JOINT WORKSHOP ON NEW TECHNOLOGIES FOR LUNAR RESOURCE ASSESSMENT

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Cover: Artist's concept of an oxygen production module at a lunar base. Oxygen is extracted from lunar soil, liquified, and put into the spherical tanks. Solid byproducts and slag are removed from the sides of the module for disposal or use elsewhere as radiation shielding. A mining module is shown in the background. NASA photo S90-46025.

JOINT WORKSHOP ON
NEW TECHNOLOGIES FOR LUNAR RESOURCE ASSESSMENT

Edited by
R. C. Elphic and D. S. McKay

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R. C. Elphic and D. S. McKay

INTRODUCTION

The Joint Workshop on New Technologies for Lunar Resource Assessment was held in Santa Fe, New Mexico, on April 6–7, 1992. The workshop grew out of discussions between Los Alamos National Laboratory and NASA Johnson Space Center in 1991 in which we realized that some new technologies might exist that would be very useful in assessing lunar resources and that might extend beyond the usual NASA circle of experimenters and investigators. We also realized that non-NASA people could probably use some information on NASA needs and requirements as well as some general background technical information about the Moon. The purpose, then, of this workshop was to bring together a number of experts from NASA, DOE national laboratories, industry, and the university community to address topics related to the exploration for and assessment of lunar resources. The workshop was jointly sponsored by NASA, DOE, and the Lunar and Planetary Institute (LPI).

About 70 people attended from a variety of backgrounds. The workshop included a series of invited keynote talks and a number of contributed talks. These talks covered existing instruments and techniques that might be applied to detecting, analyzing, mapping, and evaluating potential lunar resources as part of the long-term SEI program.

WORKSHOP STRUCTURE AND RATIONALE

The workshop included invited keynote talks on NASA's and DOE's role in SEI, lunar geology, lunar resources, the strategy for the first lunar outpost, and an industry perspective on lunar resources. After these overview talks, the sessions focused on four major aspects of lunar resource assessment: (1) Earth-based remote sensing of the Moon; (2) lunar orbital remote sensing; (3) lunar lander and roving investigations; and (4) geophysical and engineering considerations.

The workshop ended with a spirited discussion of a number of issues related to resource assessment. The discussion was aimed at creating a sensible set of lunar resource priorities, and the measurements required to perform the assessments. While this "requirements" discussion took place at the very end of the meeting, it makes sense to review it here in order to set the stage for the instrument and technology papers.

1. What Products and Resources are Important and Why?

There was a surprising consensus that oxygen, volatiles (including hydrogen), and bulk regolith for shielding or construction are the most important short-term products. These products can be derived from a variety of resource types, but iron- and titanium-rich mare regolith or pyroclastic areas may be among the best candidates. It was agreed that any instrumental method that enabled the detection and mapping of solar wind volatiles such as hydrogen would be quite valuable in a resource assessment program. In the longer term, other potential lunar products, such as glass, silicon, iron, aluminum and other metals, and sulfur, may prove useful. Such products may require specialized resources

such as sulfide deposits, halogen concentrations in volcanic terrains, or gravity concentrations of heavier oxides such as ilmenite or chromite. These potential later-stage resources were not considered to be important for immediate study, but might influence the evolution and direction of growth of a lunar outpost if found. It was felt that it is more important to concentrate on finding and using the near-term resources—oxygen, solar wind volatiles, and bulk regolith.

2. What are the Key Resource Issues with Respect to SEI Architecture?

One important resource issue is the concept of experimental resource utilization vs. economic resource utilization. It is important to view resource utilization as an experiment until it can actually be shown to work and to provide products of real use to the outpost. At such a time, major decisions can be made about which extraction and production processes should be chosen for larger-scale production, and how to best use the local resources in support of the outpost and transportation infrastructure. Precursor mission data requirements for resources clearly include chemistry, mineralogy, regolith thickness, and maturity variations. Characterization of lunar pyroclastic deposits vs. high-Ti mare soils in regard to recoverable oxygen, hydrogen, and other volatiles, regolith thickness, grain size, regolith uniformity, degree of compaction, and boulder content, are important resource issues. While some of this information will be available from the lunar resource mapper, Artemis lander missions to several candidate outpost locations would greatly aid the process of deciding the optimum site for the first lunar outpost, deciding on the best technology for resource extraction, and deciding on the strategy for the evolution of the SEI architecture.

3. From a Resource Point of View, What Should be the Strategy for Siting the Lunar Outpost?

It was argued that once a site for the first lunar outpost is chosen, it may turn out that we will revisit that site many times and build up considerable infrastructure so that it will not be feasible to start over at a different site. Therefore, although we may not need significant amounts or variety of resources initially, eventually we may need both large quantities and varied types. We must therefore try to choose a site having the potential for providing the types and amounts of resources that may be required 10 or 20 years or more into the future. The outpost site should therefore have large resource potential for oxygen and volatiles, and ideally, should also have potential access to unusual resources, for example halogen-rich deposits or phosphorous-rich material. Siting of the lunar outpost must therefore draw heavily on the precursor data, and sites with excellent long-term resource potential must have high priority, even though no short-term use for the products is defined.

4. What are the Priorities and Rationale for Surface Measurements?

The most important surface measurements will be chemistry and mineralogy, especially measurements for potential resources expected to be quite variable such as solar-wind-implanted hydrogen. In addition, regolith depth and boulder content, and general soil engineering properties will influence mining feasibility and methods as well as long-term reserves for some resources. Therefore, Artemis rovers should be equipped with such devices as sounding radar or sonar to determine regolith depth, augers or diggers to enable measurements at depth, and scoops and powdering tools for XRF/XRD/EGA measurements and Mössbauer spectroscopy. Multispectral video capability was judged to also be important for a surface package.

5. What are Key Open Areas, or Areas of Disagreement?

There was some questioning of the technology readiness of the proposed Soft X-Ray Fluorescence Imager (XRFI), in view of the fact that the technology is very new and has not yet been tested as an analysis technique on simulated or real lunar materials nor in an appropriate space environment. Tests are underway to try to resolve these questions.

A second area of disagreement is the sampling strategy for the Artemis rovers. Some people thought that regolith analysis on a regular grid with 10-m spacing would give the best information about a relatively small target area. Others felt that such a grid would simply show small-scale random variations in regolith chemistry and other properties known to exist from Apollo data. Instead, they suggested a much wider sample range extending tens of kilometers. This would reveal broader, more regional variations of importance to resource assessment and would also provide ground truth and calibration for orbital measurements.

HIGHLIGHTS OF THE WORKSHOP PRESENTATIONS

Earth-based Remote Sensing

There were several surprising and potentially important Earth-based remote sensing advances discussed. First, there is a rapidly improving ability of ground-based telescopic multispectral systems to map the Moon and to provide important information on ilmenite abundance and distribution with a resolution as good as 2 km. A new concept for image stabilization that should allow Earth-based resolution of 150 m on the Moon using the infrared band at 2.2 μm. This resolution may allow compositional mapping of target areas at high resolution. Finally, ground-based radar imaging techniques have greatly improved and current systems allow lunar resolution approaching 30 m. Recent results have shown that some areas, interpreted as pyroclastic, have extremely low surface roughness and block content.

In general, there was a consensus that ground-based observations were valuable and were continuing to improve in both the quality of the data and the spatial resolution. This is clearly an area of exploration deserving more attention and support.

Lunar Orbital Remote Sensing

Several candidate instruments for lunar orbital resource mapping were reviewed, including gamma ray/neutron spectrometers, and the XRFI. Along with proposed imaging and reflectance spectroscopy devices, such instruments would clearly provide valuable resource-related chemical mapping of the lunar surface. For the most part, the recommendations of the LPI Workshop on Early Robotic Missions to the Moon, held in February 1992, were validated, although some problems remain with some of the newer concepts.

Two instruments were discussed in connection with lunar volatiles released from the interior. One is an alpha particle spectrometer to search for lunar outgassed radon from orbit. Such radon may be a

tracer for sporadic release of lunar volatiles from the interior of the Moon. The other instrument is an ion mass spectrometer originally proposed for doing surface composition studies; it would also measure outgassed volatiles and atmospheric constituents.

Landed and Rover Instrumentation

A number of talks covered the strategies and techniques for resource exploration on the Moon's surface using rovers with various instruments attached. Electromagnetic (radar) instruments have the potential for determining regolith thickness, and piezoelectric-generated seismic pulses also could provide data on regolith thickness and buried boulders. Concepts for small teleoperated Artemis rover payloads included stereo video imagery, infrared imaging spectrometer, evolved gas analysis device, alpha/proton/X-ray fluorescence instruments, scoop, and auger drill. Other speakers suggested using laser-induced breakdown spectrometry for analyzing geologic features tens of meters distant, a Mössbauer spectrometer for determining the mineral sites of iron and the amount of ilmenite, and an X-ray fluorescence/diffraction instrument for determining the actual mineralogy of soil samples.

One talk presented a state-of-the-art neutron generator and detectors used in commercial well logging in petroleum exploration. This device can detect and measure hydrogen, carbon, and about a dozen other elements including iron and titanium. This very sophisticated system is small, rugged, and might be directly used for lunar applications. In a related talk, a lunar penetrator was proposed that uses neutron and gamma ray detectors and can detect hydrogen at levels of a few tens of parts per million. This penetrator could be targeted directly into the regolith, penetrating a few meters to provide analyses over that depth. A final talk discussed the kinds of detailed engineering properties data that might be required at an outpost site.

Geophysical and Engineering Considerations

The Moon presents unique challenges in resource detection, recovery, and utilization. One talk discussed potential problems of digging into the supercompacted regolith, which is thought to be typical at depths below a few tens of centimeters. These problems may include the inability of shovels or blades to break up the regolith at these depths. Preliminary tests indicate that a rotary wire brush might overcome these problems. In any case, this area needs more attention from the standpoint of both resource mining and site preparation for lunar outpost infrastructure emplacement and growth.

New state-of-the-art dry drilling techniques used by the DOE at Yucca Mountain, Nevada, were also presented. These methods use a recirculating gas stream to entrain the cuttings at the drilling face and to pull them back up the drill stem using a vacuum pump. A similar system might be an option for a lunar drill if system gas loss can be controlled. Lunar drilling and coring will be required by any extensive resource assessment program, and the technology for doing this needs to be better developed.

SUMMARY OF WORKSHOP RESULTS

Table 1 lists the primary (short-term) and secondary (long-term) lunar resources to be exploited when we return to the Moon. The table also shows those technologies and instruments that were discussed at the workshop and that are aimed at locating and assessing these resources.

TABLE 1.   Lunar resources and associated technologies presented at the workshop.

