Studies on the Re-use of the Mars Express Platform

A. Gimenez, J-P. Lebreton, H. Svedhem & J. Tauber
Research and Scientific Support Department, ESA Directorate of Scientific Programmes, ESTEC, Noordwijk, The Netherlands

The studies that were carried out in 2001 around the possibility of re-using the Mars Express platform have proven the effectiveness of a fast approach between ESA and the scientific community. It was only in March 2001 that ESA issued a 'Call for Ideas' to react to the identified possibility of a low-cost mission based on the re-use of the platform developed for Mars Express, which will be launched in 2003. A strict schedule was imposed, in order to benefit from these special circumstances, aiming at a launch date for the new mission in 2005, which is the next 'window' for missions to Mars. In response to the Call for Ideas, the scientific community presented a wealth of interesting and challenging proposals.

In order to proceed with the necessary studies leading to a possible decision within the year, the advisory bodies of the Scientific Programme made an in-depth but fast evaluation of all of the proposals, resulting in a recommendation to further study three of them: Venus Express, with the objective of exploring the inner planets of our Solar System, focussing on Venus; Cosmic DUNE, aimed at studying the interplanetary cosmic dust as well as the interstellar contribution; and SPOrt Express, measuring the polarisation of the Cosmic Microwave Background.

The definition studies for the three missions were carried out between mid-July and mid-October 2001, including payload, accommodation on the platform, mission analysis, and scientific performance. The results, which are summarised in the following contributions, were presented to the Solar System and Astronomy Working Groups, which made their recommendations for a possible implementation. In November, the ESA Space Science Advisory Committee (SSAC) recommended Venus Express as a candidate mission for inclusion in the Agency's Science Programme. This recommendation was finally presented to the Science Programme Committee (SPC) in December 2001 and Venus Express will thus be considered in the current planning exercises. If finally implemented, this mission will take Europe to Venus, thereby giving the scientific community complete access to all of the Solar System's inner planets (together with the Mars Express mission to the red planet and the BepiColombo mission to Mercury).

Venus Express

by J-P. Lebreton

Introduction

The Venus Express spacecraft – an Orbiter for the study of the atmosphere, plasma environment and surface of Venus – is derived from the Mars Express bus, with some modifications to cope with the hotter thermal environment at Venus (Fig. 1). The scientific payload included in the Venus Express Study comprises six instruments derived from Mars Express or Rosetta flight-spare units. In addition, during the study it was found scientifically reasonable and technically feasible to replace the standard Mars Express engineering Video Monitoring Camera by a scientific instrument known as the Venus Monitoring Camera (VMC).

Venus Express is foreseen to be launched from Baikonur in November 2005 by a Soyuz-Fregat rocket onto a direct transfer trajectory to Venus. It would arrive at Venus about 150 days after launch and be inserted into a highly elliptical polar orbit The baseline orbit selected during the mission-definition phase is a quasi-polar orbit with a pericentre altitude of ~250 km and an apocentre in the 30 000 – 45 000 km range, corresponding to an orbital period of 9.6 to 16 hours. A nominal mission duration of 2 Venusian days (480 Earth days) is foreseen.

Together with the Mars Express mission to Mars and the BepiColombo mission to Mercury, the proposed mission to Venus, through the expected quality of its science results, would ensure a coherent programme of terrestrial-planet exploration and secure for Europe a leading position in this field of planetary research. The international cooperation formed in the framework of the Mars Express and Rosetta missions will be inherited by Venus Express, and will include the efforts of scientists from Europe, the USA, Russia and Japan. The Venus Express orbiter will play the role of pathfinder for future, more complex missions to the Earth's twin planet, and the data obtained will help to plan and optimise future investigations.

Venus studies can have significant public outreach given the exotic conditions on the planet and the interest in comparing Venus to Earth, especially in a context of concern regarding the climatic evolution on Earth.

Scientific objectives
The fundamental mysteries of Venus are related to the global atmospheric circulation, the atmospheric chemical composition and its variations, the surface/atmosphere physical and chemical interactions including volcanism, the physics and chemistry of the cloud layer, the thermal balance and role of trace gases in the greenhouse effect, the origin and evolution of the atmosphere, and the plasma environment and its interaction with the solar wind. The key issues of the history of Venusian volcanism, the global tectonic structure of Venus, and important characteristics of the planet's surface are also still unresolved. Beyond the specific case of Venus, resolving these issues is of crucial importance in a comparative-planetology context and for understanding the long-term climatic evolution processes on Earth-like planets.

The above problems can be efficiently addressed by an orbiter equipped with a suite of remote-sensing and in-situ instruments. Compared with earlier spacecraft missions, a breakthrough will be accomplished by Venus Express by fully exploiting the existence of spectral 'windows' in the near-infrared spectrum of Venus' night side, discovered in the late 1980s, in which radiation from the lower atmosphere and even the surface escapes to space and can be measured. Thus, a combination of spectrometers, spectro-imagers, and imagers covering the ultraviolet to thermal-infrared range, along with other instruments such as a radar and a plasma analyser, is able to sound the entire Venus atmosphere from the surface to 200 km altitude, and to address specific questions on the surface that would complement the Magellan investigations. This mission will also tackle still-open questions about the plasma environment, focusing on the studies of non-thermal atmospheric escape. This issue will be addressed via traditional in-situ measurements, as well as via innovative ENA (Energetic Neutral Atom) imaging techniques.

