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PHOBOS EXPLORATION USING TWO SMALL SOLAR ELECTRIC PROPULSION SPACECRAFT

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Primitive bodies are exciting targets for exploration as they provide clues to the early Solar system conditions and dynamical evolution. The two moons of Mars are particularly interesting because of their proximity to an astrobiological target. However, after four decades of Mars exploration, their origin and nature remain enigmatic. In addition, when considering the long-term objectives of the flexible path for the potential human exploration to Mars, Phobos and Deimos present exciting intermediate opportunities without the complication and expense of landing and ascending from the surface. As interest in these targets for the next frontier of human exploration grows, characterization missions designed specifically to examine surface properties, landing environments, and surface mapping prior to human exploration are becoming increasingly important. A precursor mission concept of this sort has been developed using two identical spacecraft designed from low cost, flight proven and certified off-the-shelf component and utilizing Solar Electric Propulsion (SEP) to orbit both targets as secondary payloads launched aboard any NASA or GTO launch. This precursor mission has the potential to address both precursor measurements that are strategic knowledge gaps and decadal science, including soil physical properties at the global and local (human) scale and the search for in situ resources.

I. RATIONAL FOR PHOBOS EXPLORATION

Due to their proximity to Mars and mysteries of their origins, Phobos and Deimos provide a perfect location to address important scientific and human objectives for exploration. As potential targets for the flexible path for potential Human Exploration, the moons present outstanding vantage points for observations of Mars and the ability to perform telerobotic operations on the Martian surface. Observation of Mars from Phobos and Deimos offer the opportunity to achieve some of the key science and exploration goals identified by the Mars Exploration Program Analysis Group (MEPAG) including the search for Martian meteorites on Phobos and the monitoring of the Martian atmosphere.

By themselves, Phobos and Deimos are scientific targets of strong significance. Resolving the origins of the moons is a key goal driving exploration of the targets for scientific purposes. Since the moons may be captured asteroids or material ejected from Mars[1], they may be enriched in volatiles and organic material, increasing their relevance as astrobiological targets.

I.I Investigations

As the exploration of these targets would be relevant to both Human and science exploration objectives, the Phobos Surveyor mission concept focuses on investigations that address key objectives pertinent to the decadal and precursor science identified by the Planetary Science Decadal Survey (PSDS), the Small Body Assessment Group (SBAG) and the Precursor Science Assessment Group (PS-AG) recently chartered by MEPAG.

Precursor missions are responsible for collecting critical data in preparation for potential human exploration in Mars vicinity. Such data is meant to reduce risk and cost and also to optimize performance of future missions. The measurements for this type of mission could be acquired during any phase of the mission, during transit, in Mars orbit, or in the vicinity of the moons (including on the surface). The key science objectives for a precursor mission, as described by PS-AG, include: measurements of radiation flux and biological effects, electrostatic charging and plasma fields, quantification of the flux of micrometeorites, assessment of surface mobility (gravity fields, slopes), chemical composition – in particular in the context of

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in situ resource utilization (ISRU) – and characterization of the regolith mechanical properties. Realizing these objectives would also address key science questions; a single mission is capable of addressing important science and precursor objectives. As noted, the search for volatiles (ISRU), as well as chemical measurements trace themselves to the determination of the moons origin. Gravity field and high-resolution topography measurements are important constraints on their geophysical structure.

