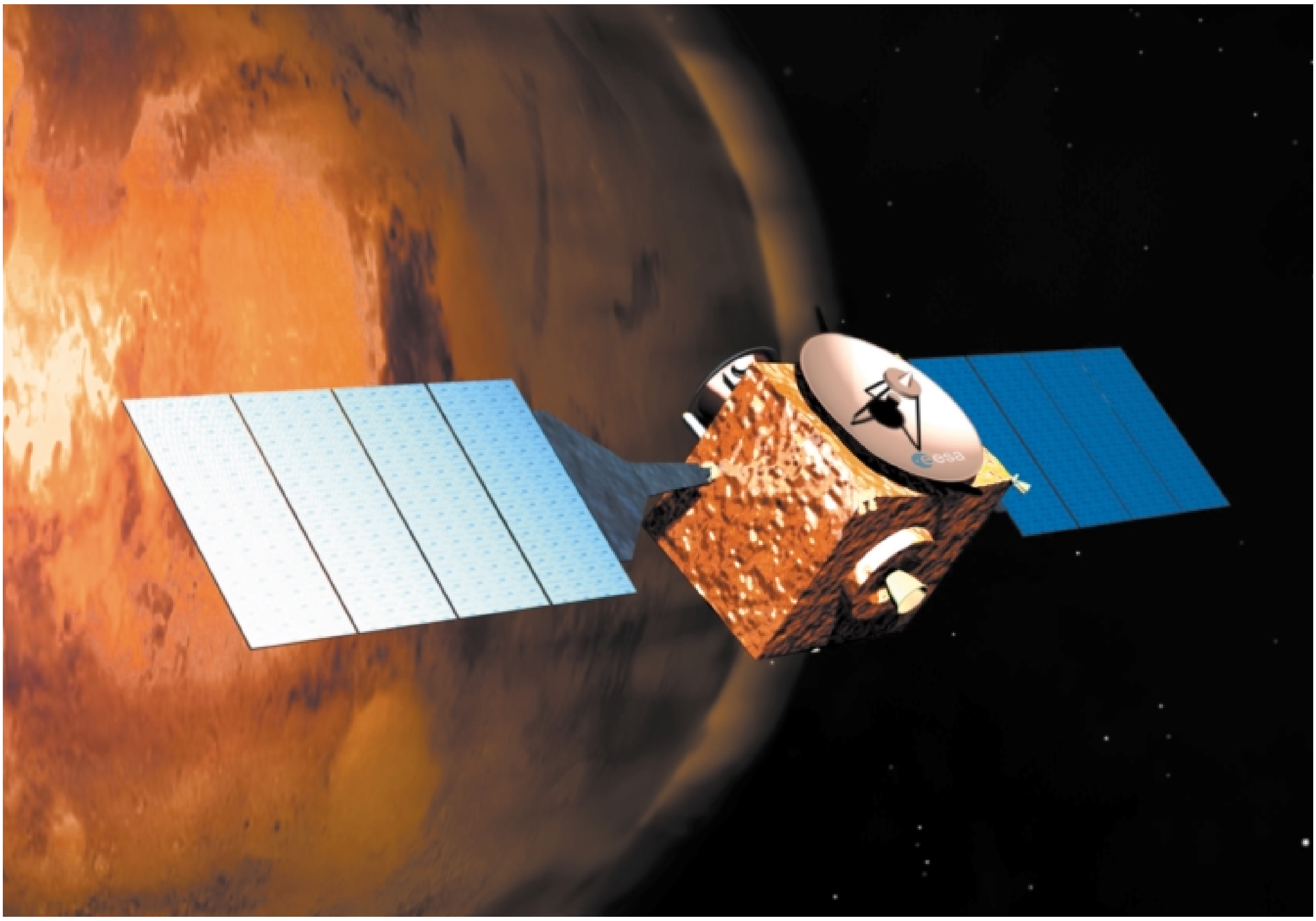
Beagle 2, a 60 kg-class Lander, will be delivered to a yet to be selected location on the surface of the planet. This Lander will focus on the geochemistry and exobiology of the Martian surface. In particular, it will study the morphology and geology of the landing site, the chemical and mineralogical composition of Martian surface rocks and soils, and the potential signatures of life, using a robotic mobile device.

ESA's Science Programme Committee (SPC) reconfirmed its support for Mars Express in November 1998, provided that the mission's implementation does not impact on other already selected missions. Following this positive recommendation and an intense and highly competitive industrial study phase, Matra Marconi Space (MMS) was chosen as Prime Contractor on the basis of a firm fixed price of 60 M€ for the entire procurement programme. Finally, ESA's Council endorsed the initiation of the definition phase, but stated that the Council at Ministerial Level in May 1999 must decide on the level of resources for the Scientific Programme. The consequent effect on the overall Science Programme will be assessed prior to transfer of the Mars Express project to the development and production phase.

New management approach

One of the major constraints imposed by ESA's science management on the mission's implementation is that the cost at completion must not exceed 150 M€. A breakdown into its major elements leads to the conclusion that the industrial procurement of the spacecraft cannot exceed 60 M€. Launch-service costs and

Figure 1. Artist's impression of the Mars Express spacecraft



ESA's internal and mission operations costs must be minimised to stay within the cost ceiling. ESA's management approach has therefore had to be changed significantly from the traditional methods employed in the past.

Many changes with respect to previous scientific missions have indeed been introduced, including industrial management of the scientific payload, establishment of direct interfaces between industry and the environmental test facilities, and simplified management and reporting requirements by ESA. Responsibility for the technical interface with the Soyuz/Fregat launch services provider, Starsem, is also delegated to industry.

Based on experience gained from the initial Horizon 2000 projects, both industry and the scientific community have acquired sufficient experience to establish and maintain a direct dialogue covering payload/spacecraft interfaces. Consequently, ESA decided to relinquish its traditional role as the interlocutor between the two parties. As part of the drive for increased efficiency, the Agency will only 'observe' the progress of the scientific payload, but will retain full control over science and instrument-performance issues. Responsibility for the timely delivery of all payload elements will rest with industry, which also has to ensure the availability of agreed payload resources.

