Mars Exploration Program and Mars Technology Program

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Abstract—The Mars Exploration Program and constituent Mars Technology Program are described. Current, ongoing and future NASA-led missions are presented, including discussions of scientific accomplishments and objectives as well as technology validations accomplished and technological enablers for future missions.

The missions summarized include (in order of actual or planned launch): Mars Global Surveyor, Mars Pathfinder, 2001 Mars Odyssey, Mars Reconnaissance Orbiter, Mars "Smart" Lander, Mars Scouts, Mars Sample Return.

Key technology areas discussed include: Navigation, Entry, Descent and Landing, Science and Surface Operations, Orbital Transport and Sample Return Technologies

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1. INTRODUCTION

The Mars Exploration Program in NASA's Space Sciences Enterprise is a science-driven technology-enabled effort to characterize and understand Mars, including its current environment, climate and geological history and biological potential. Central among the questions that the program aspires to answer is "Did life ever arise on Mars?"

Four main endeavors characterize the science strategy of the Mars Exploration Program. These are as follows: 1) Understand the potential for life elsewhere in the universe, 2) Understand the relationship to Earth's climate change process, 3) Understand the solid planet and how it evolved, and 4) Develop the technology and engineering necessary for eventual human exploration. The common thread that cross-cuts and unifies these endeavors is the program's recurring theme "Follow the water."

2. OVERVIEW OF RECENT MISSIONS

Mars Pathfinder

Launched in 1996, and landing on July 4th, 1997, the Mars Pathfinder project returned to the surface of Mars after a hiatus of 20 years since the preceding Viking mission. Utilizing much of the Viking hypersonic entry and parachute decelerator systems, the Pathfinder project introduced a novel landing system utilizing airbags instead of active propellant systems to achieve terminal deceleration after reaching the surface of Mars. The science return of the Pathfinder landing site included high-resolution stereoscopic images, meteorological data and x-ray spectrometry performed *in situ* by the first mobile science platform on the surface of Mars, the Sojourner microrover.

Mars Global Surveyor

The Mars Global Surveyor (MGS) mission, also launched in the 1996 launch opportunity, found its origins in the loss of the 1992 Mars Observer mission. Following this loss in 1993, a mission study was undertaken to attempt to recover the greatest practical subset of the Mars Observer mission objectives. The Magellan end-of-mission aerobraking experiment had recently been completed, and this technique was baselined for the MGS mission, allowing the mission to be launched carrying all but two of the Mars Observer payload instruments on a Delta 2 vehicle, contrasted with the Titan 3 used on the original MO mission. MGS has returned high resolution and wide-angle contextual images, topography and gravity maps, atmospheric occultation profiles, maps of the weak and fragmented remnant magnetic field, and spectral mineral maps observed in the infrared.

3. OVERVIEW OF MISSIONS IN IMPLEMENTATION

Mars 2001 Odyssey

The Mars 2001 Odyssey mission extends the orbital surveillance of Mars resumed by the MGS mission. Arriving at Mars October 24th, 2001, the mission will also use Aerobraking to circularize its orbit, then will continue the elemental and mineral characterization of the surface and near subsurface using gamma ray and thermal spectrometry,

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the latter at much higher resolution than available from MGS. The payload suite is rounded out by an intermediate resolution visible imaging instrument, and an experiment to characterize the Mars radiation environment in preparation for eventual human exploration.

Mars Exploration Rover

For the 2003 launch opportunity, twin rover missions will be delivered separately to Mars using the robust airbag technology first demonstrated by the Mars Pathfinder mission in 1997. These rovers will be much more capable than the microrover Sojourner carried by Pathfinder. The Rover twins will determine the geologic record of the landing site, what the planet's conditions were like when the Martian rocks and soils were formed, and help us learn about ancient water reservoirs. These missions are designed to help the science community learn about the climate on Mars and scout for regions where mineralogical evidence of water has been found. They will also provide the first microscopic view of Mars.

4. Overview of Future Missions

Mars Reconnaissance Orbiter

The next generation of Mars orbiter is intended to extend the data set in both the visible and infrared spectrometry mineral maps to much higher resolution than previous missions, with the goal for visible resolution set to a fraction of a meter. Additionally, infrared sounding of the atmosphere and ground penetrating radar are planned to continue the direct search for water above and below the surface simultaneously.

Mars "Smart" Lander

Similarly to the orbiter line, the next generation of Mars Lander is intended to extend the surface science capabilities demonstrated by previous landed missions. Additionally, however, the Mars "Smart" Lander is intended to serve as a technology pathfinder to demonstrate advanced landing and surface operations capabilities that will be required by future Mars landed missions. Many of these technologies are the subject of further discussion herein.

Mars Scouts

The Mars Scouts Missions have been added to the program architecture to complement the "roadmap" missions designed advance the strategic objectives of the program. These missions of opportunity will be competitively selected from proposals solicited from the broader science community. Orbital, Landed and Aerial opportunities are under consideration, with the latter serving as a unique opportunity to bridge the gap between the high resolution, low coverage imagery from landers/rovers and the low resolution, high covered offered by orbital missions.

Mars Sample Return

The near-term capstone of the program as currently planned culminates with a mission to return samples from the surface of Mars back to the earth. These samples, analyzed in the world's finest laboratories by the best scientists will provide a chronology of the planet's evolution, a record of climate change and the history of water, evidence of the presence (or absence) of organic and pre-biotic chemistry, as well as evidence of past or present life. Numerous technological challenges, described further herein, face this mission including the first ascent from another planetary body, autonomous rendezvous and docking in deep space, and safe, assured-containment return of the samples to an appropriate receiving facility on the surface of the Earth.

5. Technology Program Introduction

The Mars Technology Program has been chartered to develop and infuse those technologies deemed to enable or enhance missions for the future exploration of Mars. The technology is generally structured around a series of developments of potential benefit to multiple missions within the program and another series focused on the needs of specific missions. Furthermore, the Technology Program, working in conjunction with certain mission in the program queue endeavors to undertake technology demonstrations in-flight aboard designated missions in a non-critical application, in order to reduce the risks to future missions which require these technologies in mission-critical applications.

6. Navigation Technologies

The loss of the Mars Climate Orbiter mission in the fall of 1999 due to a navigation error focused attention on the current state of art for interplanetary navigation, including the strengths and weaknesses of each of the available data types. To meet the needs of future missions, with even tighter navigation accuracy requirements, the Mars Technology Program is attempting to infuse new technology into the program to allow the collection of multiple data types on each mission which will cross-check and correlate with each other and improve the overall accuracies to the levels needed to achieve the goals of future missions.

Ground-Based Approach Navigation

The traditional interplanetary navigation scheme, upon which each of the following enhancements is added, is centered upon the collection of line-of-sight tracking data collected by the ground station during routine contact periods which are used for both navigation and spacecraft command and telemetry sessions. A radio frequency (RF) carrier signal is transmitted to the spacecraft transceiver which generates a downlink signal coherently referenced to a fixed multiplier of the received transmission frequency. Using a hydrogen maser on the ground as a frequency reference, a two-way Doppler shift is observed on the returned signal proportional to the line-of-sight component of the relative velocity between the spacecraft and the tracking station. Additionally, the RF carrier signal may be modulated by the ground station with either command signals to the spacecraft, or with a series of ranging tone patterns in a specially designed side-band which the onboard transceiver is also designed to turn-around and re-modulate

on the downlink signal (together with other telemetry data generated onboard). These two data types, instantaneous line-of-sight Doppler range rate and turn-around ranging, provide a very accurate instantaneous estimation of the spacecraft position and velocity along the line of sight, and, over time, the changing geometry of both the spacecraft in orbit around the sun and the ground station (due to the spin and heliocentric orbit of the earth) allow an accurate estimation of the two-dimensional position and velocity of the spacecraft near the plane of the satellite's heliocentric orbit.

The observability of the spacecraft's position out of the plane of the orbit is poor using the techniques described above and this dimension of the position and velocity error ellipse is typically several times larger than the uncertainties in the other in-plane dimension. One way to address this geometric unobservability is by scheduling additional ground tracking assets to enable the simultaneous collection of tracking data from two (or more) ground tracking stations which can be reduced using differential Very-Long Baseline Interferometry (ΔVLBI) techniques. To achieve the maximum out-of-plane benefit from this technique, tracking station pairs with a large latitudinal separation on the surface of earth are desirable (e.g. Northern and Southern hemispheres).