Primary Resource	Measurement	Earth-based	Lunar Orbital	Landed/Roving Instrumentation	Recovery Technology
Oxygen	Geochemistry	—	GRNS *XRFI* *SIMS*	GRNS *LIBS* *EGA*	Closed-cycle drill rotary brush
	Mineralogy	VIS/IR	VIS/IR	*XRF/XRD/BaMS*	
Hydrogen (and solar wind volatiles)	Soil maturity	—	GRNS *SIMS*	*XRF/XRD/BaMS* GRNS	Closed-cycle drill rotary brush
	TiO_2 content	VIS/IR	VIS/IR *SIMS* *XRFI*	*EGA* *LIBS* MAG	
Regolith	Surface roughness	Radar	Mapping camera	—	
	Blockiness	Radar	Mapping camera	Camera Active seismics E-M sounding	Closed-cycle drill rotary brush
	Depth	—	Mapping camera	Core tube	
Secondary Resource					
Pyroclastics (S, Na, K, halides)	Location and concentration	Radar VIS/IR	GRNS *XRFI* *SIMS*	*XRF/XRD/BaMS* GRNS *EGA* *LIBS*	Rotary brush
Other volatiles (H_2O, CO_2, C, outgassed species)	Useful concentrations	Radar	GRNS α-spectrometer *SIMS*	GRNS *LIBS* *EGA*	Closed-cycle drill rotary brush
Metals (e.g., "ore"-grade Fe, Ti, Cr, etc.)	Geochemistry	—	GRNS *SIMS* *XRFI*	*XRF/XRD/BaMS* GRNS *EGA* *LIBS*	Closed-cycle drill rotary brush
	Mineralogy	VIS/IR	VIS/IR	VIS/IR *XRF/XRD/BaMS*	
Glasses	—	—	—	*XRF/XRD/BaMS*	Rotary brush

The reader will find brief papers in this volume on the various instruments, approaches, and measurements listed in the table. Italicized acronyms refer to technologies presently undergoing development. The abbreviations and acronyms can be deciphered as follows:

GRNS	Gamma Ray/Neutron Spectrometer
XRFI	Soft X-ray Fluorescence Imager
SIMS	Secondary Ion Mass Spectrometer
VIS/IR	Visible/Near-Infrared Imaging Spectrometer
LIBS	Laser-Induced Breakdown Spectrometer
EGA	Evolved Gas Analyzer
XRF/XRD/BaMS	X-ray Fluorescence/X-ray Diffraction/Backscatter Mössbauer Spectrometer
MAG	Surface Magnetometer

In summary, this was a very useful workshop that covered a number of important topics related to SEI planning for lunar resource assessment, mapping, and utilization. While the Santa Fe workshop was planned well before the Workshop on Early Robotic Missions to the Moon, it covered some of the same topics and served to validate some of the conclusions of the LPI workshop. On the other hand, the Santa Fe workshop provided a more integrated picture of the ability of ground-based, orbital, and lunar surface analysis to provide useful information on resources. Furthermore, it provided a forum for the discussion of what the important products and resources are, how they will be used, and their relationship to the broader SEI program. None of these topics were part of the LPI workshop. Finally, this workshop served to educate and calibrate a large cross section of national lab people, industry representatives, university people, and NASA people on the current state of the art in the covered topics.

Abstracts

APPLICATION OF NUCLEAR WELL LOGGING TECHNIQUES TO LUNAR RESOURCE ASSESSMENT.

P. Albats[1], J. Groves[1], J. Schweitzer[1], and T. Tombrello[2], [1]Schlumberger-Doll Research, Ridgefield CT, USA, [2]California Institute of Technology, Pasadena CA, USA.

Introduction: The use of neutron and gamma ray measurements for the analysis of material composition has become well established in the last 40 years. Schlumberger has pioneered [1,2] the use of this technology for logging wells drilled to produce oil and gas, and for this purpose has developed compact, low-power (<20 W) D,T (14 MeV) and D,D (2.5 MeV) neutron generators (Minitrons) that allow measurements to be made in deep (5000 m) boreholes under adverse conditions (temperatures to 200°C, pressures to 20,000 psi, high transient accelerations, corrosive fluids, etc.). We also make ruggedized neutron and gamma ray detector packages that can be used to make reliable measurements on the drill collar of a rotating drill string while the well is being drilled ("logging while drilling"), where the conditions are even more severe.

Modern nuclear methods used in logging measure rock formation parameters like bulk density and porosity, fluid composition (oil-water discrimination), and element abundances by weight including hydrogen concentration. The measurements are made with high precision and accuracy: For example, bulk density is measured to 0.01 g/cm^3, which translates into determining porosity to 1%.

These devices (well logging sondes) share many of the design criteria required for remote sensing in space: They must be small, light, rugged, and able to perform reliably under adverse conditions. We see a role for the adaptation of this technology to lunar or planetary resource assessment missions.

Elemental Analysis Using Pulsed Neutrons and Gamma Ray Spectroscopy: The use of a pulsed neutron generator permits time-dependent spectroscopic measurements of gamma rays so that inelastic capture or activation neutron reactions can be emphasized. The high-energy neutron inelastic and (n,x) reactions during the source neutron pulse are used to measure carbon and oxygen to help determine pore fluid content. Following the burst of neutrons, prompt gamma rays produced by thermal neutron capture reactions are measured; at later times activation gamma ray

Fig. 1. Delayed activation gamma ray spectrum shows the constituent elements of the laboratory rock formation.

Fig. 2. Comparison of in situ measured vanadium concentrations during logging with results from laboratory analysis of rock cuttings. The logging measurements were performed with a germanium detector.

can be measured. At typical logging speeds (10 cm/s), statistics are often the limiting factor in the usefulness of the measurement. Thus, present oil well, geochemical logging systems only determine the abundances of the most dominant contributors to the measured spectra—typically Si, Fe, Ca, S, Gd K, U, Th, Ti, Cl, H, and Al [3]. Stationary measurements or measurements at a series of fixed positions may be appropriate for planetary applications. The relevant elemental sensitivities depend on the neutron source used (14 MeV or 2.5 MeV neutrons), the type of detector used (e.g., NaI, GSO, LSO, Ge), the detector arrangement, the total counting time, etc. An example of a delayed gamma ray spectrum taken in a laboratory rock formation using a Ge detector in the laboratory is shown in Fig. 1. The spectrum shows lines for many of the elements in the rock; some of the prominent peaks have been labeled. Clearly, such a source-detector system can be used for elemental analysis—even of trace elements.

Results from Borehole Measurements: We have collaborated with the major scientific drilling groups: the Ocean Drilling Program, through the Lamont-Doherty Geological Observatory of Columbia University, the Swedish Siljan Ring Project, and the German Deep Well Project (KTB). KTB is drilling a well to a depth of about 10 km to investigate the changes in minerals under high temperatures and pressures. An initial stage in this project was drilling a 4-km well that was fully cored and from which cuttings were almost continuously analyzed. We used a Ge spectrometer to obtain in situ data on a wide range of elemental concentrations [4]. Because of the crystalline rocks in this well, the most useful measurements were prompt thermal neutron capture and delayed activation gamma rays. Pulsed neutrons were produced by a DT generator. Delayed activation measurements were also made using a ^{251}Cf source [5]. A typical example of the results is shown in Fig. 2 for V concentration. The subsurface measurements are those with the error bars. The data shown with "x" are the laboratory analyses on cuttings samples. Excellent agreement is seen between these two datasets, with the main difference being that the cutting samples have been physically mixed over depth and thus do not display the same extent of variation in narrow zones of changed concentration. This demonstrates how in situ measurements can be a more accurate representation of the bulk rock contents, as subsequently confirmed by analyses of core samples that show the same character as the in situ measurements.

Conclusions: We thus see that the adaptation of this well logging technique is entirely consistent with most of the needs for a robotic lunar mission (e.g., low power, small size, rugged instrumentation) and could provide a broad range of elemental data for the shallow lunar subsurface. With the neutron generator turned off, the detector would provide natural and solar-flare-produced activity data, which are likely to be proposed by other investigators; by also using the neutron generator one can obtain much more detailed composition data. One can envision dragging the generator and detector package behind a rover for mobile measurements, i.e., getting the source of radiation away from other experiments. One could also design the whole package so that it could be inserted into a shallow borehole for near-surface measurements.

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GEOPHYSICAL METHODS—AN OVERVIEW. A. Becker, N. E. Goldstein, K. H. Lee, E. L. Majer, H. F. Morrison, and L. Myer, Earth Sciences Division, Lawrence Berkeley Laboratory, Berkeley CA 94720, USA.

Geophysics is expected to have a major role in lunar resource assessment when manned systems return to the Moon (ca. 1995). Geophysical measurements made from a lunar rover will contribute to a number of key studies: estimating regolith thickness, detection of possible large-diameter lava tubes within maria basalts, detection of possible subsurface ice in polar regions, detection of conductive minerals that formed directly from a melt (orthomagmatic sulfides of Cu, Ni, Co), and mapping lunar geology beneath the regolith.

The techniques that can be used are dictated both by objectives and by our abilities to adapt current technology to lunar conditions. Instrument size, weight, power requirements, and freedom from orientation errors are factors we have considered in this paper. Among the geophysical methods we believe to be appropriate for a lunar resource assessment are magnetics, including gradiometry, time-domain magnetic induction, ground-penetrating radar, seismic reflection, and gravimetry.

Depending on weight limitations, all or some of these instruments, together with their power supplies and data acquisition/telemetry, would probably be mounted on a small rover and on a towed nonmagnetic, nonconductive trailer. Rover and trailer might be controlled remotely. To reduce power and data storage requirements, the data would probably be taken at discrete locations, rather than continuously. We envision that the rover would also be equipped with a lunar version of a GPS receiver to display and record position and elevation.

Magnetics: Two- or even three-component flux-gate magnetometers could be attached via short booms to the trailer to measure the total (scalar) magnetic field plus its horizontal and vertical gradients. These small, low-power devices are commonly used in many applications, including some of the past Apollo missions. They have a useful sensitivity of 0.1 nT, which is perfectly adequate for resource evaluation and for the mapping of lunar rock types.

Because the Moon presently has negligible, if any, internal dipole field due to a metallic core, the small magnetic fields at the surface are due to permanent magnetization, possibly TRM, of the lunar rocks. There is also a small time-varying field of external origin due to fields carried in the solar wind and the fields associated with the Earth's magnetotail. Magnetic field variations over the Moon's surface due to changes in rock magnetization may amount to ±2000 nT. A major unresolved question concerns the nature and origin of localized strong magnetic anomalies detected from orbit.

Time-Domain Magnetic Induction: The absence of water and conductive minerals gives the lunar surface environment an extremely low, and presumably uniform, electrical conductivity (less than 10^{14} S/m) to considerable depths. Solar heating of the surface will raise the conductivity several orders of magnitude within a thin layer, but this does not alter the very resistive nature of the Moon. Thus, conductivity measurements, such as the shallow-probing time-domain EM measurements done on Earth to search for conductive features like groundwater, might not be a candidate for lunar geophysics were it not for the fact that the lunar regolith and crust contain micrometer-sized particles of elemental iron and FeS. These single-domain magnetic particles are superparamagnetic, which results in a frequency-dependent magnetic relaxation loss phenomenon when rocks and soils are subjected to an alternating magnetic field [1]. This property can be exploited to determine the vertical distribution of superparamagnetic particles, information that could be used as a guide to regolith thickness and age.

The magnetic induction system might consist of a pair of coplanar, colinear coils on the trailer (Fig. 1). A transmitter coil, about 1 m in diameter, surrounds a small-diameter, multiturn detector coil. The transmitter is energized by a series of square-wave current pulses with sharp rise and decay times. During the brief time current flows through the transmitter loop, a primary magnetic field is created. At the instant the loop current goes to zero, the only remaining magnetic field is a rapidly decaying secondary magnetic field caused by a magnetic polarization current
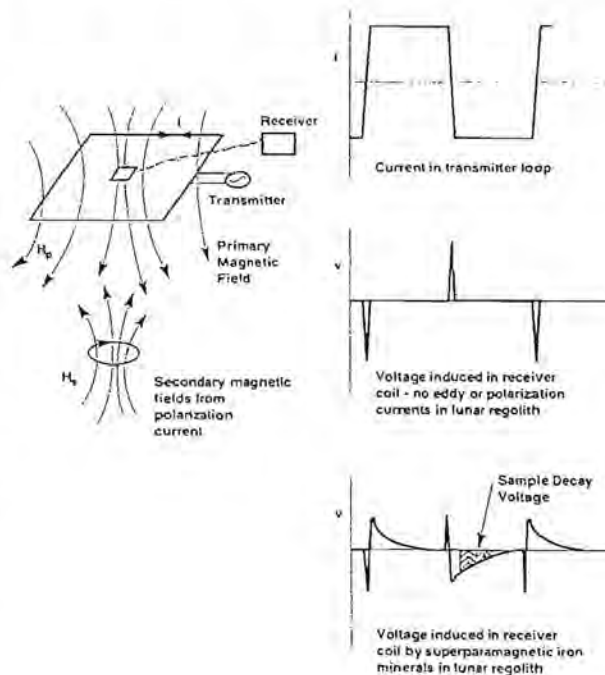

Fig. 1. Principle of a time-domain magnetic induction system.

in the lunar material. The decay current is measured in terms of a voltage induced into the detector coil. The voltage decay curve is recorded within microseconds after current in the loop goes to zero, and one can, in principle, determine from its shape and magnitude the vertical distribution of polarizable material. If one were to measure the change in magnetic field in the center of the during the current on-time, relative to its free space value, one could also obtain an estimate of the magnetic susceptibility of the lunar soil.

