ICEBREAKER: AN EXPLORATION OF THE LUNAR SOUTH POLE

The Robotics Institute, Carnegie Mellon University

Pittsburgh, PA

Introduction

The Icebreaker mission proposes to conduct a ground investigation of the southern polar region of the Moon. Several factors promote such an exploration in the early part of the 21st century. The re-invigoration of lunar research, prompted by Clementine and Prospector, has created a demand for follow-on research activity to pursue newly-generated questions on lunar origins and evolution. In light of the discovery of surface hydrogen prevalent at the lunar poles, and the persistent question of its source, surface measurements and ground truth are critical components of a next-generation lunar mission. In the context of human exploration, many believe lunar habitation should be revisited as a stepping stone for extended Mars expeditions, as well as a valuable activity in its own right. Finally, recently developed digital elevation maps of the lunar terrain at the poles may now provide ample data by which to plan a course for surface operations.

Categorically determining the origin of polar hydrogen signals and performing geological studies in the lunar south pole region will provide essential information to enrich our knowledge of lunar origins and evolution. The investigation will also determine the presence and distribution of resources necessary to support human habitation and a base for deep-space missions, such as water, rocket propellant components and construction materials. Icebreaker advocates a partnership among academic, government and commercial entities to create an economical, multi-dimensional mission.

<u>Target of Operations</u>

- South Pole Aitken basin, near crater Shackleton

<u>Science Goals</u>

- Determine the source of polar hydrogen signals
- If water ice is present, characterize its concentration, stratigraphy and lateral extent
- Perform geologic survey

<u>Additional Goals</u>

- Determine the distribution of resources for eventual human habitation
- Education and public outreach during and after mission

<u>Launch, Transfer and Landing</u>

- Liftoff aboard Boeing Delta II or similar class
- Transfer and soft landing on 3-axis lander

<u>Surface Operations</u>

- Science instruments and drill carried aboard teleoperated rover
- Sorties conducted into permanently dark regions near landing site

<u>Time Frame</u>

- January 2004 or January 2005

Mission Justification and Goals

Fundamental Science

Water Detection and Characterization

Lunar Prospector detected high concentrations of hydrogen in the polar regions of the moon. This discovery has sparked debate among lunar scientists regarding the form and origin of this hydrogen. In particular, many support the theory that the hydrogen is indicative of water-ice deposits while others support the theory that it is elemental hydrogen trapped within lunar regolith. The Icebreaker investigation will help resolve this debate.

Bistatic radar measurements taken by the Clementine spacecraft yielded inconclusive results regarding the presence of water ice[13,16]. Earth-based radar measurements of the lunar poles also do not yield a signature typical of concentrated water ice[17]. However, the neutron spectrometer aboard Lunar Prospector detected high concentrations of hydrogen isolated at the extreme latitudes of the poles. The rate of elemental hydrogen dissipation and solar wind characteristics makes the possibility of elemental hydrogen less likely. Additionally, the highest concentrations are found in the cold polar regions, which is consistent with large deposits of water ice[5]. Lunar Prospector data also suggests that if present, layers containing water ice lie within 1 meter of the surface under a shallow layer of dry regolith.

Scientists have theorized the presence of water ice at the lunar poles for decades[4,20]. The most widely accepted theory to explain lunar water deposits suggests that cometary water could have accumulated over millennia in the low-energy environment of permanently shadowed regions at the poles as a result of successive impacts[4,20]. Additional theories provide for the accumulation of water ice through a process of FeO reduction with solar wind hydrogen or lunar interior degassing[4,20]. The dominant theory for the mechanism of accumulation of elemental hydrogen is the entrapment of solar wind hydrogen. Resolving this issue involves two analyses. First is the identification of water or its absence on the moon. Second is the determination of the isotopic ratio of deuterium and hydrogen; comet water ice is known to be high in deuterium concentration while solar wind hydrogen is relatively low

If water ice is responsible for the polar hydrogen signal, additional studies must determine its distribution throughout the permanent dark, its near-surface stratigraphy beneath the lunar regolith, and its isotopic composition. Water ice may be concentrated in sheets or thinly distributed throughout regolith. Knowledge of its distribution and stratigraphy could lead to theories on the mechanism for water accumulation. Concentrations of water ice separated by layers of regolith would be possibly indicative of impact history or gardening.

Alternately, should only elemental hydrogen be present, the additional studies must gather data regarding hydrogen distribution and concentration. As in the case of water, such data could be used to support or counter the hypothesis of solar wind accumulation as its source.

The resolution of the debate over lunar water ice will provide insights into lunar evolution, comet impacts, and solar wind behavior. Identification of water ice and measurements of isotopic ratios currently require close-range, high-resolution data that can only be acquired by a ground-based mission. The ability to test the validity of the competing hypotheses of hydrogen and provide significant scientific discovery is a primary motivation for the Icebreaker mission.

Lunar Geology

The South Pole Aitken basin is one of the most actively researched regions for lunar geology. Though primarily a lunar far-side feature, the basin encompasses the south pole and territory to a few degrees north of the pole on the near side. At 2600 km in diameter, Aitken is the largest known impact crater in the solar system. Earlier lunar observations have led scientists to theorize that the Aitken impact uplifted material from the upper mantle. Clementine and Lunar Prospector data have promoted scientists to identify the South Pole Aitken region as representing one of three distinct lunar crustal “terrane” classes[6].

