

Small Satellite Mars Missions Using Electric Propulsion

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ABSTRACT

Two small satellite concepts are presented for low cost Mars system exploration. Both concepts use solar electric propulsion (SEP) to move from a low velocity Earth escape orbit to captured Mars orbits, and so are able to make use of smaller launcher vehicles, while still providing significant payload accommodation, despite their small size. Both missions achieve their Mars system operational orbits in less than 20 months from launch.

The Mars Global Atmosphere Survey (MGAS) mission design has a launch mass of 120kg. It uses a QinetiQ T5 ion engine, with around 24kg of Xe propellant, which provides sufficient ΔV for transfer to a low Mars orbit. Payload mass is around 12kg, dependent on Earth escape velocity, required final Mars orbit, and the time permitted for the transfer. The small launch mass allows a number of such spacecraft to be launched together on either Soyuz, DNEPR or Rockot-Breeze launchers, so providing a small Mars constellation. This fact was exploited by the proposed payload which uses the RF occultation method to measure temperature, density and pressure at the limb, aiding the characterisation of global circulation of the Martian atmosphere.

The Mars Phobos and Deimos Survey (MPADS), at 320kg launch mass, is a minisatellite. It uses the larger QinetiQ T6 ion engine, with around 50kg of Xe propellant, with payload mass of 60kg. The spacecraft enters a large circular Mars orbit which is gradually reduced in size by electric propulsion in order to rendezvous with the Martian moons. The mission consists of either a single satellite visiting both moons, or two spacecraft, one at each moon, with the option of providing a lander package on one.

These concepts have been studied under national funding with the aim of defining highly cost-effective options for the delivery of on-board instrumentation into Mars orbit, for remote sensing, or deployment of lander packages for Mars or Mars moon surface exploration. The mission design process reported considers all aspects of spacecraft bus, payload, trajectory and operations. The low thrust trajectory design and trade-offs are described in some detail. Mass, power and link budgets are provided for both missions, along with a description of the payloads. Both missions are considered viable using existing or near term technology

1. INTRODUCTION

While ambitious and challenging robotic missions such as Mars Sample Return and large rover/aerial vehicle deployments are planned for Mars exploration, smaller low-cost "micro" missions can serve to validate enabling technology developments, thus reducing overall technical risk and programmatic cost whilst also returning some highly focussed and complementary science data.

At the expense of a longer transfer time, solar electric propulsion with high specific impulse has the potential to offer a larger payload mass fraction than can be obtained with chemical propulsion systems. This not only translates into tangible improvements in science payload complement, but (in the case of small spacecraft) also enables mission feasibility with a reasonable science return capability. Through the exploitation of low-cost launch opportunities, multiple small vehicles can be delivered to Mars for global, distributed, simultaneous coverage of the planet either on the surface or in an orbital constellation design (for either science or infrastructure purposes).

The mission concepts presented in the following sections represent study work funded by the British National Space Centre. Both concepts are specifically targeted to answer some of the key scientific questions surrounding the Martian system. Work has focussed on science definition, mission/spacecraft design and establishing feasibility.

2. PHOBOS & DEIMOS MISSION

2.1 Mission Objectives

While many measurements have been made of the Martian moons, many questions still remain about their origin, evolution, physical nature and composition. Investigations have been patchy, due to a mixture of mission failures and the fact that study of the Martian moons is usually an objective secondary to the study of Mars itself. Objectives for a Mars Micro Mission to the Martian moons are targeted at answering the following key unanswered scientific questions:

- What is the origin of Phobos and Deimos? Were they formed in Mars orbit or are they asteroids captured from the main asteroid belt?
- Is there a link between the moons and known asteroid types?
- How have Phobos and Deimos been affected by their association with Mars? How have Mars and its environment been affected by the presence of the moons?
- Do their interiors contain frozen volatiles such as water ice?
- Are the grooves on Phobos the result of collision with ejecta from impacts on Mars or the surface expression of internal features, e.g. impact-induced cracks?
- How and why do Phobos and Deimos differ, e.g. in surface morphology and elemental composition?
- How do surface and sub-surface properties differ?