Table 1 Phobos Surveyor would address several objectives relevant to Human Exploration and Decadal Science

Decadal Science	Precursor Science	Objectives	Observable	Requirement	Instrumentation
Processes/ Origins	Soil Mechanics	Obtain Regolith Composition and search for water	Elemental	Light elements (O, C, N, H, etc.) 5%	Gamma Ray and Neutron Detector
			Mineralogical		XRS
		Evaluate Regolith Maturity	Microstructure	< 1 mm	Microscope
		Constrain mechanical properties	Angle of repose	<2 deg.	PanCam
			Response to impulse	<5% accuracy	Accelerometer
			Thermal response	<5% accuracy	Thermal Conductivity
			Crater morphology	100 m/10 m	High-Res Camera
	Risk	Constrain Dust Dynamics in Mars' Enviroment (Sources and Sinks)	Measure Dust Flux	Collection and analysis	Dust Analyzer
Processes	Risk	Topography Mapping	Photoclinometry	100 m/10 m	High-Res Camera
		Gravity Mapping	Doppler tracking	Degree 8	RSS
			Acceleration	1 m	Accelerometer
		Assess surface dynamics (dust)	Dust interaction with spikes	Imaging with resolution < 1 cm	PanCam
		Measure electrostatic charging			
		Measure radiation environment	Radiation dosage	1 mrad	Radiation monitor
Origins/ Habitability	ISRU	Distribution of Water	Neutron detection		GR&ND
			Mineralogical		XRS

I.II Measurements and Payload

The Phobos Surveyor mission proposes a reference payload that combines geophysical and chemical packages for remote (i.e. global) and in situ (i.e. local/regional) exploration. The suggested instrument package includes: gamma ray and neutron spectrometer providing elemental composition and detection of volatiles; high-resolution stereo imaging providing fine constraints on surface morphology, topography and regolith mobility; a dust analyzer to constrain the direction and magnitude of the flux of the material between Mars, Phobos, Deimos, and micrometeorites originating from outside the Martian system; and the spacecraft telecommunication system yielding high-resolution gravity measurements. In addition to the larger instrument package, the mission could carry a small surface package capable of imaging the regolith (microscope) and constraining its mechanical (penetrometer, accelerometers) and chemical properties (XRD).

Table 2 The Surveyor spacecraft could easily accommodate an invaluable instrument package

	Instrument	Mass (kg)	Power
Orbiter	Gamma Ray and Neutron Detector	15	10
	High-Resolution Stereo Camera	10	15
	Dust Analyzer	8	12
Surface Science Package	XRS	0.30	4 W
	Radiation Monitor	0.03	0.1 W
	Thermocouples	0.03	1
	Microscope	0.30	0.1
Operations and Science Support	Descent Camera (PanCAM)	0.10	0.1 W
	Accelerometer and Tiltmeter	0.06	0.002 W

II. SURVEYOR SPACECRAFT

The Surveyor spacecraft concept provides a low-cost, high reliability approach to studying two very interesting moons within our solar system. Consisting of two single-string electric propulsion spacecraft, the Phobos Surveyor mission would achieve redundancy by flying multiple units capable of transferring between the moons in the event of a failure. Each spacecraft would be constructed from currently available, well-characterized, flight proven commercial components and is capable of carry up to 40 kg of payload into orbit about Mars.

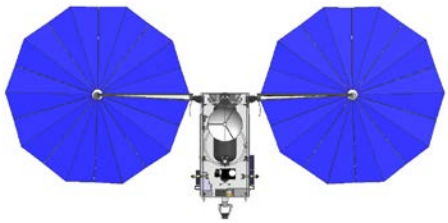

Figure 1 Phobos Surveyor would be designed solely out of flight certified commercially available off-the-shelf parts.

II.I Propulsion

The Surveyor concepts utilize a flight-proven commercial SEP system that enables architectural flexibility. Developed for commercial GEO communication satellites, EP systems like the SPT-100[2] or BPT-4000[3] are perfectly sized for the electrical power and life requirements for a Phobos precursor mission. The Russian made SPT-100 thruster has been baselined for the Phobos Surveyor mission to perform all maneuvers for the mission. Capable of

providing the ~4.5 km/s ΔV required to achieve Mars orbit, the thruster provides the perfect balance of low power and high I_{sp} that would be required for the mission.