Localized South Pole Aitken geologic studies may emphasize the search for deposits to determine composition of the upper lunar mantle and lower crust. Because of Aiken’s dominance over the lunar far side, a study of the mineral content at the south pole may simultaneously aid in characterizing substantial regions of the lunar far side. Explorations of basin-internal craters may attempt to characterize the geology resulting from the impact and the subsequent crater evolution. The investigation may find rocks metamorphosed by the high-energy impact event, as well as evidence of lava flow or crustal and mantle upwelling.

The type of investigation required for such studies can only be provided by a mobile, ground-based mission such as Icebreaker.

Preparation for Human Exploration

Presence of water on the Moon would significantly reduce the difficulty of establishing a human outpost there in the 21st century. However, aside from the possibility of harboring water, the lunar poles exhibit qualities that could be advantageous for early human settlement. Unlike equatorial regions of the moon which experience extreme diurnal variations in surface temperature (254 K ± 140 K) as the sun rises and sets, the pole temperatures vary more slowly and less dramatically (220 K ± 10 K)[7]. As on Earth, each pole experiences a summer, during which the sun climbs highest in the sky, and a winter, when the sun remains largely below the horizon. While the Earth’s spin axis is tilted 23.5° with respect to the ecliptic plane, the Moon’s is tilted a mere 1.5°. Consequently, the sun will remain above the horizon for over half a year at a time at the poles. Elevated regions surrounded by the extensive lowlands found in the Aitken basin may provide sun exposure to the surface far into the winter. Early topographic and long-term lighting measurements indicate that a region near the crater Shackleton was illuminated by the sun for a large percentage of the lunar rotation[3]. Establishing an outpost in a region with nearly continuous sun exposure would drastically reduce its dependence on power storage or nuclear power production.

Water Resource Detection and Characterization

Operations in support of eventual human habitation would focus on the discovery of water and the determination of its distribution. Water is essential to the sustenance of human life on the Moon. Mining water at the poles would enable the production of drinking water and oxygen, reducing a habitat's dependence on fully recyclable life support concepts.

The development of a space flight staging area on the moon would open space transportation avenues not otherwise available, including faster deep-space trajectories and the ability to carry far heavier payloads to the planets. Finding lunar water ice could create an industry devoted to the in-situ production of cryogenic rocket propellant for Earth-moon and deep-space orbital transfer, providing the basis for such a staging area. Water ice distribution and stratigraphy data from Icebreaker would assist scientists and engineers in designing extraction and purification techniques for in-situ resource utilization as well as aiding mission planners in locating areas suited to water processing.

Mineral and Other Resource Distribution

Icebreaker could serve to characterize the south polar environment for habitat establishment. Cataloging and measuring distributions of mineral and metallic resources could aid in planning and design of processes for ISRU in support of a habitat as well as for building materials. Measurements of terrain and its effect on lighting, communications and mobility would aid in establishing a site for future outposts and in setting requirements for lunar habitat systems.

Commercial

The extensive media coverage of the Mars Pathfinder mission reflects a public desire for connection with space exploration. Even more than Pathfinder, Icebreaker will embody the concept of robotic explorer, with long-distance treks across unknown territories over several months. People will watch to find out what lies behind the next hill or in the dark of permanent shadow. Television and internet coverage of the mission, judging by the popularity of Pathfinder, could be an enormously successful commercial venture. Such an enterprise could comprise coverage rights, television and internet advertisements, and spacecraft- and launch vehicle-mounted advertising logos. A return to the Moon's surface could also stimulate the public's interest in television documentaries that describe the design, construction, and flight of Icebreaker. For any television or internet broadcast or printed publication, high-resolution, full-color images would be the focus of public attention. Unlike the pictures taken during the Apollo missions, Icebreaker pictures will illustrate a world of extreme light and shadow, with mountains and pronounced crater rims at the horizons. As a backdrop for the stark lunar terrain, the Earth would always be visible from the rover. Such a collection of imagery would be in high public demand.

Icebreaker could also generate opportunities in the entertainment market. Icebreaker imagery, in conjunction with rover motion data recorded during its polar trek, could be incorporated into a highly-immersive, motion-based simulation ride. Participants would feel as if they were driving on the lunar pole. Offered at theme parks and science museums, a lunar exploration simulator could hold public interest long after the completion of the Icebreaker mission.

Science Instruments and Sample Acquisition

The Icebreaker science instruments and sample acquisition focus primarily on the detection of water ice and secondarily on geological composition. To meet the scientific goals of the Icebreaker mission, a suite of scientific instruments is recommended based on considerations of flight-readiness level, capabilities and versatility, ability to integrate with a rover platform (mass, power, etc.), and level of redesign effort required for this mission and rover integration. The primary recommended instruments include several types of spectrometers and an imager[19]. A cryogenic drill enables access to sub-surface materials for analysis and sample acquisition.

Laser Induced Mass Spectrometer (LIMS)

The LIMS is a long-range ($\leq$ 20 m) time-of-flight mass spectrometer which can provide information on the elemental and isotopic composition of materials, including water. LIMS also has the capability to providing molecular composition for light-weight molecules. The LIMS can accurately sample from small targets, down holes or at large distances. The source of the LIMS instrument is Los Alamos National

Laboratory, where a prototype is currently in development.