This approach is new and a rapid learning process will have to take place. Interface changes, which may also have a cost impact for industry and/or the instrument teams, will have to be negotiated between these two parties. The advantage for ESA is that it can reduce its own costs by managing the project with a smaller team of about 10 persons. A team of this size can neither deal with detailed design issues, nor can it follow all industrial activities. Specialist support will be sought from experts within ESA's Directorate for Technical and Operational Support as and when required. A conventional review cycle will be executed, but the organisation of the reviews will differ from those conducted in the past. A key feature of the Mars Express reviews will be the co-location of ESA's review team with the industrial project team. The findings and conclusions will be reported to ESA's senior management.

ESOC has been able to offer an economically attractive quotation for Mars Express mission operations, based on the maximum reuse of operational systems being developed for the Rosetta mission. This will also include the sharing of key personnel to ensure coherence between the two Mission Operations Centres. A high degree of commonality will be achieved not only because of the common on-board system, but also due the similar mission scenarios. Rosetta will be launched six months ahead of Mars Express and will be entering a period of extended of hibernation at the time of the Mars Express launch. The timing also matches very well with the interplanetary cruise and nominal science mission phase for Mars Express. The planning and execution of the instrument flight operations also rests with ESA and will be performed in collaboration with the scientific community.

International co-operation

Mars Express will play an exciting and pivotal role in the international exploration of Mars. To carry out all the data-relay services requested, the mission would have to be extended from its nominal end in autumn 2005 to about summer 2008. The associated cost will have to be covered by contributions from the organisations benefiting from the mission extensions.

ASI, the Italian Space Agency, intends to provide significant contributions by developing an orbiter-to-lander telecommunications package, offering access to a new ground station in Sardinia, and supporting both spacecraft and science operations. ESA and ASI have already signed a working agreement.

Scientists in several ESA Member States are studying the implementation of a network of three to four stations, so-called 'Netlanders', on the surface of Mars. These landers are intended to establish the first network of scientific stations on the planet's surface in order to study its internal structure and activity and to provide insight into its weather patterns. Simultaneous measurements at all lander sites are required, which will also address geology and geochemistry. Mars Express, which would already be in its extended-mission phase, could provide data-relay services.

NASA wishes to implement alternative communication links via Mars Express between Earth and its own landers and rovers, to be launched in 2003 and 2005. Mars Express will also play an essential part in the determination of the precise orbits of the sample-return canisters, after their launch from the planet in 2004 and 2006, respectively. An Earth-return spacecraft will then capture and return these canisters to Earth.

The Japanese Institute of Space and Astronautical Sciences (ISAS) recently announced a delay in the arrival of the Japanese Nozomi mission at Mars. Owing to technical problems, an alternative interplanetary trajectory has had to be chosen and Nozomi will not now arrive until 2004 (originally late-1999). New and very exciting co-ordinated measurements could be performed between Mars Express in its polar orbit and Nozomi in a highly elliptic, near-equatorial orbit. The first steps towards a close scientific collaboration have been initiated.

Payloads of Mars Express and Beagle 2

The Mars Express Orbiter's payload represents the core of the mission. Its key scientific objectives include high-resolution imaging and mineralogical mapping of the Martian surface, radar sounding of the subsurface structure down to the permafrost, precise determination of the atmospheric circulation and composition, and study of the interaction of the atmosphere with the interplanetary medium (Table 1).

Beagle 2 addresses the geology, geochemistry, meteorology and exobiology (i.e. the search for the signatures of life) of the landing site and includes a number of robotic devices. It will deploy a sophisticated robotic sampling arm, which could manipulate different types of tools and retrieve samples to be analysed by the geochemical instruments mounted on the lander platform. One of the tools to be deployed by the arm is a 'mole' capable of subsurface sampling in order to reach soil unaffected by solar UV radiation.

Table 1. Scientfic objectives of Mars Express and Beagle 2

Mars Express Orbiter
- Global high-resolution photo-geology (incl. topography, morphology, paleo-climatology, etc.) with 10 m resolution
- Global spatial high-resolution mineralogical mapping of the surface with 100 m resolution
- Global atmospheric circulation and high-resolution mapping of atmospheric composition
- Subsurface structure at kilometre scale down to the permafrost
- Subsurface/atmosphere interactions
- Interaction of the atmosphere with the interplanetary medium.

Beagle 2 Lander
- Meteorology and climatology
- Landing-site geology, mineralogy and geochemistry
- Physical properties of the atmosphere and surface layers
- Exobiology (i.e. search for signatures of life)

Table 2 summarises the payload of the Mars Express Orbiter, which includes the following instruments:

High-Resolution Stereoscopic Camera (HRSC)
HRSC will provide high-resolution, stereo, colour, multiple-phase-angle and global coverage imaging of the planet Mars. It will allow characterisation of the surface morphology and topography, determination of the geological evolution as well as the identification of geological units, refinement of the geodetic control network, analysis of atmospheric phenomena including climatology, the role of water and surface/atmosphere interactions.

Table 2. Scientific payload complement of the Mars Express Orbiter

Acronym	Instrument	Principal Investigator	Other Countries Involved	Technique
HRSC	High-Resolution Stereoscopic Camera	G. Neukum, Berlin, Germany	D, F, RU, US FI, I, UK	Push-broom scanning camera with 9 CCD's
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité,	J.P. Bibring, Orsay, France	F, I, RU	Visible- and near-infrared spectrometer
PFS	Planetary Fourier Spectrometer	V. Formisano, Frascati, Italy	I, RU, PL, D, F, E, US	Infrared spectrometer
MARSIS	Mars Advanced Radar for Subsurface and Ionospheric Sounding	G. Picardi, Rome, Italy	I, US, D, CH, UK, DK	Subsurface radar and altimeter
ASPERA	Analyser of Space Plasmas and Energetic Atoms	R. Lundin, Kiruna, Sweden	S, D, UK, F, FI, I, US, RU	Neutral- and charged-particle sensors
SPICAM	Spectroscopic Investigation of the Characteristics of the Atmosphere of Mars	J.L. Bertaux, Verrières, France	F, B, RU, US	Ultraviolet spectrometer
MaRS	Mars Radio Science Experiment	M. Pätzold, Cologne, Germany	D, F, US, A	Radio-wave propagation

