ICEBREAKER SCIENTIFIC PACKAGE: A PROPOSED SCIENTIFIC INSTRUMENT SUITE FOR A LUNAR POLAR MISSION

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CMU-RI -TR-99-28

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September 1999

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Acknowledgements

This work was prepared with the aid of Paul Tompkins and Trey Smith.

Information was provided by the following:

Dr. Jim Arnold, University of California at San Diego
Dr. William Boynton and Dr. Ralph Lorenz, University of Arizona at Tucson
Stephen Gorevan, Chunlei Jerri Ji, and Shaheed Rafeek, Honeybee Robotics
Dr. Bruce Hapke, University of Pittsburgh
Dr. Paul Mahaffy, Goddard Space Flight Center
Dr. Steve Squyres, Cornell University
Dr. Thomas Wdowiak, University of Alabama at Birmingham
Dr. Roger Wiens, Los Alamos National Laboratory

Icebreaker Scientific Package

Introduction

The Icebreaker mission proposes to conduct a robotic ground investigation of the moon's southern polar region. Icebreaker's primary goal is to determine whether or not water ice exists in the shadowed regions near the lunar pole. Icebreaker would determine the nature of the hydrogen detected near the lunar poles. Supplementary goals of the mission are to gather geological data, to conduct exploratory traversals of the surrounding terrain, to measure the prospects for long-term human presence at the poles, and to gather imagery for public enjoyment.

Searching for water ice and performing geological studies of the lunar south pole will provide essential information on the presence and distribution of resources necessary to support human habitation on the moon and a lunar base for deep-space missions as well as for fundamental scientific investigation.

Figure 1. Icebreaker rover and lander in lunar orbit, artist's conception. *Mark Maxwell*

Mission Science

Scientific Issues

Water Ice or Elemental Hydrogen

Scientists have theorized the presence of water ice at the lunar poles for decades. Bistatic radar measurements taken by the Clementine spacecraft yielded inconclusive results regarding the presence of water ice[6,8]. 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, pointing strongly to large deposits of ice. This signature is particularly strong near the north pole and in the Aitken Basin region of the south pole[2,11].

The source of this hydrogen has been much in debate by lunar scientists; comets, solar wind and lunar interior degassing have all been proposed. A leading theory suggests water from cometary impacts could slowly collect in the low-energy environment of the permanently shadowed regions at the poles, leaving deposits of ice at or near the surface. Another possibility is the reduction of iron oxide (FeO) by solar wind hydrogen. The dominant theory refuting the presence of water ice suggests the source is elemental hydrogen due to accumulation of solar wind particles. Models of the rate of atomic hydrogen dissipation and solar wind have brought more weight behind the belief that water ice can be found in abundance in this region[1,2,10].

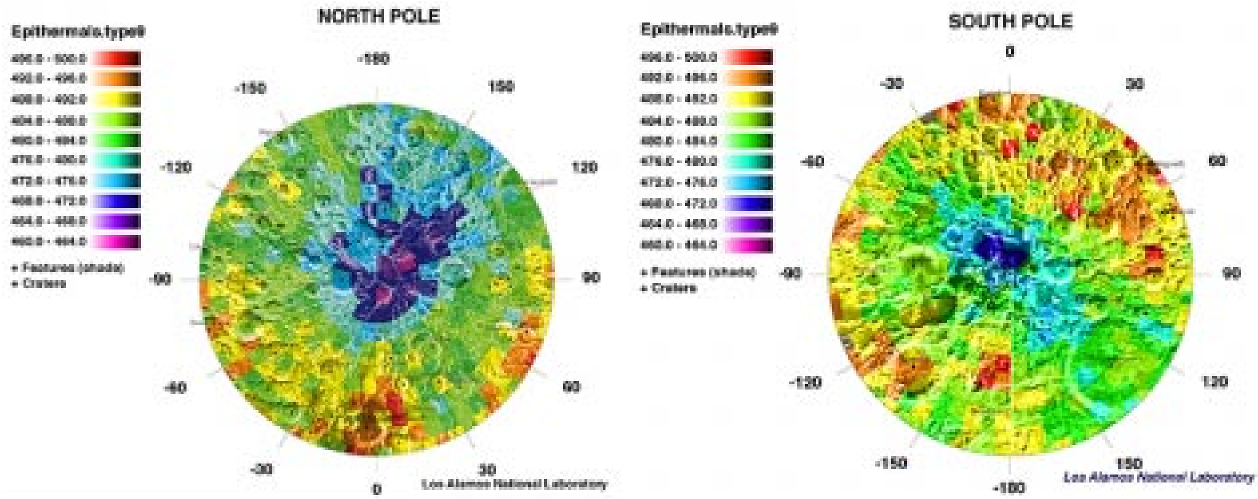


Figure 2. Lunar Prospector neutron spectrometer data, north and south poles. Dark regions indicate regions with high hydrogen concentration. *Lunar Prospector Project, NASA Ames*

Should water ice be responsible for the polar hydrogen signal, discovering its distribution throughout the permanent dark, its near-surface stratigraphy beneath the lunar regolith, and its isotopic composition would provide insight into the source, mechanism of accumulation, and abundance of the water resource. High concentrations of deuterium would be indicative of a cometary source, while low concentrations would point to an alternate mechanism. Relative concentrations of oxygen isotopes (oxygen-16 and oxygen-18) will also be of interest for determining the source of any water. The water ice may be intermixed with regolith or in nearly pure sheets[1,10].

Should elemental hydrogen, and not water, be responsible for the signal, hydrogen distribution and concentration data could support the hypothesis of solar wind accumulation, comets, or an alternative as its source.

Polar Geology and Topography

All previous surface lunar missions, manned and unmanned, have focused on equatorial at mid-latitude regions. Exploration has been done in the relatively smooth terrain of the mare; no surface-based data have been collected in the rugged highlands or crater interiors. These distinctive types of terrain dominate the polar regions of the moon, particularly the south pole. Orbital and earth-based radar studies provide only low-resolution topographical maps.

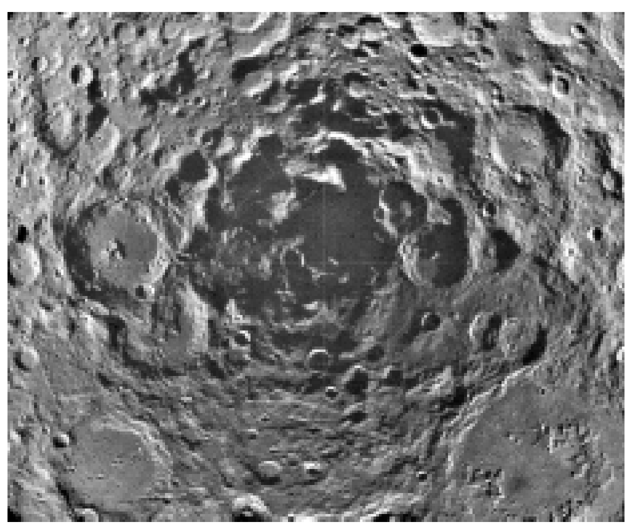


Figure 3. Clementine image of lunar south pole. *Ice on the Moon, National Space Science Data Center*

The South Pole Aitken Basin, the largest known impact crater in the solar system at 2600 km across, is one of the most actively researched for lunar geology. The Aitken Basin was formed early in the moon's history[3,7]. The Aitken Basin is shown in Figures 3 and 4 as dark regions near the south pole on the radar and topographic maps.

Though primarily a lunar far-side feature, the basin encompasses the south pole and territory to a few

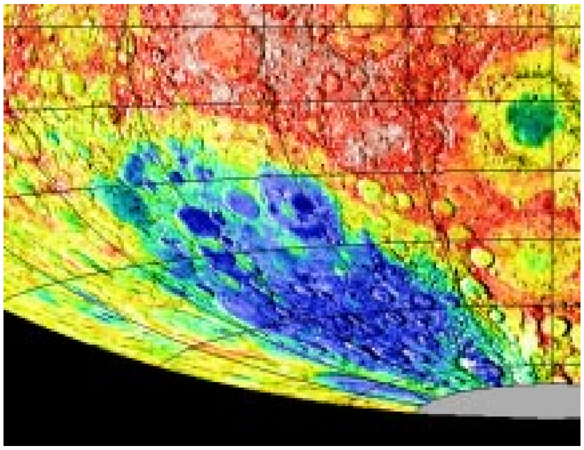


Figure 4. Aitken Basin topological map. *Ice on the Moon, National Space Science Data Center*

degrees north of the pole on the near-side. Aitken is believed by scientists to include exposures of material from the upper mantle, which has not yet been characterized in detail. Clementine and Lunar Prospector data have promoted scientists to identify the South Pole Aitken Basin region as representing one of three distinct lunar crust terrane classes (SPA). The SPA terrane class is significantly higher in iron oxide than the other classes and, despite the theorized mantle exposure, seemingly lacking the thorium seen in volcanic exposures elsewhere[3]. A geological survey of the Aitken Basin region could simultaneously provide insight into large crater formation and evolution, complex crater terrain, lunar mantle composition, and the geology of an area possibly representative of a significant portion of the lunar far side.