To address these questions requires the following measurements for each moon. Note that the investigation of Deimos would resume from a lower baseline than that of Phobos due to data already gathered by previous missions. The parts highlighted with an asterisk indicate those that are planned to be addressed in part for Phobos by ESA's Mars Express[1]:

- Global mineralogical*, elemental and topographical / morphological mapping*
- Characterisation of the internal structure* and balance between microporosity and macroporosity*
- Measurement of secular changes in the orbital parameters and the libration about the tidally-locked position

- Characterisation of the interactions between the moons and the Martian environment (e.g. dust, gas, plasma)*
- Measurement of magnetic properties
- Measurement of other key physical properties, e.g. mass*, volume*, thermal inertia, microscopic structure and mechanical properties of the regolith
- Measurement of key geochemical indicators, e.g. isotopic composition
- Measure key features relating to the possibility of sub-surface volatiles*.

By taking the same set of payload instruments to both moons within a single mission will greatly assist in resolving the mysteries of Deimos and Phobos and their context in the history of Mars, which are issues emphasized in many other mission proposals [2,3,4,5].

2.2 Mission Design

The current baseline to complete the mission objectives calls for a single low-cost mini-spacecraft of about 320kg total mass equipped with a high specific impulse ion propulsion system. The spacecraft would be launched onto a direct Earth escape trajectory on an inexpensive dedicated German/Russian Rocket launch vehicle with a low hyperbolic excess velocity (Since this study was completed, EuroRockot have increased their estimate of mass capability to low Earth escape velocities [6]). The on-board ion propulsion system is then used to transfer to Deimos and Phobos.

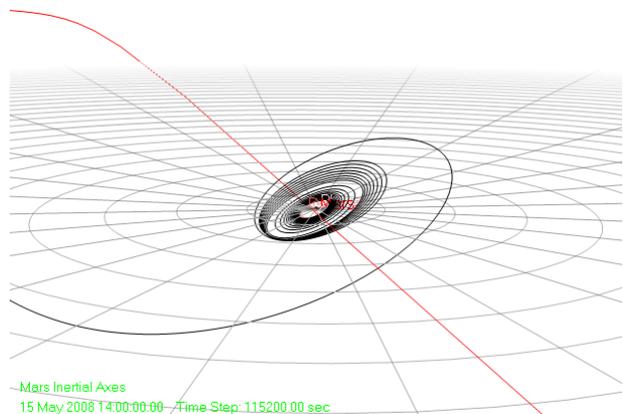


Fig. 1. Mars orbit insertion + spiral down to Phobos

The mission profile and low-thrust trajectory is shown in Table 1 and Fig. 1 respectively. From the trajectory analysis, the total mission duration is calculated to be just over 24 months from launch to completion, including 2 months of science operations at the moons.

Table 1. Mission profile for the Mars Moons mission

<i>Mission Phase</i>	<i>Description</i>
Earth escape	Rocket launch provides 1km/s hyperbolic excess velocity
1 st transfer orbit burn (6 months)	Increases apohelion and changes inclination
Coast (4.5 months)	No thrusting
2 nd transfer orbit burn (4.5 months)	Reduced relative velocity with Mars (0.46km/s)
Coast (1 day)	Prior to orbit insertion
1 st orbit insertion burn (5.5 weeks)	Changes orbit from Mars flyby to captured orbit of 100,000km, eccentricity 0.25
Mars orbit corrections (4 months)	Sequence of long and short burns to reduce orbit size and correct eccentricity and inclination slightly
Operation at Deimos (1 month)	Deimos co-orbiting and science for nominal period
Orbit change to Phobos (7.5 weeks)	Long burn with small final corrections to move from Deimos co-orbit to Phobos co-orbit
Operations at Phobos (1 month)	Phobos co-orbiting and science for nominal period

With a 1km/s Earth escape launch, the total ΔV required for the mission is calculated to be 6.8km/s to co-orbit with Deimos, then Phobos. Assuming an ion thruster with a specific impulse of 4,500s (see spacecraft design section), this corresponds to a Xenon fuel mass requirement of 44kg for a 310kg launch mass.