Ground-Penetrating Radar (GPR): During the last decade, GPR has become a staple method in shallow investigations. GPR systems working in the 100-MHz to 1-GHz range are routinely used to probe the Earth to depths of up to tens of meters. The depth of investigation is limited by a number of system and subsurface parameters, e.g., radiated power, frequency, and attenuation by wave spreading, conductive losses, and scattering, to name a few. Because lunar surface rocks have very low conductivity and low dielectric constant, radar waves penetrate more deeply into the Moon than into the Earth; radar frequency penetration may be hundreds of meters. Spatially coherent reflections, if they are detected at all from shallow sources, would provide exciting new information on the Moon's internal structure and possible presence of either conductive mineral concentrations or an ice horizon, which some scientists believe exists beneath the polar regions.

No new technology would have to be developed to add GPR to a lunar rover. Antenna design would have to be optimized for a lunar mission, antenna size dictating the lowest frequencies. Small, highly directional horn antennas could be used at frequencies over 1 GHz for high-resolution shallow soundings; 1-m electric dipoles could be used at frequencies of around 300 MHz. Currently, Sensors and Software Corp., Mississauga, Ontario, is planning to space harden and lighten a commercial GPR system for a possible French-led Mars mission in the 1998–2000 time period.

Seismic Reflection: Seismic reflection may be the most difficult geophysical technique to adapt to a lunar rover because the system must be lightweight and remotely controlled, and the technique requires physical coupling of sources and detectors to the Moon's surface.

Several source types used on Earth might be adaptable to a rover, e.g., a hammer or an accelerated weight drop onto a plate, a shotgun slug fired into the ground, or a mechanical vibrator [2]. Of these, a mechanical vibrator with sufficient moment to be useful is probably the least attractive candidate source because of its size, complexity, and power requirements. However, it should not be excluded from consideration at this time because new technology could make piezoelectric devices, such as bimetallic "benders," a candidate source if a good way were to be found to couple energy into the Moon. The accelerated weight drop produces the highest energy of all the small commercial sources, but significant redesign and weight reduction of the Bison Elastic Wave Generator is needed for a lunar source.

The seismic system would probably have only a few detectors and corresponding data channels. Detectors might be embedded into the wheels of the rover-trailer vehicle; a pressure-activated switch in the wheel would relay a signal to the driver that the detector(s) is (are) positioned for a measurement.

Gravimetry: Gravity measurements will provide the basic information for determining the Moon's internal density distribution, and thus will be an important method for discerning subsurface structures and rock-type variations. Gravity measurements are among the most tedious and time-consuming geophysical measurements to make because the meter must be very precisely leveled and elevation, terrain, and tidal correction factors must be calculated and applied before the meter readings become useful data. For example, we would need to know station elevation relative to a datum surface to much better than 1-m accuracy, the local topography to 1-m accuracy out to a radial distance of at least 10 km, and the lunar tide effect. The latter requires a nearby monitoring station.

At present there is no gravity meter that meets the specifications for a lunar resource assessment. The meter must be self-leveling to 10 arcsec or better, provide digital readings under the direction of system control, work in a low absolute gravity environment, have a precision of 0.1 mGal or better, and have an operating range of perhaps 2000 mGal. Scintrex Corp., Concord, Ontario, has redesigned its CG-3 Automated Gravity Meter for the Canadian Space Agency for possible use in the French-led Mars mission. The design calls for a smaller and lighter meter than the 10-kg CG-3, one that would be autoleveling to better than 200 arcsec, more precise leveling to be achieved by means of a numerical correction.

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TOPLEX: TELEOPERATED LUNAR EXPLORER—INSTRUMENTS AND OPERATIONAL CONCEPTS FOR AN UNMANNED LUNAR ROVER.

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We propose a Teleoperated Lunar Explorer, or TOPLEX, consisting of a lunar lander payload in which a small, instrument-carrying lunar surface rover is robotically landed and teleoperated from Earth to perform extended lunar geoscience and resource evaluation traverses. The rover vehicle would mass about 100 kg and carry ~100 kg of analytic instruments. Four instruments are envisioned: (1) a Laser-Induced Breakdown Spectrometer (LIBS) for geochemical analysis at ranges up to 100 m, capable of operating in three different modes [1]; (2) a combined X-ray fluorescence and X-ray diffraction (XRF/XRD) instrument for elemental and mineralogic analysis of acquired samples [2]; (3) a mass spectrometer system for stepwise heating analysis of gases released from acquired samples [3]; and (4) a geophysical instrument package for subsurface mapping of structures such as lava tubes [4].

The LIBS (30 kg, 7 W) uses plasma atomic emission and (optionally) mass spectrometry for elemental analysis of unreachable locations such as cliff faces. Mineralogic information is obtained by using the optical portion of the LIBS as a UV/VIS/near-IR reflectance spectrometer. The XRF/XRD instrument (10 kg, 10 W) requires powdering of scoop-and-screened or other acquired samples. Mineral structures are determined by Rietvelt analysis of powder diffraction data combined with elemental analysis by XRF. The mass spectrometer system (20 kg, 35 W) will be used to measure isotope ratios of light-element gases released from step-heated samples, and will include an evaluation of lunar H and ^{3}He resources. The geophysical instrument package (20 kg, 20 W) uses a combination of high-frequency seismic and electromagnetic sensors to measure subsurface physical properties and map struc-

tures. The LIBS pulses may impart sufficient energy into the ground to also serve as seismic sources. The following table summarizes the estimated instrument gross specifications.

TABLE 1. Instrument summary.

	LIBS	XRF/XRD	MS	Geophys	Total
Mass (kg)	30	10	20	20	80
Average regu- lated power (W)	7	10	35	20	72
Data rate (bits/s)	1 M	10 k	40 k	50 k	1.1 M

The TOPLEX operates in a mobile, exploration-and-sample acquisition mode during the lunar day and in a stationary, sample-analysis mode during the lunar night. The rover vehicle that carries the instruments is estimated to mass 100 kg and require 25 W of average power. Vehicle requirements/specifications include the following: Range – 200 km; maximum speed – 500 m/hr; communications – high-gain antenna and data rate consistent with teleoperation; endurance – 4 to 6 months; and must be self-deploying from the lunar lander. In addition, the rover will have stereoscopic vision with zoom and selectable band filtering, and a robotic arm for sample acquisition, preparation (i.e., powdering), and conveyance to appropriate instruments.

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DRILLING AND DIGGING TECHNIQUES FOR THE EARLY LUNAR OUTPOST. Walter W. Boles, Department of Civil Engineering, Texas A&M University, College Station TX 77843-3136, USA.

Introduction: The theme of this workshop is lunar resource assessment. Topics include identification, quantification, and location of useful elements on and below the lunar surface. The objective of this paper is to look at another side of the issue—how to remove soil from the stiff lunar-soil matrix once useful deposits are located.

The author has been involved with the study of digging and excavating on the Moon for several years. During that time he has overheard some disturbing comments such as the following:

"We know what works best here [on the Earth]. Just make the systems such as power and thermal control work in the lunar environment and the machine will work well on the Moon."

"Just send something up there that looks like a front-end loader with a back hoe. It will work. Don't worry about it."

Comments such as these are disquieting, to say the least, because even if a machine's subsystems are designed to operate well in the lunar environment, it may still perform its tasks poorly. Also, one cannot assume that the operational characteristics of terrestrial machines, based upon terrestrial heuristics, will be similar to machines operating on the Moon. Finally, due to the suspect accuracy of terrestrial soil-tool interaction theories, one cannot justifiably argue that these theories can be used along with terrestrial heuristics to make accurate predictions of the performance of various excavating methods on the Moon. The need is great, therefore, for quantitative and verifiable evidence of the perfor-

mance of various digging methods. This evidence is necessary for the confident selection of appropriate methods for further research and development.

The goal of this paper is to challenge comments such as those mentioned above and to cause those who think that digging or excavating on the Moon is a trivial problem to rethink the reasons for their opinions. Another goal is to encourage them to view total reliance upon terrestrial heuristics with suspicion. This paper will focus primarily upon digging since another paper will focus primarily upon drilling.

Lunar Soil: Much is known about the lunar soil. The characteristics of interest here, however, are those that tend to make the soil difficult to excavate. The soil is composed of very angular, abrasive, fine-grained particles that have re-entrant corners. As a result, they tend to cling to each other. The soil matrix is very loose (low density) at the surface and is very hard (high density) at relatively shallow depth. It is believed that the soil approaches 90% to 100% relative density at a depth of approximately 0.7 m. Additionally, it is reasonable to assume that rocks and boulders will be encountered in any digging activities. The regolith has been described as a dense, interlocking soil matrix [1].

The lunar soil, therefore, will be very difficult to penetrate below about 0.5 m. Penetration of blades, scoops, and cutters will require crushing and shearing of many soil particles since the soil nears 100% relative density at shallow depth. This crushing and shearing action requires high forces. Encounters with rocks and boulders will serve to make a difficult situation worse. Expected performance of traditional terrestrial methods, therefore, is low.

Lunar Experience: During the Apollo missions, hollow stems were augered into the lunar soil. The first attempts were only able to drill to about 1.5 m. This was due to discontinuous auger flights at splice locations on the stem. It is assumed that the soil particles seized the stem at the joint and caused the stem to fail. On later missions the stem was redesigned with continuous auger flights and depths of approximately 3 m were reached. The rate of penetration, however, had to be kept low since the stem would tend to screw itself into the soil and was difficult to remove [1].

There are two major problems regarding drilling. The first one is the removal of cuttings. The second one is cooling of the drill bit. Both these problems are usually solved on the Earth with fluids. The use of fluid to remove cuttings and cool the bit is obviously a problem on the Moon.

Shoveling on the Moon was relatively easy in the top 10 to 15 cm. Below this depth the shoveling became very difficult. Also, hammer tubes were driven to a depth of approximately 0.7 m before the resistance became too great [1]. It is interesting that this depth corresponds well with the depth at which the regolith is assumed to approach 90% to 100% relative density. In summary, these limited data tend to verify data in the previous section. It also tends to confirm that digging in the lunar regolith will be very difficult.

Excavation Methods: Typical terrestrial excavation methods include bulldozers, hoes, shovels, scrapers, draglines, bucket-wheel excavators, and continuous miners with rotating cutting heads. All these methods depend heavily upon gravity to generate downward and horizontal forces. These forces are necessary for the machines to perform well. With the gravity of the Moon approximately one-sixth that of the Earth's, one can expect a corresponding decrease of the machines' performance. For example, the maximum productivity of a 15,000-lb bulldozer on Earth, over a 100-ft haul distance, is approximately 100 yd³/h. On the Moon,
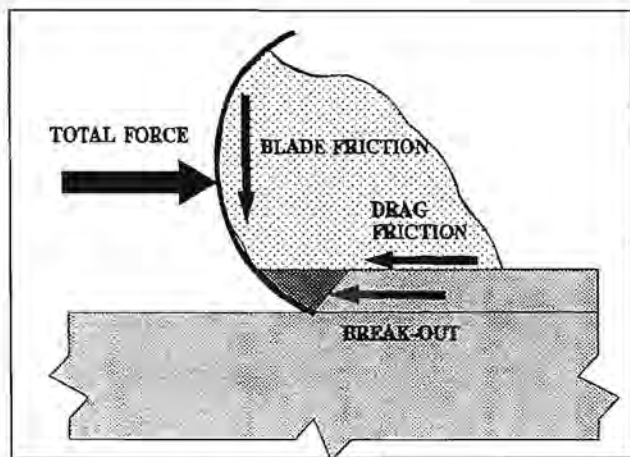
Fig. 1.   Balovnev's model.

however, with appropriate efficiency factors [2] and an assumed one-sixth reduction due to the reduced gravity, the output may plummet to only 2 or 3 yd^3/h. This seems ridiculously low for a 15,000-lb machine. Compounding this problem of low productivity is a size and power constraint. Machines that will actually be in use on the Moon will probably have about as much capability and mass as the average riding lawn mower.