The Venus Express mission will achieve the following 'firsts':
– first global monitoring of the composition of the lower atmosphere in the near-infrared transparency 'windows'
– first coherent study of the atmospheric temperature and dynamics at different levels of the atmosphere from the surface up to ~200 km altitude
– first measurements of global surface temperature distribution from orbit
– first study of the middle and upper atmosphere dynamics from O_2, O, and NO emissions
– first measurements of the non-thermal atmospheric escape
– first coherent observations of Venus in the UV to thermal-IR range (Pioneer Venus did this, but Venus Express will do it better)

Historical Context

The first phase of Venus spacecraft exploration (1962 – 1985) by the Mariner, Venera, Pioneer Venus and Vega missions established a basic description of the physical and chemical conditions prevailing in the atmosphere, near-planetary environment, and at the surface of the planet. At the same time, they raised many questions about the physical processes sustaining these conditions, most of which still remain unanswered today. Extensive radar mapping by Venera-15, Venera-16 and Magellan orbiters, combined with earlier glimpses from landers, have expanded considerably our knowledge of Venus' geology and geophysics. A similar systematic survey of the atmosphere is now in order. This particularly concerns the atmosphere below the cloud tops which, with the exception of local measurements from descent probes, has remained inaccessible to previous Venus orbiters. Many problems of the solar-wind interaction, particularly those related to its impact on planetary evolution, are still not resolved.

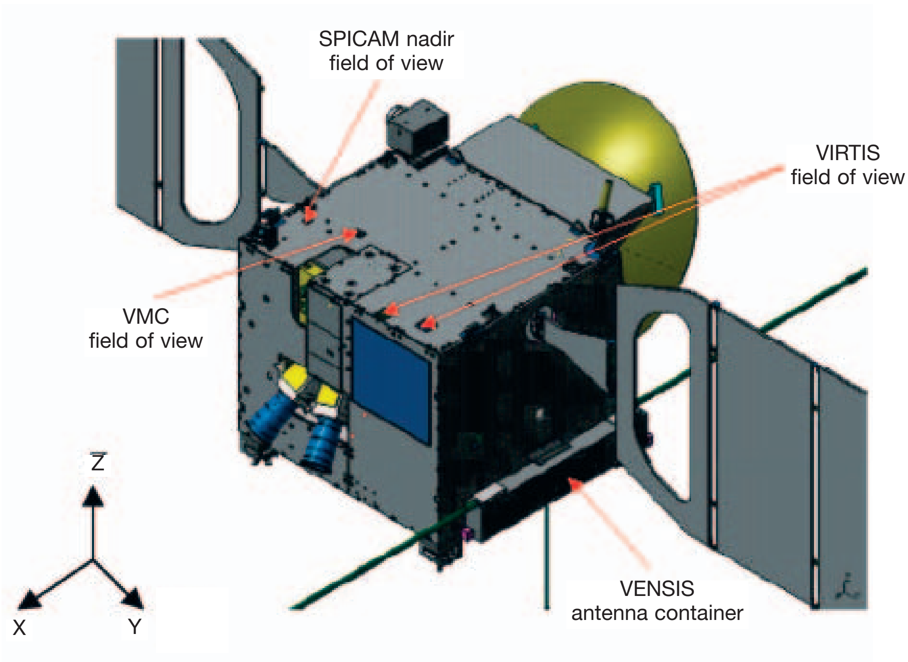


Figure 1. The Venus Express spacecraft with solar panels and VENSIS antennas deployed

– first application of the solar/stellar occultation technique at Venus
– first use of a three-dimensional ion-mass analyser, high-energy-resolution electron spectrometer, and energetic neutral-atom imager
– first sounding of the Venusian top-side ionospheric structure
– first sounding of the Venusian subsurface.

Scientific payload
In order to be able to develop a mission in less than three years, the Call for Ideas for the re-use of the Mars Express platform required that the Venus Express payload be selected from existing flight-spare units developed for previous planetary missions.

During the proposal phase, five available flight-spare instruments developed for the Mars Express and Rosetta missions that were best-suited for addressing the scientific objectives laid down above were identified. A list of potential additional instruments that were worth considering during the study phase were also identified. Following the recommendation of the Solar System Working Group, the VENSIS radar sounder was included in the payload-accommodation studies. In addition, the Mars Express engineering Video Monitoring Camera, whose main function aboard Mars Express is to take images of Beagle-2, was replaced by a scientific instrument called the Venus Monitoring Camera (VMC).