Target-Relative Approach Navigation

Using ΔVLBI to reduce the out-of-plane dimension of the orbit determination error ellipse is effective, but requires the utilization of additional ground tracking resources which can place a strain on the existing tracking network assets. An equivalent or better increase in accuracy can be achieved using target-relative navigation methods. One potential data type (previously used at outer planets, but not at Mars) is optical navigation. This method complements the radio metric Earth-spacecraft line of sight data with information about the orientation of a second line of sight (Spacecraft-Mars) extracted from images of Mars, it's moons, and the background inertial star-field taken by an onboard camera and processed either by the ground or onboard software to extract a second vector position estimate.

Additionally, it is envisioned that future Mars orbiters shall carry *in situ* radio link hardware which could be used not only to provide data relay and navigation services to landed assets, but could also serve as a radiometric beacon with a known orbital geometry to establish a cross-spacecraft radiometric link with incoming spacecraft, again providing an alternate line of sight measurement, albeit radiometric in this case. The Mars Technology Program is working to develop lightweight hardware to support both of these techniques which should be convenient to incorporate in all future Mars mission spacecraft.

7. Entry, Descent, and Landing Technologies

A number of advanced to increase both the accuracy and safety of future Mars landing systems are being undertaken by the Mars Technology Program

Guided Entry Technology and Precision Landing

All previous Mars atmospheric entries have been performed without active flight-path guidance, although the Viking system did perform one-axis attitude control to maintain a preferred orientation (generating upward lift) during entry. To achieve increased landing site accuracy, future missions are planned to use guided atmospheric entry to eliminate any entry state navigation control error, as well as errors introduced by atmospheric uncertainty or variability which can be sensed by the lander's onboard inertial navigation system. Such systems require that the entry body produce a lateral force (referred to as "lift" independent of the instantaneous horizontal orientation of this force vector), and that the onboard inertial guidance and navigation be able to control the orientation of this vector with respect to the primary retarding drag force based on sensor inputs and a previously proscribed set of guidance laws. The primary errors both in entry navigation and atmospheric uncertainty express themselves as along-track landing errors, rather than cross-track. As such, the primary control law scheme must decide how much of the entry are to be flown with the lift vector up (for steep entries, headed too far up range) and how much with the lift vector down (for shallow entries, headed too far down range). The guidance scheme must also allow for the entry system to fly with a modulated horizontal lift scheme (rolling left to right or vice versa) since the body typically produces lift throughout the entry regardless of whether any along-track force is currently required.

By drastically reducing the landing site error ellipse and simultaneously increasing the traverse capability of any onboard rover or mobility system, future landers may be able to demonstrate "Go-To" capability. This is defined as the ability to place the entry ellipse sufficiently close to a surface feature of interest such that after landing, the previously identified feature is within the traverse capability of the rover.

Entry Body Aerodynamics

A significant investment in planetary entry systems was made by the Viking project in the early 1970's. This investment covered by hypersonic entry bodies and supersonic parachute decelerator systems. The combination of the blunt-body 70 degree sphere cone and the supersonic disk-gap-band parachute decelerator have served as the basis for major Mars entry systems ever since. The basic entry body shape can be flown at an angle of attack up to at least 12 degrees to generate negative lift perpendicular to the drag direction ("Negative lift" is defined to generate a force in the direction opposite of the angle of attack, the opposite of typical lifting wing conventions). Viking itself flew with an intentional offset between the center of gravity and center of pressure, achieved by asymmetric packaging of lander equipment and ballast inside the entry body, whereas the Mars Pathfinder mission used a purely ballistic entry (no lift) with the CG and CP aligned. For future Mars entry bodies, other methods of achieving CG/CP mismatch are under consideration by modifying the aerodynamic properties of the heat shield rather than the application of

packaging and ballast to achieve this misalignment.

The Viking supersonic parachute decelerator system was qualified for openings at or below a Mach number of 2.2. In order to guarantee deceleration to this level before sinking below a safe altitude for the representative parachute descent timeline (typically taken as a constraint to decelerate prior to 8-10 km above the surface), a maximum ballistic coefficient and maximum entry mass can be derived by assuming the maximum entry body diameter which can be accommodated within the largest existing launch vehicle fairings (circa 5 meters outside diameter). Recent analysis has shown this limit to be on the order of 3000 kg entry mass. In order to safely enter and land massed larger than this at Mars (subject to the Mach number constraints of existing parachute technology), alternative entry body shapes must be considered, including bodies which fly at higher lift-to-drag ratios and, as such, can fly shallower and longer paths through the atmosphere, achieving greater decelerations of their higher entry masses prior to reaching the required Mach number for parachute deployment at a safe altitude.

Active Hazard Avoidance Landing

The final area of significant technology investment for Entry, Descent and Landing, is the pursuit of autonomous hazard identification and active hazard avoidance during terminal descent. The basic scheme is to equip the lander with appropriate machine vision sensors (either passive optical or active optical/laser or active imaging radar) to identify hazards (as defined by the landing robustness characteristics of the lander) during descent (ideally, prior to release of the lander from the parachute decelerator) at an altitude sufficiently high that the lander, upon initiating its own powered descent to the surface is able to avoid hazardous locations, identify safe haven locations and actively divert its descent trajectory to achieve a hazard-free landing.

8. Science and Surface Operations Technologies

Science Instrument Technologies

The area of science instrument technologies is characterized by two broad classes of experimentation. The first of these is hyperspectral imaging which is applicable both from orbit as well as on the surface of Mars. This class of instruments allows the rapid survey of the spectral characteristics of the instruments field of view. Typically using the infrared band for this spectral survey, the characteristic spectral signature of many different mineralogical types, several of which are able to suggest what role water may have formed in the creation of these substances (e.g. hydrothermal processes or aqueous deposits). From orbit, this can be used to identify high priority landing sites, while on the surface, this data allows the rapid identification of high priority rocks for more detailed *in situ* investigations, or sampling.

The second general area of instrument technology is characterized by more by the origin of the phenomena of interest than by any specific technology to study it, specifically, the ability to understand what lies under the surface of Mars. Mars 2001 Odyssey carries a Gamma Ray Spectrometer and a High-energy Neutron Detector, both designed to measure the response of Mars to highly energized particles impacting the planet from the solar wind. These particles have the ability to penetrate below the surface and generate a signal that gives information regarding the presence of certain elements (e.g. Hydrogen, potentially in the form of water). Future Mars missions plan to continue this subsurface sounding by bringing their own illumination source in the form of ground-penetrating radar, again with the intention of locating any potential reservoirs of subsurface water or ice formations. As with the hyperspectral imaging described above, this information can be used to identify high priority landing sites where the search for information about the subsurface of Mars can potentially be continues with *in situ* drilling experiments, carried by future landers.

Surface Operations Autonomy

Once on the surface of Mars, the ability of a science team to conduct meaningful experiments using a robotic rover as their agent is often a challenging endeavor. For solar powered rover systems where dust accumulation and seasonal environmental changes are acting, the amount of time available to a mission on the surface is a precious resource. The Mars Technology Program recognizes this fact and is continuing to advance the level of autonomous operations that the *in situ* rover is capable of performing in an endeavor to increase the amount of meaningful science which can be performed in a limited duration. The two major areas where there is an opportunity for significant enhancement enabled by autonomy are in the areas of autonomous traverse across the surface of Mars, and the area of autonomous contact science, specifically the precise establishment and maintenance of a designated position and orientation of a scientific instrument in close proximity to a surface feature designated by the science team. The Mars Technology Program continues to evolve its understanding of what the high payoff technologies are by participating with planetary scientists in ongoing field experiments conducted to simulate exploration conditions to be expected on future Mars missions.

9. Orbital Transport Technologies

A number of technologies of potential benefit to future orbiters are also under development within the Mars Technology Program.

Solar Electric Propulsion

Solar electric propulsion, while now considered a fairly common technology for geostationary station-keeping in Earth orbit, has only recently become accepted as a validated technology for interplanetary missions. This is largely based on its successful demonstration on NASA's New Millennium Deep Space 1 mission. For Mars exploration, the application is particularly attractive to address the unusually large propulsive acceleration requirements of the

return from Mars to Earth, as large decelerations for Mars missions can also be achieved with aeroassist (either gradual aerobraking without a dedicated heat shield or more impulsive aerocapture, with a dedicated heat shield).

Lightweight Propellant Tanks

The Mars Technology Program is also making an investment in the development of lightweight propellant tanks to continue to reduce the fraction of the stored propellant mass which must be invested in tank dry mass to contain a given amount of propellant.