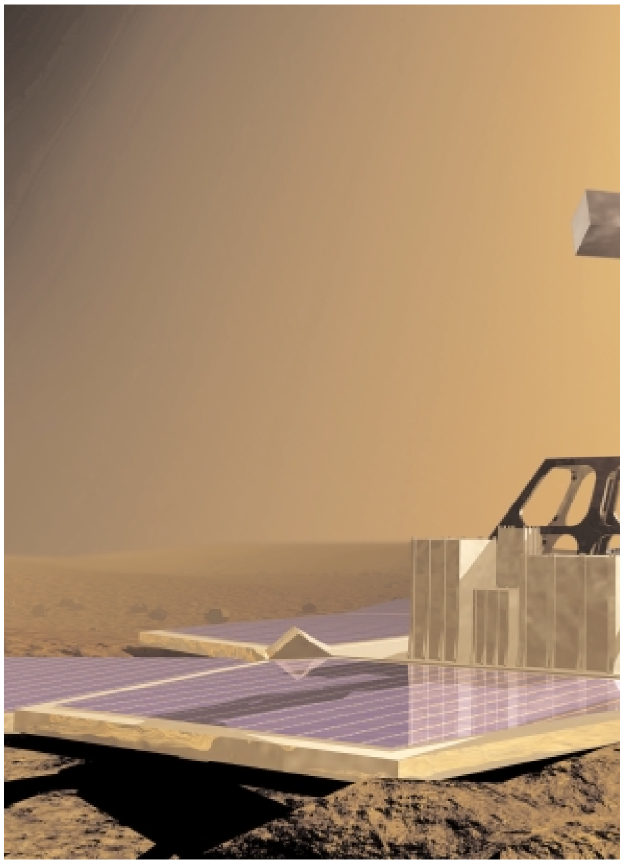


Figure 2. Artist's impression of Beagle 2 in operational configuration on the Martian surface

Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activit (OMEGA)
OMEGA is a visual and near-infrared mapping spectrometer, which will provide the mineralogical and molecular composition of the Martian surface at medium resolution and with global coverage, through the spectral analysis of the re-diffused solar light and surface thermal emission. This will allow the characterisation of the composition of surface materials (i.e. silicates, oxides, hydrates, carbonates, frost and ices), and monitoring of the atmospheric dust.

Planetary Fourier Spectrometer (PFS)
PFS is a Fourier infrared spectrometer optimised for atmospheric studies, with two channels with 10 and 20 km footprints, respectively. It will provide three-dimensional temperature-field measurements of the lower atmosphere up to 50 km altitude, minor-constituent variations (H_2O and CO_2) and the optical properties of atmospheric aerosols, which will allow the study of global atmospheric circulation. The instrument will also provide data on the thermal inertia of Mars' surface.

Spectroscopic Investigation of the Characteristics of the Atmosphere of Mars (SPICAM-UV)
This ultraviolet spectrometer is devoted to the study of the atmosphere with both nadir and limb viewing modes. It will measure the ozone content of the atmosphere as well as of the coupling of O_3 and H_2. In addition, stellar occultation techniques will provide vertical profiles of CO_2, O_3 and dust. All of these measurements are important fundamental inputs to meteorological and dynamic models of the atmosphere.

Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS)
MARSIS will investigate the subsurface structure of Mars to a depth of a few kilometres, in particular to map the distribution of liquid and ice water, allowing key issues associated with the planet's geologic, climatic and possibly organic evolution to be addressed. In addition, this multi-frequency nadir-looking instrument will provide altimetry and surface-roughness data during nighttime using its two 20 m antennas, as well as ionospheric measurements during daytime.

Analyser of Space Plasmas and EneRgetic Atoms (ASPERA)
ASPERA is an imager of energetic neutral atoms and an analyser of space plasmas. It will allow the plasma-induced atmospheric escape, as well as interaction of the solar wind with the ionosphere of Mars, to be determined. Plasma and magnetic-field interaction with the atmosphere addresses fundamental questions on the climatic and water-related evolution of Mars, with potential biochemical importance. The neutral particle imager and electron and ion spectrometer are mounted on a scanning platform.

Mars Radio Science Experiment (MaRS)
MaRS will use the Mars Express Orbiter radio subsystem to sound the neutral and ionised atmosphere at occultation, determine the dielectric properties of the surface, and observe gravity anomalies.

Beagle 2
Beagle 2 (Fig. 2) is a 60 kg-class Lander that will address the scientific objectives listed in Table 1. The consortium leader is Prof. C. Pillinger (Open University, UK). The Lander carries the following set of instruments and mechanisms for in-situ analyses:
– gas chromatography and mass spectroscopy
– sample handling system, robotic arm and a mole
– microscope, panoramic and wide-angle cameras
– Mössbauer and X-ray spectrometers
– environmental sensors.

Spacecraft design
The spacecraft is conventional in terms of the design of its body, but includes special features that will provide aerobraking in the Martian

atmosphere should this become necessary. The design is optimised for a Soyuz/Fregat launch, but is also fully compatible with a Delta-II vehicle. A body-mounted High-Gain Antenna and a pair of rotating solar arrays are the spacecraft's most obvious features. The solar array has two symmetrical wings in order to minimise the torques and forces applied during the spacecraft's insertion into orbit around Mars.

Within the overall integrated design of the spacecraft, just four main assemblies are foreseen, to simplify the development and integration process (Fig. 3):

- the Propulsion Module with the core structure
- lateral walls supporting the spacecraft avionics and the solar arrays
- shear walls and the top- and bottom-face supporting the payload units; the top face is nadir-pointing during science observation and Lander communication around Mars. It also carries Beagle 2, the associated relay antenna and ASPERA-3, and
- lateral walls to support the High Gain Antenna and the instrument radiators, respectively.

