# A Concept for Robotic Lunar South Pole Exploration

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## Abstract

The lunar south pole region may contain frozen volatiles such as water and carbon dioxide in surface depressions which are permanently dark. The low Sun angles of the region create these permanently dark areas and also provide nearby regions of long term sunlight and moderate temperatures which benefit robotic exploration. In this paper a concept for a robotic explorer named Icebreaker is presented. It is designed to take advantage of the south pole environment and to find and analyze frozen volatiles. Icebreaker is an innovative new spacecraft concept which combines the functionality of traditional landing craft and mobile robots into one integrated vehicle. This type of vehicle will allow larger science packages to be delivered to the planets. Icebreaker will acquire samples with a drill and determine the presence and composition of volatiles inside cold traps using a Regolith Evolved Gas Analyzer (REGA).

## 1. Introduction

The south pole region of the Moon provides a unique environment for robotic exploration exhibiting persistent light, opportunities for Earth communication, and most significantly the possibility of valuable frozen volatiles. Water and other volatiles may be found frozen in this area and a robotic exploration provides the ideal platform to find and analyze them. The discovery of ice would reveal a resource on the Moon which could be used for fuel, oxygen, and water. Stratigraphy in the ice deposits might provide scientists with an insight into the history of the Moon and solar system. Furthermore, the region offers many advantages for mobile robot exploration. Up to six months of continuous sunlight could power solar cells and moderate temperatures.

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This paper presents a concept for Icebreaker, a mobile robot explorer designed to exploit the unusual conditions of the lunar south pole. Icebreaker's objective is to locate and determine the composition of volatile deposits and determine if these deposits exist in stratigraphic layers.

## 2. The Presence of Ice

Is there ice on the south pole of the Moon? It has long been postulated that frozen water could be deposited on the lunar surface by comet or meteorite impacts [Arnold]. Water molecules could be trapped in extremely cold regions of permanent darkness [Arnold]. Successive deposits may build up in layers, leaving an historical record in the stratigraphy of composition. Data from the 1994 Clementine lunar orbital mission supports this theory with observations made in a bistatic radar experiment which are consistent with the presence of water ice near the south pole [Nozette et al.]. Initial estimates suggest that about one billion cubic meters of ice may exist. Observations made from the radio observatory at Arecibo, however, indicate that some of those water-like radar signatures originate from places where water cannot exist because solar radiation would sublimate any ice [Stacy et al.]. A surface mission to sample and analyze regolith composition *in-situ* would definitively verify the existence of ice.

## 3. Lunar South Pole Environment

The south pole exhibits regions of seasonal lighting favorable for robotic operations next to regions of permanent darkness which may contain frozen volatiles. Low Sun angles create the possibility that even shallow surface depressions have been lit for millennia only by the light of distant stars or, in some cases, sunlight reflected by Earth.

The Moon's axis of rotation is tilted $1.5^{o}$ with respect to the ecliptic plane. As seen from the poles of the Moon, the Sun remains visible for 6 months at a time, reaching a maximum elevation of $1.5^{o}$ above the nominal horizon. For the other 6 months of the year, the Sun remains below the horizon, reaching a maximum declination of $1.5^{o}$ [Deans et al.].

Incident sunlight strikes the surface at the poles at a grazing angle and the elevation varies very slowly. The result is a more temporally consistent surface temperature than that found in equatorial regions, with an expected range of about 225 K to 245 K in most areas [Watson et al.].

The temperature in permanently shadowed areas remains as low as 24 K, creating areas called *cold traps* [Spudis]. Because the maximum elevation angle of the Sun can be calculated, the topography necessary to produce a cold trap can be determined. Figure 1 shows the geometry of a cold trap. The arrows indicate the minimum elevation angle required for incident light to reach the crater's interior. Light incident from elevations below this angle will never strike the bottom of the crater. Ice deposits occurring in these cold traps would probably never sublimate.

It is not known whether the indentations which would provide the necessary geometry for a cold trap exist, since detailed topographic maps are not available for the lunar polar regions. However, the south pole is a lunar highland area, similar to the region in which Apollo 16 landed [Duke]. Statistics for this type of terrain have been compiled, such as the distribution of craters of various sizes and the typical ratios of depth to width for those craters. For simple craters of 15 km radius or less, common in highland terrain, the depth to width ratio is about 0.2 [Heiken et al.]. For these craters, sunlight would have to hit the surface at an angle of 11.3 degrees or greater in order to reach the bottom of the crater, much greater than the incident sunlight angle at polar latitudes.

