The Mars Express Mission: An Overview

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1. Introduction

Mars Express is not only the first ESA mission to the red planet but also the first European mission to any planet. Mars Express was launched in June 2003 from the Baikonur Cosmodrome in Kazakhstan aboard a Russian Soyuz rocket. It included both an orbiter and a small lander named Beagle 2, in remembrance of Charles Darwin's ship. It is the first 'Flexible' mission of ESA's long-term science programme (now known as Cosmic Vision) and was developed in the record time of about 5 years from concept to launch, and in the most cost-efficient manner with respect to any other comparable Mars mission.

Before Mars Express, ESA and the scientific community spent more than 10 years performing concept and feasibility studies on potential European Mars missions (Marsnet, Intermarsnet), focusing on a network of surface stations complemented by an orbiter, a concept that was further developed by CNES in the recently cancelled Netlander mission. The network concept was considered to be a high scientific priority in Europe until the demise of the Russian Mars-96 mission, which included many outstanding European scientific instruments and which may be reconsidered in the future. Mars Express was conceived to recover the objectives concerning the global study of the planet by the Mars-96 mission, and added two major new themes: water and life, following the recommendations of the International Mars Exploration Working Group (IMEWG) and the endorsement of ESA's Advisory Bodies that Mars Express be included in the Science Programme of the Agency.

The scientific investigations of Mars Express closely complement those of recent US orbital missions such as Mars Global Surveyor and Mars Odyssey, as well as the spectacular Mars Exploration Rovers. In addition, very close collaboration was established, in anticipation of future collaboration with Japan, with the Nozomi mission because the scientific objectives and orbital characteristics were complementary. Unfortunately, Nozomi did not reach the planet.

2. Mission Overview

On 2 June 2003 at 17:45:26 UT, a Soyuz rocket with a Fregat upper stage was launched from Baikonur and injected the 1223 kg Mars Express into a Mars transfer orbit. Launch windows to Mars occur every 26 months but 2003 was particularly favourable because it offered the maximum launch mass, a situation that does not repeat for another 16 years. This was important; Beagle 2 could not have been carried in the less-favourable 2005 window.

Mars Express is a 3-axis stabilised orbiter with a fixed high-gain antenna and body-mounted instruments, and is dedicated to the orbital and *in situ* study of the planet's interior, subsurface, surface and atmosphere. It was placed in an elliptical orbit (250 x 10 142 km) around Mars of 86.35° quasi-polar inclination and 6.75 h period, which was optimised for the scientific objectives and to communicate with Beagle 2 and the NASA landers or rovers being launched in 2003-2005.

The spacecraft was captured into Mars orbit on 25 December 2003. Following completion of spacecraft commissioning in mid-January 2004, the orbiter experiments began their own commissioning processes and started acquiring