Raman spectrometer

The Raman spectrometer is a short-range (< 1 cm) scattered-light spectrometer that can provide the molecular composition of materials and which can identify water. Elemental chemistry can be inferred from molecular composition. The source of the Raman spectrometer is the University of Alabama/NASA, where Raman spectrometers are being developed for the Mars Athena science package.

Active Pixel Sensor (APS) Color Imager

The APS is a high-resolution, CMOS digital color imager that can provide feature information, as well as video sequences. Pixels on the imager can be accessed individually, allowing easy windowing and feature tracking capability. In addition, the APS hardware is far more robust to radiation interference than its CCD counterpart. The source of the APS is NASA, where the APS is in development and middle-range resolution prototypes exist.

Laser-Induced Breakdown Spectrometer (LIBS)

The LIBS is a long-distance energy-emission spectrometer that can provide elemental chemistry of rocks. This spectrometer is complementary to the LIMS, with higher accuracy in elemental composition measurements. This instrument is also complementary to the Raman spectrometer; while not able to perform as complete an analysis as Raman, LIBS can perform basic analysis of materials remotely. The LIBS, like LIMS, can accurately sample down holes or at large distances. The source of the LIMS instrument is Los Alamos National Laboratory, where field prototypes are currently being tested and refined.

Neutron spectrometer

Similar to the instrument deployed on Lunar Prospector, data taken from this instrument could provide a ground comparison of hydrogen data to similar data taken from orbit. In contrast to the orbital version of the instrument, a neutron source must be incorporated to achieve a flux high enough for the required measurement accuracy. In conjunction with the other instruments capable of detecting water, the neutron spectrometer could provide a connection between local ice measurements and global data acquired from orbit. In addition, localizing hydrogen signals using the neutron spectrometer can aid in selection of sites for in-depth water analysis. The source of the neutron spectrometer is Los Alamos National Laboratory, where neutron spectrometer technology was designed for Lunar Prospector.

Cryogenic Drill

Icebreaker must incorporate a drill to enable sub-surface sample acquisition from multiple depths. A drill capable of depths up to 1 meter would provide the ability to uncover water ice deposits, if present. The drill would allow for sub-surface analysis by returning samples to the surface (keeping them thermally and physically isolated during transport) and providing down-hole access to sub-surface layers. The source of the cryogenic drill is Honeybee Robotics, where a drill (SATM) is currently in prototype phase for a future comet mission.

Capabilities

The capabilities of the science package are summarized by science goal in Table 1.

Table 1: Suggested Science Instrument Applications

Science Goal	Analysis Required	Instrument for Analysis
Wide-area hydrogen or water deposit detection	Epithermal to high-energy neutron ratio	Neutron
Water-ice detection (primary)	Molecular composition	Raman
Water-ice detection (redundant)	Elemental/ molecular composition (H, O, H_2O)	LIMS, LIBS
Origin of Hydrogen	Hydrogen isotope ratios	LIMS
Geologic survey	Elemental composition	LIBS, LIMS
Geologic survey	Molecular composition	Raman, LIMS
Terrain classification, broad surface process determination	Image analysis	APS

The science package outlined above provides the capability to[19]:

- conduct independent experiments for detecting water ice at and below the surface,
- determine isotopic ratios of hydrogen and oxygen,
- determine elemental and molecular compositions, returning subsurface samples to the surface if necessary for further investigation.
- provide wide-scale estimates of water coverage once presence is confirmed, and,
- produce high-resolution color images.

Mission Overview

Mission Timing

The Icebreaker rover will be landed on the lunar surface near peak seasonal sunlight to achieve the best possible initial conditions for the mission. Allowing sufficient time for program development, two opportunities exist early in the next decade (see Table 2).

Table 2: Near-Term Icebreaker Mission Opportunities

Opportunity 1	Opportunity 2
Sun up:	**Sun up:**
10/07/2003 - 05/24/2004	10/05/2004 – 05/23/2005
Earth up:	**Earth up:**
10/12/2003 - 10/26/2003	pre-sunup - 10/14/2004
11/09/2003 - 11/22/2003	10/28/2004 - 11/11/2004
12/06/2003 - 12/20/2003	11/24/2004 - 12/08/2004
01/02/2004 - 01/16/2004	12/21/2004 - 01/04/2005
01/29/2004 - 02/12/2004	01/17/2005 - 02/01/2005
02/26/2004 - 03/10/2004	02/13/2005 - 02/28/2005
03/24/2004 - 04/7/2004	03/13/2005 - 03/27/2005
04/20/2004 - 05/4/2004	04/09/2005 - 04/23/2005
05/17/2004 - post-sunset	05/06/2005 - 05/21/2005

Highlighted weeks feature sun elevation angles near peak.

In addition to solar power considerations, remote operation and data transfer dictate line-of-sight conditions to Earth. Each south pole sunny season contains eight Earth-up periods of roughly two weeks each. To ensure the best combination of solar power availability and Earth visibility, Icebreaker will land just before the peak of the sunny season, at the beginning of an Earth-rise. This places the Icebreaker lift-off in January of 2004 or 2005.