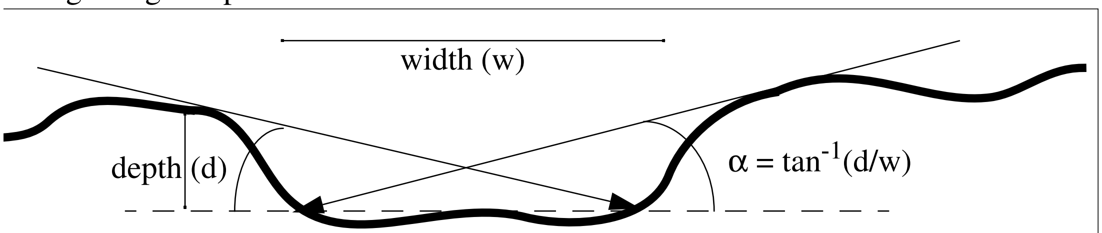


Figure 1. Geometry of a cold trap

Perhaps the largest single terrain feature on the lunar surface, the Aitken Basin provides the major topological difference between the north and south poles of the Moon. The Aitken Basin is an ancient impact crater 2,500 km in diameter and up to 12 km deep in places. Because of this feature, it is expected that more of the south pole region is shadowed from the Sun than near the north pole.

Aside from statistical models of terrain morphology and the presence of the Aitken Basin, there is direct visual evidence for the presence of permanent darkness from the imagery acquired by Clementine. While in a polar orbit, Clementine returned imagery throughout several lunar rotations showing regions which never appear to reflect sunlight. One study of this data resulted in an estimated area of 15,500 $km^2$ of permanent shadow near the south pole [Spudis].

For an observer at the lunar south pole, the Earth rises to a maximum elevation of around $7^o$ above the horizon and falls to $7^o$ below. This cycle repeats every 27.3 days [Deans et al.]. Since the Moon's rate of rotation and rate of revolution around Earth are the same, the Earth does not move appreciably in azimuth. The difference in maximum Sun and Earth elevation indicates that there may exist permanently shadowed areas from which Earth is visible for part of every month, meaning Icebreaker can operate in regions with potential for ice while providing direct line-of-sight communication.

## 4. Robot Design

Icebreaker must be capable of traversing long distances, on the order of tens of kilometers, to investigate several candidate cold traps. The design of Icebreaker is driven by the need for substantial terrainability and sustained operations in the dark shadows. Icebreaker has a 1.5 m x 1.5 m footprint and a mass of 280 kg. An artist's conception of Icebreaker is shown in Figure 2.

Figure 2. Icebreaker

### 4.1 Launch/Landing

A Delta II 7925H rocket using a 2.9 m payload fairing has been chosen as the launch vehicle. The spacecraft will approach the Moon on a direct trajectory. Initial deceleration would be performed by a Thiokol STAR 37XFP solid rocket motor.

Final deceleration uses twelve 37 lbf throttleable hydrazine thrusters mounted directly to the body of Icebreaker. These thrusters are designed to point downwards and provide control over yaw and pitch as well as vertical velocity. Spin can be removed by twelve 5 lbf hydrazine thrusters mounted perpendicularly to the main thrusters.

Several sensors are used to provide Icebreaker with position and velocity information during the final deceleration. A four beam radar will determine the altitude using time of flight and velocity using Doppler shift. NASA's Deep Space Network will provide crosstrack information. These two sensors will be augmented with an inertial measurement unit to provide position and velocity information. A CCD camera will enable hazard detection and a means for visually servoing to the desired landing spot. These sensors allow Icebreaker to land on a smooth, flat area with little or no residual velocity, eliminating the need for large shock absorbing structures.

With the final deceleration propulsion and landing sensors integrated into the rover body, Icebreaker is a new class of vehicle--the combined lander rover. The benefits of this class of vehicle are reduced volume and cost. By eliminating the duplication of power, computing and structure of a robot and a landing craft the science payload can be increased. In a long range mission a separate landing craft would have very little utility as a base station or relay after landing since visibility between the lander and rover cannot be guaranteed.

### 4.2 Locomotion

Icebreaker is a four wheeled, all wheel drive robot with drive motors mounted inside the wheels to conserve space. The front wheels are Ackerman steered while the rear wheels are connected to the chassis through a transverse bogie mechanism so that all four wheels retain contact with the surface even in the expected rough terrain.

### 4.3 Communications

Icebreaker features primary and backup S-band transponders for communication with Earth using the Deep Space Network. An antenna array, consisting of a low gain omnidirectional antenna and a switched array of six limited aperture, high gain antennae are mounted at the top of a mast in the center of the vehicle. The high gain antennae have overlapping horizontal fields of view; each antenna axis points $60^o$ away from its neighbors' in azimuth, with a $70^o$ beam width yielding a $10^o$ overlap. Vertical coverage is ensured by pointing the antennae axes at $0^o$ elevation with a $40^o$ beam width, which covers the range of elevation angles expected for the Earth on the lunar horizon and the range of pitch and roll angles expected for the terrain. An RF assembly provides all necessary functionality between the transponder and antenna array, performing such tasks as sampling the high gain antennae and switching the signal path to the one with the strongest reception. Telemetry data is compressed and transmitted at 10 kbps, with a Reed-Solomon block code and a r = 1/6 convolutional code for error correction.

