POTENTIAL FUTURE MARS MISSIONS

Sylvia L. Miller, Mars Program Planner
Julia L. Bell, Mars Program Planner (Senior Member, AIAA)
James E. Graf, Project Manager (Member, AIAA)
Steve E. Matousek, Mars Future Studies Lead (Senior Member, AIAA)

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099

Abstract. NASA has been intensively re-planning the future content of its Mars Program. The process has been inclusive with ideas being solicited and received from a broad spectrum of the community. Two synthesis workshops were held with inputs from numerous g[1]roups, including the leads of a wide variety of mission concepts that were studied in the last few months. The concepts are divided into five categories: Orbiters (with a specific example of a Reconnaissance Orbiter); Large Landers and Sample Return (discussing the features of second generation landers and how they could support a sample return mission); In Situ Concepts (with two examples: Multi-Scout and a Mars Stratigraphy Mission); Small Missions (Scouts and Micromissions); and Telecommunications. NASA's re-planning process is not complete. Hence, this paper contains just a sampling of the many potential future Mars missions.

INTRODUCTION

During the summer and fall of 2000, NASA has intensively been re-planning the future content of its Mars Program. This activity was brought about by the loss of both Mars Climate Orbiter and Mars Polar Lander in the last quarter of 1999. Part of the process has been to solicit ideas and study a wide variety of missions for consideration in the future program. The new plan is not complete. Hence what we present here is a sampling of some of the many potential mission options that have been studied in recent months. The inclusion of a particular mission concept in this paper does not imply that it is more likely to be included in NASA's new plan than other concepts not described here.

Throughout this paper, reference will be made to "opportunities" to launch to Mars. This term derives from the trajectories from Earth to Mars that are the most efficient in terms of required energy for ballistic transfers. These trajectories are classified as Type I, II, III, IV, etc., according to whether the flight angle of the transit is less than 180°, between 180° and 360°, between 360° and 540°, etc. A given trajectory type (e.g., Type I) occurs on average about every 26 months, according to the relative geometry between Earth and Mars. This periodicity defines the "opportunities" to launch to Mars, e.g., 2001, 2003, 2005, etc. Trajectory Types I and II have the desirable feature of the shortest flight times, typically in the range of six months to one year. Unless there is an overriding reason, these trajectory types will be used for spacecraft with chemical propulsion.

All of the mission concepts described in this paper assume that the spacecraft are chemically propelled. However some missions studied employ solar electric propulsion, in particular for spacecraft returning samples from Mars back to Earth.

BACKGROUND

A year ago, the architecture of the Mars Program, at least through the 2005 opportunity, was well-established.[1] Mars Global Surveyor was making discoveries that altered our most fundamental understanding of Mars and its history. After the two 1998/1999 missions, another orbiter and lander, already being assembled and tested, would be launched in 2001. Japan's orbiter Nozomi would arrive at Mars in 2003, the same year as the launch of Mars Express, an orbiter being developed by the European Space Agency. In addition, 2003 and 2005 would see launches of missions at the heart of the Mars Program, missions that would return samples of Martian rocks and soil to Earth for analysis. These missions would be carried out by a partnership between NASA and the French Space Agency, CNES. NASA would send a lander/rover in each of 2003 and 2005 to collect promising samples and loft them, in a sealed sample canister, into low Mars orbit. A French orbiter would capture one or both canisters, store them inside Earth entry probes, and return the probes to Earth. NASA would provide the capture equipment and the Earth entry probes. The French would also provide an Ariane 5 launch in 2005 for both their orbiter and NASA's lander. Their orbiter would carry four NetLanders, a small network of surface stations to be delivered on approach to Mars. In addition to their primary function related to returning samples, the landers were also being designed to carry experiments in support of NASA's possible future human exploration of Mars, as well as a subsurface drill and surface package provided by the Italian Space Agency, ASI. Micromissions, a line of smaller missions complementary to the mainline missions, were also being considered to start with the 2003 or 2005 opportunity. Some might carry science payloads and some might be dedicated to telecommunications.[2]

In the aftermath of the double mission failure last year, significant changes have been made to the program content. Early in 2000, NASA canceled the 2001 lander and closed out the sample return project. The 2001 orbiter is progressing as planned, as are Nozomi and Mars Express. The latter is also expected to deliver to Mars a small station called Beagle 2, which is being developed by a UK consortium led by the Planetary Sciences Research Institute. In July NASA selected two rover missions for launch in the 2003 opportunity. The two missions will be identical and will each deliver a rover similar to the ones that had been planned for the sample return lander missions. This 2003 rover is significantly more capable than Sojourner. The rovers will be delivered by an entry system similar to Mars Pathfinder's, with airbags. Unlike Pathfinder, however, the landing system will not be designed to operate after the landing, i.e., the rover will be self-sufficient.

In addition to these changes, NASA put in place a process to develop a longer-term plan for the Mars Program, i.e., for missions in 2005 and beyond. An executive group, including the Director for Mars Exploration (NASA HQ) and the Mars Program Manager (JPL), was established to lead the effort. One part of the process was to reach out to a broad spectrum of the community for ideas. Responses were received from industry through a request for information. NASA centers submitted letters with their concepts, as did some international organizations. Individuals were invited to submit ideas to be presented at a workshop at the Lunar and Planetary Institute (LPI) in July. In all, almost 400 unique concepts were submitted. These concepts were sorted, evaluated, and reported on at a Mars Synthesis Retreat held in late August. This was one of two retreats held by NASA to develop a robust plan for the future Mars program. Additional inputs were provided to the retreats by many groups: science, technology, public engagement, mission design, launch vehicles, international partners, and those representing human exploration. The process is not finished at this writing but is planned to be complete by Thanksgiving.

Mission examples described in this paper are divided into five main categories: Orbiters, Large Landers and Sample Return, In Situ Concepts, Small Missions, and Telecommunications.