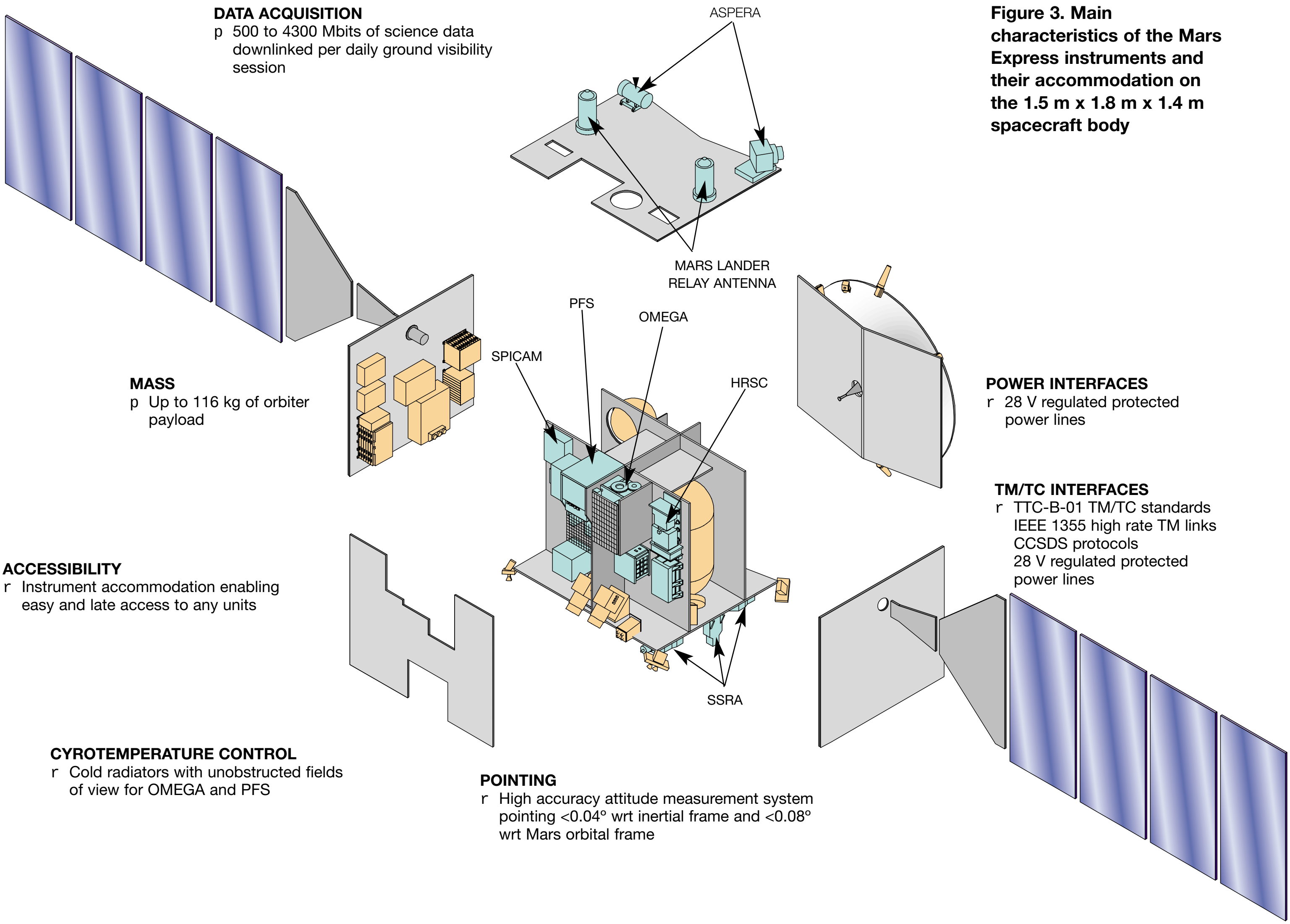


Figure 3. Main characteristics of the Mars Express instruments and their accommodation on the 1.5 m x 1.8 m x 1.4 m spacecraft body

The cost and schedule targets are to be met through the extensive use of existing and proven technologies. The procurement of recurring hardware and software, together with the standardisation of most interfaces, including those to the scientific payload, enables a simplified, low-risk development programme. Synergies with ESA's Rosetta programme are fully exploited to benefit from a contemporary, high-performance, low-risk deep-space programme by ESA. Beyond the reuse of existing items, commonality of operations between Rosetta and Mars Express allows ESOC to optimise mission-operation activities. Mars Express also takes advantage of equipment being developed for commercial telecommunications spacecraft or other small satellites. This contributes to a cost-effective solution meeting the stringent conditions of the firm fixed-price contract.

The spacecraft has to accommodate various classes of scientific experiments: nadir-pointing optical instruments, a radar/altimeter instrument with two 20 m and one 4 m tubular antennas, two particle detectors, a Lander relay terminal and, finally, Beagle 2 itself.