Icebreaker data may allow scientists to derive the location and quantity of minerals and metals for future mining and space construction operations. The availability of such materials is essential for the establishment of permanent robotic or human facilities on the moon.

Scientific Goals

The immediate scientific goals of the Icebreaker mission are:

- Verify the presence of water ice on the moon and determine its isotopic composition.
- Characterize the geological composition of the south lunar polar region.
- Collect high-resolution topographical data and color imagery.

As a result of the Icebreaker mission, it should be possible to:

- Estimate the distribution and quantity of water ice, if present, for resource utilization.
- Determine the source of the water or hydrogen for insight into solar system evolution.
- Estimate the distribution and quantity of mineral and other deposits, including lunar mantle, for geological insight and resource utilization.
- Generate high-resolution terrain maps of areas visited or examined by the rover for use in future missions, potential base site selection, and for modeling formation, evolution, and terrain of large, complex craters.

Proposed Scientific Experiments

In order to achieve the scientific goals of the Icebreaker mission, several scientific experiments are required. In addition, some experiments may be performed opportunistically to provide additional useful information.

Water Detection and Characterization

Careful analysis of the Lunar Prospector data indicates that if present, the regolith layers containing water ice reach within 0.05 to 0.40 meter of the surface[1]. A shallow layer of dry regolith covers the ice-bearing layers and must therefore be removed or penetrated in order to detect the water.

An experiment that can be conducted on the surface, at long range, and while the rover is moving is desirable for selecting sites worthy of further investigation. Hydrogen, the indicator of interest, will be sought in this manner. Sites that prove to have large hydrogen signals, like those detected by Lunar Prospector, will be targeted for in-depth analysis.

Once a site is selected for analysis, regolith will be gradually penetrated in order to expose potentially ice-bearing layers. At several depths, the regolith will be analyzed for hydrogen, deuterium, oxygen isotopes, and water content.

If ice is identified, a surface survey can be used to estimate the concentration and extent of water deposits without resorting to exhaustive sub-surface investigation. The distribution, concentration, and accessibility of any identified water deposits will be catalogued to prepare for in-situ resource utilization.

Molecular Analysis

Icebreaker will conduct molecular analysis of rocks and areas identified as surface exposures of lunar mantle material will be analyzed for mineral and molecular content. Additionally, Regolith samples from various depths will be also be analyzed for mineral content to provide depth-profiles of near-surface geology.

Geological studies conducted on the moon have revealed that the predominant minerals present on the moon include: pyroxene, plagioclase, glass, ilmenite, olivine, and silica (in order of abundance). A material named KREEP (containing potassium, rare earth elements and potassium) high in thorium content is also identified, and believed to originate in the lower crust[6]. Identifying the concentrations of these minerals should be a primary focus[25,28,30].

Elemental Analysis

Icebreaker will conduct elemental analysis of regolith and rocks. The major elements of interest include: aluminum, calcium, magnesium, hydrogen, iron, oxygen, potassium, silicon, thorium, and titanium[6,25,28,30]. As in molecular analysis, rocks, lunar mantle and regolith samples from various depths will be similarly analyzed, additionally focusing on hydrogen content. Particularly in the absence of water, the hydrogen content and concentration will be measured. Isotopes of hydrogen and oxygen (as previously mentioned) will also be measured.

Lunar Regolith Depth and Breadth Profiles

In addition to determining the depth and breadth of the water-bearing layers using the hydrogen signature and the localized depth profiles, it is desired to determine deeper depth profiles as well as broad horizontal profiles of the lunar regolith and rock layers. Experiments will be conducted with radar to sense the varying densities of different layers as the rover drives.

High-Resolution Terrain Maps

Using the Icebreaker navigational sensors (obstacle detection and cameras), local high-resolution terrain maps will be generated. These maps will be used not only in navigation but also in characterizing the lunar polar landscape, evaluating potential travel routes, and to search for potential outpost and landing site locations. The modeled terrain can also be used to generate sun and shadow profiles: these profiles can be used to help predict where ice may be found, to locate places suitable for power generation, and to consider sunlight availability for base construction.

If available, long-distance sensors will be used to augment these terrain maps to a broader area around the rover. In this case, the operator may direct the rover to particular vantage points to obtain more complete maps of the area.

Science Instruments

Primary Instruments

The scientific instruments recommended for the Icebreaker mission focus on the ability to identify water as well as other geologically important elements in the lunar regolith. Aspects considered include level of flight-readiness, capabilities and versatility, ability to integrate with a rover platform (mass, power, etc.), and redesign effort required.

A summary of the instruments considered is tabulated below, with a primary focus on capabilities and readiness for use on the Icebreaker mission. Readiness represents the maturity of the technology (not the particular instrument). Redesign indicates the amount of redesign that would be required to make current instruments using the technology ready for use on the Icebreaker rover. The capabilities listed, water detection, elemental geology, and molecular geology indicate if the technology is capable of directly or indirectly performing the analysis or if it is incapable of the analysis.

Table 1. Instrument Readiness and Capability Summary

Type	Readiness	Redesign	Water Detection	Isotope Resolution	Elemental Geology	Molecular Geology	Imaging
Raman	Near	Low	Direct	No	Indirect	Direct	No
LIMS	Near	Low	Direct	Direct	Direct	Direct	No
LIBS	Middle	Low	Indirect	No	Direct	Indirect	No
APXS	Flight	Low	No	No	Direct	Indirect	No
TDL	Flight	High	Direct	Direct	No	No	No
Mass	Flight	Middle	Indirect	Direct	Indirect	Indirect	No
Neutron	Flight	Middle	Indirect	No	No	No	No
GPR	Near	Low	No	No	No	No	Stratigraphy
Laser	Middle	High	No	No	No	No	Topography
APS	Near	Middle	No	No	No	No	Color
CCD	Flight	Low	No	No	No	No	Color

Raman Spectrometer

Provider

Raman spectroscopy is being investigated at the Physics Department of the University of Alabama at Birmingham for the Mars Athena packages in 2001, 2003, and 2005. Dr. Thomas J. Wdowiak is a principal scientist in this research, and is a co-investigator of the Mars Athena package. Dr. Wdowiak has indicated interest in working with CMU on this venture, pending resolving any conflict of interest issues[31].

Description

A laser light source is aimed at a target material. As the light falls incident on molecules, the characteristic energies of the molecular vibrations causes the light to be scattered and shifted in frequency. This type of scattering is called "Raman scattering." Some of the scattered light returns to the instrument, where it passes through a grating to separate out the different wavelengths. Each wavelength strikes a different set of cells on a CCD, where the photons are detected and counted; the greater the number of photons, the greater the strength of the signal. Measuring the wavelength and intensity of this scattered light provides a profile with peaks corresponding to specific molecules[22,31].

All types of molecules are theoretically identifiable in this method, if a grating capable of separating out the appropriate wavelength shifts is implemented on the instrument.

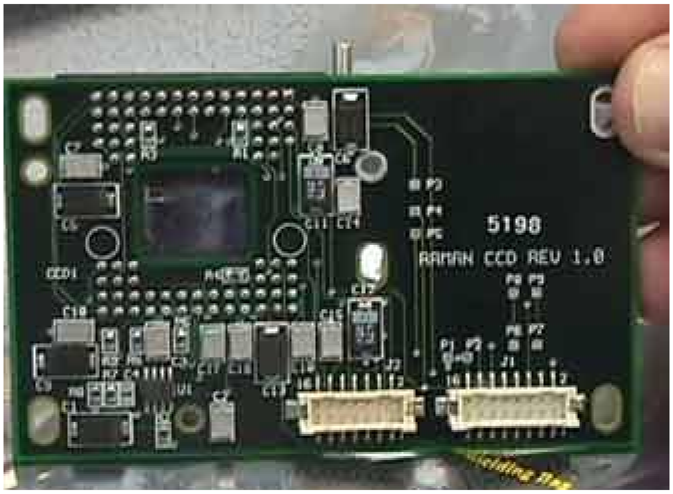
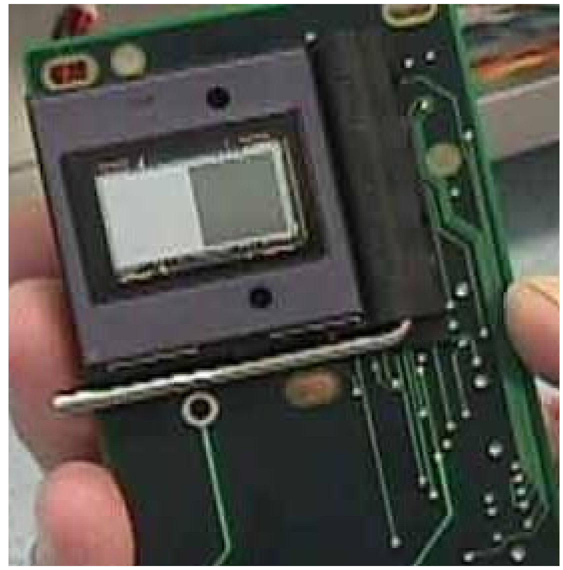


Figure 5. Athena Raman spectrometer, electronics board (above) and CCD (right). *Cornell University*



Motivation

The primary scientific goal of the mission is to verify the presence of water ice. Additionally, the instrument should be capable of working and down-hole. The Raman spectrometer is capable of both.