2.3 Spacecraft Design

The mass budget of the single spacecraft in this mission is based upon identification of known COTS components, current technology development programmes, and the application of margin where existing items require modifications. The overall mass budget (which includes margins) is presented in Table 2. Dual redundancy of critical components has been incorporated into the on-board processing & data handling unit; communications subsystem; and the attitude determination & control subsystem.

Two different payload options are being considered for the moons mission, both of which are constrained to fit within a payload mass budget allowance of 50kg. The first of which is described in Table 3, and involves a comprehensive suite of in-situ remote sensing instruments taking measurements in a close orbit around Deimos and then the lower moon Phobos.

Table 2. Single mini-spacecraft mass budget

<i>Subsystem</i>	<i>Mass (kg)</i>	<i>Mass Fraction (%)</i>
ADCS	16	5.1
Propulsion	60	19.3
Power	48	15.4
Avionics	20	6.4
Structure	70	22.4
Payload	50	16
<i>Dry mass total</i>	<i>264</i>	<i>84.6</i>
Propellant	48	15.4
<i>Wet mass total</i>	<i>312</i>	<i>100</i>
<i>Max. launch mass</i>	<i>320</i>	

Table 3. Deimos/Phobos orbiter payload option

<i>Instrument</i>	<i>Measurement</i>
Multispectral Imaging System	Surface morphology/topography/mineralogy
Radio Science Investigation	Mass, bulk density, gravity harmonics
X-Ray Spectrometer	Elemental composition
Thermal IR Spectrometer	Thermal inertia & surface distribution
Laser Altimeter	Surface topography
Magnetometer	Magnetic field
Plasma package	Electrons, ions, plasma waves
Neutron Spectrometer	Sub-surface ice
Near IR Spectrometer	Mineral composition
Radar Tomographer	Internal structure, permittivity, sub-surface ice, porosity
Dust counter	Dust rings

An option for another spacecraft equipped with a Phobos surface lander package is being actively studied. This may involve a scaled-down version of the Rosetta Lander, capitalising on the investment already made in small body lander technology. The instruments in contact with the surface are given in Table 4. The lander would be ejected in a low Phobos orbit, and de-orbited for a slow, soft landing and fixation on the surface.