ORBITERS

Orbiter missions serve several purposes. Global scientific observations are best done from a polar, low altitude (300-400 km), sun-synchronous, circular orbit.

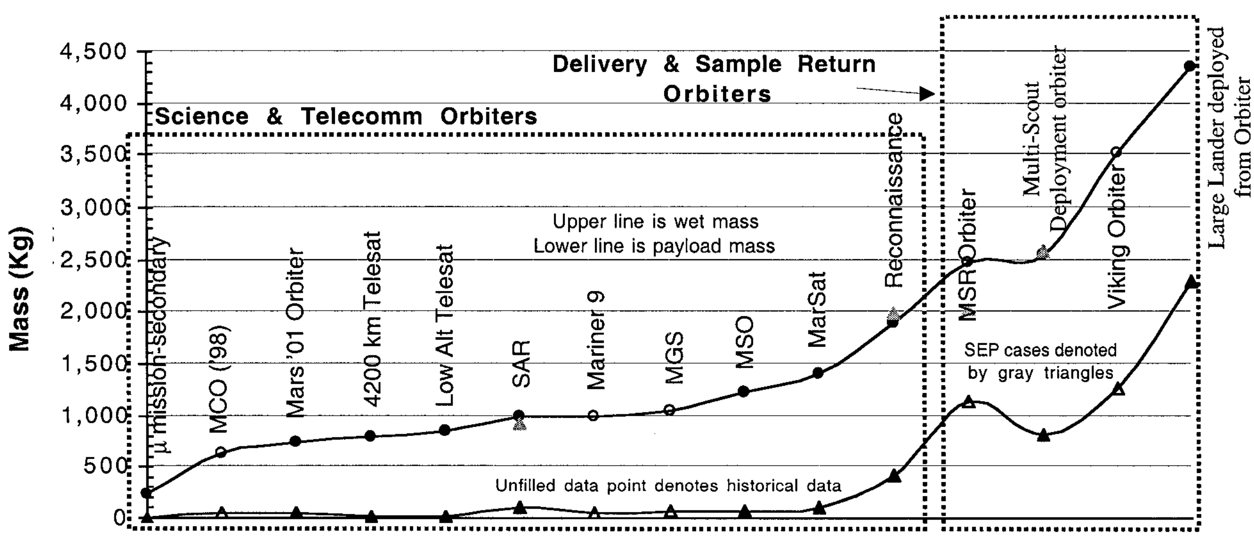

Figure 1: This graphic shows orbiter wet mass versus function. Note that scientific and telecom orbiters fall into a range of mass from about 240 kg on the low end to nearly 1900 kg on the high end. Sample return and delivery orbirers comprise the high end of the wet mass curve since they need to deliver large masses (either rutum trip propellant or payload) to Mars orbit. Note that the effect of Solar Electric Propulsion (SEP) for orbiters is to decrease the required launch vehicle by one size. Another effect not evident from the chart is that arrival conditions at Mars can be tailored to the mission (latitude, lighting conditions, Earth view during mission critical events, etc.).

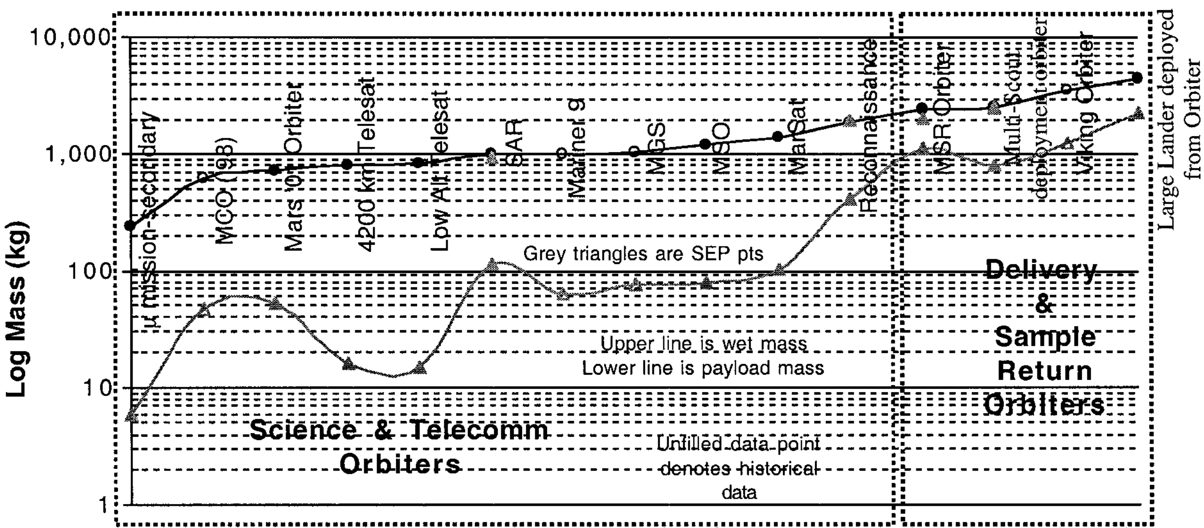

Figure 2: This graphic shows the available payload mass versus orbiter function on a log scale. Taken together with Figure 1, wet mass and payload mass can be determined for a given orbiter mission. Note that telecom orbiters appear to have less payload. However, adding in the appropriate parts of the telecom subsystem to the payload would bring the curves in line with the science orbiter payloads.

Currently, Mars Global Surveyor is in such an orbit around Mars. The 2001 Mars orbiter mission will also be in a polar, low-altitude, circular orbit. Other purposes for orbiters include delivery of atmospheric or surface probes from orbit, telecommunications and navigation relay, and return of samples back to Earth. This section concentrates on the orbiter missions for global scientific observations. Examples of some of the other types are given in later sections.