Site Selection

Ice may potentially exist at both the north and south poles. Digital elevation maps derived from Earth-based radar indicate that the south polar region contains a larger total area of permanent dark than the north[9]. This is in apparent conflict with Lunar Prospector data that indicates a higher concentration of hydrogen in the north[5]. Combined with the operationally advantageous sun conditions near crater Shackleton, along with the geologic interest in Aitken, Icebreaker proposes to target the lunar south pole.

For specific site selection, scientific goals must be matched to operational constraints, principally solar power availability and Earth communications line-of-sight. Craters are seen as having the largest probability of harboring water ice. However, for battery recharge, sunlight must be available somewhere in the crater interior. Additionally, the crater walls, which block direct solar incidence from the surface, tend to reduce the range of angles over which Earth communications is possible. Climbing the crater walls to permit recharge and communications would exceed the capability of the most agile rover. Consequently, landing within a crater is difficult operationally despite the potential for finding ice.

Within a few degrees of the poles, scientists predict that ice may occur abundantly outside of craters, in depressions and behind large positive surface features. Accessible via terrain less extreme than on crater rims, such areas are more operationally desirable and may hold ice with a probability on par with that for craters. Scientists have determined that the most illuminated area at the south pole is a massif on the rim of Shackleton crater (89.9°S, 0.0°E), which during the Clementine mission was seen to receive sunlight for more than 80% of the lunar day[3]. This massif is in close proximity to permanently shadowed regions both inside and outside the crater. Icebreaker will target this massif as a center of operations.

Launch, Transfer and Landing

A commercial expendable launch vehicle will propel the Icebreaker spacecraft into low-Earth orbit. A solid rocket motor upper stage will inject Icebreaker into trans-lunar orbit, a trajectory that will intercept the Moon roughly five days later. Once near the Moon, the lander and its rover payload will inject into a lunar polar orbit. Following several orbital revolutions, the lander will begin its descent to the lunar surface.

Guided automatically, the lander will target a pre-selected location. In the minutes just prior to touchdown, a lander-mounted camera will take a sequence of photographs of the intended landing site. The territory of each successive photograph will be contained within the field-of-view of the previous photograph, building a set of nested images with ever-increasing resolution. The descent imagery will be used later by Earth-bound operators to determine the final landing site location, and to compose an initial plan for rover operations. The targeted landing site will be an area lighted by the sun and in view of the Earth to permit solar power production and communications with the Earth. After touchdown, operators will work to drive the rover down the lander ramps to begin surface operations.

Surface Operations

Unlike previous rover-based surface missions, the Icebreaker rover will be designed to be independent of the lander after egress. Ignoring irregular terrain, the Moon's small radius places the lunar horizon at merely 2 km. To ensure a landing in sunlight despite possible landing errors, the lander may touch down several kilometers from a shadowed region, and even further from the permanent dark. Therefore, communications must extend directly between the rover to Earth.

Based on a combination of pre-mission planning, descent imagery, and initial rover imagery, the operations team will determine an initial course to seek water ice. Once the terminator between light and shadow is reached, the rover will recharge its batteries and then will drive into the dark. The collection of science data will proceed in three modes (see Table 3).

The priority to detect and characterize lunar water will dictate alternation between Exploration and Water Analysis modes. During drilling operations, geologic analysis mode may be conducted concurrently with water analysis using remote spectroscopy on nearby rocks, surface regolith, and sub-surface regolith.

The primary mission will last until the loss of Earth visibility approximately two weeks after landing. Prior to Earth-set, the rover will be driven to a point at high elevation receiving nearly continuous sunlight. The rover will be configured for warm hibernation, allowing it to endure direct sun for the two-week outage of Earth communications. After the outage, if the rover remains operational, the mission will continue for an extended operational period of at least two weeks.

Table 3: Science Analysis Modes of Operation

Analysis Mode	Purpose and Activities
Exploration	Long-distance traversals between sunlit and shadowed regions Coarse search for water ice using neutron spectrometer data Search for targets of opportunity
Water Analysis	Selection of drill site within coarsely identified potential water-ice deposit Multiple drilling and analysis cycles at the selected site
Geologic Analysis	Detection of interesting geologic features by visual inspection Spectroscopic analysis for elemental/molecular composition

Rover

General Description

Icebreaker features a rover, which will deliver a cryogenic drill and a science instrument, package to the permanent dark. The rover will be approximately 100 kg, with a footprint of 1 m by 1.5 m. The rover will be primarily teleoperated from Earth, but capable of limited autonomy for obstacle avoidance and for automated recovery in the event of communication loss. Unlike the rocky landscape of Mars as seen from Sojourner, the Moon's surface is suspected to be less cluttered, allowing faster, longer distance robotic excursions. The rover will be capable of driving for tens or hundreds of kilometers, at speeds up to 0.5 m/s (1.8 km/hr). Converted solar energy supplies power, and its thermal design will allow the rover to survive in direct sun as well as for long periods in the frigid cold of permanent dark. The body of the rover will contain the electronics and science instruments, and a mast, deployed once at the beginning of surface operations, will contain the sensors, cryogenic drill and communications electronics.