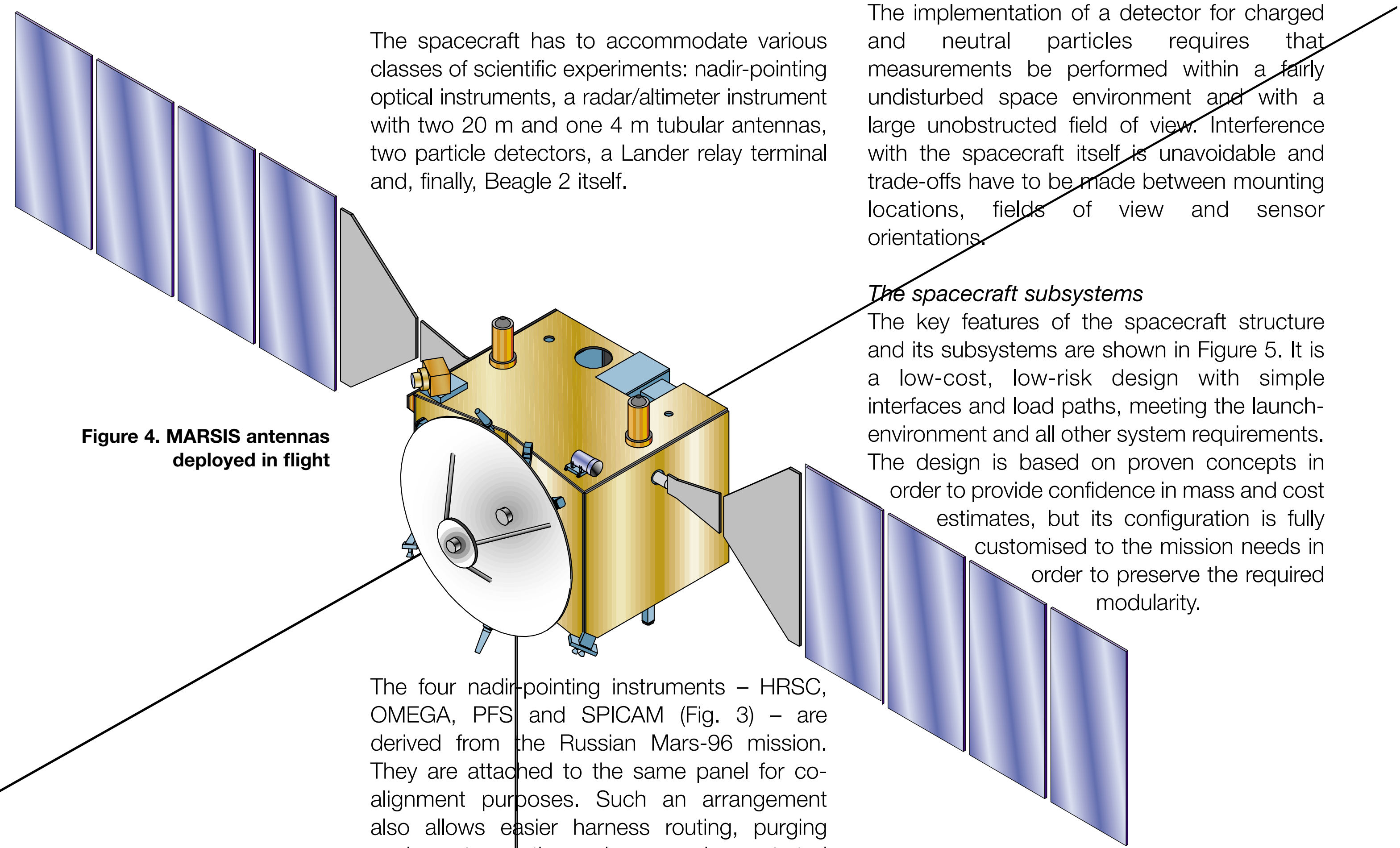


Figure 4. MARSIS antennas deployed in flight

The four nadir-pointing instruments – HRSC, OMEGA, PFS and SPICAM (Fig. 3) – are derived from the Russian Mars-96 mission. They are attached to the same panel for co-alignment purposes. Such an arrangement also allows easier harness routing, purging equipment mounting and, as was demonstrated on Mars-96, it can cope with the thermal constraints related to the orientation of their heat pipes and with the proximity of the spacecraft thermal radiators. This minimises the impacts on testing, especially in thermal vacuum, and on the overall mass budget.

The alignment of the instrument axes with the launch direction is optimal in terms of compatibility with thruster plume impingement and any eventual aerobraking. Viewing is in the anti-ram direction during low-altitude passes through the Martian atmosphere. Compatibility with aerobraking is a design requirement, but it would only be used to recover from an anomaly.

SPICAM UV, in addition to nadir-viewing, also requires special orientations of the spacecraft which allow 'Sun-occultation observations'. The incorporation of the solar occultation channel is based on a small pointing mirror in front of the opto-mechanical assembly.

After acquisition of the nominal orbit near Mars, the dipole antenna (40 m tip-to-tip; Fig. 4) and a 4 m-monopole antenna will be deployed in such a way that the dipole is oriented perpendicular to the flight and nadir directions, whilst the monopole points in the vertical direction.

The implementation of a detector for charged and neutral particles requires that measurements be performed within a fairly undisturbed space environment and with a large unobstructed field of view. Interference with the spacecraft itself is unavoidable and trade-offs have to be made between mounting locations, fields of view and sensor orientations.

The spacecraft subsystems

The key features of the spacecraft structure and its subsystems are shown in Figure 5. It is a low-cost, low-risk design with simple interfaces and load paths, meeting the launch-environment and all other system requirements. The design is based on proven concepts in order to provide confidence in mass and cost estimates, but its configuration is fully customised to the mission needs in order to preserve the required modularity.

The structure has several main functions. Firstly, it provides the mechanical interfaces to the spacecraft equipment; secondly, it secures the mating to the launcher interface for both the on-ground and launch phases; thirdly, it fulfils the launcher stiffness requirements; and fourthly it maintains the alignment of the payload elements within the demanding limits. The structure is derived from small-satellite applications, limiting the number of complex elements to a minimum. The only large