Every suggested method the author has seen in print is based upon terrestrial methods. It is the author's opinion that these methods will prove to be very limited in performance and capability. This implies that total reliance upon terrestrial methods is unwise, and innovative methods must be found that will perform well on the Moon.

Soil-Tool Interaction Theories: Most soil-tool interaction theories were developed for soil-tillage applications and focus upon draft or drawbar-pull forces. They do not consider penetration or vertical forces. Verification testing was typically conducted in soft soils. The models were developed assuming the soil to be uniform with fluid properties. The models were also developed for small tools such as tines [3–6].

One often-quoted reference of a bulldozer model is by Balovnev [7]. This model looks only at drawbar forces and attributes the total drawbar force required to four factors—dragging of the soil prism in front of the blade, friction between the blade and soil, bending of the soil layer, and break-out of the soil at the cutting edge. Bending of the soil layer is assumed to be negligible. These forces are as indicated in Fig. 1. There is no gravity factor in the model. Soil weight is a factor, however. If one reduces the soil weight appropriately and uses reasonable estimates of other factors such as an angle of internal friction of 45°, one sees that approximately 90% of the total force required is due to break-out forces while other frictional forces represent only about 10% of the total force required. This result is quite revealing because it again tends to verify that penetration of blades or cutting devices into the lunar soil will require high forces.

Current Research: The author is aware of research conducted at several universities. Studies at the University of Maryland found that the compacted lunar soil simulant was very difficult to penetrate [8]. The difficulty was so great with the testing equipment available that explosive methods were investigated in order to loosen the soil so that excavation could be performed. Research is currently underway at the University of Colorado.

The author has not seen published results of this research. He believes, however, that this research involves the use of vibration to reduce penetration forces.

Research at Texas A&M University is focusing on small-scale experiments to enable more accurate predictions of excavating forces and productivities to be encountered on the Moon for various digging methods. The objective of the testing is to compare traditional as well as innovative methods in terms of certain measures of merit such as low forces, high productivities, and low power. The testing device, as depicted in Fig. 2, will be small so that verification testing can be conducted on board NASA's KC-135 airplane to simulate the Moon's gravitational field. Once testing is complete, a better understanding of the expected performance of different digging methods will promote the selection of promising methods for further development.

One particularly interesting method that is being investigated involves the use of a rotary wire (or wirelike) brush for excavation. The concept was first proposed by the Army Corps of Engineers [9]. It was intended to sweep up loose regolith that was assumed to lie on top of a smooth rock surface. The importance of this concept, however, lies in its ability to excavate the dense lunar soil matrix and it may prove to have advantages over methods that require penetration of an implement into the stiff lunar soil matrix.

High penetration forces, for example, will not be required since the bristles will remove soil particles from the surface. As soil particles are removed, other particles are exposed and removed by subsequent bristles. This may be a major advantage since, as indicated previously, break-out forces may represent 90% of the forces required. The method may also prove to be relatively rock tolerant since the bristles will deflect over rocks and not become immobile when rocks are encountered. This may make the device relatively easy to automate. The device may also be designed to collect soil particles up to a certain size depending upon stiffness of the bristles. This has obvious advantages for subsequent processes that would otherwise require sifting or crushing to achieve a small grain-size distribution. Preliminary indications are that the wire-brush method will also be much more productive than traditional methods. Disadvantages of the method may include high rates of wear, high power consumption, and difficulties in collecting the ejected soil particles. The generation of dust may also be a problem to overcome.
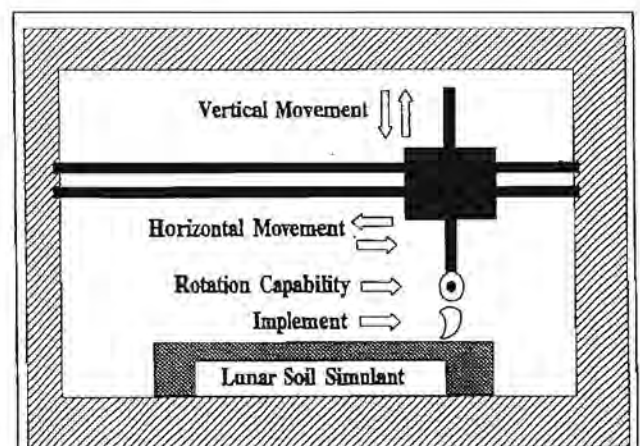

Fig. 2.   Test apparatus.

Conclusions: It is the author's opinion that there has been too much dependence upon terrestrial heuristics in suggesting digging methods for the Moon and not enough attention to basic forces, required mass, required power, and expected production rates. Progress toward more basic research is being made, however. Results of work at the University of Colorado and Texas A&M University will prove important for the selection of efficient methods. Short-term results at Texas A&M University are expected to reveal quantitative and verifiable evidence as to which methods are more promising. Long-term results are expected to include candidate methods for prototype development and testing.

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SHOCK-TREATED LUNAR SOIL SIMULANT: PRELIMINARY ASSESSMENT AS A CONSTRUCTION MATERIAL.

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In an effort to examine the feasibility of applying dynamic compaction techniques to fabricate construction materials from lunar regolith, we have carried out preliminary explosive shock-loading experiments on lunar soil simulants. Analysis of our shock-treated samples suggests that binding additives, such as metallic aluminum powder, may provide the necessary characteristics to fabricate a strong and durable building material ("lunar adobe") that takes advantage of a cheap base material available in abundance: lunar regolith.

Introduction: Because of transport cost considerations, it is clear that the vast majority of construction material for lunar structures must be indigenous. The most readily attainable material on the Moon is regolith, so an obvious question is: What is the easiest method of converting lunar regolith to a construction material?

One technology that has been used to modify materials involves the use of shock treatment [1,2]. The principal concept relies on exerting an extremely high dynamic force on a certain base material that is mixed with an agent and thus changes its properties. If such a process could be emulated on the Moon, new soil-based "lunar adobe" construction materials could be created. Although this technology has been proven on Earth, research is needed to study the feasibility of such an approach under lunar conditions and to evaluate the consequences on the design, engineering, and construction of lunar bases.

Experimental: We have performed two shock recovery experiments on samples of a lunar soil simulant. These experiments made use of the Sandia "Momma Bear" explosive loading fixtures to achieve well-characterized shock states. These recovery fixtures allow samples to be shocked in a controlled, reproducible manner. A planar shock wave is generated by detonating a high-explosive lens next to an explosive pad. The shock wave passes through an iron pulse-forming plate and into the copper fixture, which contains the 5 cm^3 powder sample. The entire assembly has cylindrical symmetry. Because of the large impedance difference between the sample and copper, and the finite lateral extent of the sample, the shock loading is not a simple, one-step uniaxial process. On the contrary, the initial loading is due to a radially converging shock wave, and the final shock state at a given position is reached by a series of shocks.

Shock pressure and temperature histories were determined numerically by two-dimensional computer simulations [3,4]. These calculations are based on the geometry of the sample holder, the type of explosive, and the initial packing density of the powder (in general, the lower the packing density, the higher the shock temperature as long as nothing else is changed). The two experiments for the present study made use of the explosive Baratol, and the peak shock pressure range was 5–10 GPa, with the peak pressure a function of position within the sample.

For the first experiment (13B917) the sample was "Minnesota Simulant" Lot 2, with particle size between 50 and 100 mesh, and a mean initial powder density of 1.896 g/cm^3. The second experiment (14B917) made use of the same simulant, with an admixture of aluminum metal; CERAC A-1189, 99.99% pure with a particle size less than 325 mesh. The mean initial powder density of the mixture was 2.051 g/cm^3. The material used in these experiments was intended to simulate the crystalline fraction of basaltic lunar regolith. The simulant was taken from the fine-grained basalt of the Duluth Complex, Minnesota, and was provided by P. W. Weiblen [5].

Results: Macrocracking was only observed in the sample with aluminum binder. It is possible that the cracking was created during the postshock handling of the compacts. The samples appear to have been compacted to densities in the range from 70 to 85%, but they had very little mechanical strength. However, strong metallurgical bonding of nonmetallic powders by weak shock in the peak pressure range of 5–10 GPa cannot be expected. A rough estimate of the threshold pressure required for shock consolidation is twice the Vickers microhardness of the solid materials. Thus, without the use of binding additives, several tens of GPa are required to consolidate lunar simulants.

TABLE 1.   Impression tests of lunar material.

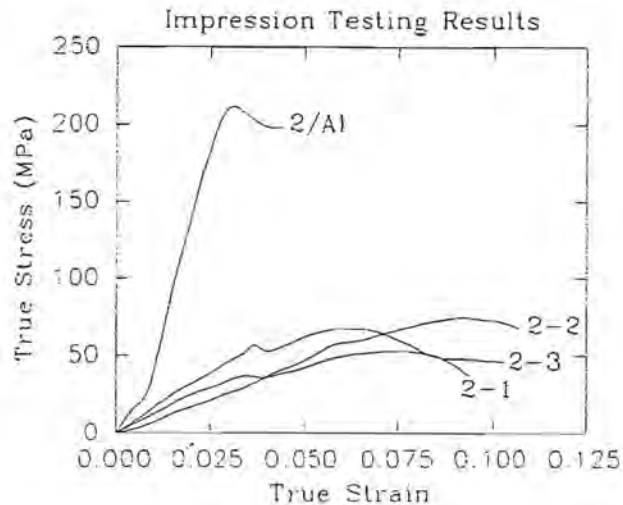| Sample	$E_c \left(= \dfrac{d\sigma_c}{d\epsilon_c} \right)$ [MPa]	σ_c^y [MPa]				σ_c^{max} [MPa]	ϵ_c^{max}	K*	n*
		0.2%	0.5%	UYP	LYP				
Lunar #2-1	1057	37.5	36.5	38	36.7	54.9	0.077	494	0.945
Lunar #2-2	1078	58.2	60.3	58.2	58.2	73.8	0.093	396	0.904
Lunar #2-3 #2/Al	1329	54.3	52.5	56.4	52.4	67.2	0.064	388	0.810
Binder	8957	175	207	—	—	210.6	0.032	5021	0.971

Impression Testing Results

Fig. 1. Results of impression tests. 2-1, 2-2, and 2-3 are samples from experiment 13B917 without binder. 2/Al is from experiment 14B917 with aluminum binder.

There are two noteworthy features that are evident from optical microscopy:

1. Compact densities are strongly influenced by the addition of aluminum particles. The metal appears to have acted as a lubricant to enhance densification through interparticle sliding and rotation.

2. Aluminum particles are well dispersed as thin boundary layers between simulant particles. This type of mixing cannot be easily achieved by conventional mixing methods. Also, thinly dispersed layers may be exploited to enhance postshock processing of shock-compacted materials by acting as an agent for dynamic reaction sintering of lunar materials.

Impression Testing: Stress vs. strain curves were determined with a WC indentor (diameter = 1 mm, cross-head speed = 0.002 in/min). Material recovered from experiment 13B917 (no binder) was sampled from three different locations (2-1, 2-2, and 2-3). One sample (2/Al) was taken from experiment 14B917 (Al binder). Stress-strain data for these four samples are summarized in Table 1, and plotted in Fig. 1. The following is a brief summary of impression testing results for the two recovery experiments.

13B917 (no binder): Samples 2-2 and 2-3 yielded nearly identical values for strengths, but the strains were not consistent. When the samples were crushed, there was not enough strain energy to cause them to fly.

14B917 (Al binder): Sample 2/Al was much stronger (see Fig. 1). Moreover, the failure mode was quite different from the other samples. The resistance to impression was very large, higher by a factor of about 3. The elastic modulus was higher by a factor of about 6. Strain energy caused the sample to shatter under maximum load, launching fragments at high velocity.

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A LUNAR PENETRATOR TO DETERMINE SOLAR-WIND-IMPLANTED RESOURCES AT DEPTH IN THE LUNAR REGOLITH.