The gimbaled SEP main engine would perform all desired maneuvers and most of the coarse attitude control maneuvers. However a small cold gas system would utilize a common propellant to perform coarse reaction control and landing capability. Though not the most efficient propulsion system, the cold gas system has been sized to provide enough thrust to safely land on Phobos without the added complexity of a separate propellant feed system. A small hydrazine could be added to accommodate missions requiring multiple landings for global measurements.

II.II Electrical Power System (EPS)

Two deployable ATK Ultraflex solar arrays[4] would provide sufficient power to operate the EP system at full power while in orbit at Mars. The 5 m^2 solar arrays produce ~4 kW of power at 1 AU and 1.7 kW of power at Mars, allowing for high power thrusting in orbit.

To maintain heritage, the Surveyor would employ a Dawn EPS architecture in which the bus voltage is unregulated, allowing for accommodation of a variable voltage range due to solar distances. To accommodate this, the Dawn power-processing unit (PPU) for the NSTAR ion thruster was designed and qualified to work over an input voltage range of 80 to 140V. Though the SPT-100 PPU has been qualified for an input voltage range of 95 to 105V, analysis has determined that the PPU is capable of handling input voltages between 80 and 120V[5]. As a result, the solar arrays are stringed at a nominal voltage of ~100V that is allowed to vary based on solar distances and array off pointing.

Developed for Dawn, the High Voltage Electrical Assembly (HVEA) would be responsible for power management by either down-converting the high voltage power and distributing it to the spacecraft avionics and instrumentation or passing the high voltage power on to the thruster PPU. The Dawn HVEA was developed to include internal redundancy and fault protection that would be unnecessary for the single-string Surveyor spacecraft. To save mass, the proposed Surveyor design modifies the original by removing the unnecessary redundant components, providing a lower mass design without altering the functionality or redesigning the hardware.

Upon entering orbit about Mars, the spacecraft would be responsible for maintaining operations while in eclipse. During the Mars Orbit phase, the spacecraft may encounter 50 min eclipse, relying on a 20 AHr secondary battery to provide power. The secondary battery would utilize high energy density cells developed for the Soil Moisture Active Passive (SMAP) mission.

II.III Command and Data Handling

The spacecraft would utilize the commercially available Broad Reach Engineering Command and Data Handling (C&DH) design. The single-string Rad-750 based architecture would provide the spacecraft with 8 Gbits of flash memory, telemetry and control interfaces, and power switching. RS-422/RS-485 ports send commands and data to the attitude control system and SEP PPU. Discreet and analog signals would provide state information of latches, temperatures and power switches. A Mil-Standard 1553B bus would be used to send commands and data to the Small Deep Space Transponder (SDST) for direct to Earth communication.

II.IV Guidance, Navigation and Control

The Surveyor Guidance, Navigation and Control (GN&C) Subsystem would provide 3-axis attitude and translational velocity directional control. Attitude determination would be accomplished via a single star tracker supplemented with an IMU used to propagate the attitude estimate during tracker outages. Eight coarse sun sensors would be used to estimate body relative Sun position. A reaction wheel assembly consisting of three GRAIL[6] heritage reaction wheels would provide fine attitude control, slewing of the spacecraft, and angular momentum storage. Momentum unloading would be achieved using a combination of the SEP main engine and the eight cold gas thrusters.

The GN&C design has been sized to stabilize the spacecraft in a "balancing broom" position atop a 1 m coilable boom while on Phobo's surface. This type of architecture would allow for simultaneous communication and solar array pointing during the landed duration. The IMU and accelerometer would provide inertial measurement feedback to the RWA to stabilize the spacecraft.

Due to the low gravity of Phobos, the cold gas RCS thrusters would provide enough thruster to safely land the spacecraft atop the coilable boom. The baseline Phobos Surveyor mission concept assumes a single landing, however the cold gas system is capable of "hopping" to multiple locations depending on leftover propellant. For missions requiring measurements from multiple surface locations, RCS thrusters with higher

I_{sp}, such as Xenon arcjet thrusters, could be used to ensure propellant reserve after the initial landing.

