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A STRATEGY FOR ROBOTIC PRECURSOR MISSIONS TO SUPPORT HUMAN EXPLORATION

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Abstract

NASA's plans to send human missions beyond Earth orbit must be informed by knowledge of the potential destinations. The planning of future robotic precursor missions to gather crucial environmental data on the Moon, near-Earth asteroids, and Mars will be guided by a set of Strategic Knowledge Gaps. These Strategic Knowledge Gaps have been defined and reviewed by the human exploration, science, and international communities, and will be incorporated into a Global Exploration Roadmap.

The Strategic Knowledge Gaps will be addressed through a portfolio of activities that are jointly planned and funded by NASA's exploration and science organizations. The initial Joint Robotic Precursor Activities (JRPA) include development of a lunar resources prospecting payload in partnership with the Canadian Space Agency; development of a small lander and flight tests of an autonomous precision landing system; imaging near-Earth asteroids with ground-based radar; and a radiation detector on the Mars Science Laboratory rover to measure the interplanetary and surface radiation environments. The activities also include research and analysis efforts to study the Moon and small bodies from both the exploration and science perspectives.

INTRODUCTION

NASA is planning to send human missions deeper into space than ever before, with the eventual goal of setting foot on Mars. NASA's exploration strategy is to focus on the development of advanced spaceflight capabilities, and to expand the reach of human missions in progressive steps as these new capabilities become available. The first steps will be taken in this decade, with the development and initial test flights of the Orion crew vehicle and the Space Launch System. In parallel, the International Space Station is being used as a test bed for new technologies, to conduct research on human health and performance, and to validate operational concepts for long missions far from Earth.

To reduce risks and design margins, knowledge about potential destinations is essential before human missions can be planned. Robotic precursor missions, ground-based measurements, and research and analysis efforts are already underway to gather the strategic knowledge needed to inform the planning of human missions to the Moon, near-Earth asteroids (NEAs), and Mars. These precursor activities are jointly planned and funded by NASA's exploration and science organizations, so they are called Joint Robotic Precursor Activities (JRPA). By integrating exploration and science objectives, NASA can pursue human and robotic exploration of the solar system more effectively and more affordably.

STRATEGIC KNOWLEDGE GAPS

The JRPA investments are guided by a set of Strategic Knowledge Gaps (SKGs) that represent the unknown environments or availability of resources at potential destinations that could impact the design of human spaceflight systems. A draft set of SKGs was defined by asking mission planners what types of information they would need about a destination to ensure a safe and successful human mission. The SKGs were then reviewed and prioritized by three independent groups that represent the external science and exploration communities: the Lunar Exploration Analysis Group (Ref. 1), the Small Bodies Assessment

Group (Ref. 2), and the Mars Exploration Program Analysis Group (Ref. 3).

The major common themes in the SKGs across these potential destinations are measuring the surface radiation environment; characterizing the physical and electrostatic properties of the regolith; and mapping the extent of volatiles and other resources. For the Moon, knowledge of solar illumination and the thermal environment near the poles is needed. For NEAs, it is important to know the uncertainty in the target asteroid's orbital position; to measure its size, shape, and spin rate; to map its gravity field and infer its internal structure; and to determine if it is a binary system or has hazardous debris orbiting around it that could limit crew vehicle operations. For Mars, the SKGs include understanding the effects of atmospheric conditions on entry, descent, and landing systems, assessing the effects of dust on human health, and ensuring planetary protection.

The integrated set of SKGs for the Moon, NEAs, and Mars was provided to the International Space Exploration Coordination Group (ISECG). The ISECG represents the space agencies of 14 countries, and it has established a shared vision and a framework for coordinating plans for human and robotic exploration of the solar system. The ISECG has developed a Global Exploration Roadmap that outlines possible pathways for exploration in the next 25 years. The ISECG plans to define an international set of SKGs using the NASA SKGs as a starting point. The international SKGs will be tied to the Global Exploration Roadmap mission scenarios, and reviewed by the member space agencies for alignment with their existing and planned robotic missions (Ref. 4). With multiple international partners cooperating to address the SKGs, the required knowledge can be acquired sooner and in greater depth.

NASA is beginning to address the highest-priority SKGs through a portfolio of activities that include development of a lunar resources prospecting payload; development of a small lander and flight tests of an autonomous precision landing system; imaging NEAs with ground-based radar; and measuring the Mars surface radiation environment with a detector on the Curiosity rover.