Aerocapture

The ability to use a planetary atmosphere to rapidly decelerate an arriving orbital asset from an interplanetary trajectory directly into orbit is referred to as Aerocapture. In contrast to aerobraking, which still requires a significant propulsive capability to capture into orbit prior to initiating the slow gradual descent to circular or near circular orbit, the aerocapture technique trades the arrival propulsive capture requirement for a dedicated heat shield (on par with those used for lander entry bodies) which can achieve single-pass deceleration into practically any orbit (including near circular) much more rapidly than aerobraking. This is achieved by targeting the atmospheric pass at altitudes as low as 60-80 km, contrasting the typical range of 100+ km altitude for gradual aerobraking circularization. This technology is being pursued jointly by both NASA and the French space agency CNES.

10. Sample Return Technologies

A number of technologies focused solely on the return of samples from the surface of Mars are also under development. For any Mars mission intending to search for evidence of life, it is of vital importance to protect the mission from the possibility of not only "forward-contamination" (contamination of Mars with organisms originating on Earth), but also against potential contamination of returned samples with "round-trip" or "hitchhiker" organisms, which lead to false positive indications for life-detection experiments performed on returned samples. Another enabling technology for sample return missions is the development of a launch vehicle capable of both being landed on and rising from the surface of Mars after a period of storage and survival while samples are being collected by other surface assets. Also, recent architectural studies have confirmed previous results suggesting in low Mars orbit is one of the most promising locations for a handoff between this Mars Ascent Vehicle and the vehicle designed to return these samples to the vicinity of the Earth. Manners of safely bringing back to the surface of the Earth any samples collected from the surface of Mars are also under investigation, considering both the use of a dedicated sample return Earth entry vehicle system or by using other existing Earth entry systems such as the shuttle. Additionally, the technology required to safely evaluate and analyze any returned samples is also a key investment area.

11. Summary

The Mars Exploration Program comprises a series of mission integrated into a coherent ongoing program

Technology development and infusion allows both the incorporation of new capabilities as well as the continuous improvement of existing capabilities.

12. Acknowledgements

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

MARS EXPLORATION PROGRAM

Mars Exploration Program and Mars Technology Program

Presentation to Futuristic Space Technologies Workshop

Charles Whetsel
Chief Engineer
MARS EXPLORATION PROGRAM

Mars Exploration Program and Mars Technology Program. Presentation to ASI Futuristic Technologies Workshop, October 15-16, AREA Science Park, Trieste, Italy, by Charles Whetsel, Chief Engineer, Mars Exploration Program.

MARS EXPLORATION PROGRAM

Presentation Overview

- **Program Overview**
  - Recent Missions
  - Missions In Implementation
  - Future Missions
- **Technology Topics**
  - Navigation Technologies
  - Entry, Descent, and Landing Technologies
  - Science Instrument Technologies
  - Orbital Transport Technologies
  - Sample Return Technologies
- **Summary**

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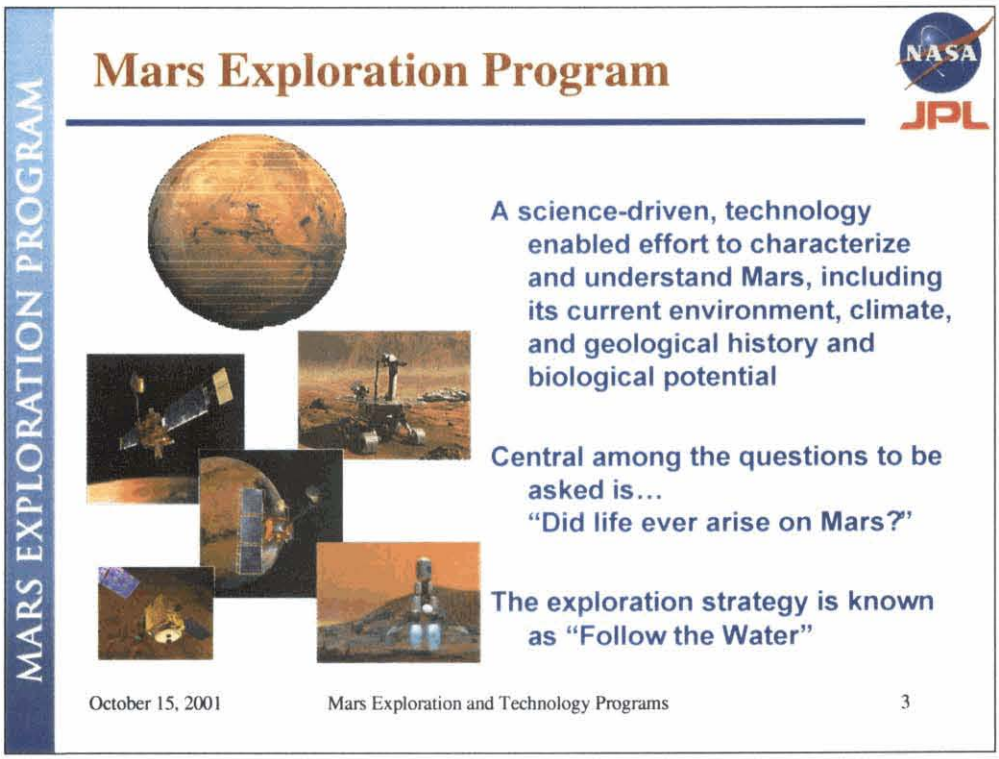

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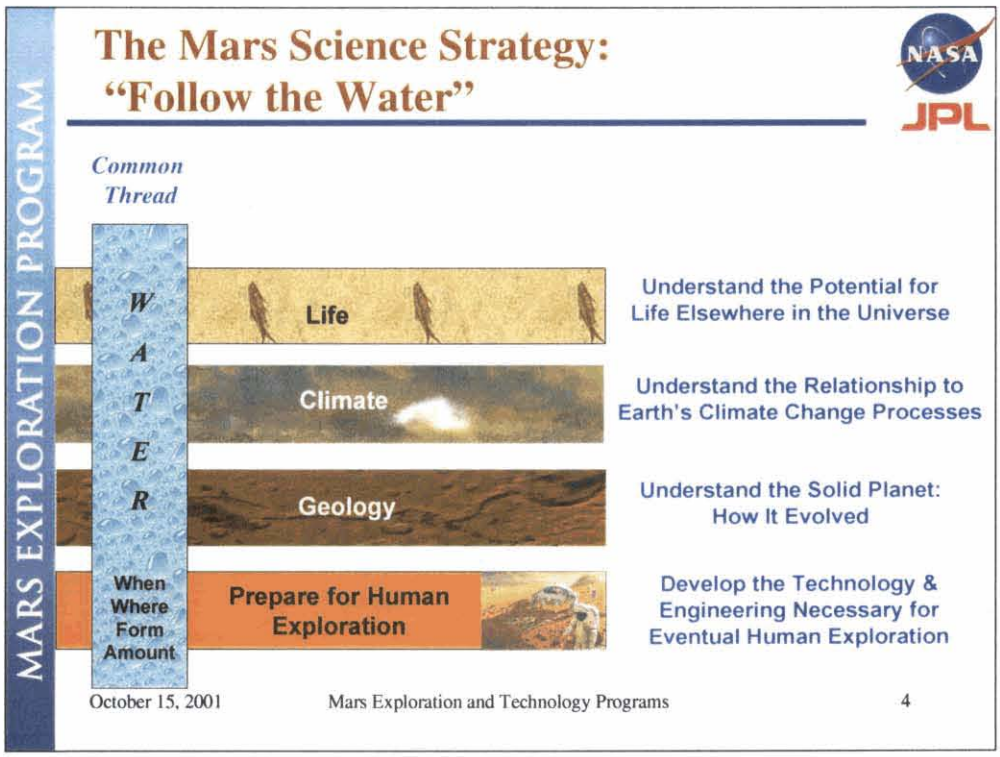