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Introduction: Several volatiles implanted into the lunar regolith by the solar wind are potentially important lunar resources. ^{3}He might be mined as a fuel for lunar nuclear fusion reactors [1]. Even if the mining of ^{3}He turns out not to be feasible, several other elements commonly implanted by the solar wind (H, C, and N) could be important for life support and for propellant or fuel production for lunar bases [2]. We propose a simple penetrator-borne instrument package to measure the abundance of H at depth. Since solar-wind-implanted volatiles tend to correlate with one another, this can be used to estimate global inventories and to design extraction strategies for all of these species.

Current Knowledge: A considerable amount is known about the distribution of solar-wind-implanted volatiles from analyses of Apollo and Luna samples. Since the energy of the solar wind is only sufficient to implant ions to depths of less than a micrometer into grains, these volatiles are only found on grain surfaces that were once exposed to the solar wind. However, the regolith is constantly gardened by impacts, so volatiles are mixed to depths of order several meters. Models predict that the hydrogen abundance of formerly exposed grains will fall off with depth in the lunar regolith (e.g., the model of [3] predicts an exponential fall-off with an e-folding distance of about 3 m). The Apollo drill cores are not much help in testing this because their lengths are short compared to the scales of interest (only one is longer than 2 m, and that one is only 3 m). In fact, the Apollo cores do not clearly show that there is any systematic decrease in volatile abundance with depth for the first 2–3 m [4]. This uncertainty could have a large impact on resource evaluation [4]: assuming that volatiles are uniformly distributed throughout the regolith (8–15 m deep) leads to a factor of 10 higher estimated global inventory than does assuming the distribution derived from the model of [3]. Furthermore, mining strategies for a resource found throughout the top 10 m or so of the regolith might be substantially different from ones for a resource found only in the top 2 or 3 m.

In the Apollo samples, most of the solar-wind-implanted volatiles correlate with one another and with other measures of soil "maturity" (extent of exposure to the solar wind) [5]. The exceptions are He and Ne, whose abundances show a strong dependence on the amount of the mineral ilmenite (and hence the Ti content). However, He and Ne also correlate with maturity if the Ti abundance is factored out [6]. Although the correlation of H content with maturity is not as strong as for some other elements in the Apollo samples (perhaps reflecting the difficulty in eliminating H contamination of the dry lunar soils), measurements of H with depth in the regolith should be indicative of all solar-wind-implanted species.

Basis of the Technique: Simple neutron counters have been shown to provide high sensitivity for the detection of low H

concentrations from orbit under the assumption of an infinitely deep homogeneous chemistry, when the major-element composition is simultaneously determined using a gamma ray detector [7,8]. Newer calculations reported here show that interpretation of these data can be in error if the hydrogen content of the near-surface regolith is not homogeneous.

Hydrogen is notable for its high efficiency in moderating cosmic-ray-induced fast neutrons to thermal energies. The ratio of thermal to epithermal neutrons (those in the process of slowing) is a very strong function of the hydrogen content. In order to get high precision at low H concentration, however, the abundances of elements that strongly absorb thermal neutrons such as, e.g., Ti, Fe, Sm, and Gd, also need to be determined.

Recent calculations [7,8] showed that a determination of the hydrogen content down to levels of 10 ppm from orbit requires only a 1% statistical precision. However, interpretation of these data is subject to systematic uncertainties that may be larger than the 1% level, depending on the nature and magnitude of H abundance variations as a function of depth. Basically, the reduced mean-scattering path of thermal neutrons caused by the presence of H tends to concentrate neutrons from surrounding material into the high-hydrogen-content side of abundance-changing interfaces. For example, comparison of a lunar meteoritic chemistry loaded uniformly with 100 ppm of hydrogen down to 200 g/cm^2 below the surface, and then with 10 ppm H to the 900 g/cm^2 level, with the same chemistry loaded with 100 or 10 ppm H uniformly down to the 900 g/cm^2 level, shows about 2% variation in subsurface gamma ray production rates (and hence in thermal neutron number density).

Instrumentation: The neutron detection is made with two identical ^{3}He gas proportional counters, one being bare and the other being wrapped in Cd. The bare detector is sensitive to both thermal and epithermal neutrons, whereas the one wrapped in Cd is sensitive only to epithermal neutrons because Cd is a strong absorber of thermal neutrons. The abundances of the strong neutron absorbers in the soil will be made with a simple scintillator gamma ray spectrometer. Although this type of detector does not offer the high sensitivity of cooled semiconductor detectors, they are more than adequate for determination of the abundances of Fe and Ti, the principal neutron absorbers on the Moon. Samarium and Gd are not easily detected with this approach, but because of our extensive database of lunar rock types, these elements can be estimated easily from the abundances of other elements that will be determined with the GRS, especially K, U, and Th.

Delivery and Support System: The instruments will be delivered to the lunar surface via a penetrator with a separable afterbody. Using the soil penetration equations of [9] and assuming a penetrability comparable to dry silt or clay, a forebody mass of 30 kg, a diameter of 7.5 cm, and an impact velocity of 100 m/s, the forebody will penetrate to a depth of about 10 m while the afterbody will remain partially exposed on the surface to maintain communication with Earth. Reduction in this maximum depth can be readily achieved by reducing the impact speed. Both parts will contain neutron and gamma detectors in order to compare the differences between the surface and deep abundances. The penetrator will be battery operated to provide a life of about one week on the lunar surface.

Conclusions: Calculations of the depth dependence of thermal, epithermal, and fast neutron fluxes and consequent capture gamma ray production rates have shown their utility in determining the depth profile of H at the 10 to 100 ppm sensitivity level. Orbital surveys of these same data are not capable of such a determination. The two techniques therefore complement one another. Whereas orbital surveys can provide comprehensive maps of suspected hydrogen concentrations due to solar wind implantation, a penetrator can provide ground truth for a small selection of sites to allow estimates of the depth dependence of such deposits and consequently an evaluation of the utility of such deposits as a source of resources to support human habitation on the Moon.

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ESTIMATING LUNAR PYROCLASTIC DEPOSIT DEPTH FROM IMAGING RADAR DATA: APPLICATIONS TO LUNAR RESOURCE ASSESSMENT.   B. A. Campbell[1], N. J. Stacy[2], D. B. Campbell[2], S. H. Zisk[1], T. W. Thompson[3], and B. R. Hawke[1], [1]Planetary Geosciences, SOEST, University of Hawaii, Honolulu HI, USA, [2]NAIC, Cornell University, Ithaca NY, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA.

Introduction: Lunar pyroclastic deposits represent one of the primary anticipated sources of raw materials for future human settlements [1]. These deposits are fine-grained volcanic debris layers produced by explosive volcanism contemporaneous with the early stages of mare infilling [2,3]. There are several large regional pyroclastic units on the Moon (for example, the Aristarchus Plateau, Rima Bode, and Sulpicius Gallus formations), and numerous localized examples, which often occur as dark-halo deposits around endogenic craters (such as in the floor of Alphonsus Crater). Several regional pyroclastic deposits have been studied with spectral reflectance techniques: The Aristarchus Plateau materials were found to be a relatively homogeneous blanket of iron-rich glasses [4,5]. One such deposit was sampled at the Apollo 17 landing site, and was found to have ferrous oxide and titanium dioxide contents of 12% and 5% respectively [6]. While the areal extent of these deposits is relatively well defined from orbital photographs, their depths have been constrained only by a few studies of partially filled impact craters and by imaging radar data [7,1]. In this work, we present a model for radar backscatter from mantled units applicable to both 70-cm and 12.6-cm wavelength radar data. Depth estimates from such radar observations may be useful in planning future utilization of lunar pyroclastic deposits.

Radar Scattering Model: The depth of a pyroclastic layer is estimated based upon the ratio of backscattered power between a mantled region and an area of unmantled terrain assumed to represent the buried substrate. Several conditions are required: (1) Only the depolarized (same-sense circular) echo is modeled, to avoid consideration of large single-scattering facets; (2) there is no volume scattering within the pyroclastic (i.e., there are no inclusions large with respect to the radar wavelength); and (3) the depolarized backscatter originates largely within the regolith substrate, and not at its upper surface. Conditions (2) and (3) are supported by previous studies of the eclipse temperatures
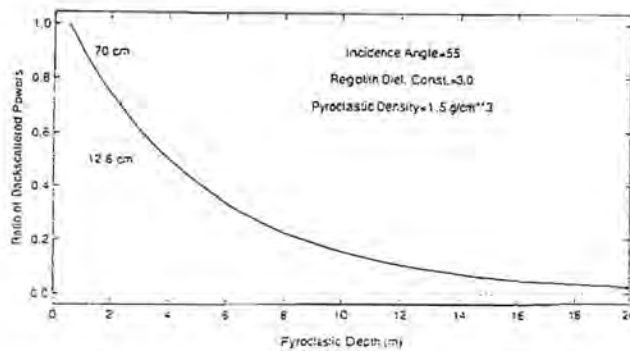
Fig. 1.

space, pyroclastic, and regolith respectively. The backscattered powers from an unmantled area are

$$Ph = 0.25 * S * (T_h{}^{t/r} + T_v{}^{s/r}) * T_h{}^{t/s}$$
$$Pv = 0.25 * S * (T_h{}^{s/r} + T_v{}^{s/r}) * T_v{}^{t/s}$$

Results: Figure 1 shows an example of this model for an incidence angle of 55°, corresponding to the Earth-based viewing geometry for the Aristarchus Plateau. The pyroclastic density was assumed to be a uniform 1.5 g/cm^3. The regolith real dielectric constant is assumed to be 3.0. Both 70-cm and 12.6-cm radar wavelengths are tested, and it is seen that the shorter wavelength is attenuated much more rapidly in the pyroclastic, as expected. The ratio between average 70-cm returns from the plateau and the mean lunar echo is ~0.30, implying a depth of 6–7 m based on these electrical parameters. This estimate is a lower bound; the actual buried highland terrain is likely much brighter than the Moon-wide average, implying a greater mantle depth.

Tests of the above model show that (1) it is relatively insensitive to variations in incidence angle between 20° and 60°, (2) it is insensitive to regolith dielectric variations from 2.5 to 4.0, (3) the scattered wave ellipticity is >85%, and (4) density variations with depth in the pyroclastic, within the narrow range permitted by realistic values of 1.5–2.0 g/cm^3, are not important unless the changes are very rapid. The value of the density at the upper surface of the layer is probably a satisfactory estimate for the overall density of such shallow deposits.

Conclusions: This technique may permit remote estimates of pyroclastic mantle depths from either Earth-based or lunar-orbital radar systems. A 3-km resolution map of the lunar nearside is available for 70-cm radar wavelength [12], and ongoing work at Arecibo Observatory provides additional data at 12.6-cm wavelength. We anticipate that such studies will be required in the planning stages of a lunar base project for resource assessment.

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of pyroclastic deposits and analysis of 70-cm backscattering from the lunar regolith [8,9].

Input parameters to the model are the radar wavelength, the radar incidence angle, and the dielectric parameters of the pyroclastic layer and the regolith substrate. The model used here permits analysis of a pyroclastic layer with varying density as a function of depth. The electrical properties of an Apollo 17 glass sample [6] as a function of density ρ are used here:

$$\epsilon_r = 2.1^\rho \quad \tan \delta = 0.0037 \, \rho$$

where ϵ_r is the real dielectric constant and $\tan \delta$ is the radar loss tangent. The real dielectric constant of the lunar regolith has been measured to be ~3.0, but may vary from mare to highland regions [10]. The incident circularly polarized wave is decomposed into horizontal and vertical polarized components, and the Fresnel transmission coefficients for each interface are calculated. Attenuation within the pyroclastic is assumed to be exp(-2αL), where L is the path length and α is the attenuation coefficient [11]

$$\alpha = k \, (0.5 * |(\tan\delta^2 + 1)^{0.5} - 1|)^{0.5}$$

where k is the radar wavenumber in the pyroclastic deposit. This expression is solved numerically in our model for the varying density within the lossy medium.