II.V Telecommunication

Direct to Earth communication would be achieved using a standard X-band uplink/downlink for science, command and telemetry. A single Small Deep Space Transponder (SDST)[7] and 100 W Traveling Wave Tube Amplifier (TWTA) would provide between 18 and 450 kbps through a 0.6m high gain antenna (HGA), depending on Mars distance from Earth. Two MER based low gain antennas (LGA) would provide low data rate transmission during interplanetary cruise.

II.VI Structure and Thermal

Surveyor would employ a low mass approach for the structural design of the spacecraft. The aluminum skeletal structure would provide support for the propulsion system, avionics and RWA. Spacecraft electronics, telecom, GN&C and instrumentation would be mounted to composite honeycomb face sheets. The simple spacecraft would only require two mechanisms, the commercially available solar array drive assemblies and an engine gimbal.

Spacecraft thermal control would be obtained by painting large portions of the external face sheets white to produce two thermal radiators on each side of the spacecraft. Due to the variation in operating power and the varying distances from the sun, thermal louvers mounted atop the radiators would be required to help control the heat. MLI, heaters and temperature sensors monitor and control the temperature of critical components within the spacecraft including avionics and propellant lines.

III. MISSION DESIGN AND OPERATIONS

Designed for secondary launch opportunities, two Surveyor spacecraft and the CSA MOOG developed ESPA Grande launch adapter[8] would require roughly 1000 kg of excess launch capability. To increase flexibility of launch opportunities, the mission concept focuses on three types: 1) co-manifested launch to Mars, 2) shared launch with a hypothetical lunar mission, and 3) as a secondary payload on an augmented launch to geo-transfer orbit (GTO).

III.I Launch and Early Operations

Mars rideshares provide the most efficient opportunity for the potential Phobos Surveyor mission, requiring the least transfer propellant, allowing for propellant usage in Mars vicinity, science payload, and time of flight to be optimized. As a SEP mission, the optimal launch time for Phobos Surveyor would occur before the optimal time for a ballistic mission. However, previous analysis of co-manifest ballistic launches shows that the Surveyor spacecraft could reach Mars orbit within three months after the ballistic arrival for modestly increased propellant usage, although still less than the other proposed secondary launches. For a co-manifest SEP launch, or an earlier launch, the trajectory could be optimized for lower propellant usage. Consequently, Phobos Surveyor could leverage any potential Mars mission as a rideshare opportunity.

If unable to utilize a Mars opportunity for rideshare, the Moon would become the means by which the spacecraft departs to Mars. To leverage the Moon, the mission would require specific targeting allowing for multiple flybys and ultimately Earth departure.

Targeting the initial lunar flyby would present some potential challenges for a direct lunar launch with a purely SEP spacecraft. Typical small injection corrections (on the order of 10-50 m/s) on direct trajectories are beyond the capability of the SEP system. There are two potential methods of addressing this: 1) delay secondary separation until after the first trajectory correction maneuver, resulting a potentially undesirable linkage between the secondary and primary vehicles, or 2) require a second burn of the launch vehicle's second stage (similar to that done for the LCROSS mission) to target a benign initial flyby. For either case, the time that would be required from launch to Earth departure for a lunar rideshare launch opportunity is roughly 6 months. Unfortunately, lunar mission launches don't always align with the optimal launch opportunity for a Mars transfer, and as a result the proposed mission may require a heliocentric Earth-Earth loop, setting it up for the next available transfer (up to 2 years).

Compared to lunar missions, geosynchronous missions with an injection into geosynchronous transfer orbit (GTO) are much more common. A GTO-bound launch vehicle can be augmented (with the addition of solid boosters for the Atlas V family) to increase the GTO injection mass, which would be used for the two Surveyor spacecraft, the ESPA Grande ring, and additional upper stage propellant required for an injection burn into a highly elliptical orbit after deployment of primary payload[9]. Once boosted from the GTO orbit, 2 months and <300 m/s are required to proceed to a lunar flyby and Earth departure similar to that used for a direct lunar launch.