Before investigating a mission concept in detail, it is useful to examine the relationship of wet mass (flight system injected by the launch vehicle) or payload mass delivered to Mars orbit versus orbiter function. Figures 1 and 2 show this relationship for past, present, and candidate future orbiters.

Many orbiter concepts have been proposed over the years. Additionally, several flight missions such as Mariner 9, Viking orbiter, and the current MGS mission demonstrate the utility of orbiters. Many types of observations are possible from orbiters. Relatively large payloads can be placed into orbit. The payload can consist of imagers (visible, infrared, and ultraviolet), spectrometers, atmospheric observing instruments, magnetometers, laser altimeters, and radars (sounding and synthetic aperture radar or SAR).

With this wide variety of possible instruments, it is important that the desired orbit be optimized for the type of observation. It is usually the case that the payload consists of instruments that have conflicting orbit desires. For the mission discussed in this section, the payload was carefully selected to include instruments that require the same orbit in order to avoid this conflict. If this study were to become a fight project, there would likely be desired orbit conflicts as new elements of the payload became necessary. Consequently, the payload and mission concept shown in the following mission description are illustrative only.

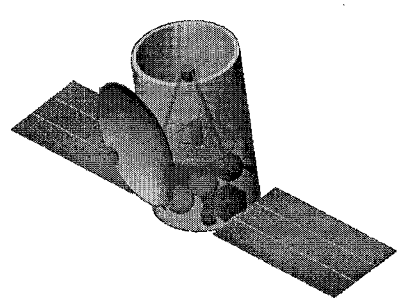

Figure 3: This JPL Team X conceptual design shows the large telescope as the dominant feature of the spacecraft. For scale, the aperture of the telescope is 2 m diameter.

Reconnaissance Orbiter

This example orbiter mission results from a desire to obtain very high resolution images of Mars. These images support site reconnaissance because objects (such as rocks) can be detected down to ~ 20 cm. Together with the 20 cm capability, slope characterization of the imaged site on the scale of ~ 40 m provides a powerful capability for surveying potential landing sites. Startling features imaged by MGS create a desire to see finer detail of the surface. 10 – 20 cm objects on the surface are generally regarded as the next level of detail beyond the current MGS highest resolution capability (~ 1 meter). To get 20 cm resolution at the surface, altitude must be minimized and aperture maximized. This leads to a large telescope in a low Mars orbit (see Figure 3).

Table 1 Reconnaissance Orbiter Mission Parameters

Mission Parameter	Value	Comments
Mars orbit	300 km circular	8 AM/PM
Imaging system primary	2m mirror diameter	Required for SNR*
Payload	410 kg	
Visible imager	20 cm	
Thermal imager	10 m	8 AM orbit for SNR
Laser altimeter	40m spot size	MGS upgrade
UHF telecom relay		For comm relay from Mars surface
Total spacecraft wet mass	1890 kg	At launch
Launch vehicle class	Delta 4540	Telescope requires larger launch vehicle fairing
Spacecraft lifetime	At least 5 years on orbit	Consumables sized for 10-year on-orbit lifetime

*SNR – signal to noise ratio. The 2-meter aperture is required to collect enough photons. Further study could reduce the aperture size by as much as a factor of two.

The orbiter described here propulsively captures into an elliptical orbit, then aerobrakes down into a 300 km circular orbit. Some options not considered in this study include aerocapture (to lower the propellant requirements) and an intermediate elliptical orbit (say 200 X 400 km) where higher resolution images might be taken at periapsis. Table 1 provides some basic mission parameter.

This orbiter can survey 500 10 x 10 km sites at 20 cm resolution in 5 Earth years. Sending this much data back to Earth requires a large telecommunications system that can relay at least 1 Mbps at X-band. Future telecomm subsystem technology that can accommodate higher data rates would allow missions like this to survey even more sites. In any case, only a small fraction of the surface can be imaged at high resolution.

Not all data acquired are limited to small regions. For example, the slope characterization by the laser altimeter is achieved on a global scale, as with MGS.

Some of the driving parameters of this reconnaissance orbiter mission are worth comment. The sheer size of the telescope drove the launch vehicle selection to a five-meter fairing. With the future NASA launch vehicles, this gives excess performance for the mission. Further study is warranted to see if the telescope could fit in a smaller four-meter fairing. The requirement for an 8 AM/PM equator crossing can result in a wait of several months from arrival to start of observations, depending upon the arrival geometry, as the orbit precesses around to the desired node. For the 2007 opportunity this phasing requirement is nine months, a time period that could be decreased considerably if a node crossing closer to 4 AM/PM is deemed acceptable. The requirements of the thermal imager SNR led to the aperture size. Optimizing for visible imaging only could dramatically decrease the aperture size. Smaller aperture size ripples through the whole concept design and could make the flight system and launch vehicle smaller.

LARGE LANDERS AND SAMPLE RETURN

Mars future landed missions include safe, accurate landing of payloads large enough to accomplish a sample return mission or moderate depth drilling (tens of meters) or to accommodate both a comprehensive science instrument suite and extensive in situ resource utilization payloads. In addition, the landers may be fixed (immovable) or have sufficient mobility capability to rove multiple kilometers on the surface. Accurate landing coupled with extensive roving capability that exceeds landing error ellipses, could

Table 2 Lander Capability as a function of Generation

Description	First Generation Landers	Second Generation Landers	Third Generation Landers
Era	1976 to 2003	2005 to 2009	Next Decade
Surface Missions	Vikings, Mars Pathfinder, Mars Polar Lander, Mars Expl. Rover	Generation-2 Class	Heavy Landers
Landed Mass (kg)	300 to 650	1300 to 1700	2500 +
Science Payload Mass (kg)	20 to 70	Fixed platform - 300 to 450 Mobile platform - 150 to 300	500 +
Duration	84 sol (solar) years (RPS*)	90 to 180 sols (solar) years (RPS*)	180 sol (solar) years (RPS*)
Mobility	Up to 1-km 100 m demonstrated	Up to 30 km (with RPS*)	Up to 100 km (with RPS*)
Delivery Accuracy	100 to 200 km major axis ellipse	6-km major axis ellipse	10 to 100 m radius
Payload Types	Local surface area analysis	in-situ investigation & utilization, subsurface sampling & MSR	deep drills, outposts, support to human missions
Hazard Avoidance	None	100 to 150-meter maneuver capability	200 to 1000-meter maneuver capability

enable "Go to" missions, missions in which a specific, selected feature (e.g., seepage site) on the surface can be investigated with a major payload complement.