All the scattered radiation within the regolith layer is assumed to be randomly polarized, with some total backscattering efficiency S. In our model, we thus combine the H- and V-polarized components within the regolith, multiply by S, and split the remaining power evenly between the two polarizations for the return trip to the surface. The energy that exits the pyroclastic is assumed to have random phase, but may have an elliptical polarization due to the differing H and V transmission coefficients. The scatter from an unmantled regolith is also calculated, and the two results are combined into a ratio of total mantled/unmantled backscatter. This cancels the S term in both expressions. The ellipticity of the final scattered wave is assumed to be close to unity. The results are plotted as a function of power ratio vs. depth for a given set of electrical and density parameters.

In mathematical terms, the H and V backscattered powers from a mantled region are

$$P_h = 0.25 * S * A^2 * (T_h{}^{s/p} * T_h{}^{p/r} + T_v{}^{s/p} * T_v{}^{p/r}) * T_h{}^{r/p} * T_h{}^{p/s}$$
$$P_v = 0.25 * S * A^2 * (T_h{}^{s/p} * T_h{}^{p/r} + T_v{}^{s/p} * T_v{}^{p/r}) * T_v{}^{r/p} * T_v{}^{p/s}$$

where A is the total attenuation factor, and the T terms refer to H- and V-polarized Fresnel transmission coefficients for the layer interfaces noted in their superscripts; s, p, and r refer to

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A GROUND-BASED SEARCH FOR LUNAR RESOURCES USING HIGH-RESOLUTION IMAGING IN THE INFRA-RED. C. R. Coombs and T. S. McKechnie, POD Associates, Inc., 2309 Renard Place SE, Suite 201, Albuquerque NM 87109, USA.

Introduction: When humans return to the Moon (". . . this time to stay . . ." [1]) lunar resources will play an important role in the successful deployment and maintenance of the lunar base. Previous studies have illustrated the abundance of resource materials available on the surface of the Moon, as well as their ready accessibility [e.g., 2–5]. Particularly worth considering are the lunar regional (2000–30,000 km^2) pyroclastic deposits scattered about the lunar nearside. These 30–50-m-thick deposits are composed
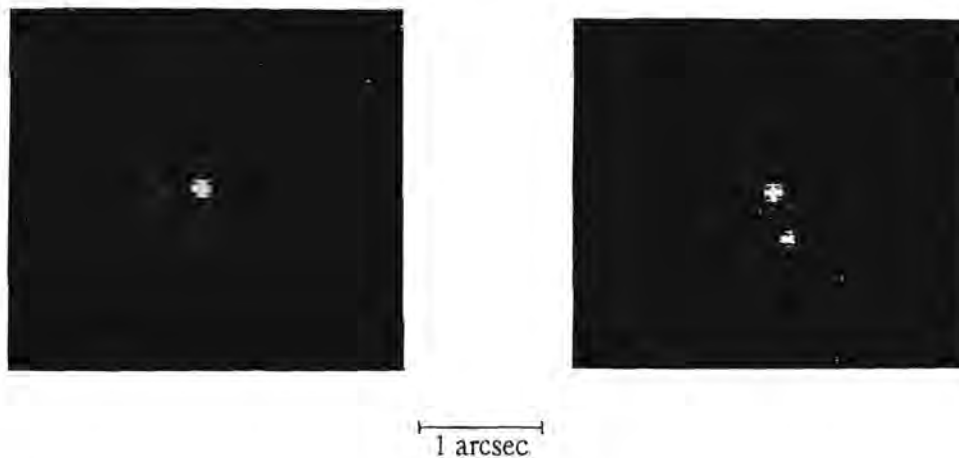
├─────── 1 arcsec ───────┤

Fig. 1.   Images of (a) Zeta Ophiuchi and (b) the 0.48-arcsec binary star Eta Ophiuchi obtained at 2.2 μm with the 4-m Kitt Peak telescope. The presence of the 0.1-arcsec cores easily allows resolution of the binary pair in spite of their close separation. Visual seeing was ~1–1.5 arcsec. Photos courtesy J. Christo (NOAO).

of fine-grained, unconsolidated titanium- and iron-rich mafic glasses and may be used as bulk feedstock for the beneficiation of oxygen, iron, titanium, sulfur, and other solar wind gases, or simply used as is for construction and shielding purposes. In this paper, we propose a groundbased observing survey of the resource-rich regions on the lunar nearside using a new imaging technique designed to obtain much higher resolution images, and more precise compositional analyses than previously obtainable.

High-Resolution Imaging: There is growing evidence that, contrary to popular wisdom, it should be possible to obtain diffraction-limited resolution at infrared wavelengths (>1 μm) from the ground without using adaptive optics. All that is needed is a telescope built to good enough optical specifications and the ability to compensate telescope motions. Left uncompensated, these motions, which are mainly caused by wind buffeting, can smear the image and cause serious loss of resolution. In this paper, an image stabilization system is proposed that will enable long-exposure imaging and spectroscopy to be carried out directly from the Earth with diffraction limited resolution.

According to recent atmospheric turbulence measurements [6–8], there is much less large-scale atmospheric turbulence than was previously thought. The lack of large structure implies much smaller RMS phase variation in the wavefronts entering the telescope. Over a 5-m aperture, the RMS wavefront height variation for 1-arcsec visible seeing is likely to be only about 0.3 μm, considerably smaller than previously thought. At visible wavelengths, these height variations will scramble the phases and give rise to badly degraded images. The phases of infrared wavelengths, however, are only partially modified by these same height variations so that only a portion of the light is scattered. Whereas this scattered portion will be imaged into a broad halo, the portion remaining intact, typically 50% of the light, will be focused into a diffraction limited core.

Figure 1 shows images of a single star and a 0.48-arcsec binary star obtained with the 4-m Kitt Peak telescope at 2.2 μm. The presence of the 0.1-arcsec core easily allows resolution of the binary. To obtain these images, a series of short exposures was taken to freeze the motion of the telescope. These were subsequently shifted and added so as to remove the motion. Long-

exposure images identical to those shown can be obtained in real time by using an image motion compensation system such as shown in Fig. 2. Motion compensation can be carried out by first imaging a reference star on to the tracking detector array. The image stabilizer control drives the tip/tilt mirror so as to stabilize the core in the reference star image. Because of the very large isoplanatic angle associated with the core (several arcmin [7]) the arrangement simultaneously stabilizes the cores of all other objects, and hence enables diffraction-limited resolution over a very large angular region.

For extended objects such as the Moon, convenient reference stars (or point objects) for stabilizing the image may not be present. However, the presence of the core in the point spread function gives rise to abrupt intensity changes across edge images. By
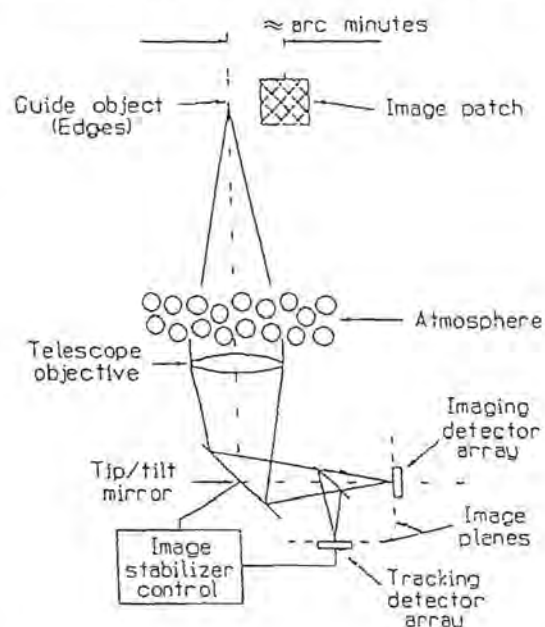

Fig. 2.   Image stabilization using a tip/tilt mirror driven by a tracking detector and control electronics that lock on to cores or edges.
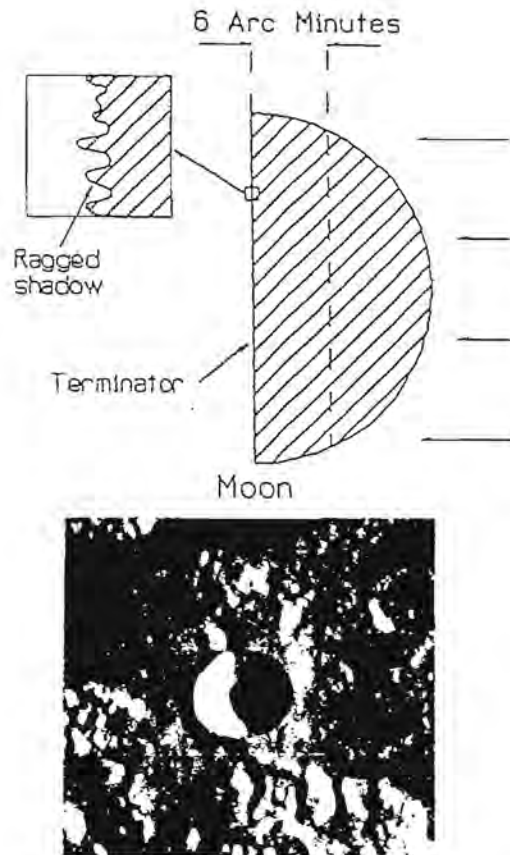
Fig. 3. The ragged edges at the lunar terminator provide suitable references for stabilizing the image. Using the configuration shown in Fig. 2 permits diffraction-limited imaging at IR wavelengths of a strip adjacent to the terminator several arcminutes wide.

tracking these abrupt intensity changes using two edges that are roughly at right angles to one another, image stabilization can be obtained to diffraction-limited accuracy. Suitable edges are found on the lunar terminator and at obliquely illuminated crater and basin edges (Fig. 3). Because the edges must lie within the isoplanatic angle of the region being imaged, it is only possible to image a strip a few arcminutes wide. Over the course of the lunar day (two weeks), however, a complete image of the lunar surface can be compiled using successive strips. With an infrared spectrometer mounted to this system, accurate compositional data will also be obtained.

The objective of this project is to conduct a lunar resource survey using image stabilization hardware of the sort shown in Fig. 2, in combination with a suitable edge-tracking algorithm. When the arrangement is used with existing 4–5-m class telescopes, 0.1-arcsec resolution (150 m) is expected at 2.2 μm. However, if the new 8-m (NOAO) telescopes are built to appropriate optical standards, diffraction-limited images should be obtained routinely at 1 μm. At this wavelength, 0.03-arcsec resolution is expected that, on the lunar surface, will result in imaging and spectroscopy being possible down to a 50-m spatial resolution element. With these resolutions, accurate geological and compositional maps may be constructed of the resource-rich regional pyroclastic deposits at a resolution currently not obtainable from Earth-based systems.

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A REMOTE LASER MASS SPECTROMETER FOR LUNAR RESOURCE ASSESSMENT. R. J. De Young and M. D. Williams, NASA Langley Research Center, Hampton VA 23665-5225, USA.

The use of lasers as a source of excitation for surface mass spectroscopy has been investigated for some time [1]. Since the laser can be focused to a small spot with high intensity, it can vaporize and accelerate atoms of material. Using this phenomenon with a time-of-flight mass spectrometer allows a surface elemental mass analysis of a small region with each laser pulse. While the technique has been well developed for Earth applications, space applications are less developed. The Soviet Union attempted to use a pulsed Nd:YAG laser to analyze the surface of the Mars moon, Phobos, using an instrument called "LIMA-D" [2]. Laser-induced ions would have returned to spacecraft hovering 50 m above the Phobos surface. Unfortunately, the mission was unsuccessful for reasons unrelated to the instrument.

NASA Langley recently began a research program to investigate the use of a laser to create ions from the lunar surface and to analyze the ions at an orbiting spacecraft. A multijoule, Q-switched Nd:YAG laser would be focused to a small spot on the lunar surface, creating a dense plasma. This plasma would eject high-energy ions, as well as neutrals, electrons, and photons, as shown in Fig. 1. Such a system is shown in schematic form in Fig. 2. Here the spacecraft is 10 km above the lunar surface, and for the parameters shown, would detect 10^7 ions per laser shot. The travel time and velocity of the elemental ions created is shown in Fig. 3, assuming a 10-eV equilibrium plasma. Detection of ions at large distance requires that the flight path be a larger than the collision mean-free path as shown in Fig. 4 where the mean-free path (km) is shown for various regions of space. The lunar environment provides very long collision mean-free paths for the detection of laser-produced ions.