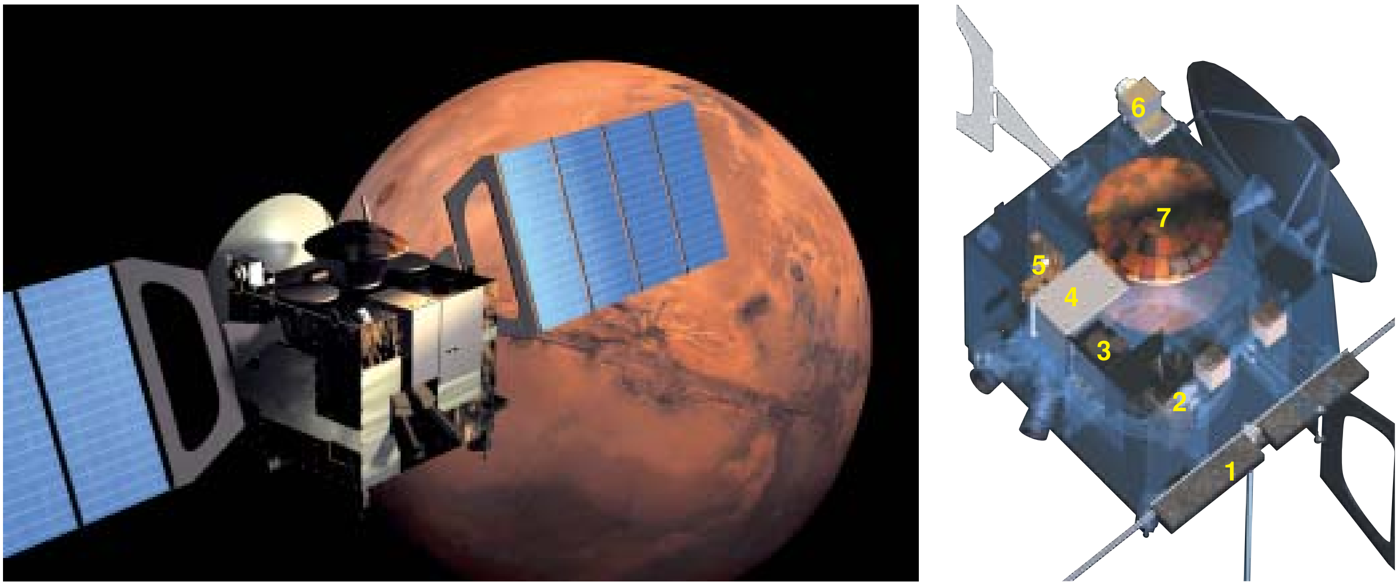

Fig. 1. Mars Express with the Beagle 2 capsule still attached. 1: MARSIS. 2: HRSC. 3: OMEGA. 4: PFS. 5: SPICAM. 6: ASPERA. 7: Beagle 2. (MaRS requires no dedicated hardware).

scientific data from Mars and its environment. The radar antenna was planned to be deployed last in order to maximise early daylight operations of the other instruments, before the natural pericentre drift to the southern latitudes. The optical instruments began their routine operational phase after the Commissioning Review in June 2004. The deployment of the radar antennas was delayed for safety modelling checks. The nominal orbiter mission lifetime is a martian year (687 days), following Mars orbit insertion and about 7 months' cruise. It is hoped that the nominal mission will be extended into a second martian year of operations in order to increase the global coverage of most orbital experiments and, eventually, to allow data-relay communications with potential landers up to 2008, provided that the spacecraft resources allow it.

The Beagle 2 descent capsule was ejected 5 days before arrival at Mars, while the orbiter was on a Mars collision course; Mars Express was then retargeted for orbit insertion. From its hyperbolic trajectory, Beagle 2 entered and descended through the atmosphere in about 5 min, intending to land at < 40 m s^{-1} within an error ellipse of 20 x 100 km. The fate of Beagle 2 remains unknown because no signal was ever received from the martian surface, neither by the UK's Jodrell Bank radio telescope nor by the Mars Express and Mars Odyssey orbiters. All of them made strenuous efforts to listen for the faintest of signals for many weeks following Beagle 2's arrival at Mars. ESA set up a commission to investigate the potential causes of the probable accident and issued a number of recommendations for future missions. The selected landing site was in Isidis Planitia (11.6°N, 269.5°W), which is a safe area of high scientific interest – this impact basin was probably flooded by water during part of its early history, leaving layers of sedimentary rocks. The area is surrounded by geological units of a variety of ages and compositions, from densely cratered highlands to volcanic flows to younger smooth plains. The lander's highly integrated instrument suite was expected to perform a detailed geological, mineralogical and chemical analysis of the site's rocks and soils, provide site meteorology, and focus on finding traces of past or present biological activity. Data from this combination of instruments could have solved the issue of life on Mars. Beagle 2's operational lifetime was planned to be up to 180 sols (about 6 months).

ESA provided the launcher, orbiter, operations and part of Beagle 2, the rest of the lander being funded by a UK-led consortium of space organisations. The orbiter instruments were all provided by scientific institutions through their own funding.

Fig. 2. Mars Express in launch configuration at Baikonur.

Most ESA Member States participated in providing the scientific payload but other countries (including USA, Russia, Poland, Japan and China) have joined in various capacities. The ground segment includes the new ESA station of New Norcia, near Perth, Australia, and the mission operations centre at ESA's European Space Operations Centre (ESOC). A second ESA station at Cebreros, near Madrid, Spain, will be used later in the mission, while NASA's Deep Space Network (DSN) will increase the scientific data return during the whole mission. The orbiter was built by Astrium in Toulouse, France, as prime contractor, together with a large number of European companies as subcontractors in each of ESA's Member States.

3. Scientific Objectives

The Mars Express orbiter is the core of the mission, scientifically justified on its own merit by providing unprecedented global coverage of the planet, in particular of the surface, subsurface and atmosphere. Beagle 2 was selected through its innovative scientific goals and very challenging payload. The combination of orbiter and lander (Figs. 1 & 2) was expected to be a powerful tool to focus on two related issues: the current inventory of ice or liquid water in the martian crust, and possible traces of past or present biological activity on the planet. The broad scientific objectives of the orbiter are:

— global colour and stereo high-resolution imaging with about 10 m resolution and imaging of selected areas at 2 m pix^{-1};
— global IR mineralogical mapping of the surface;
— radar sounding of the subsurface structure down to the permafrost;
— global atmospheric circulation and mapping of the atmospheric composition;
— interaction of the atmosphere with the surface and the interplanetary medium;
— radio science to infer critical information on the atmosphere, ionosphere, surface and interior.