The Raman spectrometer can be focused to a small target size, and can be used down-hole on a cable. The technique is also well developed, and is being used on the near-future Mars missions as part of the Athena science package. The Raman spectrometer is versatile, able to detect most molecules (including water and organic materials), and produces narrow spectra without overlap, ensuring correct identification. Elemental composition can be inferred from molecular composition.

In comparison to traditional IR absorption spectroscopy (which is also well developed and can detect water), Raman spectroscopy is much less sensitive to ambient temperatures, as it supplies energy to a target rather than relying on natural energy. This is essential is the extremely cold environment of lunar permanent dark, as natural thermal emissions are generally too weak to accurately detect and analyze.

While remote Raman spectroscopy is technologically feasible, it is not applicable to rover missions. The 2π (or greater) steradian scattering at long distances would weaken the detection signals and require large amounts of power for analysis.

Capabilities

Raman spectrometers are capable of detecting the presence of most molecular substances. Those developed by the Athena team are specifically designed for planetary minerals and water detection. The laser operates at 670 nm, providing adequate spectrum for the large shift range of the desired substances and minimizing the risk of causing photon emissions from target materials, which may contaminate results if in the same energy range as the scattered photons (generally unlikely). The Raman target size is small enough to isolate and analyze the composition of single mineral crystals[31].

The miniaturized Raman technology developed at the University of Alabama include small probes, approximately the width of a pencil, which can be lowered down drill-holes for in-situ analysis. The miniature spectrometers have gratings and detectors capable of detecting most minerals relevant for planetary exploration (at wavelength shifts near 1600 cm^{-1}) and water (at a shift near 3000 cm^{-1}) [31].

Table 2. Raman Spectrometer Characteristics

Characteristic	Value[31]
Mass	< 0.5 kg
Size	0.05 m x 0.1 m x 0.01 m electronics 0.005 m x 0.1 m cylindrical probe
Power	< 100 mW
Range	0 – 0.01 m
Sample Analysis Time	10-20 seconds typical 200 seconds for low concentrations

Technological Maturity

Flight models of the slightly larger versions of this instrument will be flown on the 2001, 2003 and 2005 Mars missions as part of the Athena package, and is therefore scheduled to be flight-qualified. The miniaturized spectrometers desired for the Icebreaker mission are not scheduled for flight qualification at this time, but are in development with this in mind[31].

Rover Integration

As with the other spectrometers, the Raman spectrometer will be integrated such that the main electronics will be housed in the instrument mast. This will allow thermal protection. The probe must be mounted on a cable that can be extended and retracted in order to allow it to drop down drill-holes for in-situ analysis of subsurface layers. For use on surface targets, the probe must be accurately and rigidly deployable. The development of such an attachment mechanism will require further study in cooperation with the instrument developers. One possible solution would be mounting the probe on the bottom of the rover so that it may be lowered to the ground for surface analysis, and lowered further down-hole for subsurface investigation.

Issues

The primary issue remaining with the Raman spectrometer is the requirement for cabling to drop the probe down a drill-hole. Fiber optics may have difficulties at low temperatures and may require special design efforts. Additionally, this makes the rigid mounting required for surface use problematic.

Laser-Induced-Plasma Ion Mass Spectrometer (LIMS)

Provider

The LIMS technology is in development at the Space and Atmospheric Sciences Group (NIS-1) of Los Alamos National Laboratory. Dr. Roger Wiens is a principal scientist for the project. Dr. Wiens has indicated willingness to work with CMU, provided an adequate scientific team is formed[32].

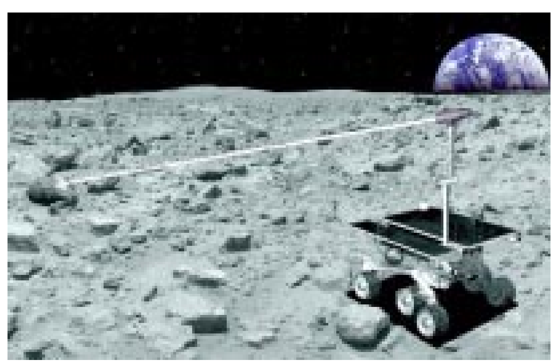


Figure 6. Conception of long-distance spectroscopy using LIBS/LIMS. *Los Alamos National Laboratory*

Description

The LIMS is a time-of-flight mass spectrometer. Particle mass and charge determine identity. As a result, knowing the flight-time provides the particle mass. For elemental analysis, larger molecules are broken down into constituent elements; each element having a unique mass provides unambiguous results for elemental analysis. Identity of larger molecules can be also be deduced by mass if not broken apart; ambiguities due to multiple molecules and elements with the same mass can be resolved via elemental analysis[18,22,32].

For analysis, the LIMS laser ablates a small sample of material. Some of the particles volatilized by this process enter the spectrometer and pass through a carbon-fiber foil. The foil, depending on its properties, can induce molecular breakdown or allow molecules to enter intact. Passing through the foil induces electron emission and marks the start-time of the flight. The particle enters a linearly-varying electric field, which induces motion along a predictable path, and then strikes a detector, which marks the stop-time of the flight. In this way, the calculation is self-contained and independent of particle energy or entry angle[18,22,32].

In environments with an atmosphere, such as Mars, a carrier gas is generally required to transport molecules into the spectrometer. In vacuum environments, such as the moon, vapor pressures of samples may be adequate to transport the sample[32].

Motivation

In the analysis of hydrogen on the moon, whether in elemental form or in water, the relative abundance of different Hydrogen isotopes must be studied. In particular, if water is found, the ratio of deuterium to hydrogen will help determine whether the water originated in comets. A long-distance method that can be used down-hole is essential if materials below the surface are to be examined without removal. The LIMS satisfies these requirements, making it ideal for this application.

Capabilities

The primary capability of the LIMS is the determination of some isotope ratios, including in particular deuterium/hydrogen and oxygen-18/oxygen-16. The LIMS can detect the presence of major elements with an accuracy of 15 %. The LIMS can also be re-tuned to accept molecular input to identify small molecules, such as water. Such analysis can be done at distances up to 20 meters[18,32].

LIMS has a narrow-beam laser, providing a localized sample. As a result, samples can be taken extremely accurately from specified targets or in holes and at distances up to 20 meters[18,32]. Typically, 20-40 laser shots may be used for target analysis, making total analysis time ten minutes or less. The laser (35 mJ with a 5-second duty cycle) atomizes a small sample with each pulse, approximately 1 mm in diameter and 2 μm deep.

Table 3. LIMS Characteristics

Characteristic	**Value**[18,32]
Mass	4.2 kg
Power	4 Watts
Sample Size	1 mm across by 2 μm deep
Range (Distance)	0 - 20 m
Detection Accuracy	2 % isotope ratios 15 % major element
Analysis Time	<10 min

All characteristics are estimates based on characteristics of other LIMS techniques and proven characteristics of the mass spectrometer used with traditional methods.

Technological Maturity

NASA funds the LIMS for development. Basic LIMS principles have been demonstrated by large systems with poor resolution. Improvements in the design, including size and mass reduction, high resolution in mass and time-of-flight, and better capability definition are currently being investigated. The mass spectrometer technology has been proven through previous research. Los Alamos expects to develop field prototypes in 2000 and to make flight systems feasible by 2003, in time for a 2004 lunar mission[32].

Rover Integration

The LIMS will be integrated such that the main electronics will be housed in the instrument mast, allowing thermal protection. The laser and detector will be mounted on an actuated platform closely attached to the mast so maintain temperatures. The support should have the ability to point between straight down and 60° upwards so that it may be pointed at cliff-sides, the ground, or down-hole. The horizontal range should be at least ±60° to allow for extensive analysis without relocating the rover platform. This actuation may require heating for motors to function in the cold.

Issues

The primary issue with LIMS is that it has not completed its development, nor flown on any previous missions. A mature but less capable backup instrument that may be available in the event LIMS is not is discussed later.

Laser-Induced Breakdown Spectrometer (LIBS)

Provider

The LIBS technology has been in development by the Space and Atmospheric Sciences (NIS-1) Group of Los Alamos National Laboratory for 18 years. Dr. Roger Wiens is a principal scientist for the project. Dr. Wiens has indicated interest in working with CMU on this project[32].