The mission capability over the next decade will evolve from today's first generation, through two more generations with ever increasing capability and with acceptable levels of risk. The differences between the generations are shown in Table 2. First generation missions started with Viking in the 1970's and extend to the launch of Mars Exploration Rover in 2003. They have a landed mass of 300 to 600 kg with science payloads of 25 to 70 kg, landing ellipses from 100 to 300 km, mobility localized to the landing site (or immovable) and, for the solar powered missions, limited life of under 90 sols (a sol is one Martian day). The one notable power exception is Viking's radio active power source (RPS) which operated for several years.

The second generation landers have landed masses of 1500 to 1700 kg with payload masses of up to 300 kg, landing ellipses of 6 km, roving capability of 10 to 30 km, depending on the power sources, and lifetimes of 180 sols (solar powered) or years (RPS). The ability to rove beyond the landing ellipse enables the second generation lander to investigate specific surface features within the direct landing latitudes of a particular launch opportunity. The use of the RPS would free up the landing site selection from solar illumination constraints. By one scenario, the second generation would extend from the 2005 launch opportunity to the end of the decade. An entry, descent, and landing (EDL) demonstrator mission could be launched as early as 2005, followed by a Mars Sample Return mission in 2009.

The third generation lander lands 2500 kg with 500 kg or more of payload with a landing precision of 100 m radius. The lander can rove upwards of 100 km. This capability could enable human exploration missions as well as deep drilling.

Second generation EDL, shown in Figure 4, differs in several ways from the first generation. Precision entry through the use of optical navigation enables accurate entry into the Martian upper atmosphere. First generation missions did not have this capability. Once in the atmosphere, the use of guided entry with a lift-to-drag (L/D) ratio of ~0.25 rather than ballistic entry with a L/D of zero sharply reduces trajectory dispersions due to atmospheric and other environmental modeling errors. Use of a second parachute at subsonic speeds offsets descent propellant and greatly increases the science payload.

Descent propulsion using larger thrust levels reduces the duration of powered descent and again increases the landed payload. The propulsion system is used to minimize the horizontal velocity envelope at touchdown, which reduces loads on the landing gear. An onboard sensor images the surface from

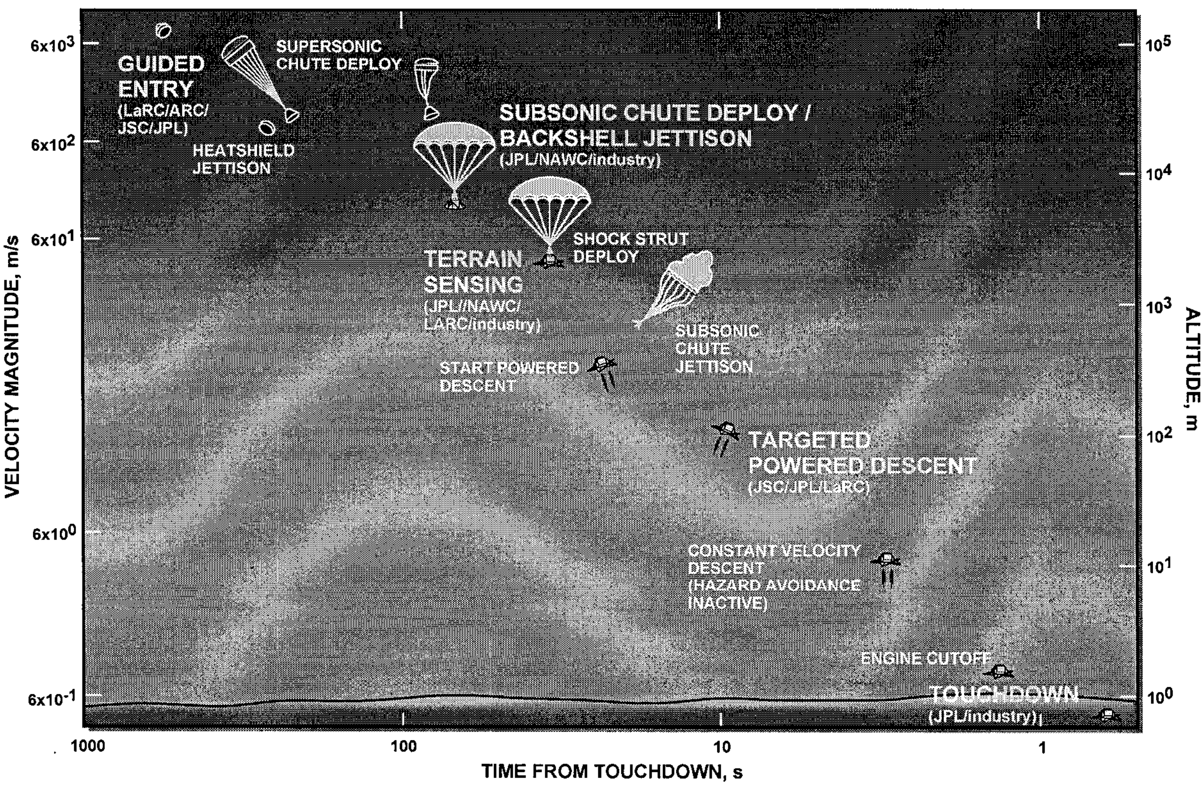

Figure 4. Key Technologies for Second Generation Landers (those identified by upper case letters)

approximately 1 km to determine hazards and to identify safe havens. The propulsion system, commanded by the onboard guidance system, maneuvers the lander to one of those safe locations.