III.II Mars Transfer

Since the lunar departure is the driving case, the propellant and trajectory analysis focuses on this potential launch option. Figure 2 shows the trajectory from Earth departure (with a V_{inf} of 2 km/s) to Mars rendezvous. With an Earth departure of 2 km/s, the SEP trajectory would not require thrusting until half way through the transfer, and from that point the trajectory would require constant thrusting to Mars rendezvous.

Upon Mars arrival, two heliocentric parameters must be accounted for: 1) solar range and 2) Mars season. Unfortunately the spacecraft would arrive at Mars at the mid-point in solar range, with Mars heading into aphelion. As a result the power available to the thruster would be heading to its lowest value. Mars orbit analysis for this mission uses the conservative power and thrust levels for thrusting during this part of the trajectory. The seasonal requirements for the proposed mission, as described later in the paper, are required for polar illumination.

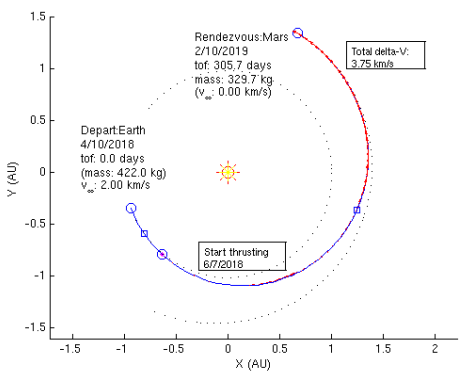

Figure 2 The SEP architecture would allow Phobos Surveyor to use the Moon for Earth departure

III.III Mars Orbit Phase

The proposed thruster for the Phobos Surveyor mission is life-limited by propellant throughput. As a result, the spacecraft would be unable to spiral down to Phobos. Consequently, the potential trajectory uses periapsis thrust arcs, shown in figure 3, to efficiently reach the Phobos orbit. Most of the thrusting would be close to the anti-velocity direction, but the current trajectory uses an implementation of Q-law[10] to change the pitch angle to slightly suppress periapsis, making the thrusting more efficient.

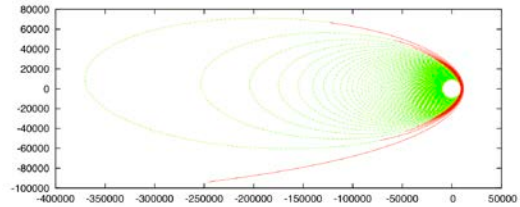

Figure 3 Potential transfer trajectory from Mars arrival to Phobos rendezvous. Red arcs are thrusting, green arcs are coasting. Transfer time is 369 days, and requires 1.106 km/s total delta-V

For the Phobos Surveyor mission concept, the transfer time has been constrained to one year between Mars arrival and Phobos orbit rendezvous. Depending on the available propellant at Mars arrival, the speed of the Phobos arrival trajectory could be adjusted. For Deimos rendezvous, the same amount of propellant would allow for a much faster arrival. However, in the event that Deimos science is lower priority, the Deimos spacecraft might need to wait in Mars sphere of influence (e.g. at Mars-Sun L1) to supplement the Phobos spacecraft in the event of a failure. The transfer from a Mars-relative C3 of zero, to Deimos, then to Phobos would likely require ~1.6 km/s for SEP thrusting in the ~1 year timeframe, within the capabilities of the Surveyor spacecraft on a favorable launch.

With the ultimate goal of landing on a pole, the Phobos Surveyor mission would also obtain excellent global imaging coverage. To do so, the mission must be conscious of the season, rendezvousing with Phobos prior to an equinox, such that the polar regions are still lit. For this case, the spacecraft would need to be able to start imaging Phobos within ~12 months to capture the North Pole with illumination. Afterwards, the mission would focus on equatorial coverage until the season progresses far enough into southern summer to image the South Pole and prepare for landing. If a North Pole landing were desired, then the mission would take a ~340-day delay in Mars orbit.