The ultimate scientific objective of Beagle 2 was the detection of extinct and/or extant life on Mars, a more attainable goal being the establishment of the conditions at the landing site that were suitable for the emergence and evolution of life. In order to achieve this goal, Beagle 2 was designed to perform *in situ* geological, mineralogical and geochemical analysis of selected rocks and soils at the landing site. Furthermore, studies of the martian environment were planned via chemical analysis of the atmosphere, local geomorphological studies of the landing site and via the investigation of dynamic environmental processes. Further studies to be performed by Beagle 2 included the analysis of the subsurface regime using a ground-penetration tool and the first *in situ* isotopic dating of rocks on another planet.

The description and detailed science goals of the orbiter and lander experiments are presented below; see also Table 1.

3.1 Orbiter scientific instruments

The Mars Express orbiter scientific payload totals about 116 kg shared by six instruments, in addition to a radio-science experiment that requires no additional hardware. The instruments can be listed in two catagories: those dealing primarily with the solid planet by observing the surface and subsurface (HRSC super/high-resolution stereo colour imager; OMEGA IR mineralogical mapping spectrometer; MARSIS subsurface sounding radar altimeter), and those studying the atmosphere and environment of Mars (PFS planetary fourier spectrometer; SPICAM UV and IR atmospheric spectrometer; ASPERA energetic neutral atoms analyser). The MaRS radio science experiment will provide insights into the internal gravity anomalies, the surface roughness, the neutral atmosphere and the ionosphere of Mars.

The camera is based on the space-qualified HRSC Flight Model 2 developed for the Mars-96 mission, with the addition of a super-resolution channel. Its major goal is global coverage of the planet at high resolution. The scientific interpretation of the data focuses on the role of water and climate throughout martian history, the timing and evolution of volcanism and tectonics, the surface/atmosphere interactions, the establishment of an accurate chronology, and the observation of Phobos and Deimos. In order to meet these objectives, the imaging capabilities of HRSC allow the characterisation of surface features and morphology at high spatial resolution (about 10 m pix^{-1} in stereo, colour and at different phase angles), surface topography at high spatial and vertical resolution with dedicated stereo imaging, surface features and morphology using nested images at super resolution (2 m pix^{-1}), terrain classification by multispectral datasets, scattering properties of the regolith and atmosphere by multi-phase angle observations, and atmospheric properties and phenomena by limb sounding and nadir observations. High- and super-resolution are obtained around pericentre, at and above 250 km.

OMEGA, derived from the Mars-96 spare model, is a visible and near-IR mapping spectrometer operating in the wavelength range 0.38-5.1 µm. It will provide global coverage of Mars by the end of the nominal mission at medium resolution (1-5 km) from orbital altitudes between 1000 km and 4000 km, and higher-resolution (a few hundred metres) snapshots of selected areas, amounting to at least a few percent of the surface. OMEGA is characterising the composition of surface materials, studying the time and space distribution of atmospheric CO_2, CO and H_2O, identifying the aerosols and dust particles in the atmosphere, and monitoring the surface dust transport processes. It is contributing greatly to understanding the evolution of Mars from geological time scales to seasonal variations and is giving unique clues for understanding the H_2O and CO_2 cycles throughout martian evolution.

MARSIS is a low-frequency nadir-looking pulse-limited radar sounder and altimeter with ground-penetration capabilities operated. It uses synthetic aperture techniques, two 20 m booms and a secondary receiving monopole antenna to isolate subsurface reflections. It is the first radar sounder to investigate the martian surface and subsurface. Its primary objective is to map the distribution of water (both liquid and solid) in the upper portions of the crust down to 3-5 km varying with geological composition (nightside). The detection of such water reservoirs addresses key issues

Table 1. The Mars Express scientific experiments.