The main characteristics of the scientific instruments are therefore as follows:

– SPICAM: a versatile UV-IR spectrometer for solar/stellar occultations and nadir observations (heritage Mars Express)
– PFS: a high-resolution IR Fourier spectrometer (heritage Mars Express)
– ASPERA: a combined energetic neutral-atom imager, electron, and ion spectrometer (heritage Mars Express)
– VeRa: a radio-science experiment (heritage Rosetta)
– VMC: a wide-angle Venus imaging camera (heritage new/Rosetta/Mars Express)
– VENSIS: a surface, subsurface and ionosphere sounding radar (heritage Mars Express)
– VIRTIS: a sensitive visible/IR spectro-imager and mid-IR spectrometer (heritage Rosetta).

Addition of a high-resolution solar occultation infrared channel to SPICAM and of a magnetometer sensor to ASPERA is under consideration.

Spacecraft configuration
The Venus Express spacecraft is derived from the Mars Express platform and is based on a box-like shape of 1.7 x 1.7 x 1.4 m^3. Power is provided by a steerable, two-winged solar array with one degree of freedom. Its symmetrical configuration is favourable for aero-braking techniques (a capability built into the spacecraft design, but not foreseen to be used at Venus) and minimising the torques and forces on the arrays and drive mechanisms during orbit-insertion manœuvres performed with the main engine. The spacecraft has a fixed high-gain antenna.

Within the overall integrated design of the spacecraft, there are just four main assemblies, to simplify the development and integration process:

– the propulsion module with the core structure
– the Y lateral walls, supporting the spacecraft avionics and the solar arrays
– the Y/+X shear wall and the lower and upper floors, supporting the payload units; the +Z face is nominally nadir-pointed during the science-observation and communications-relay phases around the planet and Aspera-3
– the X lateral walls supporting the high-gain antenna (-X) and instrument radiators (+X).

Attitude and orbit control is achieved using a set of star sensors, gyros, accelerometers and reaction wheels. A bipropellant reaction-control system is relied upon for orbit and attitude manoeuvres, using either a 400 N main engine or banks of 10 N reaction-control thrusters.

The data handling is based on packet telemetry and telecommanding. The electrical power is generated by solar arrays, and stored by a lithium-ion battery. A standard 28 V regulated main bus is available to the payload instruments.

The RF communication system is designed to transmit X-band telemetry via the high-gain antenna at rates between 28 and 230 kbps, depending on the planet-to-Earth distance. A variable telecommand rate between 7.81 and 2000 bps (overall) is foreseen.

The Mars Express platform needs to be adapted to the hotter thermal environment at Venus. The modifications required, which include adaptation of the thermal accommodation of the instruments, have been well identified during the industrial study phase and present no particular challenge.

Mission design and operations scenario
Venus has a near-circular orbit with a radius of approximately 0.72 AU, an inclination of 3.4 deg with respect to the ecliptic, and an orbital period of just over 224 days. The transfer to a Venus crossing can be

accomplished with an Earth escape velocity of approximately 2.8 km/sec, which is the minimum-energy case. The shortest possible transfer period from Earth to Venus encounter is 120 days. By contrast, the minimum-energy transfer to Mars requires a higher escape velocity, at 3.25 km/sec, and a transfer period of 220 days.

Venus Express is proposed to be launched with a Soyuz-Fregat rocket from Baikonur in November 2005 on a direct trajectory to Venus. After a transfer phase of about 150 days, it will be inserted into a highly elliptical five-day orbit around Venus. The spacecraft will be transferred to its operational orbit by lowering the apoapses to an altitude in the 30 000 – 45 000 km range.

Mission development schedule

The proposed Venus Express mission design builds on a strong heritage from the Mars Express platform and on both the Mars Express and Rosetta payloads, which are fully compatible with the Mars Express bus. Therefore, in order to save money, the spacecraft will be designed using a proto-flight-model approach, with direct integration of the flight-model payload instruments. The overall development schedule is shown in Figure 2.

Following the SPC's recommendation in December 2001, Venus Express is a candidate mission to be included within the revised ESA Science Programme that is under review. A final decision is expected in June 2002. In order to maintain a schedule compatible with a November 2005 launch date, pre-Phase-B activities on the spacecraft and payload have been initiated in February 2002.

Conclusion

The Venus Express mission-definition study demonstrated the feasibility of the proposed mission to Venus in 2005. The Mars Express spacecraft bus can accommodate Mars Express and Rosetta flight-spare experiments with little or no modification. The Soyuz-Fregat launch can deliver the spacecraft to a polar orbit around Venus with a pericentre altitude of ~250 km and an apocentre of ~45 000 km. This orbit will provide complete coverage in latitude and local solar time. It is also well-suited for atmospheric and surface sounding, as well as the studies based on solar and radio occultations. Compared with the Pioneer-Venus spinning spacecraft, Mars Express is an advanced three-axis-stabilised platform that provides significantly enhanced spectroscopic and imaging capabilities. The proposed duration of the nominal orbital mission is two Venusian days (sidereal rotation periods), equivalent to ~500 Earth days.

The Venus Express mission takes advantage of existing payload instruments, which offers a significant cost-saving aspect for the national funding of instruments. The re-use of the Mars Express platform also offers a quick and unique opportunity for a mission to Venus that fills a gap in ESA's terrestrial-planet exploration programme at a cost comparable to that of Mars Express.