Fig. 1.

Fig. 2.

Fig. 4.

Fig. 5.

Fig. 3.

ment could determine the surface composition on a centimeter-scale in one laser shot. Regions of high interest could be analyzed with fine spatial resolution. Since the plasma also generates photons and neutral particles, these could also be analyzed, providing additional information. The laser-produced plasma will have sufficient energy to create a shock wave in the lunar surface, which could derive information on the lunar subsurface.

This instrument could provide substantial benefits to planetary surface analysis, allowing smaller spatial resolution and faster analysis than other remote methods.

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AN α-p-x ANALYTICAL INSTRUMENT FOR LUNAR RESOURCE INVESTIGATIONS.   T. E. Economou and A. L. Turkevich, Enrico Fermi Institute, University of Chicago, Chicago IL 60637, USA.

An instrument using alpha backscattering, alpha-proton nuclear reactions, and X-ray production by alpha particles and other auxiliary sources can be used on lunar landers to provide detailed
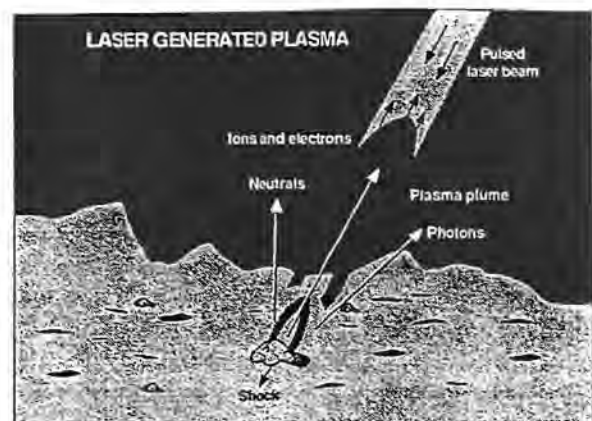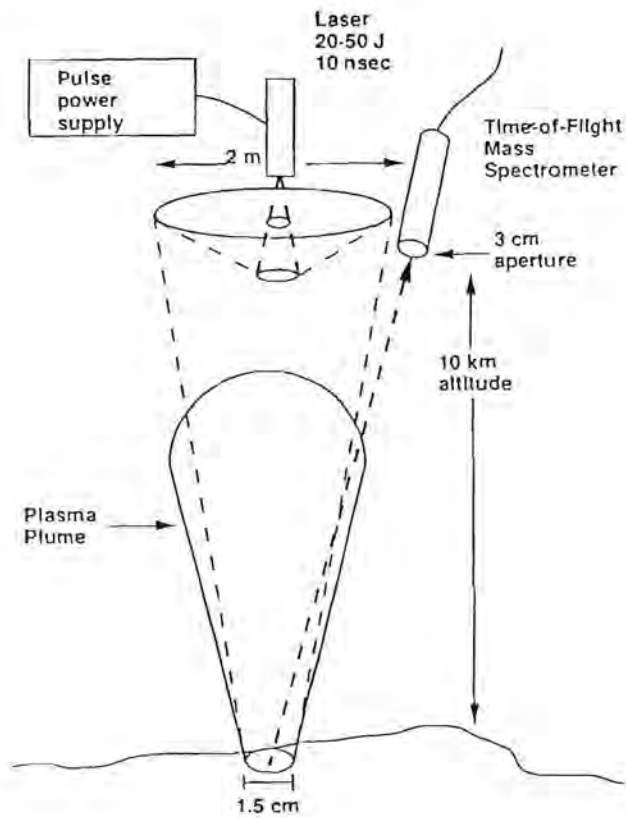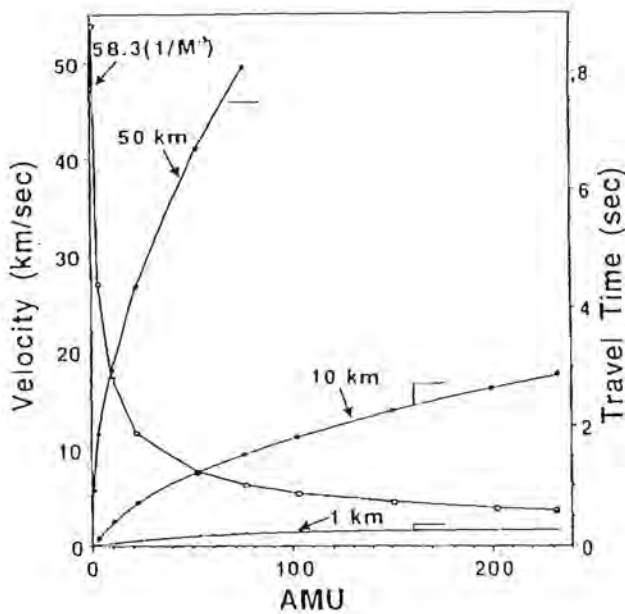
An experiment is now being set up (Fig. 5) to determine the characteristics of such a laser mass spectrometer at long flight distances. This experiment will determine the character of a future flight instrument for lunar resource assessment. Such an instru-
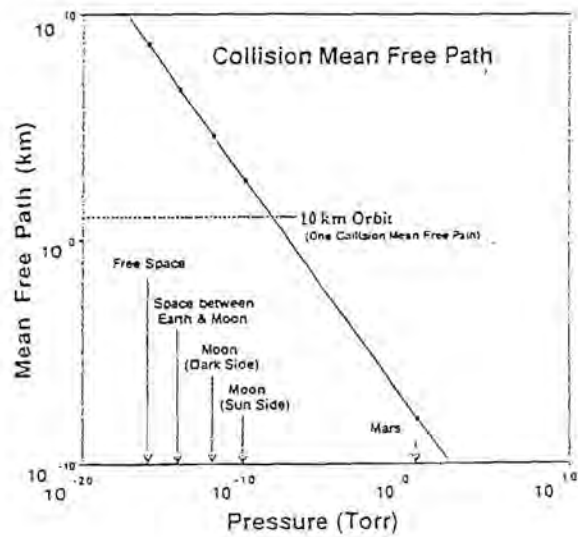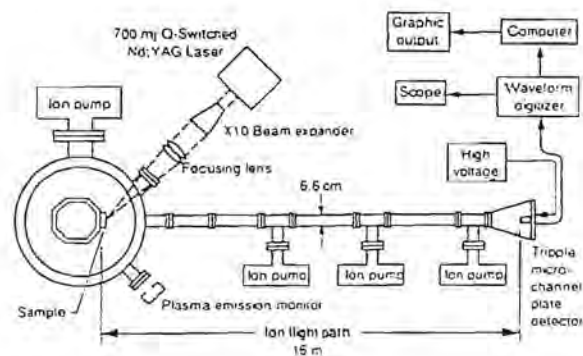
analytical information concerning the lunar surface material. This information is important scientifically and can be the basis for utilizing efficiently lunar resources to build lunar colonies in the future. This alpha particle instrument uses radioactive isotopes, silicon detectors for the alpha and proton modes, and mercuric iodide detectors operating at room temperature for the X-ray mode.

The instrument is highly developed and has significant space heritage. A similar instrument with alpha and proton modes was aboard the Surveyor 5, 6, and 7 and provided the first chemical analyses of the lunar surface in 1967–1968. During the 1970s, it was considered for the Viking missions, and the instrument was significantly miniaturized and its performance improved. An X-ray mode was subsequently added to the alpha and proton modes (α-p-x instrument [1]). Such an instrument was flown on the Soviet missions Phobos 1 and 2 targeted for the martian satellite Phobos in 1988. Unfortunately, both spacecraft missions ended prematurely before reaching Phobos.

Presently, the α-p-x instrument is on the payload of the Russian Mars '94 mission that is scheduled to land on the surface of Mars in 1995. This would provide a chemical analysis of the martian surface much more detailed than that obtained by Viking. A similar instrument is being developed for NASA as part of the straw-

TABLE 1. Expected accuracies (at 90% confidence limit) for principal chemical elements.

Element	α + p + X-ray modes Weight %	Atom %
C	±0.2	±0.4
O	±0.7	±1.0
Na	±0.2	±0.2
Mg	±0.8	±0.7
Al	±0.4	±0.3
Si	±1.2	±0.9
K	±0.2	±0.1
Ca	±0.2	±0.1
Ti	±0.15	±0.07
Fe	±0.4	±0.2

Fig. 1.   A comparison between the results on samples of lunar mare on Surveyor 5 and 6 with the data obtained later on Earth on samples brought back by the Apollo 11 astronauts from a mare site. It is seen that the Apollo data confirmed the Surveyor results to within the 90% error estimates claimed [2].

TABLE 2.   Examples of expected sensitivies for minor elements evaluated for a basalt matrix using alpha and auxiliary sources.

Element	α + p + X-ray modes Weight %	Atom %
N	0.2	0.3
F	0.05	0.06
P	0.2	0.14
S	0.1	0.07
Cl	0.1	0.06
K*	0.07	0.04
V	0.03	0.013
Cr	0.02	0.008
Mn	0.03	0.012
Ni	0.02	0.008
Cu	0.02	0.007
Zn	0.02	0.007
Rb	0.001	0.0003
Sr	0.001	0.0003
Y	0.0005	0.0001
Zr	0.0005	0.0001
Ba	0.001	0.00017
La	0.001	0.00016
Ce	0.0008	0.00013
Nd	0.0008	0.00012
Sm	0.0005	0.00007
Pb	0.005	0.0005
Th	0.005	0.0005
U	0.005	0.0005

* Sensitivity for K expected in the presence of a few weight percent of Ca.

man payload of the MESUR mission planned for Mars later in this decade.

The alpha and proton modes of the instrument can provide an analysis for all elements (except hydrogen) present in amounts greater than about 1% by atom. These modes have excellent sensitivity and accuracy for the lighter elements, in particular, directly determining the amount of oxygen in the lunar soil. This is an element of paramount significance for the lunar resource missions. The X-ray mode makes possible a determination of Ti, Fe, and other important metals with even greater accuracy. In general, the X-ray mode provides increased sensitivity for heavier elements, in many cases achieving a sensitivity of several hundred ppm.

The α-p-x instrument, due to its small size and low weight, can easily be mounted on a mobile lunar vehicle (rover or microrover), an approach that is highly desirable during the first lunar lander mission in order to increase the range of operations in the search for suitable sites for a permanent lunar base. This instrument does not require the acquisition of a sample on board the vehicle. It can be deployed to the lunar surface either directly or mounted on an arm of the rover and then selectively placed on samples of interest for analysis.

The entire instrument can be made to weigh less than 600 g and to require less than 350 mW of power. It accumulates three different energy spectra with ~15 kbit per sample and therefore imposes a very small burden on the spacecraft resources.

There are several areas where additional work is needed to optimize the instrument for lunar-type missions. A very suitable radioactive alpha source for the lunar missions is ^{242}Cm. This isotope has to be freshly prepared just before the mission. The alternative, ^{244}Cm, is more readily available, but would require

longer times for sample analyses. Early tests with these sources would be very desirable. Additional work with HgI_2 detectors and their performance under lunar conditions (e.g., high temperatures) will also have to be investigated.

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HIGH-RESOLUTION ELEMENTAL MAPPING OF THE LUNAR SURFACE.

Bradley C. Edwards, Frank Ameduri, Jeffrey J. Bloch, William C. Priedhorsky, Diane Roussel-Dupré, and Barham W. Smith, Los Alamos National Laboratory, Los Alamos NM 87545, USA.

New instruments and missions are being proposed to study the lunar surface as a result of the resurgence of interest in returning to the Moon. One instrument recently proposed is similar in concept to the X-ray fluorescence detectors flown on Apollo, but utilizes fluorescence from the L- and M-shells rather than the K-shell. This soft X-Ray Fluorescence Imager (XRFI) will be the topic of this presentation.