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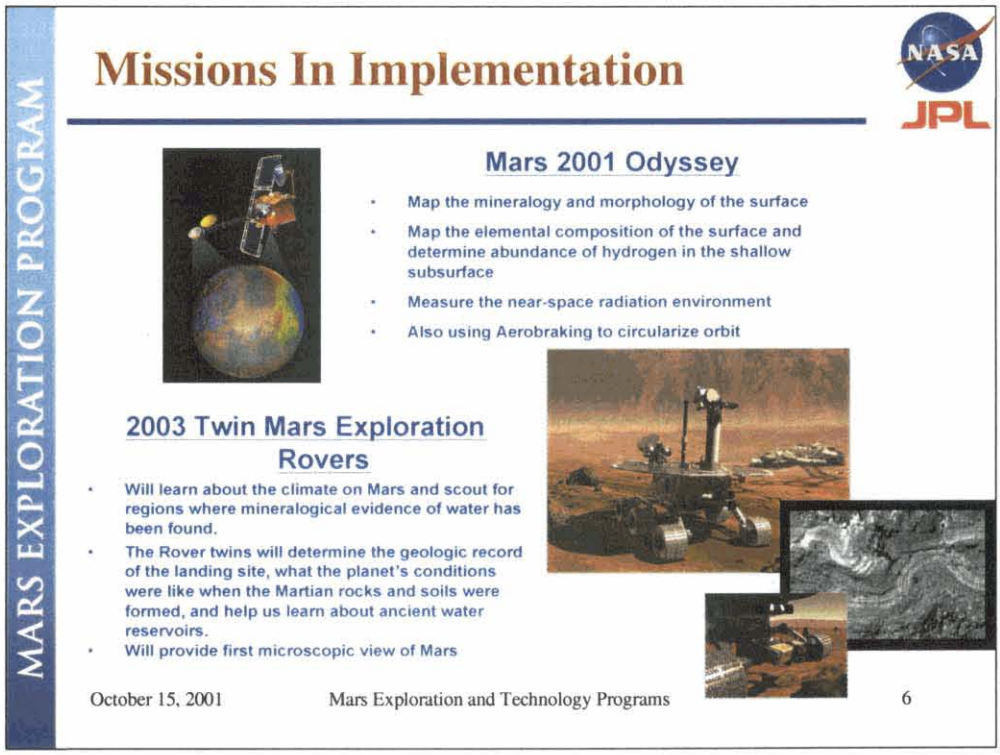

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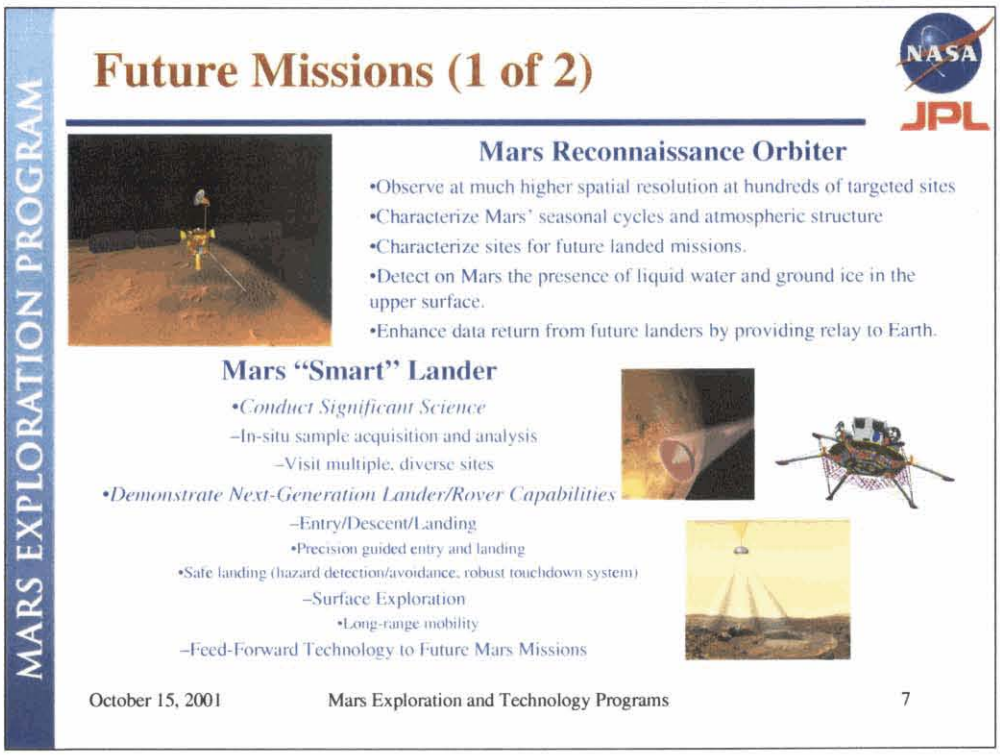

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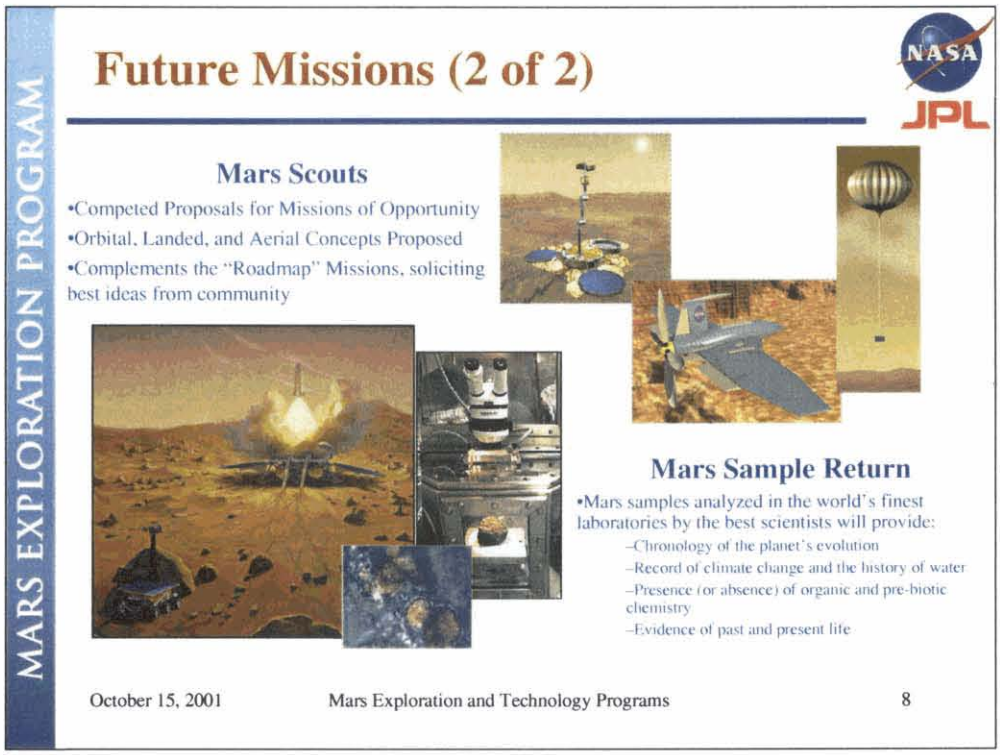

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Technology Program Themes

MARS EXPLORATION PROGRAM

- **Multi-mission Technologies**
  - Core technologies, benefiting multiple Mars missions
  - Ongoing investment in exploration capabilities
  - Advancing both engineering and science payload technologies
  - Benefits to both NASA-led missions and missions undertaken by international partners
- **Mission-Focused Technologies**
  - Designed to support specific missions
  - Capabilities advanced by that mission become available for future missions
  - Missions also "assigned" specific technology demonstration requirements to benefit applications of key technologies by future missions

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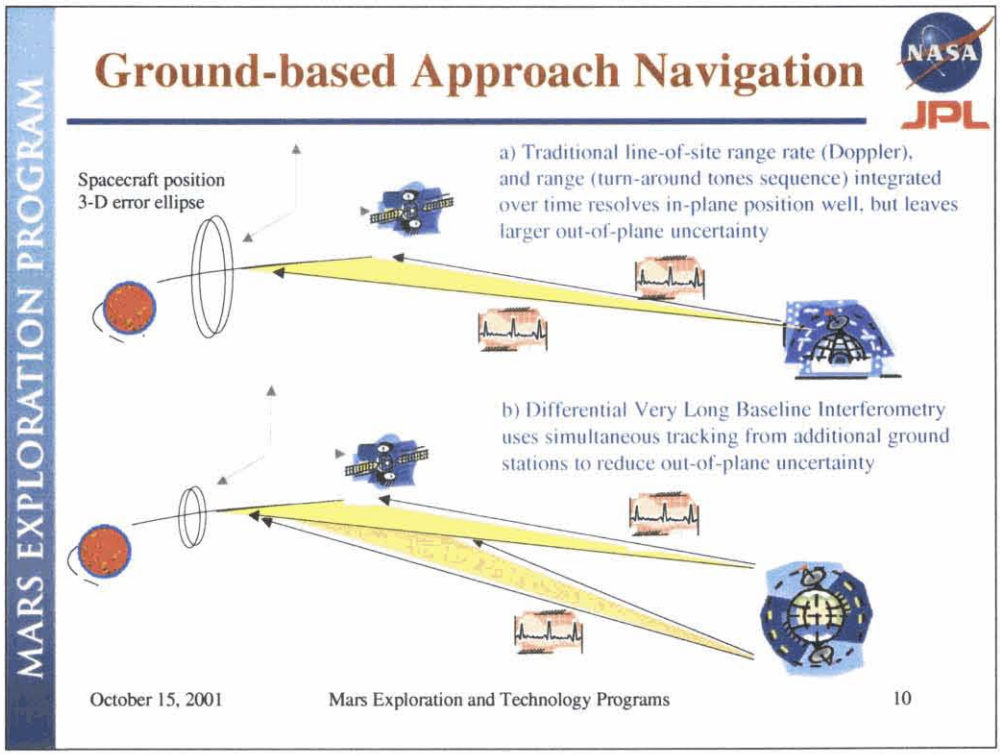