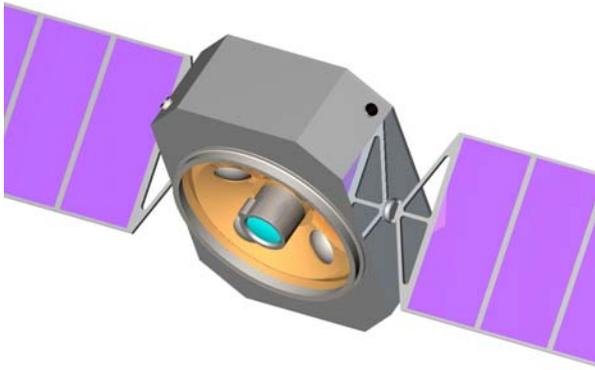


Fig 2. External view of spacecraft with ion thruster

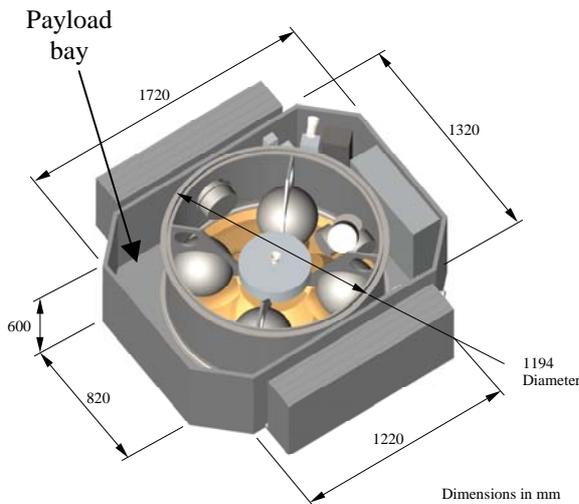


Fig 3. Internal view of spacecraft bus including ion propulsion system housing

Table 4. Phobos lander payload option

<i>Instrument</i>	<i>Measurement</i>
Panoramic cameras	Surface morphology
Sun sensor	Body libration
Alpha-X-Ray Spectrometer	Elemental composition
Sample acquisition & handling system	Delivery of samples to gas analyser, microscope
Evolved gas analyser	Chemical & isotopic composition
Microscope	Imaging of samples
Gamma ray spectrometer	Bulk elemental composition
Mössbauer spectrometer	Mineralogical composition (Fe-bearing)
Seismometer	Tidal, thermal-induced vibrations
Mutual impedance probe	Surface electrical properties, sub-surface ice
Radio science	Orbit evolution & body libration

The configuration of the mini-spacecraft platform is illustrated in Fig. 2 and Fig. 3 and described in Table 5.

Table 5. Summary of the mini-spacecraft design

<i>Characteristic</i>	<i>Summary</i>
Dimensions	312kg mass. Irregular octagon, with width 1720mm and height 600mm. Constrained in height by option to stack two spacecraft on a Dnepr launch
Propulsion	75mN thrust at Earth; 36-39mN thrust at Mars. Single QinetiQ T6 ion engine with PPU (4,500s S.I.)
Power	2.2kW BoL at Earth; 1.1-1.2kW EoL at Mars. Two QinetiQ lightweight deployable 1.1x4.0m solar array wings with 28% efficient triple-junction GaAs cells
Propellant	48kg Xenon (incl. 10% margin) stored at high pressure in four spherical titanium-composite tanks
Comms	16kbps Ka-band downlink. Fixed 0.8m HGA with central reflector feed; back to 35m DSN antenna
Attitude knowledge	Sun sensors, star tracker and gyros.
Attitude control	3-axis stabilised. Reaction wheels & QinetiQ Hollow Cathode Thrusters.

3. GLOBAL ATMOSPHERE/CLIMATE MONITORING MISSION

3.1 Mission Objectives

The primary objective of the mission is to characterise the general circulation of the atmosphere, i.e. the mean wind field, dominant wave motions, and the crucial chaotic component (eddy transport) and their variations globally with season and height. The general circulation interacts with the surface, transports dust and volatiles (water and carbon dioxide) around the planet, and influences the seasonal pressure cycle. Thus, it is a key part of the Martian climate system. A realistic goal is to obtain data incorporating several daily cycles and frequent enough to detect seasonal trends. Global coverage of more than one Martian year (i.e. about 2 Earth years) is required, since large inter-annual variations in major dust storm activity occur.

The spacecraft missions of the last several decades have observed many aspects of the Martian circulation, but without the temporal and seasonal global coverage for its full characterization. Current missions carry atmospheric sounding instruments specifically for this purpose. These instruments cannot obtain surface

pressure information, and will in due course be augmented by missions to place a number of small, long-lived stations on the surface. However, remote sensing and surface station data needs to be obtained simultaneously. The main shortcoming then will be the limited vertical resolution that results from state-of-the-art limb-sounding instruments (5km at best).

The radio occultation technique, on the other hand, can provide temperature profiles with a precision, accuracy and vertical resolution up to two orders of magnitude better than that of the best passive radiometers. It is an established technique that has already been used on a number of previous missions to Mars, and indeed Earth. However, with a single spacecraft only spacecraft-to-ground occultations are possible, which provide only small numbers of profiles and are restricted by geometry in their coverage of the planet. A multi-satellite constellation mission can apply this powerful technique to satellite-to-satellite microwave occultations to obtain much better coverage in space and time and to address the general circulation problem much more comprehensively than ever before [7]. This in turn will lead to much improved predictions of wind data for entry probe descent profiles. Furthermore, a useful offshoot of such a radio occultation constellation is the provision of a two-way Doppler navigation service for surface, aerial and orbiting assets [8].