Guidance, Navigation & Control

The primary method of rover control and navigation will be Earth-based waypoint teleoperation. On-board obstacle avoidance, images, and local maps will aid the teleoperator. The local maps will be generated autonomously on Earth-based computers, using odometry and ground and horizon landmarks as reference points. While traveling in the dark, strobe lighting will be used to illuminate the landscape. The sensors used for navigation are as follows:

- Forward and aft IR laser light stripers with IR imagers locate obstacles and characterizing terrain.

- Forward and aft CMOS active pixel sensor (APS) cameras, 512 x 512 pixels, provide visual data in sun or shadow (in conjunction with strobe light). APS cameras eliminate the need for a frame-grabber, thereby reducing the complexity of image data collection. APS pixels are individually addressable and are far more robust to radiation than their CCD counterparts.

- Forward and aft contact sensors prevent further damage upon collision.

- A sun sensor determines heading in sunlight to optimize solar array pointing during battery recharging. It is also used indirectly to determine the direction of the Earth when the Earth sensor is saturated by sunlight.

- An infrared Earth sensor aids in pointing the communications antenna while in shadow.

- Gyros, accelerometers, wheel encoders and inclinometers estimate position and orientation.

Teleoperated Driving

Unlike the Sojourner rover on Mars, Icebreaker will be close enough to Earth to allow real-time operations with electrical, software and round-trip time-of-flight delays of less than 4 seconds. Consequently, human operators on Earth will control the Icebreaker rover. Icebreaker will traverse an unprecedented distance across the lunar surface, perhaps a total of 100 km. Driving such long distances will require a robot that can travel at least 0.3 to 0.5 m/s (1.1 to 1.8 km/hr). Icebreaker will employ STRIPE[8], a teleoperation technique developed at Carnegie Mellon for applications in which latency is present and communications bandwidth is limited.

The STRIPE teleoperation scheme allows an operator to select waypoints on a 2-D image retrieved from the robot's forward-looking camera. These waypoints are converted to points in 3-D, and are sent back to the robot as intermediate goals for driving. Field tests on Earth have shown this scheme allows accurate, high-speed, teleoperated driving under high network latency and with slow image update rates.

Autonomous Obstacle Avoidance

The Icebreaker science rover must incorporate some level of autonomy to enable high-level control for driving and to enhance its reliability. Though operators will select waypoints for driving, the rover will plan its path between points to achieve its goal. This involves autonomous local mapping, planning and updates in real time[18]. For the majority of situations, operators will be able to visually detect obstacles, which could disrupt driving, thereby selecting waypoints on a path to avoid them. However, with the understanding that an operator's sensory inputs are limited in teleoperation, Icebreaker incorporates forward- and aft-looking laser light striping sensors to enable the independent detection of obstacles. The SMARTY algorithm, developed at Carnegie Mellon, is run on an Earth-based computer to produce an obstacle map given data from laser stripers. This obstacle map is superimposed on the teleoperator's camera image to assist with obstacle detection. SMARTY will also make steering recommendations for an operator. As an additional safeguard, Icebreaker will incorporate a fully autonomous obstacle avoidance process. If an operator selects a path that takes the rover toward an obstacle, the rover will detect the potential collision and intercede to prevent it.

Autonomous Path Reversal

Driving progress will depend on direct line-of-sight communications with Earth. The Earth will always be at low elevation angles, increasing the likelihood of communications blockage by local terrain features. Depending on the distance of the terrain feature, from a boulder within meters, to a crater wall kilometers away, the communications signal will degrade at different rates. Operators will be able to detect gradual degradations in signal strength, and make adjustments accordingly. Rapid loss of communications will prevent an operator response. In such a case, the rover will first attempt communications via the low-gain antenna. If this is unsuccessful after a timeout of several minutes, the rover will begin an autonomous backtrack to the last position in which link communications could be verified. The RALPH algorithm[15] allows a vehicle to autonomously follow parallel features such as the wheel tracks created by the rover. This system has been tested for road following at high speeds, and could easily be adapted for lunar rover use.

Maps and Localization

One of the greatest challenges of robot navigation in new environments is localization. Creating accurate maps and accurately locating the robot within the map is still an active area of robotics research. Traditional approaches build maps based on sensor data and use odometry and/or nearby landmarks to localize the robot within the map.

Icebreaker would augment the standard approach with data from downward-looking imagery and from the Deep Space Network. The Mars 1998 lander design incorporated an imager, which recorded images at successively lower altitudes while on its final descent[10]. Such imagery could be employed in conjunction with estimates of bearing to topographic features found at the horizon from the robot's perspective, to localize the robot near the landing site.

Another scheme might use the ranging capabilities of DSN and the fixed position of the lander to accurately determine the position of the rover on the lunar surface.

Self-Monitoring

Icebreaker would incorporate autonomous self-monitoring functions, either on-board or as part of its ground support software. This functionality will aid operators in determining the cause of anomalistic behavior, and speed their response in fixing or compensating for root problems.

Suspension, Steering & Locomotion

The rover will have four wheels, each driven independently by a brushless DC motor. Each of the front wheels is independently steered. The rear pair of wheels sits on a parallel-link, rocking-axle suspension to keep the wheels oriented vertically relative to the rover body. The parallel link suspension maintains good wheel contact with the ground as the rover crosses obstacles, while providing a stiff connection between the body and ground for drilling. The steering will be Ackerman to enforce minimal wheel slip during turns. The suspension and steering design achieves good steering performance and high positioning accuracy, without sacrificing reliability by including additional actuators[1]. If an extremely tight turn is required, the robot can perform a skid-steer point turn. Initial calculations indicate that driving on flat lunar terrain at 0.3 m/s will require 9.5 Watts, while driving up a 25 degree slope will require 27 Watts.