The landing gear of second generation landers is being designed to survive impact on 0.5 m rocks on a 30° slope, thereby greatly increasing the landing tolerance and opening up an increased number of landing sites.

Two concepts are under consideration and are shown in Figure 5. The first uses air bags with a roll arrest mechanism and a roll-over device. A second concept under consideration employs a pallet, using a solid central core coupled with outrigger struts for stabilization.

A sample return mission could employ the second generation EDL while also utilizing many of the building blocks and concepts described by O'Neil and Cazaux.[3] The landers with a launch mass of 2580 kg could be launched off an EELV and land 300 kg of science and sample return hardware on the surface. The landing gear is left at the landing site and the mobile lander, employing RPS, never returns to the launch site but roves approximately 30 km during its life. Along the way, samples are scientifically selected and stored onboard the mobile unit. At the appropriate time, the external portion of the sample containment device is sterilized and loaded into the orbiting sample container in the nose cone of the Mars ascent vehicle onboard the rover. The two-stage solid rocket injects the sample into low Mars orbit where it is captured by an orbiting spacecraft and returned safely to Earth.

IN SITU CONCEPTS

Another category of Mars missions is in situ concepts, i.e., those not covered by the large landers of the previous section. These could be landers, rovers, penetrators, small stations, balloons, aircraft, subsurface moles, or other platforms that gather data directly while in or on the surface, atmosphere, or subsurface of Mars. Small platforms will be discussed separately in a later section. Two examples of in situ concepts described here are multi-scout concepts and a Mars stratigraphy mission.

Multi-Scout

Dedicated landers offer substantial science payload capability, but even advanced long-life, long-range rovers will travel less than 100 km. As an alternative, the multi-scout mission provides broader, more diverse access by delivering small payloads to many sites. The benefits of scouts, and the multiple scout delivery concept, were recently recognized in several submissions to NASA's summer 2000 outreach effort.

All multi-scout concepts share a common structure: a dedicated host vehicle carrying several small, individual payloads (scouts) to Mars. Several types of scouts may be considered including landers (ranging from soft impacts to penetrators) and airborne platforms (balloons, gliders, and airplanes), depending on the mission's scientific objectives, landing site characteristics or other environmental factors, and

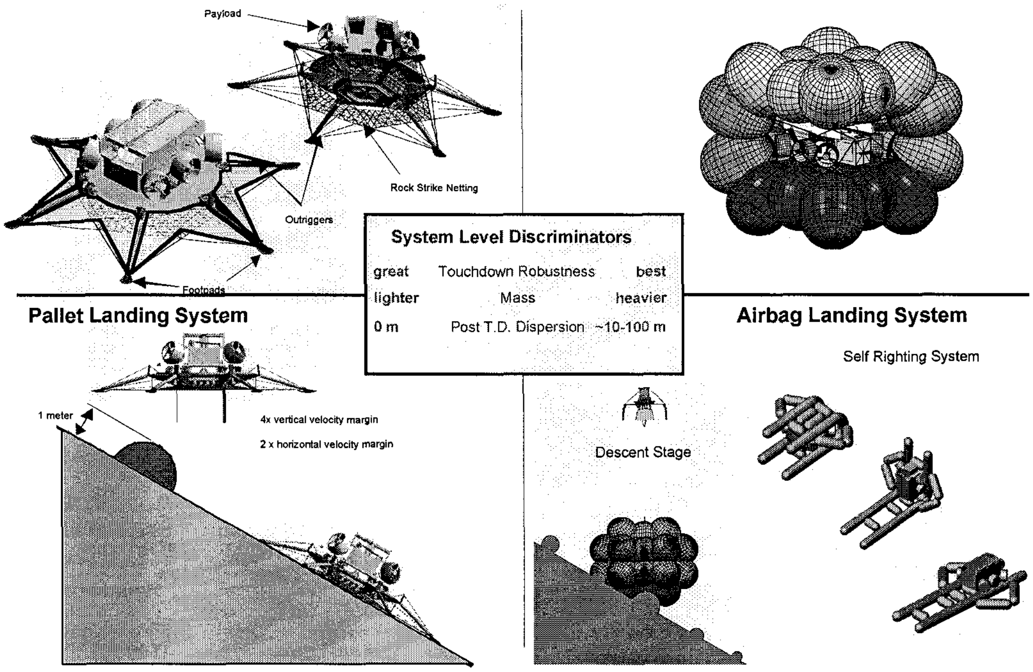

Figure 5. Key Landing Gear Technologies

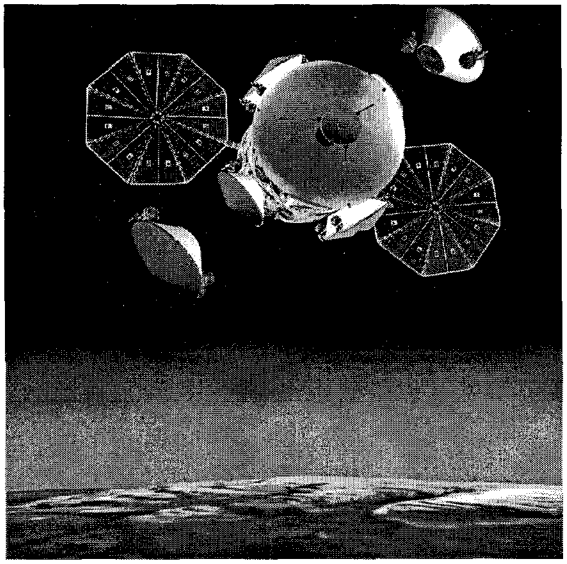

Figure 6. One concept for a multi-scout orbiter, seen end on, with two scouts being deployed to the surface. (Graphic by Corby Waste, Raytheon)

technology readiness. Several types of carriers have also been considered, ranging from cruise vehicles that deploy the scouts on approach to Mars to orbiters that release scouts from orbit and serve as a telecommunications relay for the deployed packages.