Expt. Code	*Instrument*	*Principal Investigator*	*Participating Countries*
Orbiter			
HRSC	Super/High-Resolution Stereo Colour Imager	G. Neukum *DLR/FU, Berlin, D*	D, F, RU, USA, FIN, I, UK
OMEGA	IR Mineralogical Mapping Spectrometer	J.P. Bibring *IAS, Orsay, F*	F, I, RU
PFS	Atmospheric Fourier Spectrometer	V. Formisano *CNR, Frascati, I*	I, RU, PL, D, F, E, USA
MARSIS	Subsurface-Sounding Radar/Altimeter	G. Picardi *Univ. Rome, I* & J. Plaut *NASA/JPL*	I, USA, D, CH, UK, DK, F, RU
ASPERA	Energetic Neutral Atoms Analyzer	R. Lundin & S. Barabash *RFI, Kiruna, S*	S, D, UK, F, FIN, I, US, RU
SPICAM	UV and IR Atmospheric Spectrometer	J.L. Bertaux *CNRS, Verrières, F*	F, B, RU, US
MaRS	Radio Science Experiment	M. Paetzold *Univ. Köln, D*	D, F, US, A
Lander			
Beagle 2	Suite of imaging instruments, organic and inorganic chemical analysis, robotic sampling devices and meteo sensors	C. Pillinger *Open Univ., UK* & M. Sims *Leicester Univ., UK*	UK, D, US, F, CH, RU, PRC, A, E

in the geological, hydrological, climatic and possibly biological evolution of Mars, including the current and past global inventory of water, the mechanisms of transport and storage of water, the role of liquid water and ice in shaping the landscape of Mars, the stability of liquid water and ice at the surface as an indication of climatic conditions, and the implications of the hydrological history in the evolution of possible martian ecosystems. Secondary MARSIS objectives include subsurface geologic probing, surface roughness and topography characterisation at scales from tens of metres to km (dayside), and ionosphere sounding (dayside) to characterise the interactions of the solar wind with the ionosphere and the upper atmosphere. At the time of going to press, the radar booms had not been deployed.

The Planetary Fourier Spectrometer, also derived from a Mars-96 model, is a double-pendulum IR spectrometer optimised for atmospheric studies. It covers the wavelength ranges 1.2-5 µm and 5-45 µm with a spectral resolution of 2 cm^{-1} and a spatial resolution of 10-20 km. The main scientific objectives are the global long-term monitoring of the 3-D temperature field in the lower atmosphere, the measurement of the minor constituent variations (water vapour and carbon monoxide) and D/H ratio, the determination of the size distribution, chemical composition and optical properties of the atmospheric aerosols, dust clouds, ice clouds and hazes, and the study of global circulation and dynamics. PFS will also determine the thermal inertia (from the daily surface temperature variations), the nature of the surface condensate and seasonal variations of its composition, the scattering phase function, pressure and height for selected regions, and is studying the surface-atmosphere exchange processes.

SPICAM is a UV and IR spectrometer devoted to studying the atmosphere. It is focusing on atmospheric photochemistry, the density-temperature structure of the atmosphere (0-150 km), the upper atmosphere-ionosphere escape processes, and the interaction with the solar wind. The UV sensor is looking through the atmosphere either at the Sun or stars to obtain vertical profiles by occultation, or to the nadir to obtain integrated profiles, or at the limb to obtain vertical profiles of high-atmosphere emissions. The IR sensor is used only in the nadir-looking mode (column abundances and H_2O, CO_2 and O_3 cycles). SPICAM measurements are addressing key questions into the present state of the atmosphere, its climate and evolution. SPICAM and PFS are highly complementary.

The ASPERA energetic neutral atom analyser is studying plasma domains at different locations along the spacecraft's orbit, focusing on the interaction of the upper atmosphere with the interplanetary medium and the solar wind, and characterising the near-Mars plasma and neutral gas environment. The scientific objectives are being met by studying remote measurements of energetic neutral atoms in order to investigate the interaction between the solar wind and the atmosphere, characterise quantitatively the impact of plasma processes on atmospheric evolution, and obtain the global plasma and neutral gas distributions in the near-Mars environment. *In situ* measurements of ions and electrons complement the energetic neutral atom images; they have never been obtained before and provide undisturbed solar wind parameters. A similar instrument was carried by the Japanese Nozomi mission.

The MaRS radio science experiment does not require dedicated hardware but it is performing radio sounding experiments of the neutral martian atmosphere and ionosphere to derive vertical density, pressure and temperature profiles as a function of height, and the diurnal and seasonal variations in the ionosphere. It is also determining the dielectric and scattering properties of the martian surface in specific target areas with a bistatic radar experiment for the first time, and is determining gravity anomalies in the crust in order to investigate the structure and evolution of the interior. Precise determination of the mass of Phobos and radio sounding of the solar corona during superior conjunction with the Sun are also among the objectives. The experiment relies on the observation of the phase, amplitude, polarisation and propagation times of radio signals transmitted by the spacecraft and received at ground stations on Earth. This experiment has a significant heritage from its equivalent on the Rosetta mission.