Description

The LIBS uses a laser to ablate solid material, break down molecular bonds and excite electrons to higher energy levels. These electrons return to lower energy levels, emitting light at frequencies characteristic of the element. The light is detected, and elements are identified by the presence of peaks of energy at their characteristic frequencies. Light detectors are custom-selected to target the spectra of desired elements; other elements whose spectra fall within this frequency range can then also be detected[19,22,32].

Accuracy of analysis is aided in two ways. The laser can eliminate potentially contaminated material prior to analysis. Successive firings of the laser ablate more material, increasing sample size or sample area as well as increasing absolute levels of low-concentration materials[19,32].

Motivation

In order to determine the elemental composition of the lunar regolith and rocks, including hydrogen and oxygen, an elemental spectrometer is required. The LIBS is recommended because of its speed of analysis, ability to analyze concentrated samples at a distance, versatility, and small mass and power consumption. Other instruments with similar capabilities, (such as various particle spectrometers) require close contact and long analysis periods, and target larger sampling areas. Additionally, detection thresholds are typically higher and some critical elements, such as hydrogen, are often undetectable.

The LIBS will be tightly integrated with the LIMS, eliminating duplication of parts, which provides an advantage in system integration. When integrated with the LIMS, a single laser is used for both instruments. This reduces mass and power requirements, and can allow for simultaneous analysis by both. The LIBS can provide independent confirmation of the Raman and LIBS elemental analysis. The provision for dual methods of detection and analysis increases certainty and reduces risk.

Capabilities

The LIBS instrument is designed for elemental analysis. The elements detected by the current LIBS prototype include: aluminum, calcium, carbon, chromium, hydrogen, iron, magnesium, manganese, oxygen, phosphorus, potassium, rubidium, silicon, sodium, sulfur, and titanium. Other elements that may also be detected by LIBS are barium, beryllium, boron, copper, lead, lithium, mercury, nickel, strontium, tin, and zirconium[19,32]. Current accuracy ranges from 0.001% to 0.1%, and is element specific. Sample preparation and analysis takes 2 to 5 seconds per laser pulse, or less than three minutes per target. As with LIMS, LIBS samples are extremely localized[19,32].

All characteristics and parameters are based on the current field prototype.

Table 4. LIBS Characteristics

Characteristic	**Value**[19,32]
Mass	1.5 kg
Size	1000 cm^3
Power	2.3 Watt
Sample Size	1 mm across by 2 μm deep
Range (Distance)	0 - 20 m
Detection Accuracy	0.001 - 0.1 % concentration
Analysis Time	< 3 min
Data Rate	1.6 kbits/sec

Technological Maturity

A field prototype has been developed and tested. The LIBS is entering the flight prototype phase in the fall of 1999, and the first test results are expected in the summer of 2000. As with LIMS, Los Alamos anticipates the ability to produce flight models by 2003[19,32].

Rover Integration

The LIBS can be integrated entirely with the LIMS instrument, and need not be independently integrated with the rover. If used independently however, the LIBS will be integrated in the same manner as that described for LIMS.

Issues

The primary issue with the LIBS instrument is the fact that it has not completed its development, nor flown on any previous missions. There is some concern about flight-readiness for the proposed 2004 mission date. A mature backup instrument (APXS) is discussed later.

CMOS Active Pixel Sensor Color Camera (APS)

Provider

The APS has been developed by the JPL MicroDevices laboratory, led by Dr. Bedabrata Pain[12]. The camera is commercially available from Photobit[20]. No contact has been made with either JPL or Photobit for obtaining a space-qualified CMOS APS.

Description

The CMOS APS camera uses silicon semiconductor technology. Images are produced in the ultra-violet, visible, and near-infrared frequency ranges. Each cell detects individual photons that strike it, amplifying the signal by converting it into an electric current. The photon detector and readout amplifier are part of each pixel, allowing the integrated charge to be converted into a voltage that can be measured. Pixels are addressed individually by column and row[12].

Figure 7. DICE package, including CMOS APS. *Center for Space Microelectronics Technology, JPL*

Motivation

The need for high-resolution color images on a lunar mission encompasses several aspects. Color images are always of interest for studying the terrain features and have commercial value. Additionally, high-resolution images are necessary for accurate, high-speed, teleoperated navigation in order to provide a remote operator adequate visual information.

The CMOS APS camera has many advantages over other imaging methods for this purpose. The APS has small size and mass, produces images rapidly, uses little power, and integrates all of the necessary function on-chip; all of these make it ideally suited for a small rover platform. Additionally, the CMOS technology allows for has a larger array size, a lower noise level and higher radiation tolerance than CCD cameras. Pixel addressability allows for zooming and windowing images. The camera is highly programmable. The technology for generating semiconductors has been developed to a low-cost, high-speed industry, thus reducing the cost and time of building instruments.

Capabilities

The APS cameras are versatile in their capabilities and models. In all cases, high-resolution images are produced and stored in 8- or 10-bit monochrome or 8-bit color. High dynamic range and signal-to-noise ratios provide high performance while using low power and being small[12,20]. Typical characteristics are shown below.

Table 5. CMOS APS Imager Characteristics

Characteristic	**Value** **NASA prototype**[12]	**Value** **PB-300**[20]
Mass	0.125 kg	Unavailable, similar
Size	7.5 by 2.5 by 3 cm	Unavailable, similar
Power	5 mW (per 100K pixels) 3.3 V	300 mW (maximum) 5 V 6 mA
Resolution (Pixel Size)	< 20 µm	7.9 µm
Image Size	512 horizontal 512 vertical	640 horizontal 487 vertical
Noise	5 e^- RMS	15 e^- RMS > 20 db SNR
Efficiency	25-50 %	Unavailable
Frame Rate	30 frames/sec	0-39 frames/sec
Dynamic Range	> 75 db	75 db

The characteristics listed here compare a commercially available color camera and the NASA current prototype.

Technological Maturity

The technology is well developed for terrestrial applications and is under development at NASA for space applications. At this time, it is unknown if any versions of the camera are space qualified or in the process of space qualification. Research is ongoing into higher resolution for the color cameras[12,20].

Rover Integration

Two APS cameras for color imaging will be positioned near the top of the rover instrument mast. This high position will provide longer ranges of view. The cameras are not actuated in order to reduce complexity.

Issues

The primary issue with the APS camera is the lack of space qualification. Because of the nature of the APS CMOS, however, it possesses superior radiation tolerance than that of CCD cameras. A more traditional, space-hardened CCD camera is proposed as a backup later in this document.

Sample Acquisition and Transfer Mechanism Cryogenic Drill (SATM)

Provider

Honeybee Robotics (New York, New York) is currently an active researcher in drilling and sample collection. A sample acquisition drill was developed for the Champollion mission (now cancelled), designed for drilling in space and into ice. Honeybee Robotics has indicated interest and willingness to collaborate on this project[27].

Description

The drill has three degrees of freedom: augur axial position, augur rotational position, and SATM rotational position. Motors at the top of the unit control the drilling motions, and a motor on the base controls the rotational motion of the unit, used for sample transfer[27].

The drill collects samples in a collection chamber near the drill tip. To collect a sample, the outer part of the drill bit rotates backward relative to the inner shaft of the drill. The relative motion aligns doors in the inner and outer parts of the drill, opening a path to the sample collection chamber. Further forward rotation of both inner and outer shafts of the drill bit forces material into the sample chamber. Once sample collection is complete, the outer part of the drill bit is rotated forwards relative to the inner part, closing the door[27].

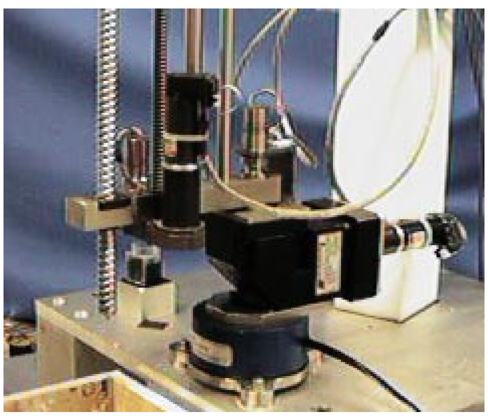


Figure 8. SATM, photographic close-up of augur. *Honeybee Robotics*

Once a sample is collected, the drill is brought back to the surface. A brush cleans the drill bit in order to prevent contamination from materials at other stratigraphic layers. The drill is moved to align with the analysis units, opening the door to the analysis unit. The augur is lowered into the unit, and a push-rod within the drill's sample chamber expels the sample so that it may be deposited within. After withdrawing, the drill closes and seals the analysis unit[27].