Power

The rover incorporates a vertically-mounted solar array to optimize power collection at polar sun elevation angles. The rover is estimated to require approximately 80 Watts (on average), with a maximum of 160 Watts. In order to achieve these power levels, solar energy will be collected via a gallium arsenide solar array of approximately 1 m^2 area, with an efficiency of 19% expected. A 50% safety margin for a 9-hour sortie into permanent dark requires 1092 W-h of storage capacity, accomplished with 20 kg of silver-zinc batteries. Both the solar arrays and batteries will require adaptation to the extreme thermal environment in which the Icebreaker mission will operate. Solar cells and batteries can lose efficiency at high temperatures, and can be permanently damaged at thermal extremes and through cycling.

Sorties into the permanent dark require the use of battery power for long-distance driving, communications and sporadic drilling. The rover's dependence on solar power will force return trips to illuminated areas for battery recharge. On the other hand, the use of a Radioisotope Thermoelectric Generator (RTG) would alleviate the need for battery recharging, far increasing the capability of the rover. An RTG would enable the robot to spend months in a the permanent dark without the need for a special hibernation mode, further increasing the chances of finding ice and deriving detailed crater data. However, public opinion of the danger of such power sources may prevent Icebreaker from incorporating such a device.

Thermal

To date, no space system has been targeted for such a wide range of extreme temperatures as seen at the lunar poles. While in sunlight, the science rover will be subjected to direct solar radiation, requiring a means to reject heat to maintain thermal stability. The rover will regularly drive into regions of permanent dark, where surface temperatures are estimated to be as cold as 40 K. Traditional approaches for protecting components from low temperatures can prove fatal to the components in the sun and vice-versa. For such thermal extremes, the rover must be able to reconfigure itself to either trap heat within its core, or reject heat to space.

The rover thermal properties will be dominated by the deployment state of the solar panel (the array will be deployed to cool and charge, and stowed to conserve heat). Components of the rover must be organized within a "warm electronics box" (WEB) such that the effects of thermal production of each component can be modeled and passively controlled. The insulation of the components and surface reflectance properties must also be considered. The type of insulation chosen must be able to prevent each component from exceeding its temperature range in both extreme cold and extreme heat. To effectively eliminate the ground conduction path to the rover, its wheel design will incorporate fiberglass spokes.

Sources of additional heat, either electric or Radioisotope Heater Units (RHUs) will be required for surviving the coldest regions for extended periods. The current design positions RHUs in the wheels to heat wheel motors in the dark, as well as in strategic locations within the WEB and instrument mast. Should an isotope power source (RTG) be employed, it may also have the benefit of contributing to the solution of the thermal design.

An initial lumped parameter analysis indicates that, given the proposed solar panel deployment capability, the rover body steady state temperature can be maintained between 272 K and 292 K in shade and sun respectively. The instrument mast, far from the warmth of the body electronics, will vary between 188 K and 277 K.

Additional Environmental Hardening

Aside from equipping the rover for such a wide thermal range, the greatest challenges in the Icebreaker design will be protecting against radiation and dust. Without the protective cover of an atmosphere, the lunar surface receives a wide range of radiation from the sun and cosmos. All components must be hardened to withstand the constant bombardment by solar wind radiation, and software must be robust to occasional data errors from high-energy solar and cosmic radiation. Dust may also prove a difficult factor. Apollo astronauts found that the fine, electrostatically charged lunar dust readily accumulated on the surface of the Lunar Roving Vehicle and on spacesuits[7]. The activity of driving will likely raise dust particles which, without preventative measures, could adhere to the surfaces of the rover. Also, clouds of statically-charged lunar dust are theorized to levitate over 10 meters near the moon’s sunlight/shadow terminator. The rover, alternately searching permanently shadowed regions for water and recharging in the sun, must pass through and spend extended periods of time in the terminus region, which might be clouded. This dust may hamper the performance of solar arrays and optical sensors, and could significantly increase the rover’s tendency to absorb radiated thermal energy. Icebreaker will generally stow its solar array during driving operations to avoid undue dust accumulation, and will employ dust fenders on each of its wheels to minimize the amount of dust raised during periods of motion.

Communications

In order to achieve near real-time teleoperation as a primary control mode, the communication system must quickly transfer image data to Earth (210 kbits per image after 10x compression). The rover will require an additional communications link between itself and the lander for flight and post-landing check-out.

Using X-Band, an 11-cm medium gain antenna could provide the primary communications at high data rates and low power consumption (150 kbps at 14.9 Watts). An omnidirectional antenna will act as a backup for the medium gain antenna in case of pointing loss, and for initial acquisition procedures.

Icebreaker may alternatively incorporate “reflectarray” technology developed at NASA[12]. These small, lightweight antennas are electronically steered, improving overall pointing performance, reducing the number of actuators deployed with the system, and improving the communications bandwidth by decreasing the beam width required for robust data transfer.