Although not considered as part of the scientific payload, two subsystems on the spacecraft were planned to benefit particularly from Beagle 2 operations. The Mars Express Lander Communications (MELACOM) subsystem is the orbiter-to-lander data relay transponder, with the primary mission of providing data services for the lander. Mars Express was scheduled to fly over the landing site every 1-4 sols and was to relay scientific data to the UK-based Lander Operations Centre via ESOC. The Visual Monitoring Camera (VMC) also remained as part of the orbiter. This standalone digital camera imaged the successful separation of Beagle 2 before arrival at Mars.

3.2 Lander scientific instruments

Although Beagle 2 (Fig. 3) did not accomplish its mission because it was most likely lost during the entry, descent and landing, it is still relevant to review the various scientific instruments and robotic tools, given the importance of the investigations and the high standards to which they were built. It is hoped that another opportunity will allow all or some of these instruments to fly again to Mars to undertake the search for life.

The lander's scientific payload totalled less than 10 kg, shared between six instruments and two dedicated tools to sample the surface and subsurface materials of Mars, plus a robotic sampling arm with 5 degrees-of-freedom. Two were mounted directly on the lander platform: the Gas Analysis Package and the Environmental

THE ISSUE OF WATER

Today, liquid water cannot exist on the surface of Mars because of the low atmospheric density (6 mbar). However, there is ample evidence that liquid water flowed freely in the early history of Mars, as witnessed by dry riverbeds in the heavily cratered Noachian southern highlands. The early climate appears to have been warm and wet (although there are renewed doubts about this) until about 3.8 billion years ago, much like the Earth's at about the same age. This was when life appeared on our planet, as evidence from Greenland indicates. So, if the conditions were similar on both planets, it appears reasonable for biological activity to have flourished on Mars as well. Soon after 3.8 billion years ago (in geological terms), surface conditions changed dramatically, creating the cold and dry place of today, as modest erosion rates at the Mars Pathfinder site illustrate. There is also growing evidence that the young smooth northern plains were once covered by a liquid-water ocean extending over a third of the planet. The question is thus: where has all this water gone? Was it lost into space through natural degassing, including atmospheric erosion through large impacts, or is it still somewhere on Mars, probably below the surface in ice form, as in terrestrial permafrost? Recent Mars Odyssey gamma-ray spectroscopy data have revealed a significant concentration of H^+ ions adsorbed to the first few microns of soil in both polar caps. However, in light of similar results on the Moon from Lunar Prospector, where we know from rock samples there is no water at all, these data only indicate an existing mechanism concentrating H^+ from the solar wind towards the poles. Therefore, most of the Mars Express orbiter instruments are directed towards settling this issue, in particular through radar subsurface sounding (MARSIS), surface mineralogical mapping (OMEGA), establishment of a detailed chronology of geological evolution (HRSC), imaging of atmospheric escape (ASPERA) and the study of the H_2O, CO_2 and dust cycles in the atmosphere (PFS and SPICAM). Never has a mission to Mars been so focused on producing the water inventory of the planet, and never has it been so well equipped to find out.

THE ISSUE OF LIFE

The Mars Express mission planned to address the issue of the emergence of life in the cosmos and, in particular, life signatures on Mars both directly and indirectly. The majority of orbiter instruments are looking for indications of favourable conditions for the existence of life, either at present or during the planet's past, and particularly for traces of liquid, solid or gaseous water. The HRSC camera is imaging ancient riverbeds, the OMEGA spectrometer is looking for minerals with OH^- radicals formed in the presence of water, the MARSIS radar will look for subsurface ice and liquid water, the PFS and SPICAM spectrometers are analysing water vapour in the atmosphere, and ASPERA and MaRS are studying neutral-atom escape from the atmosphere, in particular O_2 coming from water and carbonates. The instruments on Beagle 2 were designed to look for the presence of water in the soil, rocks and atmosphere, and in particular to look for traces of life with direct measurements, such as the presence of a larger amount of the light C^{12} isotope compared to the heavier C^{13}, which would have indicated the existence of extinct life, or even the presence of methane, indicative of extant life together with other organic compounds. Results from a single instrument will most likely not allow the issue of life on Mars to be settled, but all the measurements taken together will allow us to build a scenario pointing, or not, in the direction of present or past life on Mars. Either way, the cosmobiological implications would be far-reaching: we would know if life is a common occurrence in the Universe or not. In this debate, comparing the geological evolutions of Earth and Mars is obviously a fruitful exercise because the planets share seasons, polar caps, a transparent atmosphere and aeolian activity, for example. Our other planetary twin neighbour, Venus, must not be forgotten in view of its similarities with Earth in terms of internal activity and recent resurfacing. Comparative planetology is the key to our understanding of Solar System evolution, including cosmobiology. Since NASA's Viking missions in 1976, it is the first time that the exhaustive search for life is so central to a space mission to Mars, even after the failure of Beagle 2.