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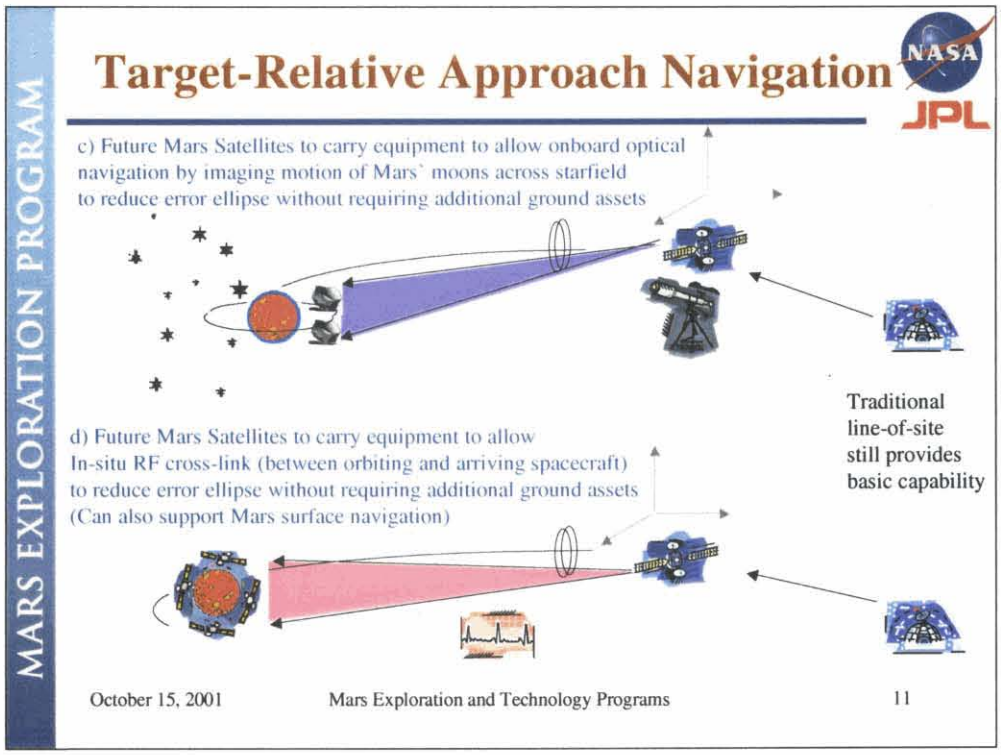
The traditional interplanetary navigation scheme, upon which each of the following enhancements is added, is centered upon the collection of line-of-sight tracking data collected by the ground station during routine contact periods which are used for both navigation and spacecraft command and telemetry sessions. A radio frequency (RF) carrier signal is transmitted to the spacecraft transceiver which generates a downlink signal coherently referenced to a fixed multiplier of the received transmission frequency. Using a hydrogen maser on the ground as a frequency reference, a two-way Doppler shift is observed on the returned signal proportional to the line-of-sight component of the relative velocity between the spacecraft and the tracking station. Additionally, the RF carrier signal may be modulated by the ground station with either command signals to the spacecraft, or with a series of ranging tone patterns in a specially designed side-band which the onboard transceiver is also designed to turn-around and re-modulate on the downlink signal (together with other telemetry data generated onboard). These two data types, instantaneous line-of-sight Doppler range rate and turn-around ranging, provide a very accurate instantaneous estimation of the spacecraft position and velocity along the line of sight, and, over time, the changing geometry of both the spacecraft in orbit around the sun and the ground station (due to the spin and heliocentric orbit of the earth) allow an accurate estimation of the two-dimensional position and velocity of the spacecraft near the plane of the satellite's heliocentric orbit.

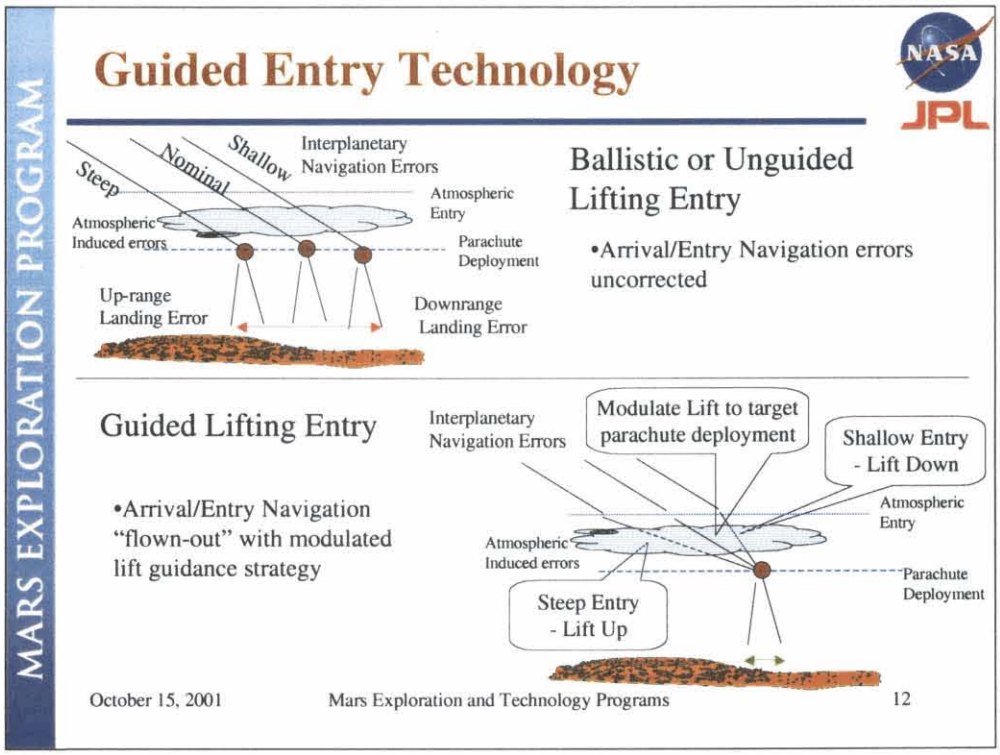
The observability of the spacecraft's position out of the plane of the orbit is poor using the techniques described above and this dimension of the position and velocity error ellipse is typically several times larger than the uncertainties in the other in-plane dimension. One way to address this geometric unobservability is by scheduling additional ground tracking assets to enable the simultaneous collection of tracking data from two (or more) ground tracking stations which can be reduced using differential Very-Long Baseline Interferometry (ΔVLBI) techniques. To achieve the maximum out-of-plane benefit from this technique, tracking station pairs with a large latitudinal separation on the surface of earth are desirable (e.g. Northern and Southern hemispheres).