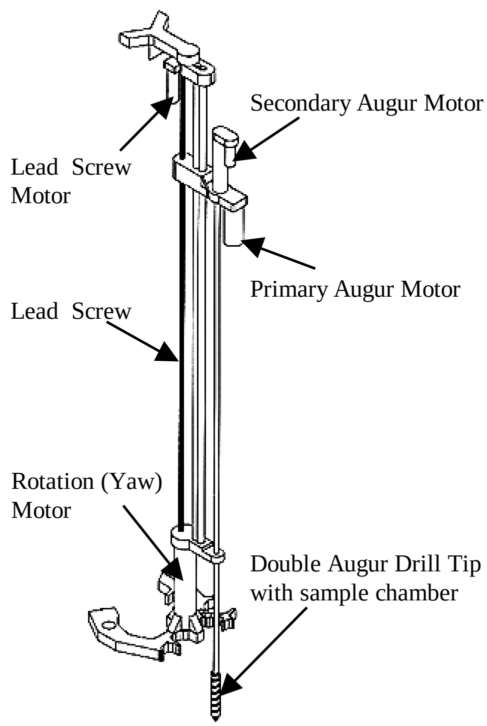


Figure 9. SATM sketch. *Honeybee Robotics*

Motivation

In order to search for water ice that is below the lunar surface, some type of excavation must be undertaken. The water ice is expected to be within one meter of the surface, so deep drilling is not required. The parameters of the

SATM fit within the range required. Additionally, the SATM has been designed for another water-ice search mission (Champollion) and is being space-qualified.

In addition to meeting our depth requirements for samples, the advantages of using this technology as a base for the Icebreaker sample acquisition are several. A functioning prototype of this drill already exists at Honeybee Robotics, and Honeybee Robotics has demonstrated viability for several space missions. The SATM design was developed for low temperature operation for the Champollion comet mission, originally scheduled for 2003 but now cancelled. No other space-qualified portable drilling mechanisms more fully meet requirements; technologies such as sonic drilling have not been fully developed at this scale and are not anticipated to be available for missions in 2004.

A primary justification for choosing Honeybee Robotics as a supplier is its history of space involvement. Honeybee Robotics is a primary supplier of space-qualified drilling mechanisms. In addition to the Champollion Mission, Honeybee Robotics' technology is behind the Mars Mini-corer to be used in the 2001 and 2003 Mars surface missions. NASA has used honeybee Robotics' actuators, drills, and sample acquisition mechanisms since 1990.

Capabilities

The SATM drill can reach depths of up to 1.2 meters. The drill can collect small regolith samples and return them to the surface for analysis; laboratory tests have indicated that such samples can be returned without being contaminated by material from other levels. Samples that are returned to the surface can be temperature controlled within ±5°. The SATM drill can also be used to expose deeper surfaces to distance by penetrating and removing regolith overlying a small target area. The drill can operate with low axial force if necessary to prevent the rover from lifting off the ground[27].

Table 6. SATM Characteristics

Characteristic	**Value**[27]
Mass	6.5 kilograms
Height	1.45 meters
Width	0.1 meter, 0.3 meter base and bracket
Depth	0.36 meter
Drill Stroke	1.2 meter
Drilling Rate	0.33 meter/hour (limestone)
Axial Force	80 Newtons nominal (-350 to 350 Newtons)
Drilling Torque	0.655 Newtons at 300 rpm
Rotational Speed	300 rpm nominal
Voltage	14 to 16 Volts
Current	Varies (current controlled)
Power	20 Watts nominal, 35 Watts peak
Interface	RS422 Serial
Computing	On-board
Operational Temperature Range	-80° C to +60° C
Sample Ejection Push-Rod Force	0 to 170 Newtons
Sample Ejection Push-Rod Stroke	0.3 meters
Sample Size	1.0 cubic centimeters
Feedback (Internal)	Current, absolute positions, rotational speed, force

Technological Maturity

A prototype of this drill has been tested, but is not yet space qualified[27].

Rover Integration

The drill will mount on a stiff frame near the center of mass of the rover. The rover's instrument mast will contain the drill this frame. The frame and mast will be mounted on the base of the rover with a pivot. This rigid, enclosed mast will aid in rigidity and thermal control. The positioning of the drill close to the center of mass allows the rover to withstand greater drilling torque and axial forces without slippage or lifting off the ground.

To prevent reduction of ground clearance for driving, the bottom of the drill bit is mounted flush with the floor of the rover's body. The drill is 1.45 meters tall with the drill screw fully retracted, which places the top of the mast at nearly 2.0 meters above the ground.

The drill and instrument mast stow horizontally for launch, flight, and landing. This reduces the effects of launch forces on the mast, as well as the size of the envelope required to contain the rover. A spring-loaded device activates the one-time deployment of the instrument/communications mast. The deployment mechanism includes an axle pin with dual redundancy to reduce the risk of deployment failure. Once deployed, the mast latches into place.

As the drill is actuated, it cannot operate in the low temperatures of permanent dark. Heating elements will be required on the motors for operation in these regions.

Issues

The primary issue remaining with the SATM drill is drill depth. It is desired to be able to drill at least 1.0 meter below the surface, and the current drill allowing for ground clearance only allows for drilling 0.75 meters down. This may be adequate to detect water, but extending the drill or changing the mounting to allow for deployment closer to the ground must be considered.

Neutron Spectrometer

Provider

The Los Alamos National Laboratory Space and Atmospheric Sciences Group has developed neutron spectrometer technology, such as the one used by Lunar Prospector to collect data on the moon from orbit. Dr. Bill Feldman is a principal scientist for the project. Contact has been made with Dr. Robert Wiens regarding collaboration with the neutron spectrometer as well as the LIBS and LIMS instruments, and has indicated interest in the project[32].

Description

High-energy neutrons only lose energy when colliding with particles near their own mass; more massive molecules cause the neutrons to merely bounce off while light particles absorb more energy into their own motion. Thus, neutrons are primarily slowed by the presence of hydrogen, the only element with approximately the same mass as a neutron. A neutron spectrometer detects neutrons, either naturally occurring or reflected from a source. Neutrons passing through helium-3 (contained in reservoirs) produce emissions of energy; these emissions are detected. Screening out low-energy neutrons (below 0.25 keV) with a cadmium shield isolates the high-energy neutrons. Comparing the total neutron flux with the high-energy neutron flux, the low-energy neutron flux can be calculated. The level of low-energy neutron flux is then proportional to the amount of hydrogen present in the material. High noise levels are reduced by integrating over long periods of time and by increasing the neutron flux, such as by using a neutron source to augment the natural radiation[11,22,32].

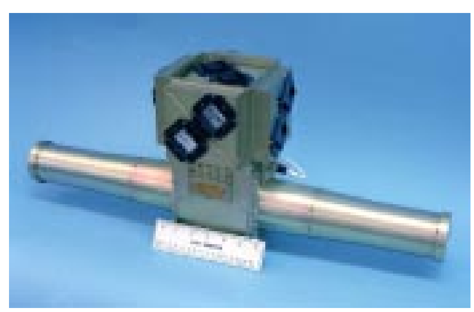


Figure 10. Lunar Prospector's neutron spectrometer. *Lunar Prospector, National Space Science Data Center*

Motivation

While drilling and specifically analyzing small samples can confirm that water ice is present, wide-range distribution of the ice cannot be characterized by systematic drilling in the short mission time-frame. Once water has been identified, following the hydrogen signal detectable by a neutron spectrometer would allow for estimation of the distribution of the water by extrapolation.

Capabilities

A neutron spectrometer similar to that used on Lunar Prospector would be able to detect water when present at greater than 0.01 % composition. The Lunar Prospector spectrometer was used in orbit, and could collect large numbers of neutrons from a wide area of the lunar surface in order to provide a detectable signal[11,32].

Table 7. Neutron Spectrometer Characteristics

Characteristic	Value[11,32]
Mass	1 kg
Size	0.6 m x 0.25 m x 0.1 m
Power	1 – 3 W
Detection Limit	0.01 % water
Sensitivity	50 ppm

Technological Maturity

The technology of neutron spectrometers has been flown in several missions, including Lunar Prospector, and is therefore well developed. No specific instrument designed for ground-space space operations has been prototyped, but only the addition of a neutron source would be required in order to increase the local neutron flux to a range where detection is accurate[11,32].

Rover Integration

The main electronics of the neutron spectrometer will be mounted within the body of the rover. The detector must be mounted slightly away from the rover body to prevent false signals if any rover components contain hydrogen. A neutron source will be required to amplify the local signal. This neutron source should be placed on the drill so that it may be lowered to various depths to concentrate analysis on specific layers. When raised with the drill for driving, the neutron source will amplify the ambient neutron signal and provide more generalized information as the neutrons are reflected through the regolith back to the rover.

Issues

No issues other than the placement of the detector to avoid contamination remain.

Other Desired Instruments

Miniature Ground Penetrating Radar

Provider

A low-mass version of the ground penetrating radar is in development by Dr. John Grant of NASA Headquarters. Preliminary contact as been made with Dr. Grant regarding this issue, however it appears that a conflict of interest with another project may prevent Dr. Grant from participating[24].

Description

A radar signal is sent into the ground. The signal is reflected and absorbed differently by each component of the regolith. Time-of-flight and energy absorption of the signal differs according to the density of the layers passed through. The signal is transmitted and received by an antenna. The RF wavelength of the emitted signal is directly related to the antenna length[24].