Acknowledgement

The ESA Venus Express Study was directly supported by the Mission Science Coordinator and Principal Investigator Teams. The Industrial Study was led by Astrium France, with support from Astrium UK.

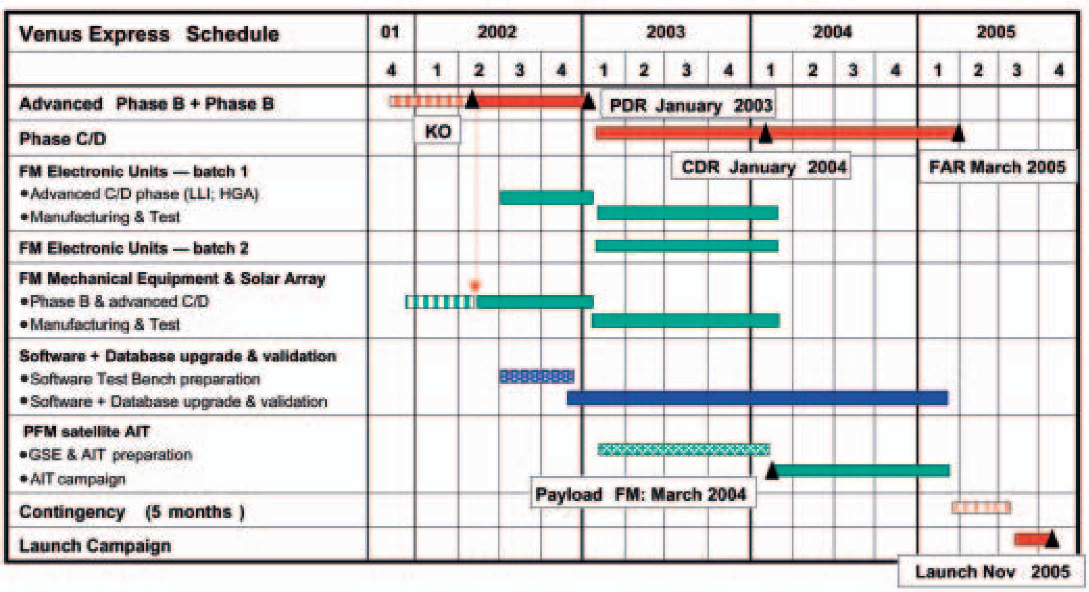


Figure 2. The Venus Express mission schedule

Cosmic DUNE

by H. Svedhem

Introduction

The Cosmic DUNE (Cosmic DUst Near Earth) mission is dedicated to the investigation of interstellar dust, an important but little-studied component of the interstellar medium. It also addresses many of the questions concerning the interplanetary dust complex, which has only been partially studied previously. The mission has been judged to have high scientific merit and has been found feasible both technically and programmatically. The payload selected is largely based on existing, but nonetheless advanced, instruments already flying on other spacecraft and can be accommodated on the spacecraft with only minor modifications to the Mars Express bus (Fig. 1). The operational requirements at both mission and payload level are low.

Scientific objectives

The Cosmic DUNE observatory is designed to characterise interstellar and interplanetary dust in-situ, in order to provide crucial information not achievable with remote astronomical methods. Galactic interstellar dust constitutes the solid phase of matter from which stars and planetary systems form. Interplanetary dust, from comets and asteroids, represents remnant material from bodies at different stages of early Solar System evolution. Thus, studies of interstellar and interplanetary dust with Cosmic DUNE in Earth orbit will provide a comparison between the composition of the interstellar medium and primitive planetary objects. Hence, Cosmic DUNE will provide insights into the physical conditions during planetary-system formation. This comparison of interstellar and interplanetary dust is highly important for both planetary science and astrophysics.

The discoveries of interstellar dust in the outer and inner Solar System during the last decade suggest an innovative approach to the characterisation of cosmic dust. Cosmic DUNE establishes the next logical step beyond NASA's Stardust mission, promising four major advances in cosmic-dust research:
– analysis of the elemental and isotopic composition of individual cosmic dust grains
– determination of the size distribution of interstellar dust
– characterisation of the interstellar dust flow through the planetary system
– analysis of interplanetary dust of cometary and asteroidal origin.

Additionally, in supporting the dust science objectives, Cosmic DUNE will characterise and monitor the ambient plasma conditions near the Earth's magnetotail.

Scientific payload

The science payload consists of a dust telescope, comprising space-proven instruments based on dust-detection techniques successfully used on Giotto, Vega, Cassini, Stardust, Rosetta and other missions. They are optimised for: (i) large-area impact detection and trajectory analysis of micron-sized and larger dust grains, (ii) determination of the physical properties of sub-micron-sized grains, such as flux, mass, speed, electrical charge, and coarse chemical composition, and (iii) high-resolution chemical analysis of cosmic dust. Previous experiments by the proposing team using similar instruments have shown that the heavy-element and isotopic compositions of carbon, hydrogen and nitrogen (C, H and N) can be measured.