### 4.4 Power

Electrical power for operation is provided by 48 kg of AgZn rechargeable batteries. This mass represents about 7 kWh of energy, or enough for an estimated thirty hours of operation in complete darkness. Electrical power for recharging secondary batteries is provided by GaAs solar cells. Two 1.5 $m^2$ fixed flat panels are mounted vertically on the top of the chassis, so that the normal to the cell surface is on the horizon. For flat terrain, no articulation is necessary in the vertical direction, since the sunlight incidence angle varies by only about $1.5^o$ from the horizon. Horizontal articulation has been excluded since it presents severe form factor constraints on several other components and introduces a reliability concern. This means that Icebreaker will at times be required to operate using only battery power even when in direct sunlight, and that the entire vehicle will have to be oriented so that the solar panels face the Sun when recharging becomes necessary.

### 4.5 Navigation

Icebreaker's primary mode of operation will be a hybrid teleoperation/ autonomous control scheme where the human operator on Earth specifies a series of waypoints [Wilcox et. al.]. The waypoints are chosen from a binocular viewpoint given by a stereo pair of monochrome, 640x480 pixel CCD cameras. Each compressed image takes approximately 25 sec to transmit to Earth through the high gain antenna. Due to the large communication delay, Icebreaker will travel to each waypoint autonomously. A scanning millimeter wave radar unit is used to collect the information to create a depth map of the environment. From the depth map, slopes exceeding $20^o$, boulders larger than 20 cm diameter, and other potential obstacles can be avoided. The radar unit has a frequency of 94 GHz and uses a single $3^o$ beam that scans across an $80^o$ field of view in front of Icebreaker.

A panospheric camera is used to provide a wide field of view image to the operator. It is composed of a single camera pointed up at a spherical mirror [Whittaker et al.]. The panospheric camera returns a field of view of $360^o$ in azimuth and $90^o$ below to $30^o$ above the horizon in elevation. This image can determine if Icebreaker is in a cold trap by measuring the elevation angle of all points on the horizon and comparing them to the maximum expected Sun elevation angle at that location. Human teleoperation also benefits from the wide field of view.

Icebreaker must be able to determine its position both globally and locally. Global position is determined using a star tracking camera. The startracker camera provides a position reference for the rover, to an accuracy of 100 to 700 meters, by comparison of the star field with an on-board star map. Local position estimation will be accomplished through dead reckoning using an inertial measurement unit and shaft encoders on the drive motors. The inertial measurement unit uses a three axis fiber optic gyroscope and a three axis silicon accelerometer.

### 4.6 Sample Acquisition and Analysis

Once Icebreaker has entered a cold trap sampling is accomplished by using a drill which is composed of two concentric rotating bits. The inner bit has a custom drill tip to chisel material. When the drill reaches the desired depth the outer housing stops rotating. The inner bit penetrates the material, opening an annulus between the housing and the drill stem. Material is chiseled into fragments and accumulated in the space between the drill stem and the housing. The inner bit is then retracted, sealing the sample between the inner and outer augers. The two part stem is then retracted and the sample is transported to an onboard Regolith Evolved Gas Analyzer (REGA) for analysis.

## 5. Conclusion

The south pole of the Moon represents an ideal location for robotic exploration of space. Opportunities for Earth communications coincide with regions of long duration light and moderate temperatures, caused by low Sun angles, facilitating robot operations. These same low Sun angles create the cold traps with their potential bounty of frozen volatiles.

Icebreaker is a hybrid vehicle serving as both a lander and rover, combining mass, power, and size budgets for what is traditionally thought of as a two-component payload in order to deliver a larger science package to the surface and increase the total science return. Icebreaker incorporates a sensor suite tailored for several modes of operation, including autonomous landing, teleoperated waypoint navigation, autonomous hazard detection, and sample analysis, along with the mechanical configuration which allows traversal of large distances on expected lunar terrains and the ability to acquire regolith samples. Icebreaker could allow scientists to validate the presence of ice and determine a stratigraphic record of ice found.

The impact of such a discovery would be far-reaching, having implications on what is possible or affordable in terms of the exploration and development of our Moon, solar system and the far reaches of space by humans in the near to distant future.

## 6. Acknowledgments

The observations, technologies, and analyses of this paper have been excerpted from the technical report: "Icebreaker: A Lunar South Pole Exploring Robot". The design of Icebreaker was the result of a robotics course offered by Carnegie Mellon University. The authors would like to recognize and thank N. Keith Lay, Gregory A. Fries, Alex D. Foessel and Diana LaBelle who also participated in the class and contributed many of the ideas presented in this paper. Special thanks to Dr. Michael Duke of Lunar Planetary Institute and Gordon Woodcock.

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