Motivation

The ground penetrating radar allows for deep depth-profiles over broad areas without requiring digging or drilling. Ground penetrating radar can identify water and ice deposits when occurring in high concentrations.

Capabilities

GPR produces depth-profiles of subsurface layers distinguished by density. In this way layers with different compositions or compression can be identified. Other objects, such as rocks or ice pockets, can also be identified.

Table 8. GPR Characteristics

Characteristic	**Value**[24]
Mass	0.5 kg
Size	0.15 m x 0.15 m x 0.15 m
Power	5 W
Depth	20 m

In this instrument, the antenna is cable-like so that it can be dragged behind a rover. The cable can be extended or retracted to achieve a range of wavelengths, thereby allowing the detection of a wide variety of subsurface features[24].

Technological Maturity

The general GPR technology is well developed and has been used terrestrially for many years for stratigraphic measurements. The miniaturized version, designed with planetary rover applications in mind, is in the field prototype phase[24].

Rover Integration

The primary electronics box will be mounted on the interior of the rover body. The antenna will be dragged behind the rover.

Issues

The primary issue of the miniature GPR is availability, as Dr. Grant believes that there is a conflict of interest with another project. Only if this conflict is resolved, or if another source of low-mass GPR is found, would this become a viable instrument to include on the mission.

3D Laser Imaging Sensor

Provider

Riegl Laser Instrument Systems of Austria, with branches in Florida, Japan, and Sweden, developed the LMS-Z210 laser sensor[21]. Some research is also being conducted at K^2T of Pittsburgh, Pennsylvania[17]. These sensors are commercially available for terrestrial applications from both companies.

Description

A laser is directed to a target, where it reflects off the opposing surface and onto the detector; the time-of-flight of the laser pulse indicates distance to the target. A three dimensional image is obtained by systematically scanning the laser over the target landscape. Adjacent individual scans can be merged to create seamless maps covering wide areas of terrain.

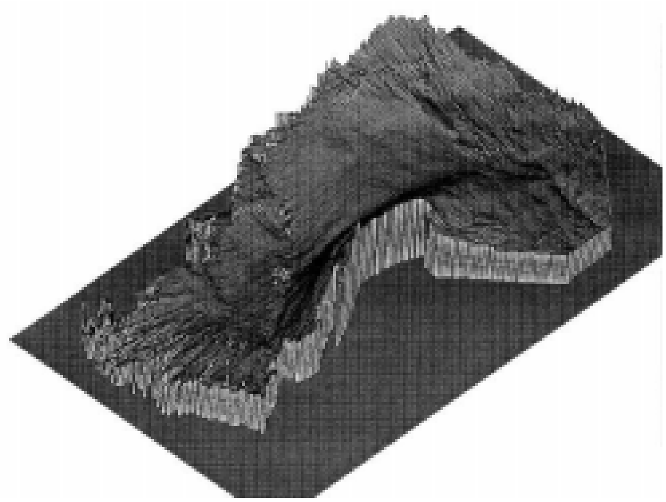


Figure 11. Example laser image topographic map.

Motivation

The purpose of the laser imaging system is to obtain three-dimensional, high-resolution maps of terrain near the rover. These maps will be useful in planning the robot's path and for identifying interesting target points. Additionally, more accurate maps of some regions will provide useful data for mission and path planning of future missions. Real-time speed is essential if the maps are to be used for robot navigation in high-speed driving.

Capabilities

The laser imaging systems can produce wide-range, long-distance maps of the terrain. These maps are high resolution and have high-accuracy due to small target spot sizes. Images can be produced real-time and processed off-board on Earth-based computers for navigation[17,21].

Table 9. Laser Imager Characteristics

Characteristic	**LMS Value**[21]	**K^2T Value**[17]
Mass	13 kg	25.5 kg
Size	435 x 210 mm	38.7 x 33.0 x 52.0
Power	11 - 18 V 3 A	40 mW 120/220 VAC, 24VDC
Measurement Range	2 - 350 m 80° vertical 300° horizontal	2.3 – 60 m 60° vertical 360° horizontal
Resolution	0.025 m	0.02°
Accuracy	0.025 - 0.1 m	0.02° – 0.04°
Target Size	3 mrad	5 mm
Scanning Rate	20 horizontal scans (5° vertical) per second	Unavailable

The characteristics listed are based on terrestrial models, and do not include additional electronics.

Technological Maturity

The laser imagers are well developed for terrestrial applications, but have not yet been adapted or tested for space. No space-hardened versions are currently planned[17,21].

Rover Integration

If a small imager is developed, it can be mounted on the rover instrument mast. It should be mounted high on the mast in order to provide a long-distance view.

Issues

Several issues remain with laser imagers. First, the large size, mass, and power make them unwieldy for rover use. Additionally, they must be space-hardened. Lastly, the amount of computation time required for processing laser data and the lag-time in transmission may be too slow for some aspects of rover navigation. Should these issues be resolved, the laser imager is highly recommended for the mission. Imagers in the present form are not recommended due to mass concerns.

Alternative Instruments

Due to the low technological readiness level of some instruments and the questionable availability of others, several alternatives are suggested here. For each alternative discussed, its corresponding primary instrument is mentioned and the capabilities are compared.

Tunable Diode Laser (TDL)

A tunable diode laser detector is proposed as a backup instrument for the LIMS for the measurement of isotopic ratios and for the LIMS/Raman water detection capability.

Provider

Tunable diode lasers have been supplied for multiple Mars missions by the Jet Propulsion Laboratory with aid from the Lunar and Planetary Laboratory of the University of Arizona and the University of California at Los Angeles. Dr. Bill Boynton and Dr. Ralph Lorenz of the University of Arizona (integral in the development of Mars 98 TDL technology) have indicated willingness to aid in the design and construction of a tunable diode laser device for water detection on Icebreaker[26].

Description

The fundamental principle of tuned diode lasers is that molecules in gaseous states absorb laser light at characteristic frequencies. The laser produces light of at a frequency corresponding to a frequency of light that is absorbed by the desired substance and not by any other substances. If the concentration of the substance is high, the light will frequently interact with it and be absorbed; if the concentration is low, the interaction will be rare and the absorption will be less. Thus, the amount by which the laser light energy is attenuated indicates the concentration of the substance in the sample. Longer path lengths through the sample amplify the absorption peaks by allowing the light to interact with the material over a longer period of time. Thus, longer path lengths increase the accuracy and lower the detection threshold of the instrument. In order to increase the path length, the sample chamber contains mirrors at both ends. The laser emits light through a hole in one mirror and into the sample chamber. The laser light reflects between the mirrors until it passes through a second hole (in either mirror) and strikes a brightness detector behind it[26].

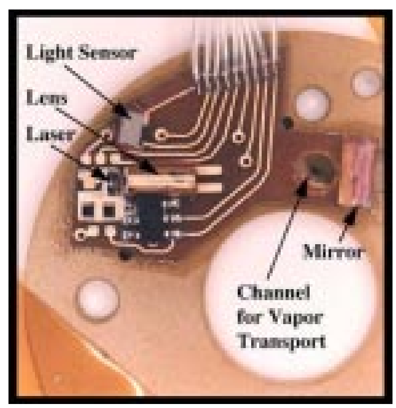


Figure 12. Deep Space 2 Mars Microprobe TDL electronics. *JPL*

Tunable diode lasers improve the basic diode laser capabilities by electronically tuning the laser through a sequence of frequencies over a small range. A single TDL device can detect substances with similar but distinct absorption bands, such as H2O and D2O, as it looks for absorption at each subsequent frequency. In order to maintain the proper tuning of the laser it must be maintained at a constant temperature[26].

Motivation

The TDL technology is well established for the Mars exploration program and is currently being used to look for water in Martian soils and atmosphere[15,23,26].

Capabilities

Tunable diode laser sensors can accurately determine the concentration of particular gaseous substances within gaseous samples, such as atmospheres. Water and carbon dioxide are the most commonly measured materials using TDL sensors in space missions. Additionally, concentrations of isotopic variations of these substances can be determined by examining results at energies corresponding to the different isotopes. A single diode laser can distinguish hydrogen from deuterium and well as the carbon isotopes from each other, as each isotope has absorption lines near, but not overlapping, those of the other isotopes [15,23,26].

The tunable diode laser capabilities listed in the following table are based on the smallest, most recent Mars TDL sensor, the Mars Microprobes of Deep Space 2. This sensor was specifically designed for small size as well as water detection[15]. Water has absorption peaks near 2.7 and 1.5 μm for all isotopes[26].

Table 10. TDL Characteristics

Characteristic	**Value**[15]
Mass	11 grams
Volume	5.2 cubic centimeters
Power	1.5 Watts peak
Computing	On-board chip
Operational Temperature Range	> -120° C
Sample Size	100 milligrams
Analysis Time	minutes
Precision	1 %
Detection Range (Concentration)	7.5×10^{10} to 5×10^{15} molecules / cm^3

Technological Maturity

The TDL technology is well developed and flight-ready. A small, single-analysis TDL is being used for water detection on the Mars 98 mission as part of the Deep Space 2 Mars Microprobes. A large, multiple-use TDL is being used for water and other volatile detection as part of the Thermal Evolved Gas Analyzer on the Mars 98 Mars Polar Lander. No instruments particularly designed for multiple uses, low-temperatures, and small rover platforms have been yet deeloped[15,23,26].