The instruments utilise different detection methods and thereby complement each other to yield robust measurements for more reliable statistical analysis. A plasma monitor supports the dust charge measurements. The viewing directions of all dust instruments are co-aligned with narrow fields of view. About 1000 grains are expected to be recorded by this payload every year, with 10% of these providing elemental compositions.

The following instruments make up the scientific payload:

– Cosmic Dust Analyser: CDA is an impact ionisation detector with an aperture of 0.1 m^2, capable of measuring dust masses above 10^{-15} g and velocities from 1 to 100 km/s. It measures rough composition, at a resolution of about 50 amu, for those particles entering the central part of the detector.
– Cometary and Interstellar Dust Analyser: CIDA is a high-resolution impact ionisation time-of-flight mass spectrometer with a resolution of 250 amu and an aperture of 0.012 m^2 . It is mounted outside, but co-aligned with, the dust telescope.
– Dust Detector System: D2S consists of two parts, an upper part for particle-trajectory determination, based on grid wires detecting the electrostatic charge on the particles, and a lower part, based on a permanently polarised PVDF film. When a particle hits the film, part of the film is vaporised and a proportional charge is detected. The aperture is 0.11 m^2 and the mass threshold is 3×10^{-12} g. Particle charges above 10^{-15} C are detected.

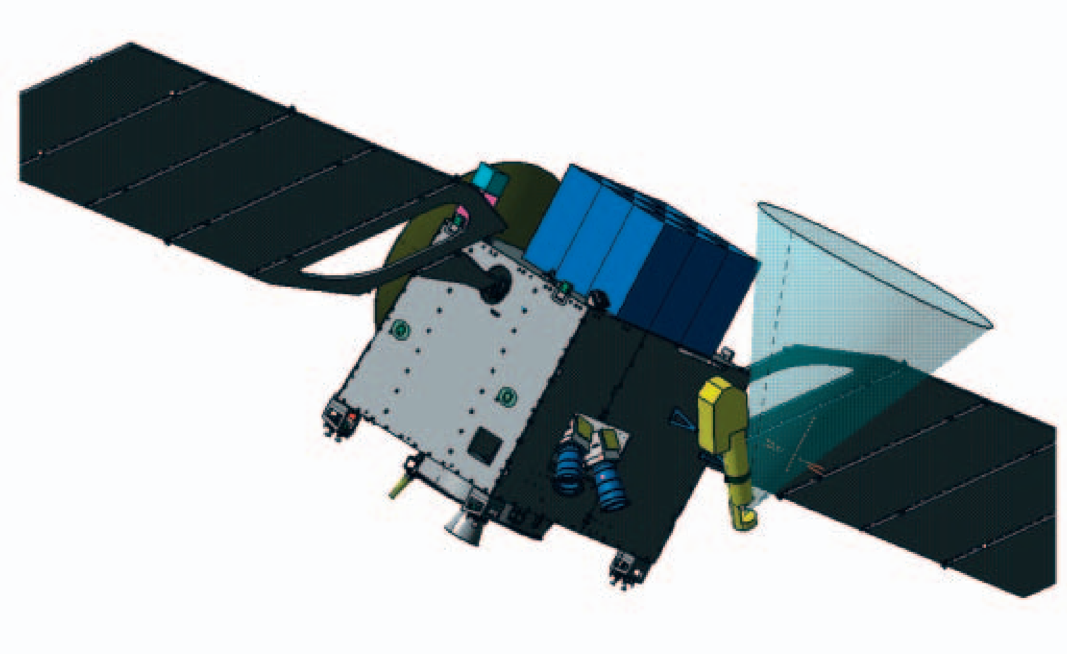
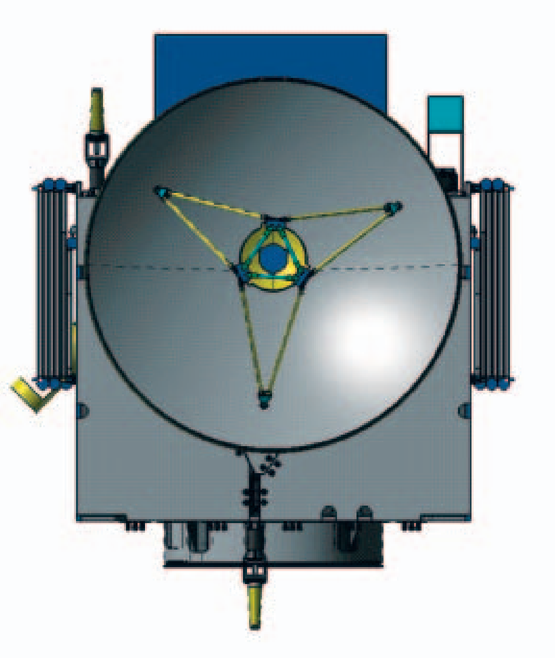


Figure 1. The Cosmic DUNE dust-telescope payload integrated on the Mars Express bus. The nine D2S modules form a telescope with a 25° half-width and a sensitive area of 1 m^2. ISIDE and CDA are attached to the impact plane of D2S, with each replacing one PVDF impact module (lower left). CIDA is attached to the side (optimum mounting angle 40 deg), while PLASMON is mounted with a stand-off structure to measure the solar wind

- Impact Sensor for Interstellar Dust Exploration: ISIDE is a piezo-electric-based momentum sensor with an active area of 0.06 m^2. It can detect particle impact momentums above 10^{-9} Ns.
- Plasma Monitor: PLASMON will characterise the environmental electrons, ions and magnetic field in the 0.35 – 4200 eV, 40 – 8000 eV, and 10 pT – 1000 nT ranges, respectively.