Target-Relative Approach Navigation

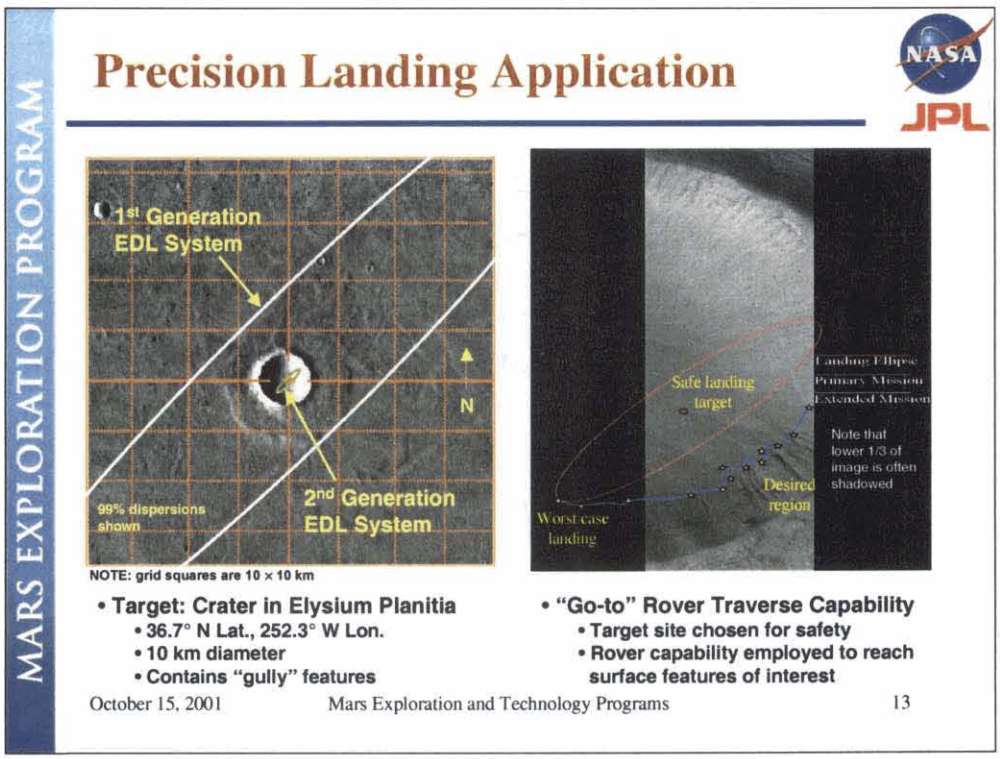
Using ΔVLBI to reduce the out-of-plane dimension of the orbit determination error ellipse is effective, but requires the utilization of additional ground tracking resources which can place a strain on the existing tracking network assets. An equivalent or better increase in accuracy can be achieved using target-relative navigation methods. One potential data type (previously used at outer planets, but not at Mars) is optical navigation. This method complements the radio metric Earth-spacecraft line of sight data with information about the orientation of a second line of sight (Spacecraft-Mars) extracted from images of Mars, it's moons, and the background inertial star-field taken by an onboard camera and processed either by the ground or onboard software to extract a second vector position estimate.

Additionally, it is envisioned that future Mars orbiters shall carry in situ radio link hardware which could be used not only to provide data relay and navigation services to landed assets, but could also serve as a radiometric beacon with a known orbital geometry to establish a cross-spacecraft radiometric link with incoming spacecraft, again providing an alternate line of sight measurement, albeit radiometric in this case. The Mars Technology Program is working to develop light-weight hardware to support both of these techniques which should be convenient to incorporate in all future Mars mission spacecraft.

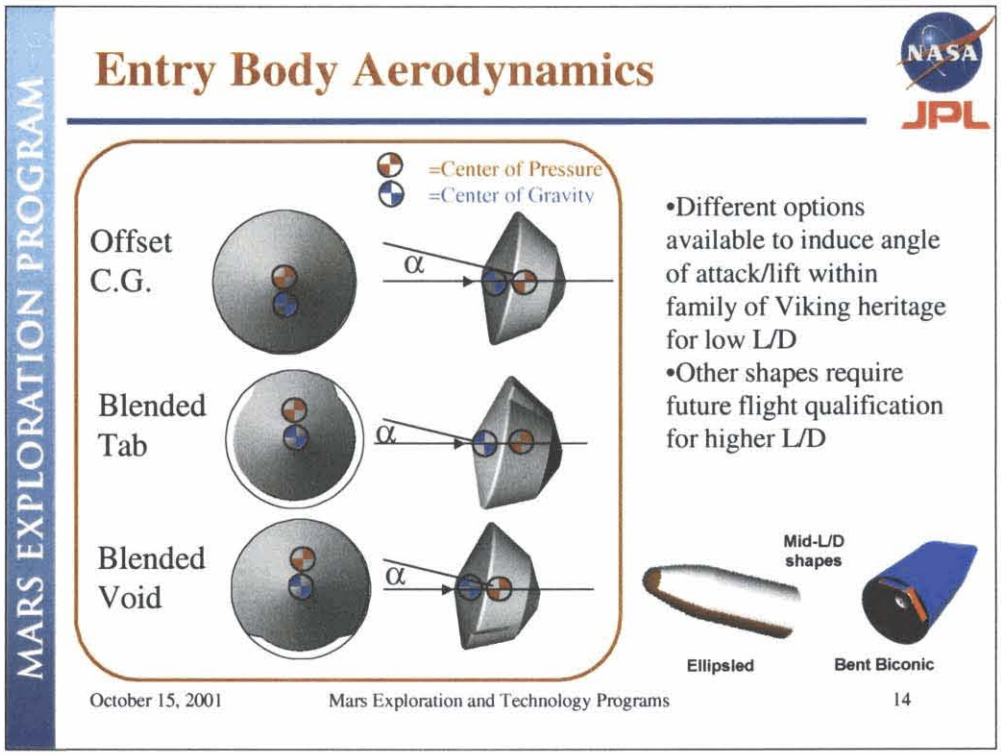


Guided Entry Technology and Precision Landing

All previous Mars atmospheric entries have been performed without active flight-path guidance, although the Viking system did perform one-axis attitude control to maintain a preferred orientation (generating upward lift) during entry. To achieve increased landing site accuracy, future missions are planned to use guided atmospheric entry to eliminate any entry state navigation control error, as well as errors introduced by atmospheric uncertainty or variability which can be sensed by the lander's onboard inertial navigation system. Such systems require that the entry body produce a lateral force (referred to as "lift" independent of the instantaneous horizontal orientation of this force vector), and that the onboard inertial guidance and navigation be able to control the orientation of this vector with respect to the primary retarding drag force based on sensor inputs and a previously proscribed set of guidance laws. The primary errors both in entry navigation and atmospheric uncertainty express themselves as along-track landing errors, rather than cross-track. As such, the primary control law scheme must decide how much of the entry are to be flown with the lift vector up (for steep entries, headed too far up range) and how much with the lift vector down (for shallow entries, headed too far down range). The guidance scheme must also allow for the entry system to fly with a modulated horizontal lift scheme (rolling left to right or vice versa) since the body typically produces lift throughout the entry regardless of whether any along-track force is currently required.



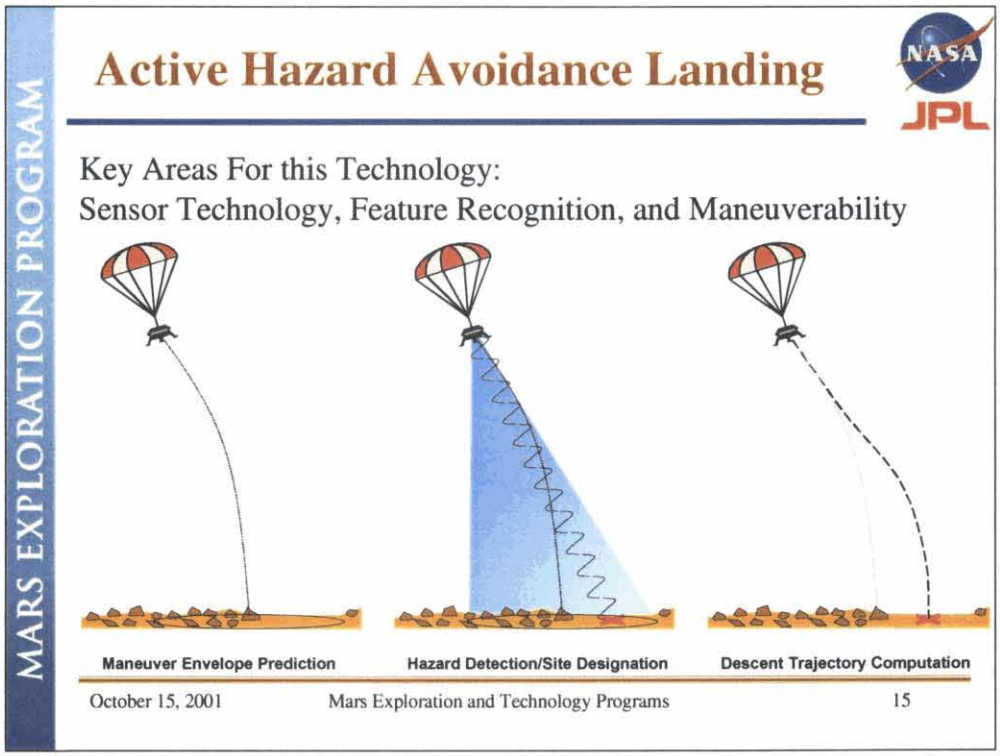
A representative application of precision landing is shown. By drastically reducing the landing site error ellipse and simultaneously increasing the traverse capability of any onboard rover or mobility system, future landers may be able to demonstrate "Go-To" capability, in which the entry ellipse can be placed sufficiently close to a surface feature of interest such that after landing, the previously identified feature is within the traverse capability of the rover.