Rover Integration

In order to allow the laser to make a long path-length through a gaseous sample, two methods may be used:

- Sample Return: A sample may be returned from down-hole to the surface and deposited in a sample chamber where it is volatilized by a heat source. The SATM drill has this capability. Sample return may lead to sublimation of some of the water ice, reducing concentration measurements.
- On-Drill Analysis: A sample could be analyzed nearly in-situ by building a sample chamber of the interior of the drill shaft. The laser and detector could be incorporated into the top of the drill, where they may be thermally controlled. A mirror would be required inside the drill at the bottom of the sample chamber in order to reflect the light back to the detector. This would also require a heat source at the drill tip in order to volatilize the sample and a means of sending power to it. These modifications may require increases in the drill diameter and power.

Issues

The primary issue remaining is the method of integrating the TDL with the rover in order to maintain temperature and sample integrity and permitting analysis. Should the TDL be selected for the mission, a design effort toward this goal would be required.

Alpha-Proton-X-Ray Spectrometer (APXS)

The APXS elemental analysis capability is proposed as a backup for LIBS elemental analysis and Raman molecular analysis.

Provider

The Max Planck Institute Department of Chemistry, Mainz Germany, developed the alpha and proton spectrometers for the Mars Pathfinder mission. The University Of Chicago developed the x-ray spectrometer for Pathfinder. Steve Squyres of Cornell University is developing the APXS for Athena. No contact has been made toward acquiring an APXS, as this is a backup instrument choice.

Description

Target materials are bombarded by particles from a radioactive alpha-particle source. As a result of the bombardment, the target materials emit radiation (alpha, proton, or x-ray). Characteristic emission spectra are associated with particular elements, and the presence of elements can be inferred by detecting this characteristic spectrum. Individual detectors are required for capturing the different types of radiation, and the three types of analysis are done sequentially[13,16,22].

Figure 13. APXS Spectrometer. *Cornell University*

Motivation

The primary motivation of the APXS as a choice of backup instrument is its capability to do an elemental analysis of materials. It can replace the function of the LIBS, and is a well-established technology that has flown previously. Mass, size, and power requirements fit well into a rover-scale budget.

The APXS is not proposed as a primary instrument because of its inability to detect hydrogen, its long analysis times, and its inability to do long-distance analysis.

Capabilities

The APXS can measure all major elements, excluding hydrogen. Primary among these are carbon, nitrogen, oxygen, sodium, magnesium, aluminum, silicon, sulfur, potassium, calcium, chromium, manganese, iron, nickel, and zircon[13,16,22].

Table 11. APXS Characteristics

Characteristic	**Value**[13,16]
Mass	0.58 kg
Size	0.05 m x 0.05 m sensor 0.1 m x 0.16 m electronics
Power	1 W, ±7 - ± 15 V
Temperature Range	-120° C +
Accuracy	Varies with element and concentration, generally > 80%
Analysis Time	10+ hours/sample

Technological Maturity

The APXS has flown on several space missions, including Mars Pathfinder, and is scheduled to fly on the upcoming Mars 2001 and 2003 missions[13,16].

Rover Integration

Resulting from the requirement of contact with the target sample, the APXS must be mounted on a robotic manipulator arm in order to be able to examine various targets near the rover.

Issues

The APXS cannot perform all of the desired experiments. It cannot detect hydrogen, and in the absence of LIBS/ LIMS and Raman no direct measurement of hydrogen would be available. Additionally, the APXS must be nearly in contact with samples and cannot be lowered down-hole; this would require that samples be brought to the surface for analysis, possibly compromising sample integrity. The requirement for an arm would add a large amount of complexity to the rover and increase risk of failure. Lastly, the APXS requires nearly 10 hours for a complete analysis of a single target while remaining in contact with the target. This would severely limit the number of analyses that could be taken, and vastly reduce the effectiveness of the mission.

Neutral Mass Spectrometer

As mass is the primary means of distinguishing isotopes, a mass spectrometer of some type is proposed as an alternative to LIMS for isotopic analysis and water detection. As previously mentioned, no other time-of-flight spectrometer currently is adequate to the needs of a rover mission. However, a neutral mass spectrometer could be used and is proposed here as the alternative to the LIMS isotope ratio experiment as well as a backup to the elemental/molecular compositional analysis of the LIBS, LIMS, and Raman spectrometers.

Provider

NASA has developed neutral mass spectrometers for the Venus Pioneer missions in 1979 and for the Nozomi/Planet-B Mars mission launched in 1998, developed by Dr. Paul Mahaffy of NASA Goddard. No contact has been made toward the Pioneer project. Dr. Mahaffy has indicated potential interest in participating with CMU on the Icebreaker project[29].

Description

Neutral mass spectrometers rely on a gaseous sample, as do all mass spectrometers. General mass spectrometers rely on the effects of electric fields on charged particles. Neutral mass spectrometers ionize particles with an electron stream upon entering the spectrometer such that even neutrally charged molecules interact with the electric field and can be detected. Interaction with the electric field causes the particles to follow predictable paths according to their mass and charge; the location of the detector struck therefore relates to the mass and indicates the identity of the particle. The method of particle detection and signal amplification is similar to that of other mass spectrometers, as described for the LIMS[14,29].

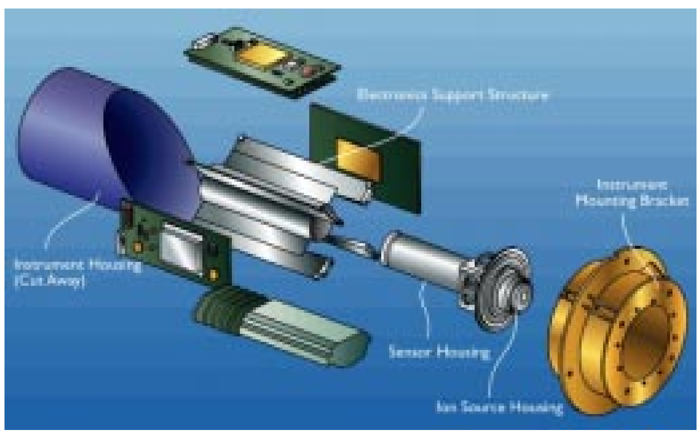


Figure 14. Expanded view of Nozomi/Planet-B neutral mass spectrometer components. *Planet-B, NASA Goddard*

In general, a high temperature source is used to volatilize the sample and a carrier gas such as helium is used to transport the particles within the spectrometer. In the case of water detection and in the presence of other laser-based ablation techniques on-board other instruments, a high temperature oven may not be required. Additionally, in the vacuum environment of the moon, vapor pressure (rather than a carrier gas) may be enough to cause transport of the sample within the spectrometer[14,29].

Motivation

A mass spectrometer is the most accurate way to measure and distinguish elemental isotopes, as mass is the defining characteristic of isotopes. In particular a neutral-mass spectrometer, capable of identifying non-charged particles (such as water) is desired. The neutral mass spectrometer has a strong flight history, with orbital and landed missions to Mars and Venus. The most recent flight model, on-board the Nozomi/Planet-B spacecraft, was launched in 1998 and is scheduled to reach Mars in late 1999.

Capabilities

The Nozomi mass spectrometer is capable of distinguishing hydrogen from deuterium and the isotopes of oxygen (16 and 18) and carbon (12 and 13). This is accomplished by detecting the slight differences in mass between ions containing hydrogen, carbon, and oxygen. Additionally, it can identify the presence of all light ions, such as those from water, carbon dioxide, methane, ammonia, etc. The level of detection threshold is below 1% concentration[14,29]. Water can be inferred from the presence of hydroxide and hydrogen ions, and occasionally the ionization of water itself into H_20^+[14,29].

Table 12. Neutral Mass Spectrometer Characteristics

Characteristic	**Value**[14,29]
Mass	2.7 kg sensor 1 kg electronics
Size	0.215 m x 0.27 m x 0.427
Power	8 W
Temperature Range	> -50° C operational > -90° C non-operational
Detection Threshold	0.5 % concentration
Detection Range	1 – 67 AMU
Analysis Time	< 10 minutes

Technological Maturity

Neutral mass spectrometers have been used on Venus Pioneer and the Nozomi/Planet-B Mars missions[14,29].

Rover Integration

This spectrometer would be integrated into the rover in much the same way as the LIMS, on a mast with the capability of pointing.

Issues

The primary issue with the neutral mass spectrometer is its high mass and power, compared to the LIMS time-of-flight mass spectrometer. Additionally, it is not capable of detecting water directly, and its sensitivity is less than the LIMS for determining isotope ratios. Lastly, if the neutral mass spectrometer is selected for Icebreaker, the design issues that were mentioned previously (regarding carrier gas and sample volatilization) must be investigated further.