Many parameters must be considered when designing a multi-scout mission, including the number of scouts, the deployment scenario, telecommunications strategy, and operational complexity. As the mass of each scout is lowered, the number of scouts that can be delivered is increased and a greater diversity of access is achieved. However, a low mass limitation significantly influences the scout design, particularly for scouts that must carry a robust EDL system. An orbiting carrier addresses many problems including providing a telecom relay and offering targeting flexibility that is not available with scenarios that release the scout on approach. However, the lower mass required by carriers that release the scouts on approach makes that design more desirable for some applications.

One example of the multi-scout concept recently studied is a mission to deploy six to eight soft-landed scouts to the surface from Mars orbit (Figure 6). Each scout delivers approximately 5 kilograms of science payload, with a total scout mass of about 100 kilograms including the de-orbit stage, heat-shield, soft-landing system, communications system, and other required infrastructure. The strawman payload includes a multi-spectral stereo imager, a visible-to-near-infrared point spectrometer, a descent imager, and a meteorology package. The lifetime of each scout ranges from about 2 weeks to 1-2 months depending on the selected landing site (particularly latitude) and season since the scouts in this design rely on solar power.

An alternate option for this concept is for one of the deployment packages itself to contain many (perhaps ten) penetrators or small landers. They could either operate independently or together as a network. The scout containing the penetrators is released with a single heat-shield from the carrier vehicle. It then drops the penetrators one at a time as it travels through the atmosphere, leaving a linear array on one region of the surface. One implementation would be to create a closely spaced network capable of conducting active seismic sounding on the cliff top above a site recently identified by MGS as a possible water seepage region. The objective would be to determine whether or not a layer of water was present and to estimate its depth to an accuracy of 10%. Further work is needed on this concept to determine if the knowledge of the relative positions of the network elements can be determined with sufficient accuracy. Furthermore, more insight is needed into what kind of layers such a network could identify (and, in particular, could it distinguish water, gas and ice saturation?)

Multi-scout provides access for focused exploration and reconnaissance over a broad area with substantial flexibility in investigation platforms and site selection. The ability to optimize each scout payload to a specific environment and experiment enables the performance of both specialized investigations and global in-situ measurements. Thus, for some applications, multi-scout missions after promising alternatives to large landed missions.

Mars Stratigraphy Mission

A second candidate in situ concept is a mission which sends a rover down the face of a cliff or slope to analyze the stratigraphy. An example of such a mission at one of the cliffs of Valles Marineris (Figure 7) was described by Budney, Miller, and Cutts at the LPI workshop and is summarized here.

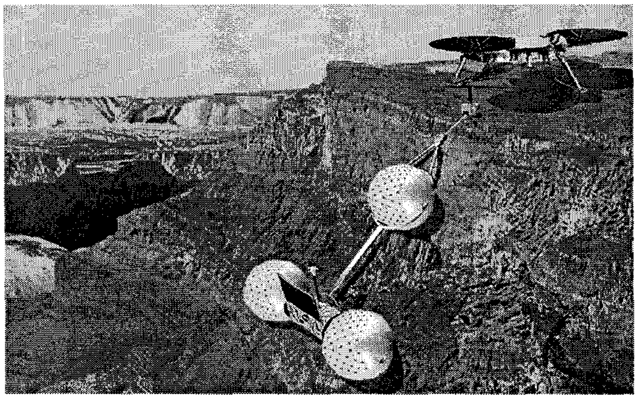

Figure 7. A rover rolls down a slope of Vallis Marineris and collects data to identify the geologic history of the layered deposits. (Graphic by Corby Waste, Raytheon)

A new rover with inflatable wheels rolls over the edge of the cliff or slope, after anchoring a tether, and descends for 2 km. The science objective is to identify the geologic history of the layered deposits. Specific science requirements for the mission include:

1. Examine a cliff or ridge containing at least 2 km of exposed layering.
2. Determine the mineralogy and chemistry of layers at 1-m intervals down the stratigraphic column.
3. Determine the mineralogy and age of core samples collected from layers at 100-m intervals down the stratigraphic column.
4. Determine morphology of layers continuously along the stratigraphic column.
5. Provide context for layers continuously along the stratigraphic column.

Measurement requirements include:

1. Composition of layers (mineralogy and chemistry). This could be accomplished using Raman and X-ray fluorescence spectrometers. The latter would require technology development.
2. Age dating with an accuracy to ± 100 My or better. By starting the age dating at the top of the stratigraphic column, age estimates derived from cratering statistics can be compared. Instrument technology development would be required to accomplish this measurement.
3. Multispectral imagery.

Operational requirements include:

1. Rover requirements:
   a. Rover must find cliff edge or ridge.
   b. Rover must be able to be lowered over cliff edge and operate on slopes up to 90 °.
   c. Rover must stop every 1-m interval for science measurements.
   d. Rover must be able to acquire samples for analysis by drilling to 5 cm.
   e. Rover must be able to communicate to Earth through a communications orbiter in low equatorial orbit.
2. The landing accuracy must be ≤ 20 km to limit the time that the rover will need to traverse the distance to the cliff edge to about 50 days.
3. A safe, soft landing must be achieved at an altitude of up to 4.5 km.
4. Ground interactions: At the dating site, images of the local scene will be acquired and downlinked to the science team. These and other data will allow the science team to select locations for collecting samples for analysis.