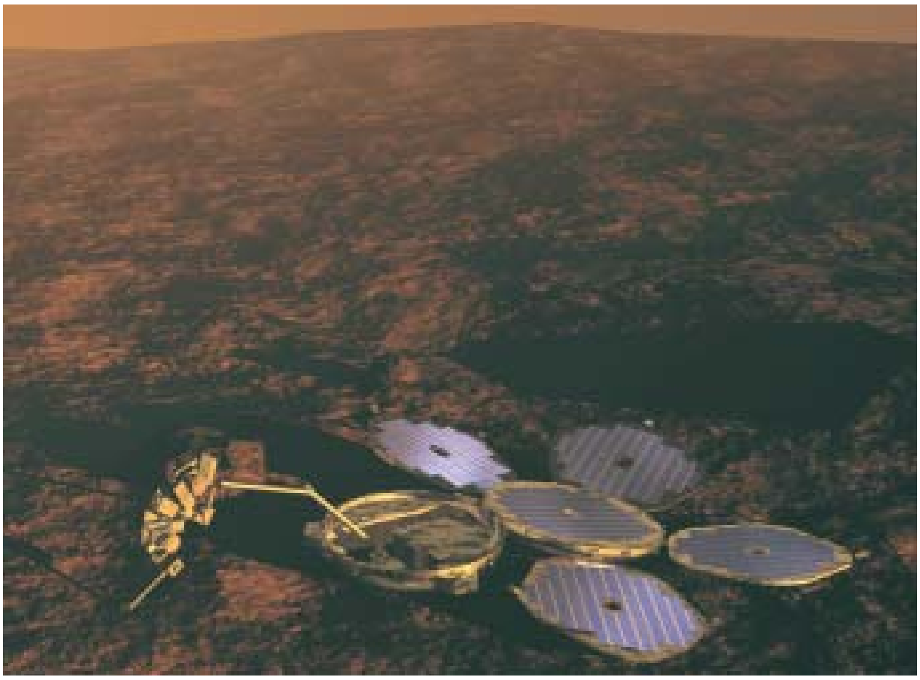

Fig. 3. Beagle 2 operating on the surface of Mars.

Sensor Suite. The others were housed within an innovative structure called the Payload Adjustable Workbench (PAW) at the end of the robotic sampling arm: the Stereo Camera System, Microscope, X-ray Spectrometer and Mössbauer Spectrometer, together with a set of tools that included the Rock Corer Grinder, the PLanetary Underground TOol and other support equipment such as a sampling spoon, a torch and a wide-angle mirror. The PAW also carried one of the ESS sensors. The science-payload-to-landed-structure ratio is about 1/3, the highest so far of any planetary lander.

The Gas Analysis Package (GAP) is designed for quantitative and qualitative analysis of sample composition and precise isotopic measurements. It can process atmospheric samples and soil or rock chippings acquired by the sampling tools. These are deposited via an inlet system into one of eight miniaturised ovens. Gases are analysed directly (such as those present in the atmosphere), after their release from samples by heating, or those resulting from a byproduct of chemical processing (e.g. CO_2). GAP is very flexible and can investigate processes dealing with atmospheric evolution, circulation and cycling, the nature of gases trapped in rocks and soils, low-temperature geochemistry, fluid processes, organic chemistry, formation temperatures and surface exposure ages, and can also assist in isotopic rock dating.

The Environmental Surface Suite (ESS) contributes to the characterisation of a landing site and to meteorological studies through the measurements from 11 parameter-sensors scattered around the lander platform and PAW. Measurement of the UV and radiation flux at the surface together with the oxidising capability of the soil and atmosphere provides insights into exobiological investigations. In addition, the measurement of atmospheric temperature, pressure, wind speed and direction, dust saltation and angle of repose complements the *in situ* environmental experiments.

The Stereo Camera System (SCS) consists of two identical CCD cameras and integrated filter wheels. A primary engineering objective of the Beagle 2 SCS was the construction of a Digital Elevation Model (DEM) of the landing site from a series of overlapping stereo image pairs. The DEM was to be reconstructed on Earth and used to position the PAW with respect to target rocks and soils. The investigation of the landing site included 360° panoramic imaging, multi-spectral imaging of rocks and soils to determine the mineralogy, and close-up imaging of rocks and soils to infer the texture. Observations of the day and night sky, Sun, stars and Deimos and Phobos allow the identification of atmospheric properties such as optical density, aerosol properties and water vapour content. The SCS also supports the determination of the landing site location by providing panoramic and celestial navigation images. Furthermore, the observation of lander surfaces and atmospheric effects allows the identification of dust and aerosol properties in the atmosphere.