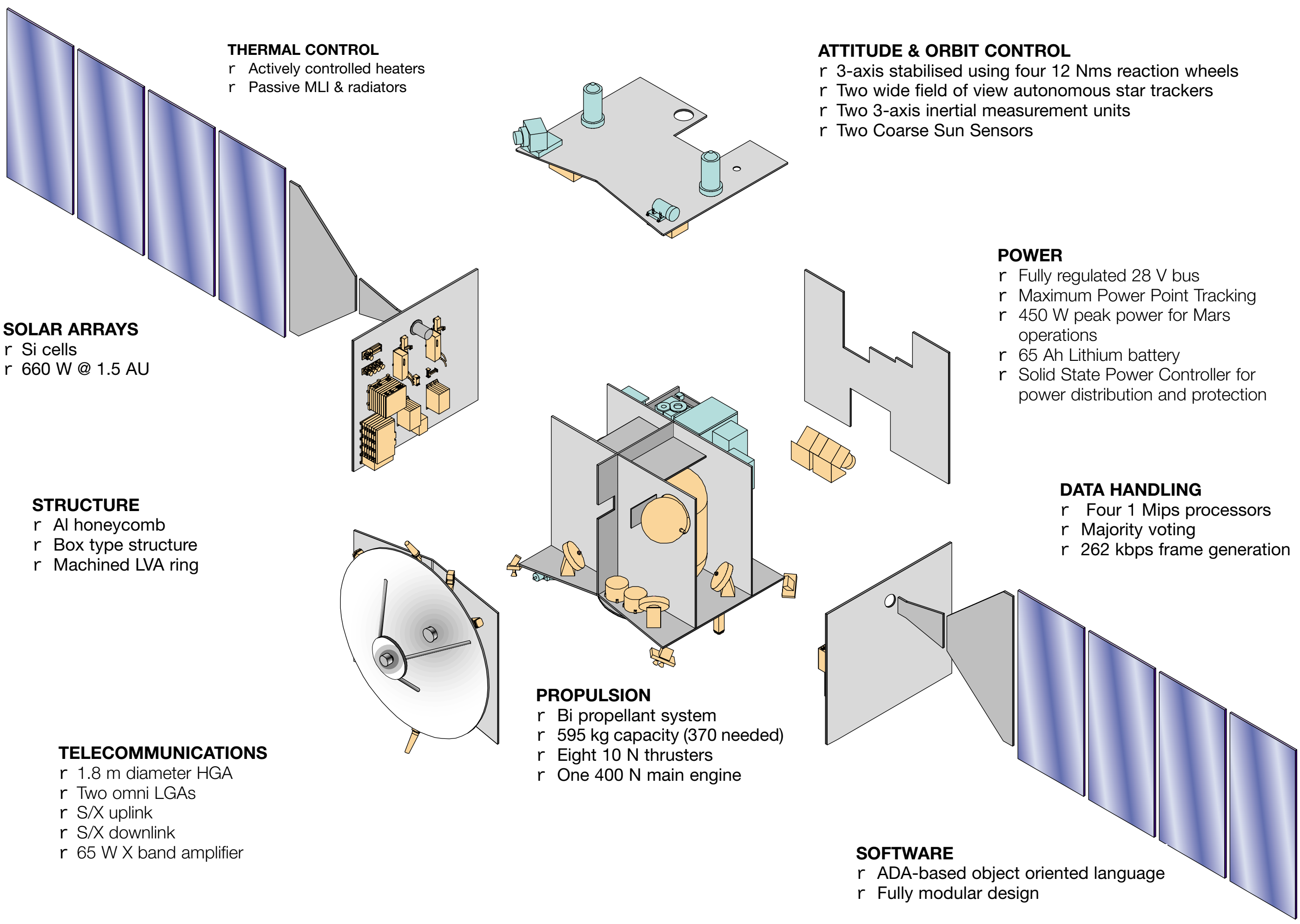


Figure 5. Spacecraft structural elements and key subsystem features

cylindrical element is the Launch Vehicle Adapter. The remaining structural items are principally flat, standard panels with aluminium skins and aluminium honeycomb.

Thermal control

The thermal-control subsystem is designed to maintain all equipment within allowed temperature ranges during all mission phases. Most of the spacecraft units are collectively controlled within a thermal enclosure. For more demanding units like payload sensors (HRSC and OMEGA optics, PFS and SPICAM sensors) featuring their own thermal control, special precautions are taken by individually insulating them and by providing them with dedicated radiators to ensure the correct temperature levels. External units (MARSIS antennas, ASPERA units) are insulated from the spacecraft, as they have to withstand greater temperature ranges than the others. Beagle 2 is thermally decoupled from the spacecraft to avoid heat leaks after Lander ejection.

Attitude and Orbit Control System (AOCS)

The AOCS architecture selected for Mars Express is inherited from Rosetta. Attitude and orbit control is achieved using a set of star sensors, gyroscopes, accelerometers and reaction wheels. A bi-propellant reaction-control system is used for orbit and attitude manoeuvres by either the 400 N main engine or banks of 10 N thrusters.

Six main modes cover the mission's operational phase. The Mars Pointing Mode and the Inertial Pointing Mode enable the spacecraft to follow variable attitude profiles along the orbit. The Main Engine Boost Mode controls the major trajectory corrections during the interplanetary cruise, the Mars-orbit insertion and acquisition of the final orbit. The Fine Trajectory Correction Mode performs small corrections of the trajectory using the 10 N thrusters. The Aerobraking Mode will be used for recovery should an anomaly leave too little fuel for nominal orbit acquisition. The Slew Manoeuvre Mode uses the reaction wheels for the transitions between all of these modes. Backup modes, to be used in the case of a serious anomaly, are covered by the Sun/Earth reacquisition modes.

Propulsion

A bi-propellant system, based on the heritage of earlier telecommunications spacecraft, has been adopted to meet the requirement for a high-performance, low-cost propulsion system with minimum mass. Throughout the interplanetary cruise, the system will operate in a pressure-regulated mode using only the 10 N thrusters. A few days before Mars orbit insertion, the main engine will be primed and its thrust calibrated by making specific manoeuvres. This will ensure that the main engine can be used safely for the Mars orbit insertion and acquisition of the operational orbit. Should a main-engine failure be detected at this stage, a set of the 10 N thrusters would be used to carry out the capture manoeuvre. In this case, only a degraded orbit around Mars could be established, but aerobraking could help to achieve the nominal orbit. The pressurant and main-engine assemblies will be isolated once the spacecraft has reached its final orbit; the rest of the mission will be performed in blow-down mode with the 10 N thrusters only.

Electrical architecture

The long propagation times for signals from Earth and Mars (up to 20 minutes) and the limitations due to the fact that only one ground station near Perth, in Australia, is foreseen in the nominal mission design, require a high level of autonomy within the spacecraft systems. In addition, the large volume of data generated by the instruments requires a very high data transmission rate to the ground station. Finally, the spacecraft must also be able to cope with a highly variable environment due, for instance, to the changing distances between the Sun, Mars and Earth, which result in large variations in the solar flux and data-transmission rates.

The data-handling architecture is organised around the two Control and Data Management Units (CDMU). Their tasks are to decode and execute the commands from the ground, format housekeeping and science telemetry, manage the on-board data distribution, and do all of the real-time computation onboard. The CDMU features two MA3-1750 Processor Modules, and a 10 Gigabit solid-state mass memory is used to store housekeeping and science data telemetry until its transmission to the ground. It also collects science data from some high-rate instrument interfaces. The communications link with the Earth can switch between S-band or X-band frequencies. Low-gain antennas allow omni-directional transmission and reception at S-band, while a parabolic high-gain antenna allows high-rate data transmission and telecommand reception at S- and X-band.