PROSPECTING FOR LUNAR ICE

NASA is planning to send a robotic precursor mission to the polar regions of the Moon around 2017 to prospect for lunar ice and other volatiles. If approved, this mission would directly address SKGs to understand the lunar resource potential, and to characterize the chemical and physical properties of the regolith. Validating the feasibility of extracting water and oxygen from the lunar regolith could enable a new architecture for human exploration that is based on in-situ resource utilization. The mission would also improve our scientific understanding about how the Earth-Moon system acquired its volatiles. Ultimately, this first prospecting mission could help to open new markets for lunar resources and commercial lunar transportation services.

NASA and the Canadian Space Agency (CSA) are collaborating on the development of prototype systems to enable the lunar ice prospector mission. These include an in-situ resource utilization payload called RESOLVE (Regolith and Environment Science and Oxygen and Lunar Volatiles Extraction), and a rover provided by CSA called Artemis Junior.

The RESOLVE payload will consist of a subsurface sampling drill from CSA, a small oven to heat the sample, and a miniature gas chromatograph and mass spectrometer to characterize the water and other volatiles extracted from the lunar regolith. A neutron spectrometer and a near-infrared spectrometer will be used to find regions of high hydrogen concentration, and determine the best spots to drill. RESOLVE will also demonstrate the production of oxygen from regolith using the hydrogen reduction process (Ref. 5).

In July 2012, RESOLVE was installed on the Artemis Junior rover, and the system was demonstrated in a field test at Mauna Kea, Hawaii where the volcanic terrain is similar to that found on the Moon (Fig. 1). The test simulated mission operations in which the rover traversed more than a kilometer, located widely separated hydrogen-rich spots, and drilled several holes to acquire samples of the volcanic soil. The rover was driven remotely from the CSA mission control center in Montreal. The next steps are to refine the design of the mission, and conduct thermal and vacuum testing to further reduce risks.

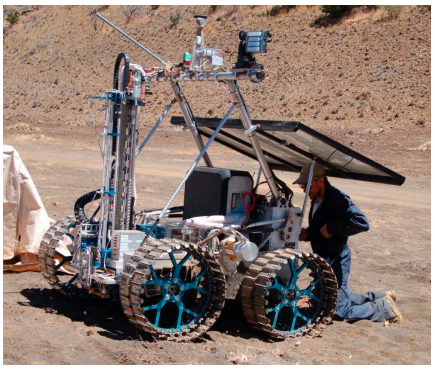


Fig. 1: Testing RESOLVE lunar in-situ resource utilization payload in Hawaii

LUNAR ENVIRONMENTS

The accumulation of abrasive lunar dust on rovers and space suits could degrade materials, seals, mechanisms, and electronics. Lunar dust ingested into the body may also be hazardous to human health. In addition to prospecting for resources, the RESOLVE mission will gather critical data on lunar soil mechanics and dust by measuring the forces required for drilling and rolling across the surface. Further informing our understanding of lunar dust, the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission, to be launched in 2013, will investigate the tenuous lunar atmosphere and the processes by which electrostatically charged dust particles are transported above the Moon's surface (Ref. 6).

Planning lunar mission operations will require knowledge of the solar illumination and thermal environments near the lunar poles so that the rover's solar arrays can generate sufficient power and it can survive the extremely cold lunar night. The Lunar Mapping and Modeling Project (LMMP) has developed software tools for archiving, integrating, visualizing, and analyzing multiple environmental and topological data sets returned from precursor missions such as the Lunar Reconnaissance Orbiter (Ref. 7). Using LMMP, mission planners and scientists will be able to discover essential knowledge about the lunar environment.

The NASA Lunar Science Institute sponsors research on questions of fundamental importance in understanding the formation, evolution, composition, and resource potential of the Moon (Ref. 8). This virtual institute is jointly funded by NASA's science and exploration organizations. The research includes experimental and theoretical investigations of lunar dust and the polar environments. NASA plans to expand the scope of the institute's research to include asteroids and other small bodies.

LANDING SYSTEMS DEVELOPMENT

The lunar ice prospector mission will need to land close to hydrogen-rich spots on the edge of a polar crater in variable lighting conditions. To enable autonomous precision landing within several meters of a target, NASA is developing an Autonomous Landing and Hazard Avoidance Technology (ALHAT) system.