Entry Body Aerodynamics

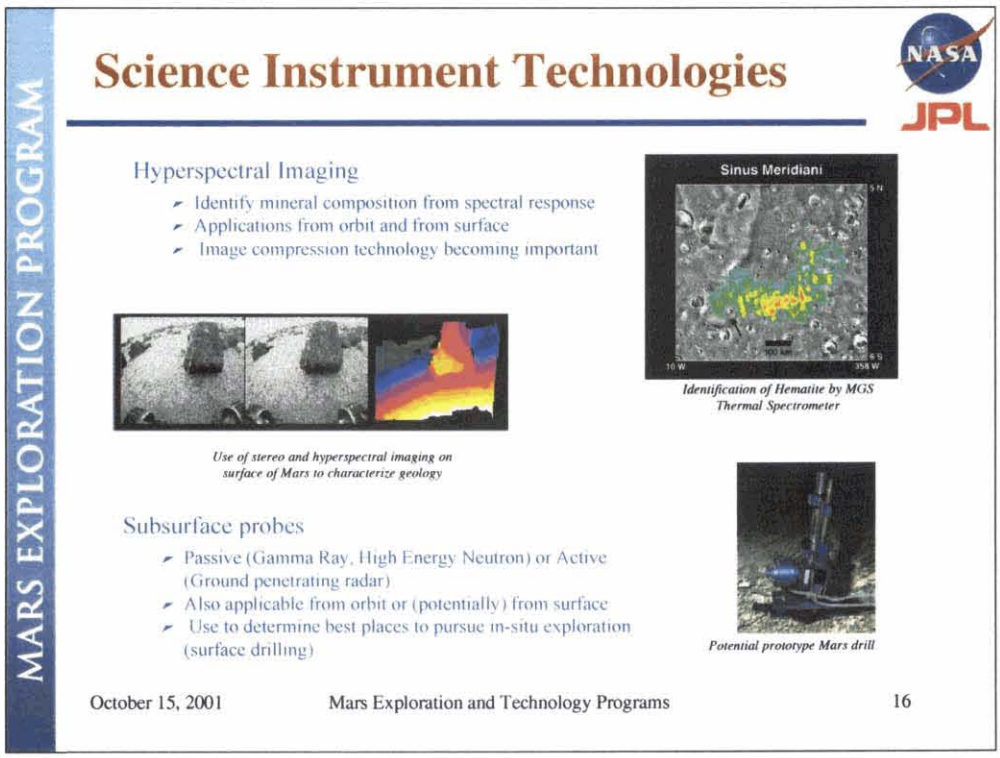
A significant investment in planetary entry systems was made by the Viking project in the early 1970's. This investment covered by hypersonic entry bodies and supersonic parachute decelerator systems. The combination of the blunt-body 70 degree sphere cone and the supersonic disk-gap-band parachute decelerator have served as the basis for major Mars entry systems ever since. The basic entry body shape can be flown at an angle of attack up to at least 12 degrees to generate negative lift perpendicular to the drag direction ("Negative lift" is defined to generate a force in the direction opposite of the angle of attack, the opposite of typical lifting wing conventions). Viking itself flew with an intentional offset between the center of gravity and center of pressure, achieved by asymmetric packaging of lander equipment and ballast inside the entry body, whereas the Mars Pathfinder mission used a purely ballistic entry (no lift) with the CG and CP aligned. For future Mars entry bodies, other methods of achieving CG/CP mismatch are under consideration by modifying the aerodynamic properties of the heat shield rather than the application of packaging and ballast to achieve this misalignment.

The Viking supersonic parachute decelerator system was qualified for openings at or below a Mach number of 2.2. In order to guarantee deceleration to this level before sinking below a safe altitude for the representative parachute descent timeline (typically taken as a constraint to decelerate prior to 8-10 km above the surface), a maximum ballistic coefficient and maximum entry mass can be derived by assuming the maximum entry body diameter which can be accommodated within the largest existing launch vehicle fairings (circa 5 meters outside diameter). Recent analysis has shown this limit to be on the order of 3000 kg entry mass. In order to safely enter and land massed larger than this at Mars (subject to the Mach number constraints of existing parachute technology), alternative entry body shapes must be considered, including bodies which fly at higher lift-to-drag ratios and, as such, can fly shallower and longer paths through the atmosphere, achieving greater decelerations of their higher entry masses prior to reaching the required Mach number for parachute deployment at a safe altitude.



Active Hazard Avoidance Landing

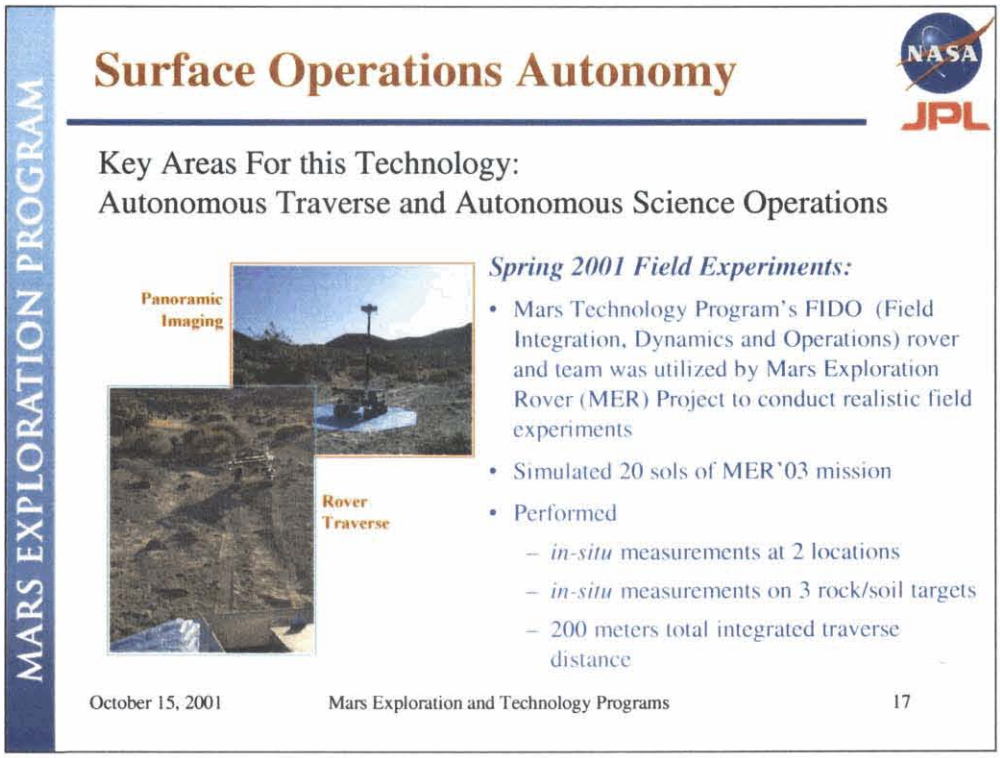
The final area of significant technology investment for Entry, Descent and Landing, is the pursuit of autonomous hazard identification and active hazard avoidance during terminal descent. The basic scheme is to equip the lander with appropriate machine vision sensors (either passive optical or active optical/laser or active imaging radar) to identify hazards (as defined by the landing robustness characteristics of the lander) during descent (ideally, prior to release of the lander from the parachute decelerator) at an altitude sufficiently high that the lander, upon initiating its own powered descent to the surface is able to avoid hazardous locations, identify safe haven locations and actively divert its descent trajectory to achieve a hazard-free landing.



Science Instrument Technologies

The area of science instrument technologies is characterized by two broad classes of experimentation. The first of these is hyperspectral imaging which is applicable both from orbit as well as on the surface of Mars. This class of instruments allows the rapid survey of the spectral characteristics of the instruments field of view. Typically using the infrared band for this spectral survey, the characteristic spectral signature of many different mineralogical types, several of which are able to suggest what role water may have formed in the creation of these substances (e.g. hydrothermal processes or aqueous deposits). From orbit, this can be used to identify high priority landing sites, while on the surface, this data allows the rapid identification of high priority rocks for more detailed in situ investigations, or sampling.