Electrical power is generated by a two-winged solar array with 11 m^2 of silicon cells and a tip-to-tip wing span of about 12 m. The array is oriented towards the Sun by a rotating drive mechanism. A 64.8 Ah lithium-ion battery supplies the power needed during eclipses. A ‘maximum power point tracker’ always keeps the solar-array power generation at its most efficient. The +28 V regulated power bus distributes power to all users via a Power Distribution Unit with solid-state switches.

Spacecraft development plan

The overall development and verification approach is designed to ensure the meeting of all requirements, and delivery on time and within the allocated budget. This is secured by early procurement and validation, whilst thorough testing and verification minimises the risk. The major guidelines for the development and verification approach for Mars Express are:
- use of recurrent equipment wherever feasible and the restriction of development activities to a small number of items
- risk-reduction actions as early as possible in the programme
- development of spacecraft subsystems or modules as independently as possible
- spacecraft qualification and acceptance verification programme.

In a totally new approach for ESA (Fig.6), the industrial team will be responsible for the management of all scientific-payload interfaces, with the Agency remaining responsible for scientific performance and operational aspects. The development programme for each instrument will be defined by the Principal Investigator and approved by MMS for the interface aspects, with the objective of achieving timely delivery of a fully qualified flight instrument. The test sequences, validated at instrument level, will be reused at system level. For this purpose, spacecraft interface simulators will be proposed to the scientific teams to support the development of their instrument. The validation and model philosophy at system level requires that the instrument-model philosophy includes a structural model, an engineering model, or at least an electrical simulator for advanced system electrical and functional validation, and a flight model.

Payload management

A novel scheme is being implemented for instrument interfaces on Mars Express. The spacecraft contractor has responsibility for the instrument interface management, the allocation of resources, the provision of an acceptable environment for the instruments, timely delivery of the instrument models, progress monitoring and the administration of changes and non-conformances. The Principal Investigators, together with ESA, remain responsible for the scientific performances of the instruments and related in-flight operations.

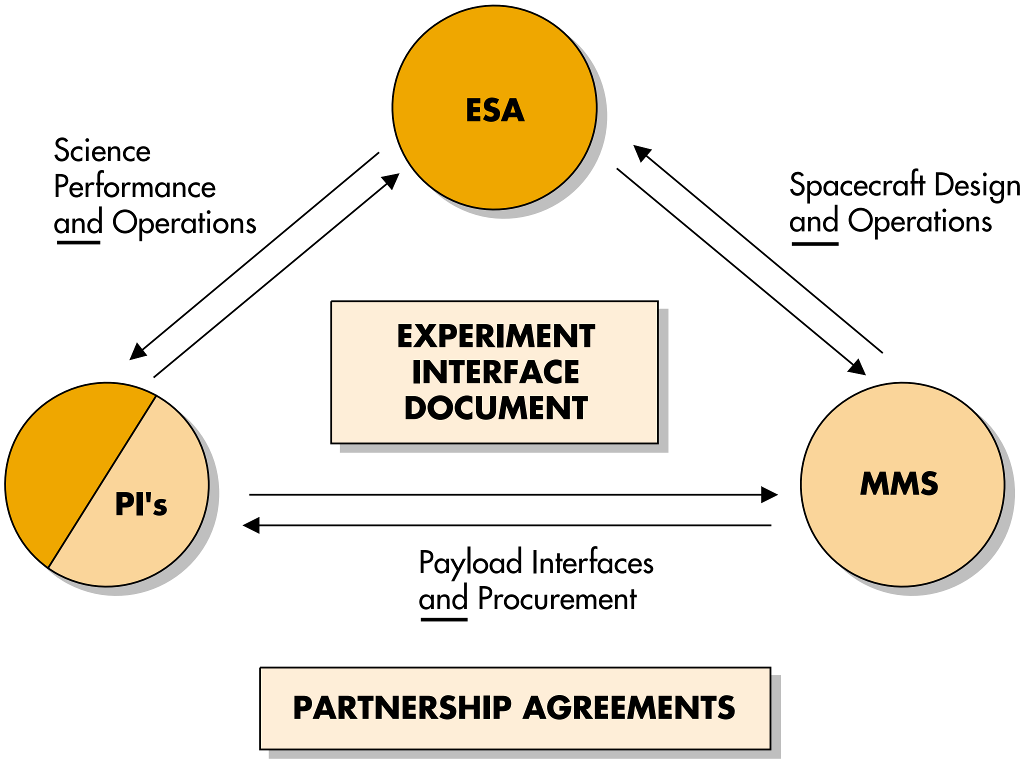


Figure 6. A new relationship between Principal Investigators, ESA and industry

MMS bases the management of the instrument interface on the requirements contained in the Experiment Interface Document (EID-A), as a document applicable to both Principal Investigators and Industry, covering all technical and programmatic aspects. A partnership agreement between MMS and the Principal Investigators has already been established and forms the basis for the EID-A. As part of that agreement, the Principal Investigators will support the industrial team in the timely establishment of the detailed interface control document for the instruments. Progress monitoring, instrument reviews and active participation by the scientists in the instrument verification on the spacecraft will ensure timely delivery of and satisfactory in-orbit performances by the payload.

Planning

The ultimate objective is to execute the launch within the window opening on 1 June 2003 and closing eleven days later. To this end, MMS aims to deliver a fully qualified spacecraft as early as November 2002. The current planning features a three-month margin at spacecraft level with respect to the specified delivery date.

The spacecraft definition phase (Phase-B) will be completed by the end of 1999 (Fig. 7). A detailed plan has been established for this phase and procedures will be implemented to monitor the technical progress against the plan. Commencing in summer 1999, Equipment Suitability Reviews will be held to assess the compatibility of the recurring units with the system requirements. Early activities – for instance the procurement of long-lead items, test-equipment manufacturing and breadboard manufacturing – will be initiated halfway through the design phase in order to protect the schedule. A Preliminary Design Review in November 1999 will conclude the design phase and, upon its successful completion, the go-ahead will be given for the development and production phases (Phases-C and D), nominally starting in January 2000.