ALHAT consists of a suite of laser sensors, cameras, and relative navigation algorithms (Ref. 9). During the initial high-altitude descent phase, ALHAT uses terrain relative navigation techniques that compare camera images of the lunar surface to terrain features stored in a database to calculate the lander's position. During the terminal descent phase, which begins about 50 meters above the surface, ALHAT uses a flash lidar sensor to construct three-dimensional images of rocks and craters in the landing area. The flash lidar is mounted on a two-axis gimbal so that it can be pointed to cover the landing area with a mosaic of several images. Hazard relative navigation algorithms running on a multi-core processor identify a safe landing spot and calculate the vehicle's trajectory. A laser altimeter and a laser Doppler velocimeter provide inputs to the lander's inertial measurement unit (IMU). During the last few meters of the descent, the laser sensors may become obscured by dust kicked up from the surface by the lander's engines, so the IMU is used to navigate to the landing spot by dead reckoning.

To test the ALHAT system under realistic flight conditions, NASA has developed a small lander test bed called Morpheus (Ref. 10). The Morpheus lander will also be used to demonstrate other advanced vehicle technologies such as LOX-methane propulsion. The throttleable main engine produces 4,400 pounds of thrust, and the reaction control system thrusters are integrated with the main propulsion system. Morpheus completed 20 tethered flight tests in which the lander was suspended from a crane so that its flight dynamics and control systems could be validated (Fig. 2). Unfortunately, during the first free flight attempt in August 2012, the lander crashed and was destroyed due to a control system malfunction. A new lander is being built from spare parts.

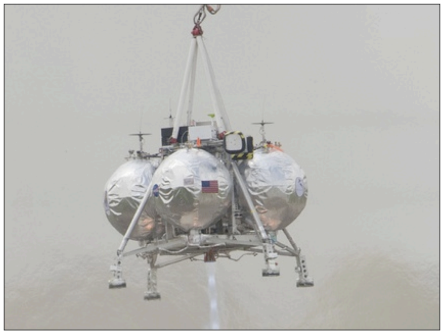


Fig. 2: Tethered flight test of Morpheus lander

A series of free flights with ALHAT installed on the new lander is planned in the spring of 2013 at the Kennedy Space Center. The lander will take off from the ground and fly up to an altitude of 500 meters. At a slant range of about one kilometer from the target, the ALHAT system will then autonomously maneuver the vehicle to land safely in a hazard field that simulates a planetary surface.

The Moon has mass concentrations in its crust that cause gravitational anomalies that may affect the

trajectory of a lander or a spacecraft in low lunar orbit. The Gravity Recovery and Interior Laboratory (GRAIL) mission that was launched in 2011 is mapping the gravitational field of the Moon with high resolution to determine its interior structure (Ref. 11). This gravitational information will be used by precision landing systems to correct for the effects of mass concentrations.

DETECTING NEAR-EARTH ASTEROIDS

One of NASA's exploration goals is to send a human mission to a NEA around 2025. However, only a handful of potential targets that are accessible by a human mission in that time frame have been detected thus far (Ref. 12). A longer list of candidate NEAs is needed to provide flexibility in mission planning.

To be a good candidate for human missions, a NEA must have the right orbit, size, shape, and spin rate. For NEAs that approach within 0.1 AU of Earth, this information can be obtained using ground-based radar. The 70-meter Deep Space Network antenna at Goldstone, California has been equipped with a chirp waveform radar and digital receiver. The Goldstone Radar can image NEAs with a resolution of 4 meters (Ref. 13). It has imaged 16 NEAs in the past year. The radar images can be used to construct a three-dimensional shape model of the asteroid (Fig. 3). Using ground-based radar to image NEAs is substantially cheaper than sending robotic precursor missions to scout potential targets.