The Microscopic Imager (MIC) investigates the nature of martian rocks, soils and fines at the particulate scale (few mm). Such studies would have provided important data to fulfil Beagle 2's exobiological objectives in the form of direct evidence of microfossils, microtextures and mineralisations of biogenic origin, if present. In addition, identifying the physical nature and extent of the weathering rinds/coatings on rocks and soils contributes to the geological characterisation of a landing site. Atmospheric and global planetary studies also benefit from detailed knowledge of dust morphology. The MIC was the first attempt to image and assess directly individual particles of sizes close to the wavelength of scattered light on another planet. The acquisition of complete sets of images for each target allows the 3-D reconstruction of sample surfaces in the visible and UV.

The primary goal of the X-Ray Spectrometer (XRS) is to determine, *in situ*, the elemental composition and, by inference, the geochemical composition and petrological classification, of the surface material at the landing site. Major elements (Mg, Al, Si, S, Ca, Ti, Cr, Mn, Fe) and trace elements up to Nb are detectable. The instrument employs X-ray fluorescence spectrometry to determine the elemental constituents of rocks, using a set of four radioisotope sources (two ^{55}Fe and two ^{109}Cd) to excite the sample. Crude radiometric dating of martian rocks *in situ* was to be performed using the ^{40}K/^{40}Ar method. For this, the XRS needs to make a precise measurement of K on a 'fresh' sample of rock. The Ar component is determined by the GAP as part of a suite of experiments performed on a core sample extracted from the same specimen.

The Mössbauer Spectrometer (MBS) allows a quantitative analysis of Fe-bearing materials in rock and soil materials. The Fe-rich nature of martian deposits enables relative proportions of Fe in olivine and pyroxene to be determined using the Mössbauer technique, together with magnetite in basalts. Owing to the abundance of Fe-bearing minerals on Mars and their formation being linked to the history of water on the planet, MBS measurements are particularly important. Also, these results provide information about rock weathering in general, and oxidation in particular. The MBS uses gamma rays from the decay of ^{57}Co to ^{57}Fe. The generated spectra allow the characterisation of the mineralogical make-up of rocks and soils, and hence their petrological classification. In conjunction with the X-ray spectrometer, the Mössbauer spectrometer complements the *in situ* geochemical and petrological work, and provides support for the GAP measurements.

The Rock Corer Grinder (RCG) on the PAW is a combined tool that addresses the scientific prerequisite that all the PAW instruments have access to pristine material on a suitably prepared rock surface to avoid the effects of weathering rinds and geometric effects that can seriously compromise instrument performance. The RCG removes the altered material and produces a flat, fresh surface suitable for both types of spectrometer measurements. After the *in situ* analyses have been completed, a sample from the ground patch is extracted by the coring action of the device, and delivered to the GAP inlet port for chemical analysis.

The PLUTO (PLanetary Underground TOol) is another PAW tool to retrieve soil samples from depths down to about 1.5 m and, depending on the terrain, from under a large boulder. This capability is very important for exobiological investigations because materials preserving traces of biological activity would be found at depth within the soil or rocks, where they would be unaffected by solar-UV radiation. In addition to its main function as a soil sample-acquisition device, PLUTO allows *in situ* temperature measurements as a function of time and depth as it travels below the surface. The ground-intrusion behaviour also allows the mechanical properties and layering of the soil to be estimated.

Coordination between Mars Express orbital observations and Beagle 2 experiments had to be carefully planned, so that the lander could provide ground truth to the orbiter through its detailed geological and chemical analysis, and the orbiter could provide the landing site regional context for the Beagle 2 experiments. Detailed studies of the Beagle 2 landing site have also been carried out.

4. Science Operations

The 'G3-UB' baseline orbit of Mars Express has a quasi-polar inclination of 86.35°. In order to fine-tune observation parameters such as illumination, a manoeuvre was performed to transition from a G3-U to a G3-B orbit a few weeks after Mars orbit insertion. The total number of orbits during the nominal mission is 2293, which corresponds to slightly more than 3 orbits per sol. Good illumination conditions for a systematic coverage of the whole surface is a major requirement for the global coverage strategy. Priorities are dictated by scientific goals (e.g., polar coverage, regions of interest, targets of opportunity) and, at the beginning of the mission, by the need to fly over the lander site in the Isidis Planitia area. Beagle 2 communication contacts were repeatedly attempted for more than a month, and were expected to vary between once a week to once a day during nominal Beagle 2 operations. The lander lifetime, a main driver of the orbiter's early science operations, was estimated to be about 6 months as a result of decreasing illumination and dust building up on the lander panels.