Challenges for the industrial team

Mars Express is a formidable challenge for European industry in that it involves executing a very ambitious scientific mission within a stringent cost cap, but without breaching the Agency's standard procurement rules. The mission requirements are very specific and so far unprecedented in Europe. The design and verification effort at system level is therefore completely tailored to this mission and requires strong up-front engineering and rigorous management at spacecraft level.

The intensive reuse strategy necessary to achieve attractive equipment costs coupled with low risk left little flexibility for achieving the required geographical-return targets. New elements or modifications introduced to customise the design to specific mission needs have provided more latitude in this respect. The recurrent units are drawn mainly from ESA's Rosetta programme.

The costs associated with the tasks undertaken by the Prime Contractor remain

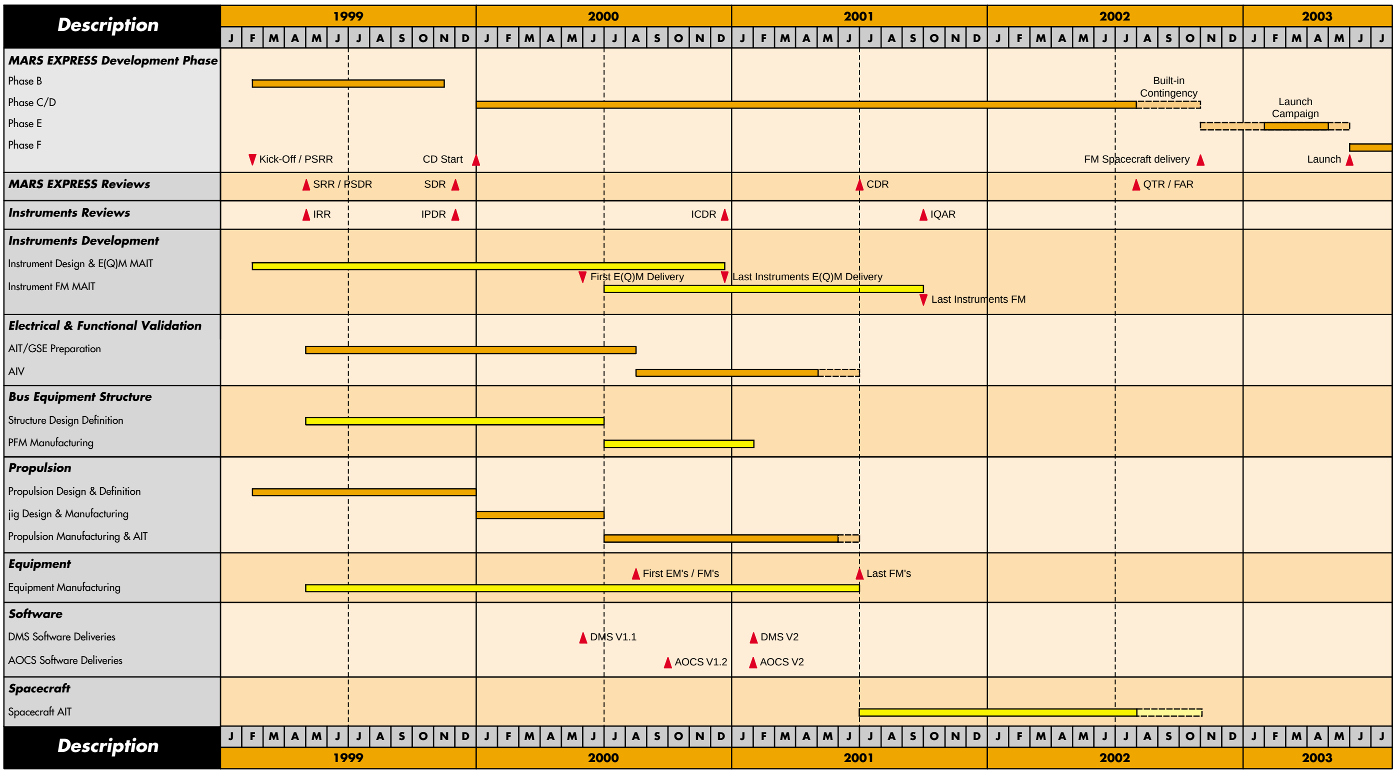


Figure 7. Activities and key events in the procurement of the Mars Express spacecraft

well below those of other programmes in absolute terms, but represent a higher percentage of total programme cost. This stems from the fact the total and unit costs are much lower than for earlier science missions, whereas the prime engineering and management tasks are those associated with a low-risk, high-performance, deep-space scientific spacecraft. These tasks will be shared very efficiently between several companies. New approaches have been introduced to handle the resulting challenges.

In this context, the selection of a skilled and motivated industrial project team with clear objectives is critical to success. All team members must be focused on:
- cost as a paramount parameter
- reuse of existing designs, especially during the detailed definition phase
- in-depth understanding of requirements, particularly scientific requirements, as the best way to avoid over-design
- mission customisation of the spacecraft must be maintained for a limited number of elements and interfaces.

Secondly, there has to be a clear division of responsibilities and clean interfaces between the industrial team, ESA and the scientific teams. The breakdown of activities that has been chosen is the most efficient possible based on company skills and cost efficiency. The spacecraft interfaces with the payload are under direct industrial management, enabling straightforward problem-solving.

The management methods and tools used in the procurement phase must allow cost and scheduling targets to be achieved with minimum risk. Risk minimisation for new developments and elements requires the selection of reliable subcontractors. The numerous interfaces between spacecraft, ground segment, test centre and launcher call for efficient management by an experienced industrial team.

Last but not least, good people management has a role to play in the overall effort towards successful implementation of Mars Express. A small but fully empowered industrial project team will facilitate communications with the scientific teams and with ESA. Hands-on management is emphasised, with the direct involvement of the project manager in technical decisions and the delegation of cost and schedule responsibility to project team members.