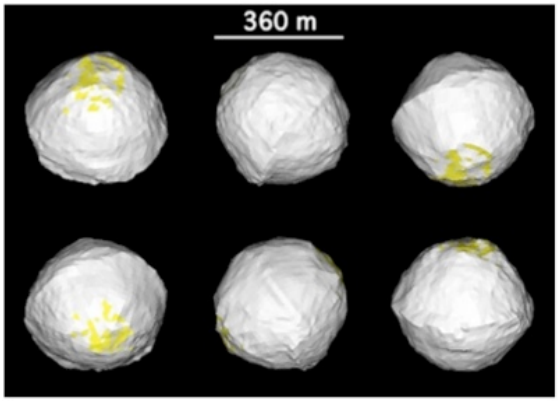


Fig. 3: Shape model of asteroid 2005 U55 obtained by Goldstone Radar

To detect NEAs that are farther from the Earth, a space-based infrared telescope will be needed to image asteroids against the cold background of space. The B612 Foundation is planning to launch the privately-funded Sentinel mission in 2017 to detect 98 percent of the population of NEAs (Ref. 14). The spacecraft will be placed into an orbit around the Sun, near the orbit of Venus. This will provide the optimal vantage point to map the locations and trajectories of Earth-crossing asteroids. NASA is providing tracking, data analysis, and technical assistance to the Sentinel project through a non-reimbursable Space Act Agreement. NASA is also studying the possibility of flying an infrared sensor on a geosynchronous satellite that would detect small asteroids passing very close to Earth.

NEA SCOUTS

Precursor missions to NEAs will fill in the blanks left after initial detection by ground and space-based observations. About a dozen asteroids have already been investigated up close with missions such as NEAR (Near-Earth Asteroid Rendezvous), Galileo, Hayabusa, Rosetta, and Dawn. The next mission will be OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer) in 2016, which will return a sample from the carbonaceous asteroid 1999 RQ36 (Ref. 15). This mission will address SKGs for asteroids by investigating the physical properties of the regolith, and mapping the distribution of volatiles and mineral resources.

The requirement to qualify a NEA as a potential destination is counterbalanced by the cost of these precursor missions. Multiple asteroids would have to be characterized to identify a suitable target before a human mission could be launched, and to provide alternate destinations in case the human mission is delayed. To make these scouting missions more affordable, NASA is studying concepts for low-cost microspacecraft with solar electric propulsion and a minimal payload of instruments. Several of these NEA scouts could be launched on a single mission, and each microspacecraft could visit a different asteroid. To inform the design of a human mission to an asteroid in 2025, the NEA scouts would have to be launched in 2017 so that the data could be returned and the target asteroid selected approximately five years before the human mission is launched.

MEASURING RADIATION ON MARS

A key SKG that must be addressed for all destinations is measurement of the surface radiation environment. This knowledge is needed to assess the risks to human health and to develop effective radiation shielding and other countermeasures. A Radiation Assessment Detector (RAD) onboard the Mars Science Laboratory (MSL) rover is measuring the energy spectrum of heavy ions from galactic cosmic rays, and the secondary charged particles, neutrons, and gamma rays produced when cosmic rays interact with the atmosphere and soil (Fig. 4). The data acquired by

RAD will be used to calculate the total radiation dose that a human would receive while on the surface. The surface radiation environment will be compared to in-space measurements to understand how radiation penetrates the Mars atmosphere. RAD operated for seven months during the interplanetary cruise to Mars, and it detected several major solar particle events while it was inside the spacecraft's structure (Ref. 16). These data will be used to validate models of radiation transport through spacecraft materials.

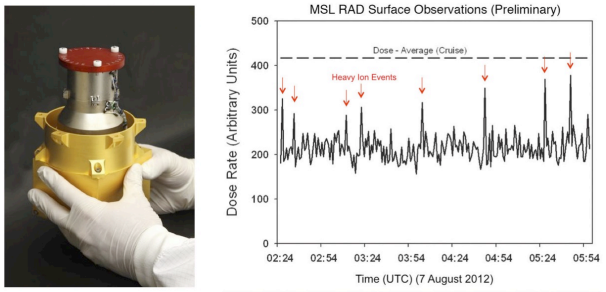


Fig. 4: Radiation Assessment Detector and initial data from surface of Mars

ENTERING THE MARTIAN ATMOSPHERE

Current technology for entry, descent, and landing (EDL) is not capable of delivering the heavy payloads that will be needed for human missions to Mars. To design the next generation of EDL systems, improved knowledge of entry vehicle aerothermodynamics and the density of the Martian atmosphere is essential. Spacecraft heat shields are typically designed by conducting arcjet tests on small samples of the thermal protection system material, and extrapolating the results using analytical models to predict the heat shield's large-scale performance. Until recently, no in-flight data on heat shield performance had been obtained during actual Mars entry. In August 2012, the MSL Entry, Descent, and Landing Instrumentation (MEDLI) experiment measured the pressures, temperatures, and material ablation rates at various points on the MSL heat shield when it entered the atmosphere of Mars (Fig. 5). These engineering data will be used to validate and improve analytical models that predict the aerothermal, aerodynamic, and thermal protection system performance. MEDLI also gathered data on atmospheric density and winds (Ref. 17).

