Mercury Sample Return using Solar Sails

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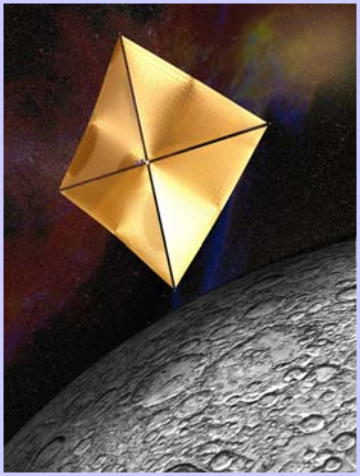

INTRODUCTION

A conventional Mercury sample return mission requires significant launch mass due to the large Δv required for the outbound and return trips, and the large mass of a planetary lander and ascent vehicle. Solar sailing can be used to reduce lander mass allocation by delivering the lander to a low, thermally safe orbit close to the terminator. Propellant mass is not an issue for solar sails so a sample can be returned relatively easily, without resorting to lengthy, multiple gravity assists. The initial Mercury sample return studies reported here were conducted under ESA contract ESTEC/16534/02/NL/NR, PI Colin McInnes, Technical Officer Peter Falkner[3,4,5]. Updated solar sail capabilities were developed under the Ground System Demonstration program, funded by the NASA's In-Space Propulsion Technology (ISPT) Program.

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SCIENCE OBJECTIVES

It is important to ascertain the surface age of Mercury to understand its geologic history, however accurate rock dating of Mercury surface samples is only possible on Earth. A high-latitude landing site is required due to thermal constraints, and prior imaging of this site from the orbiter at a resolution of better than 1 meter per pixel is necessary. Even at high latitudes, landing in direct sunlight, or in permanent shadow would be undesirable. A landing site within a suitable crater, in partial shade, but with some light reflected from the crater walls is preferable, with a sample drilled from a rock outcrop within the crater.[2] Baseline science objectives therefore are to acquire a surface sample of 350 g of surface regolith though a precision landing at a carefully selected high latitude landing site in partial shadow, within a suitably aged crater, with high resolution imaging for documentation during terminal descent. Sample pre-selection and pre-analysis will be conducted in-situ during landing site characterization using a robotic arm and small mobility device (20 m range).[1]

MISSION DESIGN

A baseline mission concept has been proposed which uses a 275 x 275 meter solar sail with an assembly loading of 5.9 g/m² to deliver a lander, Sail Cruise Stage (SCS) and on-orbit science payload to a forced 100 x 7500 km Sun synchronous orbit at Mercury using a 2.85 year minimum-time trajectory, with a sail characteristic acceleration of 0.25 mm/sec². From this initial orbit, the on-orbit science payload is used to survey potential landing sites for a period of up to 130 days. The solar sail then descends to a 100 km polar orbit where a 1455 kg Mercury Descent Vehicle (MDV) is separated and descends to the south polar Bach region of the planetary surface using a blowdown bi-propellant system. A surface science phase of 4 days duration then takes place with the acquisition of 4 core samples and limited exploration using a small surface mobility device. Following sample acquisition, the Mercury Ascent Vehicle (again using a blow-down bi-propellant system) delivers a small 15 kg Sail Rendezvous Vehicle (SRV) (cold gas system) containing the samples into a 100 km polar orbit. A dedicated rendezvous stage has been sized to avoid issues associated with the use of hot gas propulsion in close proximity to the sail film. After a 10 day hibernation in the 100 km polar orbit to allow the solar sail orbit plane to match that of the rendezvous vehicle, final proximity maneuvering takes place along with sample transfer. The solar sail then spirals to escape, executes a 1.01 year minimum-time return trajectory to Earth and finally delivers the samples to Earth using aerocapture with a 17 kg ballistic Earth Return Vehicle (ERV) at parabolic approach speed.