The second general area of instrument technology is characterized by more by the origin of the phenomena of interest than by any specific technology to study it, specifically, the ability to understand what lies under the surface of Mars. Mars 2001 Odyssey carries a Gamma Ray Spectrometer and a High-energy Neutron Detector, both designed to measure the response of Mars to highly energized particles impacting the planet from the solar wind. These particles have the ability to penetrate below the surface and generate a signal that gives information regarding the presence of certain elements (e.g. Hydrogen, potentially in the form of water). Future Mars missions plan to continue this subsurface sounding by bringing their own illumination source in the form of ground-penetrating radar, again with the intention of locating any potential reservoirs of subsurface water or ice formations. As with the hyperspectral imaging described above, this information can be used to identify high priority landing sites where the search for information about the subsurface of Mars can potentially be continues with in situ drilling experiments, carried by future landers.



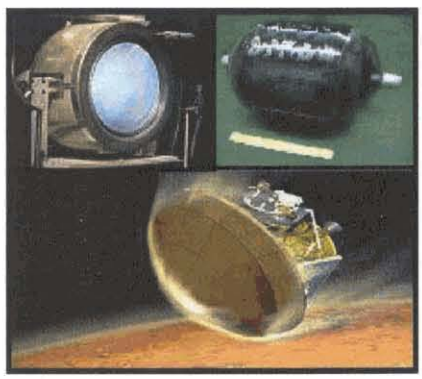
Surface Operations Autonomy

Once on the surface of Mars, the ability of a science team to conduct meaningful experiments using a robotic rover as their agent is often a challenging endeavor. For solar powered rover systems where dust accumulation and seasonal environmental changes are acting, the amount of time available to a mission on the surface is a precious resource. The Mars Technology Program recognizes this fact and is continuing to advance the level of autonomous operations that the in situ rover is capable of performing in an endeavor to increase the amount of meaningful science which can be performed in a limited duration. The two major areas where there is an opportunity for significant enhancement enabled by autonomy are in the areas of autonomous traverse across the surface of Mars, and the area of autonomous contact science, specifically the precise establishment and maintenance of a designated position and orientation of a scientific instrument in close proximity to a surface feature designated by the science team. The Mars Technology Program continues to evolve its understanding of what the high payoff technologies are by participating with planetary scientists in ongoing field experiments conducted to simulate exploration conditions to be expected on future Mars missions.

MARS EXPLORATION PROGRAM

Orbital Transport Technologies

Solar Electric Propulsion - Under study for potential use in sample return trajectories, requiring large delta-v's for return from Mars. Demonstrated Specific Impulse >3000 seconds.



Lightweight Propellant Tanks - Reduce percentage of fuel mass needed for structural containment

Aerocapture - Pursuing jointly with CNES

- Significant advantage for rapid deceleration into near-circular Mars orbit with minimal delta-V, using heat shield
- Complements existing Aerobraking technology (slow deceleration without heat shield)

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A number of technologies of potential benefit to future orbiters are also under development within the Mars Technology Program.

Solar Electric Propulsion

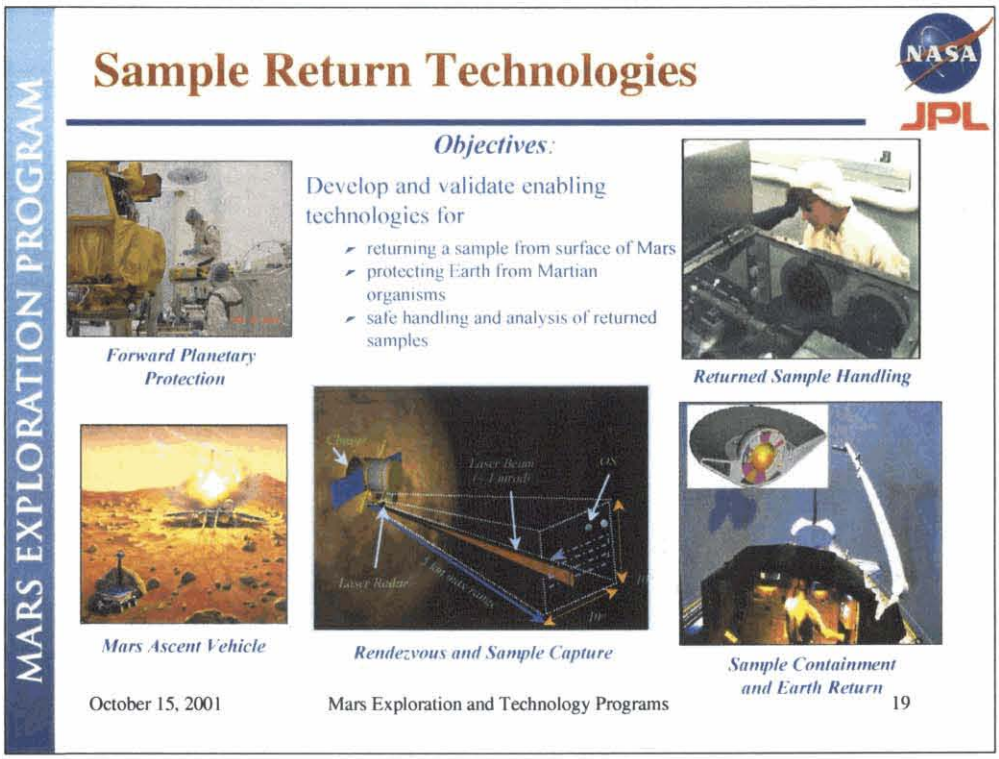
Solar electric propulsion, while now considered a fairly common technology for geostationary station-keeping in Earth orbit, has only recently become accepted as a validated technology for interplanetary missions. This is largely based on its successful demonstration on NASA's New Millennium Deep Space 1 mission. For Mars exploration, the application is particularly attractive to address the unusually large propulsive acceleration requirements of the return from Mars to Earth, as large decelerations for Mars missions can also be achieved with aeroassist (either gradual aerobraking without a dedicated heat shield or more impulsive aerocapture, with a dedicated heat shield).

Lightweight Propellant Tanks

The Mars Technology Program is also making an investment in the development of lightweight propellant tanks to continue to reduce the fraction of the stored propellant mass which must be invested in tank dry mass to contain a given amount of propellant.

Aerocapture

The ability to use a planetary atmosphere to rapidly decelerate an arriving orbital asset from an interplanetary trajectory directly into orbit is referred to as Aerocapture. In contrast to aerobraking, which still requires a significant propulsive capability to capture into orbit prior to initiating the slow gradual descent to circular or near circular orbit, the aerocapture technique trades the arrival propulsive capture requirement for a dedicated heat shield (on par with those used for lander entry bodies) which can achieve single-pass deceleration into practically any orbit (including near circular) much more rapidly than aerobraking. This is achieved by targeting the atmospheric pass at altitudes as low as 60-80 km, contrasting the typical range of 100+ km altitude for gradual aerobraking circularization. This technology is being pursued jointly by both NASA and the French space agency CNES.



A number of technologies focused solely on the return of samples from the surface of Mars are also under development. For any Mars mission intending to search for evidence of life, it is of vital importance to protect the mission from the possibility of not only "forward-contamination" (contamination of Mars with organisms originating on Earth), but also against potential contamination of returned samples with "round-trip" or "hitchhiker" organisms, which lead to false positive indications for life-detection experiments performed on returned samples. Another enabling technology for sample return missions is the development of a launch vehicle capable of both being landed on and rising from the surface of Mars after a period of storage and survival while samples are being collected by other surface assets. Also, recent architectural studies have confirmed previous results suggesting in low Mars orbit is one of the most promising locations for a handoff between this Mars Ascent Vehicle and the vehicle designed to return these samples to the vicinity of the Earth. Manners of safely bringing back to the surface of the Earth any samples collected from the surface of Mars are also under investigation, considering both the use of a dedicated sample return Earth entry vehicle system or by using other existing Earth entry systems such as the shuttle. Additionally, the technology required to safely evaluate and analyze any returned samples is also a key investment area.

MARS EXPLORATION PROGRAM

Summary

- **Mars Exploration Program comprises a series of missions integrated into a coherent ongoing program**
- **Technology development and infusion allows both the incorporation of new capabilities as well as the continuous improvement of existing capabilities**

The Mars Exploration Program comprises a series of mission integrated into a coherent ongoing program

Technology development and infusion allows both the incorporation of new capabilities as well as the continuous improvement of existing capabilities.