The Mars Atmospheric and Volatiles Evolution Mission (MAVEN), to be launched in 2013, will study the upper atmosphere of Mars to determine how it evolved over the history of the planet. MAVEN will investigate the processes by which Mars loses carbon dioxide, water vapor, nitrogen, and other volatiles to space (Ref. 18). Improved knowledge of the upper atmosphere will aid in the design of future entry systems.

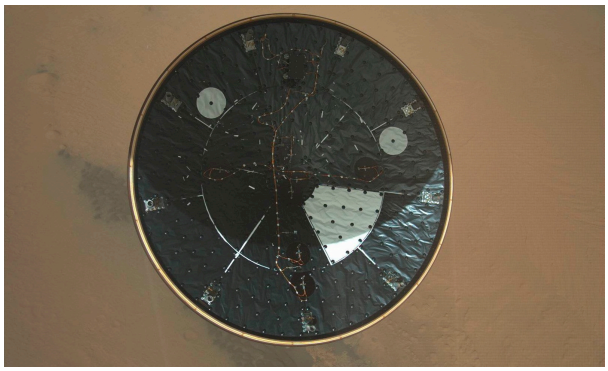


Fig. 5: MEDLI sensors on MSL heat shield as it falls away from the rover during the descent to Mars

SAMPLE RETURN

NASA's Mars exploration program is studying various options for a mission in 2018 that would combine science, exploration, and technology demonstration objectives. This mission may test capabilities needed for a future Mars sample return mission. A rock sample from Mars could help to answer the question: Did life arise elsewhere in the solar system? In the next decade, robotic missions that return samples from the Moon, NEAs, and Mars could be conducted in concert with human missions to cis-lunar space. A payload of samples launched from a robotic lander on Mars could rendezvous with the Orion crew vehicle at the Earth-Moon L2 Lagrange point. The astronauts would retrieve the samples and return them to Earth in the Orion capsule. By using crewed missions to return the samples, robotic missions could obtain a greater mass of samples, and the samples could be quarantined at L2 to ensure planetary protection before they reach Earth. In the near-term, sample return from the Moon's South Pole Aiken Basin is a high scientific priority to determine the composition of the lunar crust, and it would provide an early demonstration of similar capabilities needed for a later Mars sample return mission.

CONCLUSION

By coordinating NASA's science and exploration programs, critical knowledge needed for the planning and design of human exploration missions can be gained more effectively and affordably. NASA's strategy for robotic precursor missions to support human exploration is guided by a set of SKGs that have been defined for the Moon, NEAs, and Mars. Many activities are already underway to fill these gaps, including instruments on science missions to acquire

essential information for exploration, development of new autonomous precision landing technologies, ground-based observations, and research and analysis efforts (Fig. 6). The SKGs are being incorporated into the Global Exploration Roadmap, and they will soon provide a more definite framework for international collaboration on human and robotic missions. When humans begin to venture into deep space in the next decade, the robotic precursor strategy that we are pursuing now will have made it possible. And who knows? We may discover something that changes our approach for human spaceflight completely.

	Strategic Knowledge Gaps	GRAIL	RESOLVE	Goldstone Radar	Sentinel	NEA Scout	MSL	MAVEN	Sample Return
Moon	Volatiles prospecting		✔						
	Radiation environment								
	Gravity field	✔							
	Soil mechanics		✔						
NEAs	Uncertainty in orbital position			✔	✔	✔			
	Spin rate			✔	✔	✔			
	System type (Binary?)			✔	✔	✔			
	Activity & debris					✔			
	Soil mechanics								
	Gravity field / internal structure					✔			
Mars	Atmospheric Properties for EDL						✔	✔	
	Radiation Environment						✔		
	Biohazards								
	ISRU								✔
	Dust toxicity								✔
	Soil mechanics								
	Planetary Protection								✔

Fig. 6: Current and planned robotic precursor activities to fill SKGs

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