Lander

The Icebreaker lander will carry the rover from liftoff to landing near the lunar south pole. Incorporating a bipropellant propulsion system, the lander will execute mid-course correction maneuvers, reorientations and spin changes during the coast from the Earth to the Moon, will inject into lunar orbit, and will take the rover safely to the surface of the Moon.

During coast, the lander will be flown in a three-axis stabilized mode. Absolute attitude determination will be performed using a star sensor, with attitude propagation accomplished with rate gyros in all three axes. Attitude control thrusters and reaction wheels will enable attitude control and stabilization. During final descent, the lander will make use of inertial measurement units and Doppler radar in a three-axis stabilized autonomous descent mode. The primary thruster will be sized to enable a hover prior to landing for final touchdown site selection. Long shadows expected from rocks and microcraters at the pole should be a sufficient aid in visually selecting a final resting place for the lander and its cargo. The lander has its own solar panels, secondary batteries and an independent low-gain communications system for on-orbit and post-landing operations.

Launch

The Boeing Delta II[2] is the primary launch vehicle option for Icebreaker, though other vehicles in the same class are also under consideration. The Delta II is a medium capacity expendable launch vehicle derived from the Delta family of rockets built and launched since 1960. Since then there have been 260 Delta launches. Given the payload mass to the lunar surface and the required plane change for insertion into lunar polar orbit, Icebreaker would likely use the Delta II 7925 configuration. The 7925 incorporates nine graphite epoxy solid rocket strap-ons for liftoff and the Thiokol STAR 48B as a third stage for trans-lunar orbit injection. The Delta II has the highest reliability record of any Western launch vehicle.

Ground Communications Network

The NASA Deep Space Network (DSN) has been selected as the baseline ground antenna system for the Icebreaker mission. Its three primary facilities at Goldstone, California, Canberra, Australia, and Madrid, Spain are distributed around the globe for nearly full space coverage at lunar distances. Each DSN site consists of a collection of antennas, 9, 26, 34 and 70 meters in diameter: the smallest, fastest slewing antennas are optimally used for low-Earth orbit applications, and the largest antennas for deep-space communications or high data rate applications. The operators are the most experienced space mission operators in the world, having supported every NASA deep space mission flown.

Initial link budget calculations indicate that the 34-meter antennas are appropriate for the lunar surface mission baseline[11]. These antennas produce the signal strength required to receive medium and low data rate transmissions from the lunar surface and from orbit. The Icebreaker mission baselines the DSN 34-meter antennas due to their wider availability than 70-meter antennas. The mission includes some particularly critical events that may require the extra data transmission potential and signal margin from the 70-meter dishes, such as lander vehicle descent and initial rover excursion into shadowed regions. In addition, the DSN 70-meter dishes may be requested during anomalous situations requiring high signal strength to establish communications or for high data-rate imagery downlink.

In addition to communications services, the DSN provides a highly accurate ranging capability. Measurements taken by DSN antennas include spacecraft line-of-sight range rate, line-of-sight range, and azimuth and elevation. Once enough data has been gathered, estimates of lunar transfer orbit accurate to the level of centimeters and centimeters per second are possible. Also, lander and rover position on the Moon may be estimated within several hundred meters after many hours of ranging.

Carnegie Mellon University Robotics

The Carnegie Mellon University Robotics Institute has a strong basis in developing robotics technology for harsh environments, long life and long distance traverses, resource extraction, and site preparation for construction. Robotic systems such as Dante I and II, Nomad, and Pioneer have been designed for the hazardous environments of volcanoes, Antarctica as preparation for the moon, and the Chernobyl clean-up, respectively. Demonstrating long-distance traverses and long-life systems is an ongoing focus of the Nomad program, in addition to demonstrating automated scientific exploration by identifying and classifying Antarctic meteorites. Coal mining machines, earth digging machines, earth-moving vehicles, and agricultural machines have also been automated.

Programmatics

Icebreaker will be proposed as a NASA Discovery mission. Discovery program missions must, above all, have a solid scientific objective and a reliable plan for meeting the objectives. Therefore, the formation of the Icebreaker team must emphasize the search for a strong scientific membership, including Principal Investigator, one or more Co-Investigators, instrument developers, and data analysts, archivists and publishers.

The current Icebreaker team membership includes LunaCorp, a company devoted to the prospect of lunar exploration and commercial development, and Carnegie Mellon University.

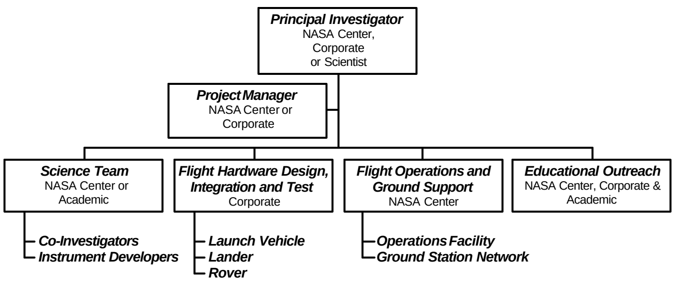

Figure 1 : Proposed Icebreaker Team Structure

The principal Icebreaker programmatic goal is to establish a multi-element team comprising a NASA center partner, a primary corporate aerospace partner, and a dedicated team of scientists representing both the lunar science and human exploration communities. Primary roles to be filled are:

- Science leadership,
- Science instrument development,
- Program management,
- Lander development,
- Launch vehicle supply and integration,
- Spacecraft and rover fabrication, integration and test,
- Operations facilities and support, and
- Education and outreach

Conclusions

The Moon is of interest to many different parties including lunar and planetary scientists, developers of systems for human space exploration and colonization, commercial pioneers of space, and the general public. A discovery of water on the lunar poles would reinvigorate lunar settlement discussion and action, as well as solidify the notion of the moon as a target for space enterprise. Given its proximity to Earth, the moon is an ideal place to practice techniques and test technologies for human life on extra-terrestrial bodies, as well as a place for settlement in its own right.