III.IV Phobos Operations

A variety of trajectories could be used to obtain short-range imagery of the entire surface of Phobos. The simplest of these is a distant retrograde orbit, which is essentially a Mars orbit similar to that of Phobos, with a slight eccentricity variation to avoid impact. The stable orbit could be adjusted to cause periodic closer approaches to the leading and trailing sides of the target.

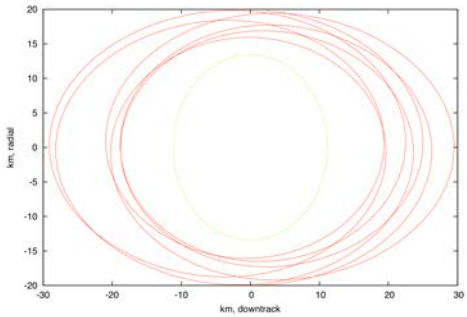

Figure 4 Potential distant retrograde orbit

For polar imaging, orbits with a semi-major axis 100 km higher than Phobos could utilize gravity perturbations from the moon causing the spacecraft to dip down for polar flyovers before returning to higher altitudes, as shown in figure 4. These events occur every ~3 weeks due to period differences without the need for thrusting. Similar orbits also exist that could potentially produce more frequent flyovers for modest ΔV.

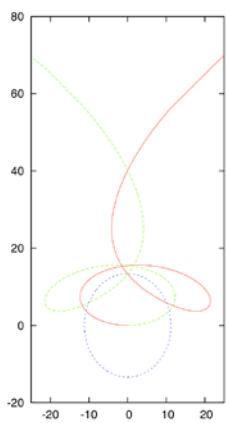

Figure 5 Proposed multiple polar flyby trajectory, viewed from the Phobos north obit pole. Approach trajectory is in red, departing trajectory is in green. Minimum altitude is 300 m over the pole and 2.5 km at the additional crossing of the Phobos figure.

Before landing, the spacecraft would ideally be in a polar orbit about Phobos, such that some of the ΔV required could be provided by the more efficient SEP system. To land safely, the spacecraft would require autonomous control, similar to JPL's proven AutoNav system used for Deep Impact[11]. Requiring more thrust than available from the SEP thruster, the final descent would utilize the cold gas RCS thrusters to perform the 10-15 m/s ΔV. Due to the low I_{sp} of cold gas thrusters, trades using more efficient resistojet thrusters or a more complex hydrazine monopropellant system could be conducted.

Once on Phobos surface, the spacecraft would balance atop a large coilable boom while performing science operations. The GN&C system would utilize the high precision IMU and star tracker measurement to provide attitude feedback to the reaction control system. Torque provided by the RWA would be used to maintain stability and orient the spacecraft atop the boom for Earth communication. Fortunately the Sun's elevation relative to the surface varies very little over the course of the surface operations. As a result, only rotation in azimuth would be required for the arrays to track the sun and the spacecraft antenna to point to Earth. Offsetting the center of gravity of the spacecraft with respect to the contact point of the boom would allow gravity to dissipate any stored momentum, providing a desaturation of the RWAs.

IV. CONCLUSION

As humans takes the next step toward exploration of Mars, Phobos and Deimos become targets of increasing interest for science and exploration purposes. Phobos Surveyor offers a unique, innovative and lower cost approach to addressing important Human Exploration and Decadal Science objectives using multiple low cost, highly reliable SEP spacecraft. The flexible launch architecture would provide a paradigm shifting approach to flying Mars missions. The unique capabilities of using lunar flybys to achieve Mars orbit from a GTO or lunar launch would enable focused missions to Mars to be launched more often.

V. ACKNOWLEDGEMENTS

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