SRV Component	Mass (kg)	Contingency (%)	Total mass (kg)
Sample container	2.0	-	2.0
SRV Payload Mass	**2.0**	**-**	**2.0**
Attitude control	3.1	10	3.4
Command & data	0.5	10	0.6
Power	2.0	10	2.2
Mechanisms	0.1	10	0.1
Telecomm	1.1	10	1.2
Thermal	1.0	10	1.1
Structure	2.0	10	2.2
SRV Bus Mass	**9.8**	**10**	**10.9**
Thrusters	0.2	15	0.23
Valves, pipes	0.1	15	0.1
Propellant tank	0.1	15	0.1
Propulsion Mass (Dry)	**0.4**	**15**	**0.43**
SRV Dry Mass	**12.2**		**13.3**
System contingency	-	1	0.1
Total SRV Dry Mass			**13.4**
Propellant for rendezvous	1.0	15	1.1
Total SRV Mass (Wet)			**14.5**

Table 1: Sail Rendezvous Vehicle (SRV) system sheet mass breakdown

MAV Component	Mass (kg)	Contingency (%)	Total mass (kg)
SRV	14.5	-	14.5
MAV Payload Mass	**14.5**	**-**	**14.5**
Attitude control	4.5	10	4.9
Command & data	2.5	10	2.7
Power	2.3	10	2.5
Mechanisms	0.5	10	0.6
Telecomm	0.0	10	0.0
Thermal	2.0	10	2.2
Structure	5.2	10	5.7
MAV Bus Mass	**17.0**	**10**	**18.6**
Thruster	15.0	15	17.3
Valves, pipes	2.9	15	3.3
Propellant tank	9.5	15	10.9
Propulsion Mass (Dry)	**27.4**		**31.5**
MAV Dry Mass	**58.9**		**64.6**
System contingency	-	1	0.65
Total MAV Dry mass			**65.3**
Propellant for Dv1	0.5	15	0.6
Propellant for Dv2	94.8	15	109.0
Total Propellant Mass	**95.29**	**15**	**109.6**
Total MAV Mass (Wet)			**174.9**

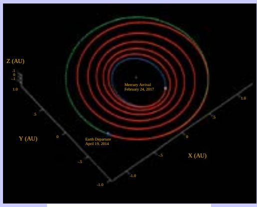
Table 2: Mercury Ascent Vehicle (MAV) system sheet mass breakdown

MDV Component	Mass (kg)	Contingency (%)	Total mass (kg)
MAV	174.9	-	174.9
Surface instruments	2.9	-	2.9
MDV Payload Mass	**177.8**		**177.8**
Attitude control	15.0	10	16.5
Command & data	4.0	10	4.4
Power	8.8	10	9.7
Mechanisms	22.0	10	24.2
Telecomm	0.0	10	0.0
Thermal	3.0	10	3.3
Structure	83.0	10	91.3
MDV Bus Mass	**135.8**	**10**	**149.4**
Thrusters (5 of 6kN)	50.0	15	57.5
Valves, pipes	8.3	15	9.5
Propellant Tanks	83.0	15	95.5
Propulsion Mass (Dry)	**141.3**	**15**	**162.5**
MDV Dry Mass	**454.9**		**489.7**
System contingency	-	1	4.9
Total MDV Dry Mass			**494.6**
Propellant for Dv1	4.0	15	4.6
Propellant for Dv2	830.8	15	955.4
Total Propellant Mass	**834.8**	**15**	**960.0**
Total MDV Mass (Wet)			**1454.6**

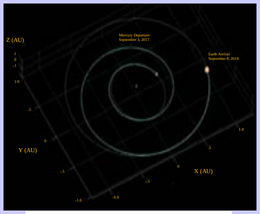
Table 3: Mercury Descent Vehicle (MDV) system sheet mass breakdown

SCS Component	Mass (kg)	Contingency (%)	Total mass (kg)
Lander (SRV/MAV/MDV)	1454.6	-	1454.6
Science payload	31.6	-	31.6
ERV	**16.5**	**5**	**17.3**
SCS Payload Mass	**1502.7**	**1503.5**	
Attitude control	14.1	10	15.5
Command & data	10.0	10	11.0
Power	40.2	10	44.2
Mechanisms	161.0	10	177.1
Telecomm	24.6	10	27.1
Thermal	50.0	10	55.0
Structure	65.4	10	71.9
SCS Bus Mass	**365.3**	**10**	**401.8**
Total Sail Payload Mass			1905.3