Mars Express is recording science data onboard and dumping it during ground station passes. The daily data volume varies throughout the year from less than 1 Gbit to about 6 Gbits, via the single New Norcia ground station with its 35m antenna and 8 h daily coverage. The use of NASA's Deep Space Network is planned in order to increase the capacity.

As one of the various actors in Mars Express science operations, the Payload Operations Service (POS) was established at the Rutherford Appleton Laboratory, (Chilton, UK) to support the Mars Express Project Scientist Team (PST), the Principal Investigators (PIs), the Mission Operations Centre (MOC) and the Lander Operations Centre (LOC). The POS carried out the development, implementation, testing and operations of the system and tools required to support Mars Express science operations under contract from ESA. The PST and PIs compile the Master Science Plan (MSP) to schedule the acquisition of science data by the spacecraft in a way that is consistent with the scientific objectives and the resources available during the observation time. The MSP represents the basis of all payload operations timeline planning during the various phases of the mission. The high-level scientific planning is performed by the Science Operations Working Group (SOWG), which includes representatives of all the PI teams. PST and POS both interface with the MOC, the PI institutes and the LOC.

4.1 Data distribution

To further the potential use of the Mars Express scientific data, as well as to benefit from a new scientific perspective, ESA established a participating programme for Interdisciplinary Scientists (IDSs) and Recognised Cooperating Laboratories (RCLs). The six selected IDSs (half being non-European) bring their expertise in various multidisciplinary fields, such as the space environment, surface-atmosphere interactions, geological evolution or cosmobiology, in order to support various PI teams by typically combining data from several instruments into investigations from a fresh viewpoint. The RCLs have IDS guidance to prepare themselves for interpreting the data when they become available to the public after the 6-month proprietary period and distributing them further into the geoscience community and/or country they represent, as these RCLs have been selected to encourage scientific groups from areas new to space activities to participate in ESA planetary missions. In addition, ESA is building a scientific data archive for all planetary missions as a repository of European planetary data after the 6-month proprietary period (see below).

4.2 Data archiving

The Planetary Science Data Archive (PSA) is an online archive that provides data search and access via the Internet of ESA's planetary missions, data-formatted to NASA's Planetary Data System (PDS) standards. Following the request by Mars Express PI teams for the archive to offer additional functionality on top of the delivery of PDS-compliant data sets, the reuse of an existing astronomy scientific data archive architecture was adopted because it offered significant cost benefits over developing an entirely new system. This archive will be located at the European Space Astronomy Centre (ESAC), Villafranca, Spain, while expertise exists in the PST at ESTEC. Detailed requirements have been defined for the PSA by representatives from a wide variety of disciplines, who will support the testing and overall future functionality of the PSA. The PSA will support scientists looking for data on specific topics, particular instruments or given locations on the planet, as well as helping the general public and educators, interested in visually appealing or easy-to-interpret data.

5. International Collaboration

International collaboration beyond the ESA Member States, through participation in either instrument hardware or scientific data analysis, is important for diversifying the scope and quality of the mission's the scientific return. Three major partners are contributing to the mission: USA, Russia and Japan. NASA provided a major share of MARSIS and is supporting Co-Investigators in most of the scientific payloads. NASA is also making its DSN available to increase the science data download throughout the mission, including critical manoeuvres. Russian scientists are involved in most of the orbiter experiments as many of these originated on Mars-96 as joint collaborations between European and Russian institutes. Other non-ESA countries participating in the mission include Poland and China.

Collaboration with Japan is a special case, although the high expectations were unfortunately not met. Turning the malfunction of the Nozomi spacecraft soon after launch in 1998 into a positive event, the Mars Express and Nozomi Science Working Teams began a close collaboration because both missions were then expected to reach Mars at the same time. In the end, however, Nozomi could only fly past Mars because its technical difficulties could not be overcome to enter orbit. This collaboration included scientific data exchange and analysis, as well as the ongoing exchange of scientists from all the instrument teams. The missions were highly complementary in terms of orbits and scientific investigations, with Nozomi focusing on the atmosphere and in particular its interaction with the solar wind from a highly-elliptic equatorial orbit, while Mars Express is devoting a large share of its mission to the surface and subsurface from polar orbit. Never before was a planet expected to be simultaneously observed from two different geometries by two orbiters of different space agencies. This tandem exploration was planned to pave the way for even closer cooperation in the future between Europe and Japan to other targets, such as Mercury.

Further details on the Mars Express mission and its Beagle 2 lander can be found at *http://sci.esa.int/marsexpress/* and *http://www.beagle2.com/*