CCD Camera

A CCD camera modeled on the Imager for Mars Pathfinder (IMP) camera technology is proposed as a backup to the APS camera.

Provider

The University of Arizona developed the color imager used for the Mars Pathfinder mission. As this is a backup instrument, no contact has been made for obtaining one[16].

Description

The IMP is a pair of charged couple device (CCD) cameras. CCDs are composed of an array of cells of metal oxides, which store charge proportional to the number of photons striking the cell. Thus, high intensity light will produce higher charge levels. These charges are transferred as electrical currents that can be converted to digital data representing an image[16].

In the IMP, each monochromatic CCD is equipped with a set of filters to select a color for imaging. Each filter allows the CCD to measure intensity within a particular color range. Full-color images are obtained by combining data from successive, different-colored images, such a red-green-blue[16].

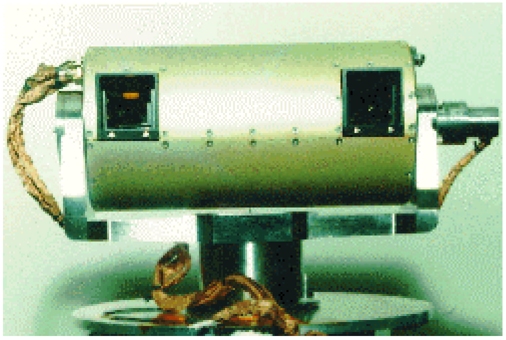


Figure 15. IMP sensor head. *JPL*

Motivation

The primary motivation of proposing IMP as backup is that it has been flown and is currently accepted space technology.

Capabilities

The IMP is capable of generating medium-resolution (256 by 256 0.23-micron pixels) color images in stereo pairs. The images are relatively low in noise, but can have higher signal to noise ratios. The CCD is sensitive to a broad range of light frequencies. Images are of a wide range and can be taken with a varying exposure time, depending on the level of light available[16].

The characteristics listed in the table below were taken from the NASA documents regarding the Mars Pathfinder imager, IMP. As the Icebreaker mission does not require stereo images, the size and mass of the camera would be much reduced.

Table 13. Mars Pathfinder Imager Characteristics

Characteristic	Value[16]
Mass	Unavailable
Size	0.25 x 0.1 x 0.1 m (estimate)
Image Size (each eye)	256 x 256 pixels
Resolution (Pixel Size)	23 x 23 µm
Range	±180° azimuth -67° to +90° elevation
Noise	15 e^- readout 350 maximum SNR
Image Time	0-32 seconds exposure 1 second readout
Spectral Range	440-1000 nm

Technological Maturity

The IMP was flown as part of the Mars Pathfinder lander and a single camera in a new case could be used in its current form for the Icebreaker mission[16].

Rover Integration

A pair of single CCD cameras of the IMP type would be integrated into the instrument mast in a method similar to that described for the APS.

Issues

The IMP would be adequate for the Icebreaker mission, though it has some weaknesses compared to the APS. These are discussed in the APS section of this document. Additionally, the Icebreaker mission does not require stereo imaging, so only one camera (rather than the full stereo pair of the IMP) would be required.

Science Operations

The operations considered here are those relevant to the scientific goals of the mission. Operations relating to driving, navigation, power consumption, etc are not discussed.

General scientific operations of the Icebreaker rover will fall into three alternating modes. The first of these modes is the Exploration Mode, during which general exploration and data collection occur. The second mode is the Geological Analysis Mode, which is a brief pause in exploration to conduct elemental chemistry experiments on selected targets. The final mode is the Water Analysis Mode, during which sites selected for further examination during the exploration will be analyzed, for water in particular.

Exploration Mode

All rover driving will be done in Exploration Mode. The rover operator will select targets from the images provided by the rover; the rover will drive toward these targets, in sequence, while autonomously avoiding hazards overlooked by the operator. In this mode, Earth-based computers will use sensor data to produce maps to aid the operator and to be stored for later use. Also while in this mode, the rover will collect neutron spectrometer data; the data will be sent back to the Earth where it will be autonomously analyzed. Areas with high hydrogen concentrations will be called to the attention of the operator. Lastly, while operating in Exploration Mode, the operator may choose sites for elemental analysis or water analysis.

Water Analysis Mode

Water Analysis Mode is the mode in which the rover conducts subsurface exploration in an attempt to identify water ice. Once the rover has reached a site targeted for water analysis, the rover will be instructed to commence analysis. A single water analysis will consist of uncovering regolith samples at several depths and analyzing the regolith at each depth for water (as well as elemental and molecular composition). In this way, a depth-profile of the site is developed. After each water analysis cycle, the data will be sent back to Earth for further in-depth analysis.

The drill will attempt to reach the desired depth (reporting failure if unable). Once the depth is reached, the operator will be notified. The operator will commence analysis by implementing the Raman spectrometer to directly identify water. The spectrometer will conduct molecular analysis of regolith at that depth simultaneously.

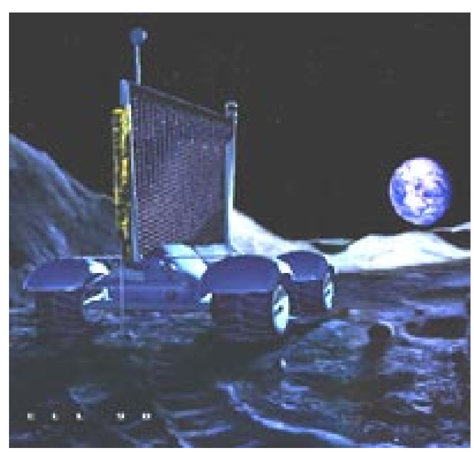


Figure 16. Icebreaker rover in shadow near lunar pole. *Mark Maxwell*

Upon completion of Raman analysis, the LIBS/LIMS instrument will then be implemented. If water is found to be present, LIMS will seek to determine the isotopic ratios for hydrogen and oxygen; if no water is present, LIBS will be used to identify the presence of elemental hydrogen and oxygen. In each case, the instrument will be pointed down the drill-hole in order to analyze the regolith at the bottom, newly-uncovered layer. Elemental analysis of the regolith will also be conducted simultaneously by the LIBS.

Geological Analysis Mode

Geological Analysis Mode will be entered at the instruction of the operator. The operator will select a target within an image provided by the rover. This target will be a regolith area, a rock, or other feature. The operator will select such targets based on visual inspection of the rover images. The implementation of analysis will depend on the operator's determination.

If the operator chooses a close target, or one that is desired for close inspection, the rover will drive to the target. Once in place, the rover will autonomously deploy and point the Raman spectrometer probe to conduct molecular analysis of the target. If long-distance spectroscopy is required due to the traversal time or inaccessibility, the LIBS/LIMS will be pointed and implemented to conduct elemental analysis of the target. In each case, upon confirmation of selecting the correct target, the rover will begin an analysis. Once complete, the data will be send to Earth for analysis. The LIBS/LIMS may also be implemented for elemental analysis on close targets if further information is requested by the operator or in the event of a Raman failure.

This mode allows for the elemental analysis of opportunistically discovered features of interest during the rover's Exploration Phases. This mode will generally be short, on the order of a few minutes, while analysis on the selected target is completed. Once complete, the rover will return to Exploration Mode.

Figure 17. Icebreaker rover and lander, artist's conception. *Mark Maxwell*

Science Package Summary

The science package outlined in the section on Primary Scientific Instruments provides the capability to:

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

A summary of the primary scientific instruments currently recommended for use on the Icebreaker mission is shown in the following table. Instruments of high priority are those upon which the mission most depends; the functions of these instruments must be performed in some form as part of the mission. Middle priority instruments can be removed if budget or mass concerns arise without significantly reducing the capabilities of the rover or significantly increasing the risk of mission failure.

Table 14. Science Package Summary

Instrument	Scientific Function(s)	Mass	Power	Priority
LIBS	Elemental Analysis (distance)	1.5 kg	2.3 W	Middle
LIMS	Water Detection Elemental Analysis Isotopic Ratios	4 kg	4 W	High
Raman	Water Detection Molecular Analysis	0.5 kg	100 mW	High
APS	Color Imaging	0.125 kg	300 mW	High
Drill	Local Depth Profiles	6.5 kg	20-35 W	High
NS	Water Detection (wide-scale)	1 kg	2 W	Middle

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12. Center for Space Microelectronics Technology, Jet Propulsion Laboratory, NASA, "CMOS APS," at *http://csmt.jpl.nasa.gov/APS/aps_what.html*.
13. Cornell University, "Missions to Mars, APEX Athena, " at *http://athena.cornell.edu/enter.html*.

14. Goddard Space Flight Center, NASA, “Planet-B/Nozomi Neutral Mass Spectrometer,” at *http://webserver.gsfc.nasa.gov/java/planetb.html*.

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