The following list represents the measurement objectives:

- temperature to <1K accuracy with 0.1-0.5 km vertical resolution from 0 to 80 km altitude;
- atmospheric water concentration and relative humidity with 1-10% precision and better accuracy and 0.1-1 km vertical resolution from 0 to 40-60 km altitude depending on conditions;
- CO₂ density, and therefore bulk pressure, versus height with 0.1% accuracy and 0.1-0.4 km vertical resolution from 0 to 80 km altitude;
- winds to 10m/s from 0-60 km altitude and 1-2 m/s accuracy
- boundary layer structure including its variations over the diurnal cycle.

These objectives are based on the capabilities of the technique and the specific requirements of general circulation models.

3.2 Mission Design

For ground-breaking science on Martian atmosphere circulation and climate, several hundreds of globally-distributed satellite-to-satellite radio occultations are required per day. This can be satisfied by as few as 4 spacecraft operating in, for example, different near-

polar orbital planes at a common altitude of about 1000km altitude. This is taken as a preliminary design and optimisation of the operational orbits needs to be performed in further, more detailed studies. In order to achieve a 4 spacecraft constellation within the constraints of a single low-cost Mars Micro Mission, the mission design consists of 4 micro-satellites equipped with ion propulsion launched onto a direct Earth escape trajectory by a single inexpensive Russian Dnepr launch vehicle [5]. The mission profile is presented in Table 6.

Table 6. Mission profile for the Mars atmospheric constellation mission

<i>Mission Phase</i>	<i>Description</i>
Earth escape	Dnepr launch provides 1km/s hyperbolic excess velocity
Transfer to Mars (18 months)	1 st burn, coast, 2 nd burn to reduce Mars excess velocity
1 st orbit insertion burn (7 weeks)	Changes orbit from Mars flyby to captured orbit of 100,000km, eccentricity 0.25, near-polar inclination
Mars orbit corrections (8 months)	Sequence of long and short burns to reduce orbit size and correct eccentricity and inclination slightly
Operation orbit (24 months)	1000km altitude circular orbit at near-polar inclination

As a result of the trajectory analysis, it is calculated that the total mission duration is just over 4 years and that 9.2km/s delta-V is required of each spacecraft to attain the operational Mars orbit of the constellation. Assuming an ion engine with a 4,500s specific impulse, only 22.4kg of Xenon is needed for a 120kg spacecraft.

3.3 Spacecraft Design

The mass budget (including margins) of each of the four micro-spacecraft in this mission is presented in Table 7. Again, dual redundancy in the ADCS and avionics subsystems is included.

The identical payload within each spacecraft in the constellation does not contain any instruments as baseline. Instead, the payload contains an ultra stable oscillator and signal processing package interfacing with the on-board communications subsystem to transmit satellite-to-satellite radio occultation signals at X-band, and receive/process signals with a very high timing and phase accuracy. Higher-level processing through inversion models is then performed in order to gain the temperature, pressure, and wind profiles for each occultation. Existing equipment for radio occultation is available with a mass within the 14.8kg

payload mass budget, leading to the possibility of adding passive radiometers for complementary science.

Table 7. Single micro-spacecraft mass budget

Subsystem	Mass (kg)	Mass Fraction (%)
ADCS	6.7	5.7
Propulsion	15.1	13.7
Power	22.8	20.5
Avionics	10.1	9.2
Structure	16.1	16.2
Payload	14.8	13.5
<i>Dry mass total</i>	<i>97</i>	<i>78.9</i>
Propellant	23	21.1
<i>Wet mass total</i>	<i>120</i>	<i>100</i>
<i>Max. launch mass</i>	<i>250</i>	

The configuration of the micro-spacecraft platform is illustrated in Fig. 4 and Fig. 5 and described in Table 8.