Nine of the D2S units make up the dust telescope, seven of them where the PVDF detectors are used, one where CDA is used, and one where ISIDE is used as a 'focal plane' instrument. The total payload mass is 63 kg and the power required is 53 W.



Spacecraft configuration

The differences in accommodation between the Cosmic DUNE and Mars Express satellite configurations concern only the payload. All instruments point towards +Z, except PLASMON which points towards -X (i.e. towards the Sun). The alignment-accuracy requirements are not severe, being about 0.5° for all instrument lines of sight.

All instrument sensors apart from CIDA are accommodated on the +Z wall of the platform. The CIDA sensor is accommodated on the external face of the platform +X wall. The main instrument electronics boxes are housed in the two enclosures located in the +X part of the platform, where they replace the Mars Express payload. The large D2S sensor box occupying most of the volume above the +Z face (the 'Dust Telescope') is a lightweight structure and cannot carry any additional mechanical loads. The original +Z low-gain-antenna support will have to be extended upwards to offer an adequate field of view. The +Z Sun-acquisition sensor's location will also have to be modified.

The functional architecture of Cosmic DUNE is very similar to that of Mars Express, being modified only to accommodate the new instruments. Owing to the low data rates between the spacecraft and the payload, the 1355 IEEE high-speed data bus is not used for any payload element. All of the main electronics units of the instruments are linked to the OBDH bus via the RTU. Two instruments (CDA and PLASMON) will require cover mechanisms, actuated by pyrotechnic devices after launch.

The satellite operates in two different modes: the observation mode, in which the satellite and its solar array are kept in an inertially fixed attitude typically for 1 to 4 weeks, and the communications mode in which the satellite is pointed towards the Earth for 1 or 2 days for transmitting the payload data stored in the onboard mass memory. In observation mode, the spacecraft's health is monitored from Earth via the low-gain antennas. Spacecraft housekeeping actions (reaction-wheel management, station-keeping, etc.) are performed in communications mode only, to avoid disturbing the instrument observations.

The power-budget figures for Cosmic DUNE are: spacecraft bus (communications on) 479 W, payload 54 W, and a 10% system margin, totalling 673 W. Cosmic DUNE's solar array will be a recurrent version of the Mars Express solar array. The total power requirement of 673 W calls for a 5.8 m^2 solar array. The present Mars Express solar array is about 11 m^2 in size. The fuel budget is sized for the Soyuz three-stage worst-case situation and the specific impulse (I_{sp}) for the main-engine boost is taken as 316 sec (this includes simultaneous firing of the small thrusters for satellite attitude control). The delta-V for station-keeping (4 m/s) is provided by small thrusters with an I_{sp} of 285 sec. The AOCS fuel and residuals are taken from Mars Express figures, which are worst-case figures for orbit at the second Lagrangian point (L2), where only the solar radiation pressure creates perturbing torques. For Cosmic DUNE, the fill ratio is 74% (with 5% margin), which is well within the allowed limits.

The adaptation of the Mars Express platform for the Cosmic DUNE mission presents no technical difficulties. The satellite development drivers include:
– New payload interfaces: these will necessitate modifications to the platform structure, thermal control, and electrical system and an early payload electrical interface validation activity is therefore proposed in the development plan.
– The satellite magnetic moment needs to be characterised for the plasma instrument (PLASMON).
– The Mars Express satellite has not been designed with magnetic-cleanliness requirements in mind.

Mission design and operations scenario

Cosmic DUNE is designed for a Lissajous orbit around the second Lagrangian point (L2) of the Sun–Earth system. In this position, which is about 1.5 million km from the Earth and on the opposite side of the Earth as seen from the Sun, the spacecraft appears stationary in a reference frame with the Sun–Earth line fixed. The spacecraft will orbit the Sun as well as the Earth once per year. This orbital position can be easily reached with the Soyuz/Fregat launch combination, and the transfer orbit can be phased such that very little fuel is required for the L2 orbit insertion.

This operating location has been selected because it is a stable orbit sufficiently far from the Earth to avoid confusion due to debris particles orbiting the Earth. The interstellar dust particles that have been found to enter the Solar System from a well-defined direction at about 26 km/s will be encountered at a relative velocity of about 56 km/s during northern winter. This will enhance the chances of detecting the smallest particles. On the other hand, during northern summer these particles will be encountered from the apparent opposite direction at 4 km/s. This will improve the separation of the interstellar from the interplanetary population. Cosmic DUNE's operation would be organised in blocks of two to four weeks, within which the inertial pointing would be constant in order to collect sufficient data for reliable statistical analysis. During these observing blocks, no mechanical action is allowed on the spacecraft to minimise noise effects. The resulting de-pointing of the solar panels can be accepted thanks to the large available power margin. The payload produces a modest amount of data and telemetry sessions are only required at one- to four-week intervals.