Icebreaker may become the first mobile surface system deployed for space exploration designed and built by a university laboratory, showing that successful space systems can be produced in small commercial and academic settings. With funding coming from multiple sources including NASA Space Science (Code S), Human Exploration (Code M), and companies devoted to space industry and education, Icebreaker could demonstrate how fruitful research and discovery can be accomplished while simultaneously promoting space enterprise.

Icebreaker will use newly developed technologies for its task. Icebreaker will utilize burgeoning technologies developed under NASA research and transferred to the commercial and academic sectors to overcome the numerous difficulties in surviving on and exploring the lunar south pole.

References

1. D. Apostolopoulos. “Systematic Configuration of Robotic Locomotion.” Carnegie Mellon University Robotics Institute Technical Report CMU-RI-96-30, 1996.
2. The Boeing Company. “Delta II Payload Planners Guide.” Copyright 1996.
3. D. B. J. Bussey, M. S. Robinson, P. D. Spudis. “Illumination Conditions at the Lunar Poles,” in Lunar and Planetary Science XXX, abstract #1731, Houston, TX, March 1999.
4. J. R. Arnold. “Ice at the Lunar Poles.” Journal of Geophysical Research, 84:5659, 1979.
5. W. C. Feldman, S. Maurice, A. B. Binder, B. L. Barraclough, R. C. Elphic, D. J. Lawrence. “Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles.” Science, September 1998.
6. J. J. Gillis, L. A. Haskin, R. L. Korotev, M. A. Wieczorek. “Major Lunar Crustal Terranes: Surface Expressions and Crust-Mantle Origins,” in Lunar and Planetary Science XXX, abstract #1670, Houston, TX March 1999.
7. G. H. Heiken, D. T. Vaniman, B. M. French, eds. “Lunar Sourcebook: a user’s guide to the moon.” Cambridge University Press, 1991.
8. J. Kay. “STRIPE: Remote Driving Using Limited Image Data.” Ph.D. Thesis, Carnegie Mellon University School of Computer Science, January 1997.
9. J. L. Margot, R. F. Jurgens, M. A. Slade. “Locations of Cold Traps and Possible Ice Deposits Near the Lunar Poles: A Survey Based on Radar Topographic Mapping,” in Lunar and Planetary Science XXX, abstract #1897, Lunar and Planetary Institute, Houston, TX, March 1999.
10. L. Matthies, C. Olson, G. Tharp, S. Laubach. "Visual Localization Methods For Mars Rovers Using Lander, Rover, And Descent Imagery." International Symposium on Artificial Intelligence,

Robotics, and Automation in Space (i-SAIRAS), Tokyo, Japan, July 1997.

11. NASA. "DSN Telecommunications Interfaces: 34-meter Beam Waveguide Antennas." DSN Document 810-5, Module TCI-31.

12. NASA Lewis Research Center website http://ctd.lerc.nasa.gov/5640/reflectCON.html

13. S. Nozette, C. L. Lichtenberg, P. Spudis, R. Bonner, W. Ort, E. Malaret, M. Robinson, and E. Shoemaker. "The Clementine Bistatic Radar Experiment." Science, 274:1495–1498, November 1996.

14. C. A. Peterson, B. R. Hawke, P. G. Lucey, G. J. Taylor, D. T. Blewett, P. D. Spudis. "Remote Sensing Studies of Highland Units on the Lunar Farside," in Lunar and Planetary Science XXX, abstract #1624, Houston, TX, March 1999.

15. D. Pomerleau. "RALPH: Rapidly Adapting Lateral Position Handler." IEEE Symposium on Intelligent Vehicles, Detroit, MI, September 25-26 1995.

16. R. A. Simpson. "Clementine Bistatic Radar: Reanalysis." American Astronomical Society/ Division of Planetary Sciences Meeting, 30:5203+, September 1998.

17. N. J. S. Stacy, D. B. Campbell, P. G. Ford. "Arecibo Radar Mapping of the Lunar Poles: A Search for Ice Deposits." Science, June 1997.

18. A. Stentz. "The Focused D* Algorithm for Real-Time Replanning." IJCAI, 1995.

19. A. Stroupe. "Icebreaker Scientific Package: A Proposed Scientific Instrument Suite for a Lunar Polar Mission." Carnegie Mellon University Robotics Institute Technical Report CMU-RI -TR-99-28, September 1999.

20. K. Watson, B. C. Murray, and H. Brown. "The Behavior of Volatiles on the Lunar Surface." Journal of Geophysical Research, 66:3033, September 1961.