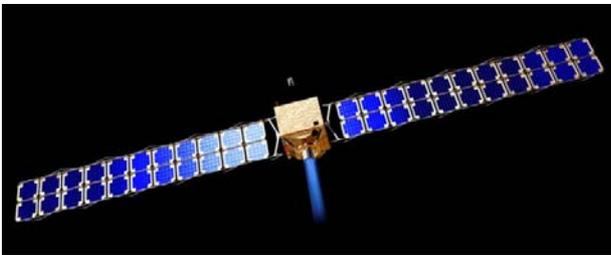


Fig. 4. External view of micro-spacecraft with ion thruster firing

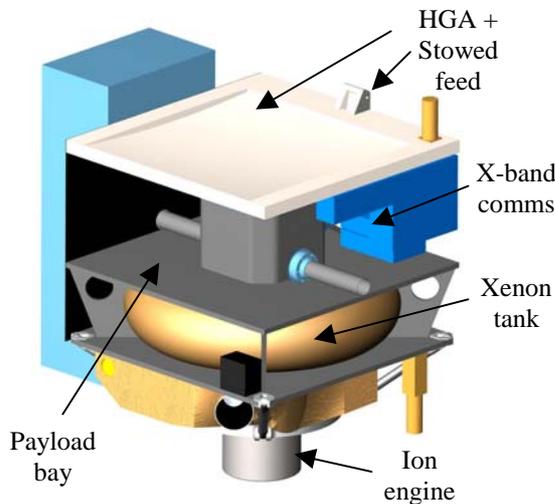


Fig. 5. Internal view of micro-spacecraft

Table 8. Micro-spacecraft design summary

Characteristic	Summary
Dimensions	120kg mass. Bus Box 600x600x710mm.
Propulsion	25mN thrust at Earth; 15mN thrust at Mars; QinetiQ T5 ion engine with PPU (4500s S.I.)
Power	1,170W BoL at Earth; 500W EoL at Mars. Two lightweight deployable 0.7x3.3m solar array wings with 28% efficient GaAs cells.
Propellant	23kg Xenon stored in 18 litre toroidal tank
Comms	1.4kbps X-band downlink. Fixed 0.5m HGA with deployable feed; back to 35m DSN dish.
Attitude control	3-axis stabilised. Reaction wheels & QinetiQ Hollow Cathode Thrusters. Sun sensors, star tracker & gyros.

5. CONCLUSIONS

Two mission concepts have been developed for low-cost, small spacecraft Mars missions on the basis of:

- Stated and anticipated requirements for the mission.
- Consideration of the key science questions and issues in the Martian environment.
- Consideration of past, current and proposed future missions to Mars.

The mission concepts are:

- **Mars Global Atmosphere/Climate Monitoring.** A mission using 4 micro-satellites in a constellation performing high vertical resolution point-to-point radio-occultation measurements through hundreds of sections of the atmosphere per day. Data will be used to improve models for planning future entry/descent systems, aerobots and surface landers, in addition to providing a future Martian weather forecasting service.
- **Mars Phobos & Deimos Survey.** A single mini-satellite mission to both Martian moons for in-situ measurements of a range of properties, with the alternative option of ejecting a package onto Phobos for surface science activities at the end of the nominal mission. Further characterisation of material composition on the moons may also establish them as potential mining targets for further in-situ resource utilisation.

These concepts have been formulated around low-cost platforms equipped with advanced low-thrust ion propulsion systems as primary propulsion for transfer to Mars, Mars orbit insertion, and operational Mars orbit acquisition. A mission design and trade-off study was conducted in order to ensure feasibility within tight

mass, size and cost constraints of a “small” Mars mission.

Both missions outlined in this paper are considered feasible using current or near-term technologies, and viable in terms of their low cost but highly significant science return. Both are thought to be effective in terms of technology demonstration/validation and provision of unique and useful science and infrastructure capabilities.

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