A mission duration of 2 years is required. The first year of observations would focus on interstellar dust, while the second year would also include a number of observations dedicated to the different interplanetary dust types. A possible one-year extension would allow dedicated studies of specific sources like ß-Pictoris and other dust-rich nearby stars, meteor streams, or other targets of opportunity.

Acknowledgement

The ESA Cosmic DUNE Study Team consisted of:
– E. Grün, Max-Planck-Institut für Kernphysik, Heidelberg, Germany
– A-C. Levasseur-Regourd, Univ. Paris VI/ Aeronomie CNRS, Verrieres, France
– N. McBride, The Open University, Milton Keynes, United Kingdom
– P. Palumbo, Università Parthenope, Naples, Italy
– R. Srama, Max-Planck-Institut für Kernphysik, Heidelberg, Germany.

SPOrt Express

by J. Tauber

Introduction
SPOrt Express – the Sky Polarisation Observatory for reuse of the Mars Express Platform – is a proposal for a mission to measure the polarisation of the Cosmic Microwave Background (CMB) and the polarised emission from the Milky Way at microwave wavelengths. It is based on the SPOrt-ISS experiment, which is being developed to fly on the International Space Station starting around 2005. Instrumentally, there are two main modules in SPOrt Express: LARMI (Low Angular Resolution Multifrequency Instrument) which measures the Stokes Q and U parameters of the sky emission with 7.0 deg angular resolution at four frequencies between 22 and 90 GHz, and HARI (High Angular Resolution Instrument) which measures Q and U with 0.5 deg angular resolution at 90 GHz only. LARMI is essentially identical to the payload of SPOrt-ISS, whereas HARI is a new addition allowed by the Mars Express bus.

Accommodation of the SPOrt Express experiment on the Mars Express bus was studied for ESA by Astrium in Toulouse (F) between July and October 2001. That study indicated that only minor modifications to the bus would be needed (Fig. 1). The main critical item identified was related to the low temperature required to be passively achieved, and the associated cryogenic testing at system level, which could become relatively complex.

In parallel, a study team was formed by ESA to address the scientific questions raised by its Astronomy Working Group (AWG) in its pre-evaluation. In short, the study team's mandate was to examine the scientific merit of SPOrt Express, particularly in the context of the capabilities of other ongoing experiments such as MAP (a NASA mission in operation) and Planck (an ESA mission under development and due for launch in 2007).

Scientific objectives
Measuring the polarisation signature of the Cosmic Microwave Background (CMB) has very high scientific interest, due to its potential to provide original information on the characteristics of the early Universe. Of particular interest for SPOrt Express is its ability to shed light on the epoch at which the re-ionisation of the intergalactic medium took place. Many experiments dedicated to this problem, both ground- and balloon-based, are already gathering data or in development. There are high expectations that MAP and Planck will detect and image at least the brightest polarised components of the CMB. The community is also starting to design the next generation of CMB observatories based in space, which will undoubtedly be dedicated to the measurement of polarisation.

There are two major components to the science case for SPOrt Express: CMB-related science, and Milky-Way-related science. The study team concentrated on the CMB element of the scientific case, trying in particular to put it into the current context of similar ongoing space- and ground-based experiments.

Observationally, the objective of SPOrt Express is to make maps of the linear polarisation of the sky (via the Stokes parameters U and Q; the parameter I – which parameterises intensity – is not accurately measured by the receiver concept; and since the CMB is not expected to generate circular polarisation, no emphasis is put on measuring V). The maps will be used to estimate the angular power spectra of the E(or gradient)-component and B(or curl)-component of the CMB. The E-component is expected to be the brighter of the two and is therefore the main target for SPOrt Express.