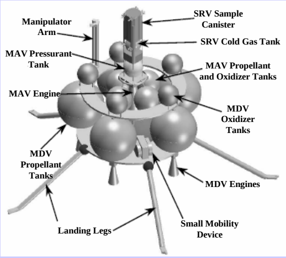
Table 4: Sail Cruise Stage (SCS) system sheet mass breakdown



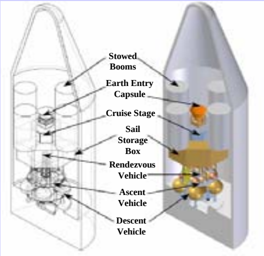
Earth - Mercury Trajectory



Mercury - Earth Return Trajectory



Mercury Lander Concept



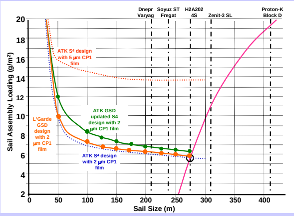
Mercury Sample Return Launch Configuration

Comparison of Solar Sail, Chemical and Electric Propulsion Options

Parameter	SOLAR SAIL	CHEMICAL	SEP
Launch Vehicle	H2A 202-4S	Ariane 5E **	Atlas V 551
Launch Mass (kg)	2353	6500 **	5775
C3 (km 2 s -2)	0	11.6 **	7.8
Mission Duration (yrs)	4.4	7.2 **	6.9
		** Chemical/SEP,	

SAIL DESIGN

A square solar sail is envisaged, using tip vanes for attitude control, sized to provide adequate slew rates for the planet-centered mission phases. The spacecraft (sail payload) is mounted centrally, within the plane of the solar sail, so that both faces of the core structure are free to be used as attachment points for the lander, and Earth return capsule. An outbound trip time of 2-3 years is desirable to be competitive with solar electric propulsion (SEP) and chemical mission trip times. This is enabled by a characteristic acceleration of 0.25 mm/s². The chosen sail conceptual design used in this paper is based on the ATK Scaleable Solar Sail Subsystem (S[4]), since it can be extrapolated to large sail dimensions.[6] This design is based on coilable booms, and the boom linear density as a function of length can be combined with NASA/LaRC/SRS 2 or 5 µm CP1 film to obtain the sail assembly loading as a function of sail side length. It is assumed that conventional coatings are used, with aluminum (85% reflectivity) on the frontside and chromium (64% emissivity) on the backside. Shown below is the necessary sail assembly loading as a function of sail side length, for delivery of a 1905 kg spacecraft to Mercury with a characteristic acceleration of 0.25 mm/s². It can be seen that the intersection of the 2 µm CP1 ATK S[4] sail design curve with the 0.25 mm/s², 100 km orbit payload curve yields the sail design point, with an assembly loading of 5.9 g/m² and sail dimensions of 275 x 275 m. Included are updated curves based on the 20 meter GSD for the ATK and L'Garde.



TECHNOLOGY DEVELOPMENT

NASA's In-Space Propulsion Technology (ISPT) Program is investing in technologies that have the potential to revolutionize the robotic exploration of deep space. For robotic exploration and science missions, increased efficiencies of future propulsion systems are critical to reduce overall life-cycle costs and, in some cases, enable missions previously considered impossible. The ISPT Program is developing technologies from a Technology Readiness Level (TRL) of 3 through TRL 6.

Solar sail propulsion uses sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, reflective material. Because the Sun supplies the necessary propulsive energy, solar sails require no onboard propellant, thus reducing payload mass. With photonic pressure providing continuous thrust, sailcraft can conduct missions not available with conventional or electric propulsion:

- high-inclination orbital maneuver plane changes
- fast flyby missions to the outer planets or extra-solar system
- orbit in non-Keplarian orbits (above the pole of a planet) and
- hover indefinitely at a point in space

Over a two and one-half year period dating from 2003 through 2005, ISPT matured solar sail technology from laboratory components to full systems, demonstrated in as relevant a space environment as could feasibly be simulated on the ground. Two 20 meter square solar sail designs were manufactured, subjected to launch vibration and ascent vent profiles and deployed under high vacuum at NASA Glenn Research Centers' Plum Brook Space Power Facility[7,8].