The landing site selected for this study is 14 ° S and 68 ° W, near the southern canyon wall of Valles Marineris. The lander/rover reaches this site in 2009, having been launched in 2007 on a Type IV trajectory.

The flight system includes a cruise stage, an entry and descent system (heatshield, backshell, and parachute), and a soft lander which carries the rover as its only payload. The cruise stage controls the flight system from Earth to Mars. On approach, the cruise stage is discarded. Alternatively, if sufficiently equipped, it could enter into Mars orbit to become a communications orbiter, making this mission self-sufficient and contributing to the infrastructure at Mars. The rest of the flight system enters into the atmosphere and performs active lift-vector roll control to achieve the required landing accuracy. After the entry and descent system is discarded, the final soft landing is achieved with active thruster control and a hazard-avoidance system. After landing, the rover is inflated and deployed from the lander system and finds its way to the cliff edge. There it anchors a tether and uses it to lower itself down the slope or cliff for a 200-day investigation.

Technology development would be needed for the inflatable rover and the tether system, including the anchor, in addition to some of the science instruments as already described.

SMALL MISSIONS

Small missions are well suited to Mars and are discussed here as a separate category. These missions could help increase the diversity of science investigations at Mars, provide flexible, low-cost access to Mars, and allow us to react to new discoveries more quickly than with moderate-to-large, mainline missions. In addition, small missions to Mars may be particularly suitable for competition.

Blaney, Leschly, and Wilson described these missions at NASA's Synthesis Workshop on August 23, 2000. For this discussion, small missions are divided into two types: Scouts and Micromissions. A Scout requires a host carrier to get to Mars, i.e., it is carried piggy-back on another Mars-bound spacecraft. It typically has a mass of less than 100 kg, is a probe carrying in situ science, and costs \$30-120M to develop. A Micromission, on the other hand, is defined to be a stand-alone mission that either is launched on a dedicated launch vehicle (Taurus or low-end Delta II) or is a secondary mission on a launch to Geosynchronous Transfer Orbit (GTO). A Micromission might have a mass of up to about 350 kg for a dedicated launch on a low-end Delta II or just 240 kg as a secondary launch. In the latter case, some of this mass would have to be allocated for propellant (and associated tankage) needed to deliver the flight system from GTO to Mars. A Micromission could be an orbiter with remote sensing experiments or it could carry an in situ probe. In fact, the payload of a Micromission could be a Scout. The development cost of a Micromission is expected to be in the range of $100-200M.

Many concepts for Scouts have been suggested in recent years. NASA's summer 2000 outreach effort to solicit ideas for future Mars missions yielded almost 30 such concepts from the July workshop at LPI alone. Additional Scout concepts were received from NASA centers and industry. In general, Scouts provide focused in situ science using small platforms specifically suited for the objectives. Platforms include small landers, small rovers, gliders and airplanes, balloons, penetrators, and networks. Recognized examples of Scouts are: Deep Space 2 microprobes, Beagle 2, NetLanders, and the 100 Kg Scout probe described earlier for a multi-scout mission concept. This last Scout concept may represent the high end of Scout mass and cost range, while the Deep Space 2 microprobes may represent Scouts at the low end. (The failure of the Deep Space 2 microprobes should not rule out the concept of inexpensive Scouts, but rather the lessons learned from this mission must be applied to future efforts.)

From its summer outreach effort, NASA also received numerous responses describing Micromissions (at least 6 from the LPI workshop alone). Earlier science workshops, and several missions proposed through the Discovery Program, revealed numerous concepts as well. Examples of Micromissions launched as secondary payloads are Dynamo and the Mars Airplane. Dynamo is a French-led orbiter planned for launch in 2005 or 2007 with a goal to better understand the magnetic, geologic, and thermal history of Mars and characterize current atmospheric escape. A 10-kg payload would be carried into a highly elliptical orbit for a 2-year mission on orbit. The Mars Airplane was studied in the fall of 1998 for a possible launch in 2003 to commemorate the 100th anniversary of the Wright Brothers' first flight. In this concept, it was estimated that 45 kg would be available for the entry probe (a Scout), including the airplane itself. An example of a Micromission with a dedicated launch vehicle is a recent study of a small, nadir-pointed orbiter to recover much of the science lost on Mars Climate Orbiter. It is estimated that a spacecraft with a 10-kg science payload could be launched in November 2004 on a Delta 2326 launch vehicle on a Type IV trajectory arriving at Mars in February 2007. A low, sun-synchronous orbit could be achieved for a two-year mission on orbit. With either type of Micromission (secondary or dedicated launch), a significant mass constraint accompanies the low launch cost and hence the science must be highly focussed.

One application that has been given a lot of attention over the last three years is to use the secondary capability of the Ariane 5 on commercial launches to GTO, as summarized in Blamont and Counil's concept presented at the July 2000 LPI workshop. A ring, called the Ariane-5 Structure for Auxiliary Payloads (ASAP5), has been developed to carry such spacecraft. Located below the main payload, this ring has 8 slots for small payloads. A preliminary design was developed by Ball Aerospace and JPL for a single-string spacecraft bus that takes up 2 of the 8 slots and that has sufficient propellant to deliver payloads to Mars from GTO, with the assistance of lunar and Earth flybys. To allow time for these flybys, launches must take place some months earlier than the normal launch opportunities to Mars. However, a benefit of these flybys is that the launch periods can be 3 to 6 months long, allowing the flexibility that might be required for launching with a commercial payload. Preliminary estimates of payloads that can be delivered to Mars with this spacecraft design are given in Table 3 for 4 different Mars trajectory opportunities: 2005, 2007, 2009, and 2011. A common bus, such as the Ball concept, could be developed and used at multiple opportunities for low recurring cost. Further evaluation of this design is needed to address the reliability issue inherent with a single string bus. One technique for managing the risk is to fly multiple spacecraft and accept the associated higher cost.