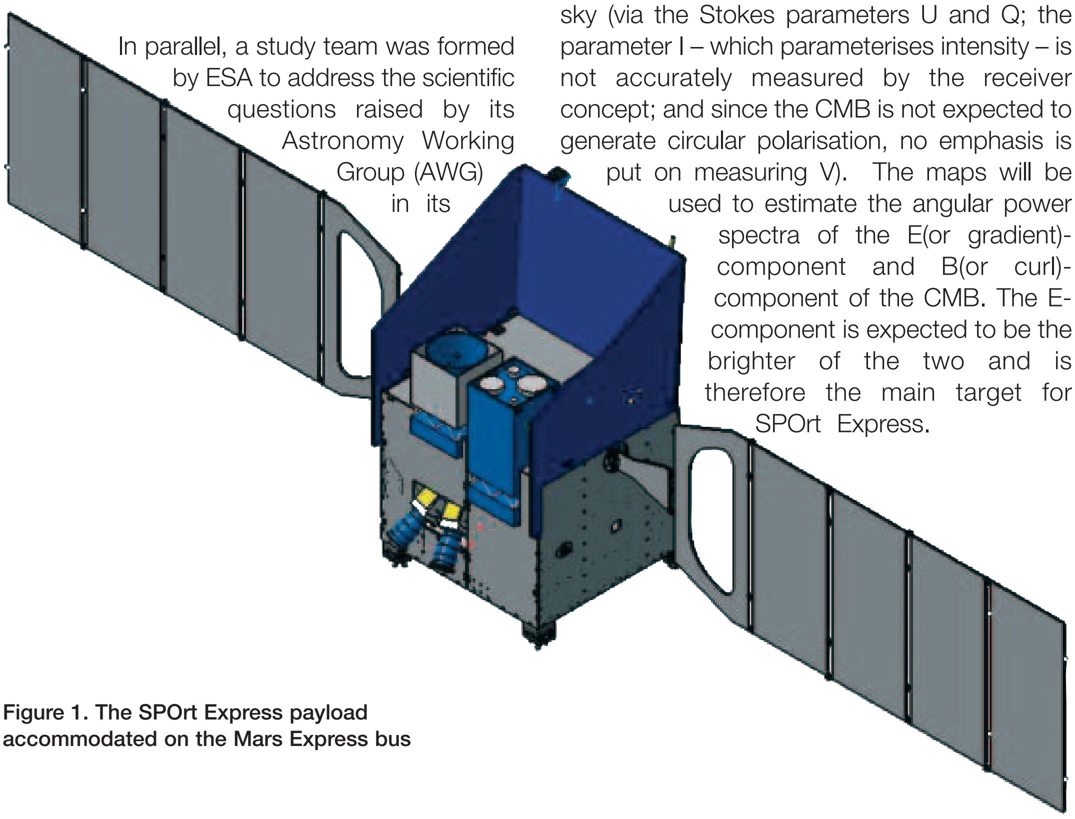


Figure 1. The SPOrt Express payload accommodated on the Mars Express bus

Scientific payload

Much of the scientific case for any CMB experiment rests on its instrumental performance, and the Team therefore looked closely at this aspect. The critical performance phase space for CMB experiments includes such parameters as sensitivity, sky coverage, frequency coverage, and angular scale coverage. It is generally agreed that the best CMB experiment will cover as much of this phase space as possible, which implies a better ability to recover the angular power spectrum of CMB emission, and therefore to extract cosmological parameters.

When only comparing the nominal performances of the SPOrt Express payload with that of Planck, it is apparent that the latter is superior by a significant factor. However, instrumental systematic effects, rather than the nominal performances, may turn out to be the limiting uncertainty in the measurements of Q and U. The SPOrt Express design has a definite advantage over Planck in this respect, exploiting a receiver concept that has been designed from the start to measure polarisation, and is robust and effective at suppressing such systematic effects. It was assumed that in the case of SPOrt Express, instrumental systematic effects would have a negligible impact.

Under the above assumption, the analysis by the study team indicated that the following main objectives could be achieved by the baseline concept presented in the SPOrt Express proposal:

- it would obtain all-sky maps of galactic foregrounds at 22 and 32 GHz
- it would make measurements of the CMB polarisation with a significance that depends on cosmological parameters: the current analysis shows a detection at a significance level between 1 and 7σ (depending mainly on the level of cosmic re-ionisation)
- it would make a measurement of the optical depth of the re-ionised cosmic medium (with a 1σ confidence level of ~0.03 if τ_{reion} = 0.05).

In addition to the above nominal performance, the study team identified some potential enhancements to the (CMB-related) scientific return of SPOrt Express which could be achieved through relatively minor modifications to the payload concept: (a) changing the observing strategy from a (shallow) all-sky survey to a (deeper) scan of a small patch of the sky (as allowed by the three-axis pointing capability of the Mars Express bus); and (b) increasing the angular resolution of the HARI module (which appears achievable within the volume and mass constraints of the Mars Express bus).

Conclusion

Unfortunately, after weighing all scientific and programmatic considerations, the AWG felt *'unable to recommend implementation of the SPOrt Express payload with the re-use of the Mars Express platform. Nevertheless, recognising the compelling scientific importance of measuring CMB polarisation, the AWG sees this as a key area in which ESA should be involved in the future. Therefore, the AWG supports and encourages the community to continue to develop approaches to CMB polarisation studies, with the aim to provide a strong proposal for consideration at the next available ESA mission opportunity'.*

Acknowledgement

The ESA SPOrt Express Study Team consisted of:

- S. Volonte (ESA HQ), Chair
- J. Tauber (ESA RSSD), Study Scientist (and Planck Project Scientist)
- E. Carretti (IASF), SPOrt Express Project Manager
- A. Challinor (Cambridge Univ.)
- S. Cortiglioni (IASF), SPOrt Express Principal Investigator
- P. De Bernardis (Univ. Roma)
- R. Laureijs (ESA RSSD, ISO team)
- P. Leahy, supported by A. Wilkinson (Jodrell Bank)

Additional support was provided by J. Hamaker (Dwingeloo) and K. van 't Klooster (ESA/ ESTEC). The accommodation study was carried out by a team of Astrium (Toulouse, F) engineers, led by C. Koeck.