Table 3 Payload Mass Available for ASAP5 Micromission

Payload	Traj. Type	2005	2007	2009	2011
Probe Mass (kg)	I	41	43	49	64
	II	43	55	61	64
	III	56	63	64	67
	IV	57	64	67	62
Orbiter Instrument Mass (kg)	I	-1	-3	0	13
	II	0	16	23	22
	III	-10	-4	-2	22
	IV	14	-8	1	17

Notes:
1. Probe mass includes entry, descent, and landing system. Actual science instrument mass is 5-10%.
2. Assumes ASAP5 secondary launch on GTO mission.
3. Assumes 240 kg total spacecraft mass (Ball/JPL design).
4. Type IV opportunity in 2005 required 2001 project start. (Launch August 2004).
5. Negative orbiter instrument mass indicates that performance is inadequate even without any instruments.

Currently, interplanetary payload capabilities similar to ASAP5 but on U.S. launch vehicles do not exist. Mass is too constraining (typically less than 100 kg) and the opportunities exist on government launches only and these are usually to low Earth orbit. Conceptual designs for larger secondary payloads (>200 kg) on Delta IV and Atlas V launch vehicles have been proposed by industry. To more fully exploit this potential for planetary launches, however, expanding the manifest process to include commercial GTO launches may need to be explored.

TELECOM

Telecommunications infrastructure plays an important role in the future of Mars exploration. Currently, each new mission carries its own communications system for relaying data to Earth. In some cases, existing orbital assets are used as a back-up or enhancing relay; however, no mission has depended on a telecom asset that was not developed and delivered as part of the primary mission. While reliance on other assets can present an additional risk to a mission, it can also brings significant benefits.

Communicating across the Earth-Mars distance (0.4-2.7 AU) requires significant power and generally yields relatively small data rates with current technology. To significantly increase the data rate requires increased power, larger antennas, and often a trade-off between time spent collecting and transmitting data. These factors can be substantially reduced if a relay station can be used to complete the link to Earth.

By establishing communications standards for all missions and designing for extended lifetimes beyond the nominal science mission, science orbiters can be an integral element of the telecom network. However, the nearly polar orbits that are often optimal for science missions provide poor global telecom coverage to all but the very high latitudes, offering only 1-2 short passes per sol to more equatorial regions. Better coverage of the lower and mid-latitudes can be achieved with mid-latitude orbiters. Thus, the addition of a dedicated telecom relay, whose orbit is optimized to provide maximum coverage to those regions where future landed assets are likely to be deployed, provides a significant increase in the relay capability by offering longer passes (on the order of one hour or more) 3-4 times per sol, and even continuous coverage with Areostationary satellites.

Several alternatives have been investigated for orbiting telecom relay satellites. These include low and mid-altitude telesats (in circular orbits from 800 to 4200 km), higher altitude satellites in Areostationary orbits, elliptical orbiters, and in the most aggressive concepts, networks that include multiple, dedicated telecom orbiters in a variety of orbits.

Low to mid-altitude relays are particularly useful for small landed assets with limited power. Using omni-directional UHF antennas to provide the Mars-to-relay-orbiter link, the volume of data returned to Earth can be increased by an order of magnitude over what is currently available with direct-to-Earth links from landed assets. Also, the lower power required to transmit the data provides the potential for more power for engineering and scientific uses. Areostationary assets, while requiring more transmit power from the landed or airborne platform, offer the possibility of constant communications, as opposed to the few passes per day that can be achieved using direct-to-Earth or by relaying through most science orbiters.

In the near-term, most of the landed missions that are being considered have relatively short lifetimes, on the order of 30-90 days. In this case, the expense associated with developing, deploying, maintaining, and operating a dedicated telecom relay with limited use between landed missions must be traded against the significant improvement in data return that is possible during the mission. Thus, many trades must be evaluated before committing to dedicated telecom relays. However, as we expand our exploration of the surface to include long-lived rovers and outpost scenarios, the role of the telecom satellite becomes increasingly important.

CONCLUSION

Many valuable mission concepts have been developed in recent months for consideration in NASA's new plan for the future of the Mars Program. When this plan is complete in November, the missions therein will receive more in-depth study as part of an overall program system engineering effort. They, along with the 2001 and 2003 missions, will contribute to the successful legacy of Mars Pathfinder and Mars Global Surveyor.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of Dr. Sam Thurman in the EDL conceptual design for the Second Generation Lander; Dara Sabahi in the EDL conceptual design and systems design; Tom Rivellini in the landing gear design; and Howard Eisen in the EDL and systems design; Barry Goldstein and his team for the design of the 100-kg scout; Eric Slimko and his team for the seismic sounding multi-scout concept; Charles Budney for his description of the Mars Stratigraphy Mission; Dr. Diana Blaney, Kim Leschly, and Dr. Gregory Wilson for their presentation on Small Missions; Dr. Charles Edwards and Sheldon Rosell for the telecommunications concepts; and the many dedicated members of JPL's Team X, and Maureen Coss for the layout and production of this paper.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

[1] Jordan, James F. and Sylvia L.Miller, "The Mars Surveyor Program Architecture," *Journal of Space Mission Architecture*, No. 1, Fall 1999, pp. 1-10, JPL Document No. 410-57-1.

[2] Matousek, Steve, Kim Leschly, Bob Gershman, and John Reimer, "Mars Micromissions" 13th Annual AIAA/USU Conference on Small Satellites, SSC99-VII-6, August 23-26, 1999, Logan, Utah.

[3] O'Neil, William (NASA-JPL) and Christian Cazaux, (CNES-Toulouse), "The Mars Sample Return Project", IAF-99-Q-3.02, 50th International Astronautical Congress, 408 October 1999, Amsterdam, The Netherlands.