As was proven by the Apollo missions, the elemental composition of the lunar surface can be mapped using X-ray fluorescence from lunar orbit [1,2]. However, the spatial resolution and precision of the Apollo experiments were limited by both exposure time and flux. Although future missions will have longer lifetimes, the flux for K-shell fluorescence is still a primary limiting factor and imaging keV radiation with a wide field of view is difficult. However, the L- and M-shell fluorescence may provide a solution because the much more intense solar radiation at less than 1 keV will make the lower energy fluorescence flux up to 10^4 times more intense.

The theory behind the XRFI was discussed recently in Edwards et al. [3] and indicates that the fluorescent emission should be intense enough to be observed from lunar and even Earth orbit. Preliminary concepts and designs have been worked out for an XRFI that could be flown in lunar orbit in three years. XRFI is one in the suite of instruments on the Lunar Resource Mapping mission. The proposed instrument will provide maps with high

Fig. 1. Diagram of current ALEXIS telescope design. A similar design is to be used for the XRFI instrument on the LRM mission.

spatial resolution (1 km) of the surface distribution of a valuable suite of elements (Al, Mg, Si, Ca, Na, Fe, Ti, etc.).

Although this design is not ideal for the lunar study, optimized instruments with improved capabilities are only in the conceptual stage and may not be feasible for many years.

The XRFI set of soft X-ray telescopes would fly in lunar orbit to observe the fluorescent emission. The telescopes are of the same design to be used on the ALEXIS mission with a normal incidence multilayer mirror, a microchannel plate detector, and thin film filters. The technology, facilities, and software developed and tested for ALEXIS are to be directly applied to the XRFI.

Each telescope would be tuned to an energy that corresponds to an L- or M-shell fluorescent line. The intensity of each line is proportional to the elemental abundance, surface structure, and incident solar flux level. Details of the instrument, its requirements, specifications, and limitations will be presented.

Results from current feasibility studies of the XRFI concept being done at Brookhaven will be discussed and presented along with their implications. Future plans for studies, design, and construction of the XRFI and the lunar community's involvement is also a planned topic for this presentation.

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LUNAR AND ASTEROID COMPOSITION USING A REMOTE SECONDARY ION MASS SPECTROMETER.

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Laboratory experiments simulating solar wind sputtering of lunar surface materials have shown that solar wind protons sputter secondary ions in sufficient numbers to be measured from low-altitude lunar orbit. Secondary ions of Na, Mg, Al, Si, K, Ca, Mn, Ti, and Fe have been observed sputtered from sample simulants of mare and highland soils [1]. While solar wind ions are hundreds of times less efficient than those used in standard secondary ion mass spectrometry, secondary ion fluxes expected at the Moon under normal solar wind conditions range from ~10 to >10^4 ions $cm^{-2} s^{-1}$, depending on species. These secondary ion fluxes depend both on concentration in the soil and on probability of ionization; yields of easily ionized elements such as K and Na are relatively much greater than those for the more electronegative elements and compounds. Once these ions leave the surface, they are subject to acceleration by local electric and magnetic fields. For typical solar wind conditions, secondary ions can be accelerated to an orbital observing location. The same is true for atmospheric atoms and molecules that are photoionized by solar EUV. Here we discuss the instrumentation to detect, identify, and map secondary ions sputtered from the lunar surface and photoions arising from the tenuous atmosphere.

Solar Wind-sputtered Secondary Ions and Surface Composition: Our laboratory experiments subjected three simulants of Apollo soil samples to ion bombardment, and measured the relative efficiencies of solar wind ions in sputtering secondary ions. The
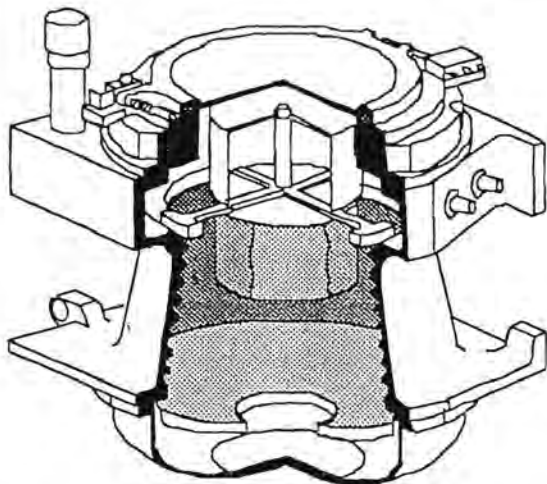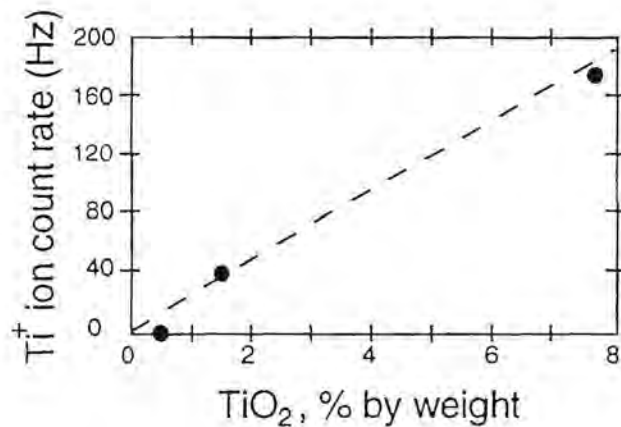
Fig. 1. Intensity of secondary Ti$^+$ ions sputtered by 1.5-keV H$^+$ vs. bulk TiO$_2$ measured by electron microprobe.

simulants were replications of an Apollo 11 high-Ti mare basalt soil, an Apollo 15 low-Ti mare basalt soil, and an Apollo 16 aluminous highland soil. They were left in rocky, not powdered form. These simulants were subjected to bombardment by Ar and Ne ions at 5-keV energies, and the solar-wind-like ions of H and He at 1.5- and 4-keV energies respectively. The very different nuclear stopping powers of these ions in the target materials allowed us to study the relative sputtering efficiencies. Ar$^+$ at 5 keV, with its much larger nuclear stopping power, is about a factor of 400 more efficient than 1.5-keV H$^+$ in sputtering secondary ions. The major geochemical elements Na, Mg, Al, Si, K, Ca, Ti, Mn, and Fe are nevertheless detectable.

While we have a first-order understanding of secondary ion sputtering, it is not immediately obvious that the observed ion yields can be linked with great accuracy to the simulants' composition. The simulants were analyzed by electron microprobe to establish their detailed composition. The observed secondary ion fluxes can then be compared with the microprobe results. One example is shown in Fig. 1, where observed Ti$^+$ fluxes from the three simulants are plotted vs. the weight percent of TiO$_2$. The results show that the sputtered Ti$^+$ secondary ions correspond to the true composition with accuracies of better than 10% for the high-Ti basalt, and about 20% for the low-Ti simulant. The highland simulant produced a statistically insignificant Ti$^+$ count rate. Similar but poorer results were obtained for the elements Al, Fe, Ca, and K. The response of Mg ions did not correlate well with composition under any circumstances. Sodium content did not vary enough between samples to do the comparison. We believe the cause of this poor correlation is that sputtered materials redeposited on adjacent surfaces (all three simulants were in the same vacuum chamber). This led to cross contamination between the samples. In the future we intend to redo the experiment one sample at a time to prevent this problem.

The relative total secondary ion yields sputtered by Ar, Ne, and He demonstrate a well-behaved exponential dependence on nuclear stopping power. However, the 1.5-keV H$^+$ yield is about an order of magnitude larger than predicted; H is a more efficient sputterer than one might expect. Yields of the various constituents of the simulants depend upon both the elemental concentration and ionization potential of the species, or alternatively its electronegativity. This dependence of positive secondary ion yield on ionization potential was suggested first by Anderson and Hinthorne

[2]. In addition, it should be remembered that the secondary ion yields from regoliths are less than that from solid rocky targets [3].

Once the secondary ions are ejected from a surface grain, they are subject to ambient electric and magnetic fields. Sunlit surfaces emit photoelectrons and, up to about 80° solar zenith angle, are positively charged; shadowed regions may become negatively charged to −100 V. In most sunlit regions the secondary ions will be accelerated away from the surface by the positive surface charge; the influence of this field extends out one or two Debye lengths, typically a few meters. Thereafter, the ions are exposed to the solar wind $\mathbf{V} \times \mathbf{B}$ electric field, which normally points approximately toward either ecliptic north or south. For typical conditions, this electric field is so intense it dominates the secondary ion equation of motion, and the ions simply "fall" along the electric field lines. Figure 2 shows several characteristic ion trajectories in typical solar wind conditions. However, in regions of remnant magnetism on the lunar surface, local magnetic field intensities may (1) deflect and decelerate the incoming solar wind and (2) may trap the sputtered secondary ions [4]. Nevertheless, these high surface field regions are limited to 10–30-km size scales, about the size of an ion mass spectrometer "pixel" from a 100-km orbit. Moreover, even secondary ions that are locally trapped may drift to weaker field regions where they can be picked up by the solar wind electric field. Quantitative simulations of secondary ions in remnant fields confirm this escape scenario.

Detection and Mapping of Outgassed Volatiles: In addition to detecting sputtered secondary ions from the lunar surface, a high-sensitivity, high-mass-resolution orbital ion mass spectrometer can detect and map atmospheric ions. The ion mass spectrometers placed on the lunar surface during Apollo proved that this measurement can be made. The known atmospheric constituents include Ne, Ar, Na, and K; other species are likely. Apollo surface atmospheric measurements showed a high correlation of global atmospheric Ar content with deep lunar seismic activity; increases in the Ar density followed every moonquake. The relationship between deep seismics and volatile venting is not understood. Moreover, arguments based on the Apollo alpha spectrometer measurements of radon (cf. [5]) suggest that volatile transport from subsurface reservoirs can on occasion be substantial. It is important to measure episodic lunar volatile venting and establish those regions that are most active.

Atmospheric constituents that have been photoionized by solar EUV will be accelerated by the solar wind electric field in the same way as surface-sputtered ions. These photoions travel from their creation point along the electric field into the instrument. In this way an ion mass spectrometer can actually sound the atmospheric structure. More importantly, the instrument can detect atmospheric transients such as volatile venting episodes without actually being over the site of activity. The vented volatile atoms and molecules hop along the surface ballistically, random walking their way around the Moon; as this diffusive "wave" passes by the spacecraft, an increase in the flux of photoions produced nearby will be detected.

The 3-D Linear Electric Field Ion Mass Spectrometer: We discuss here the design of a secondary ion mass spectrometer that can be flown in lunar orbit or on an asteroid rendezvous mission. In order to map elemental composition of the Moon or asteroid, high sensitivities and high mass resolutions (m/Δm ~ 50 at FWHM) are necessary. A new design using a three-dimensional Linear Electric Field (LEF3D) time-of-flight spectrometer meets these

requirements. A similar design presently being developed for the Cassini mission is currently undergoing prototype testing.

Our mass-measuring technique, based on the motion of ions in a region of linear electric field (LEF), is quite simple. For a z-directed electric field $E_z(z)$ that increases linearly with distance along the axis, z, $E_z(z) = -kz$, where k is a constant solely dependent upon the electromechanical configuration of the device. Since the electrostatic force on a particle is qE, where q is the particle charge, the equation of motion for the particle in the z direction is that of a simple harmonic oscillator of mass m. A particle entering the LEF region at z = 0 will return to the z = 0 plane after completing half of an oscillation cycle, i.e., when $t = \pi/\omega = \pi (m/qk)^{1/2}$.

This timing is accomplished by passing the arriving ions through an ultrathin carbon foil; secondary electrons produced at the foil are accelerated in the LEF region to a detector that starts a timing clock. Positive ions emerging from the foil enter the LEF region and are reflected as described above, and are counted at a second detector that provides the stop signal for that ion's time of flight.

However, another feature of the mass spectrometer described here involves the analysis of molecular ion species. In addition to providing start timing pulses, the carbon foil also dissociates molecular ions. All ions are electrostatically energy-selected and arrive at the foil with a known energy/charge. Passing through the foil, it is dissociated into fragments that all travel with nearly the same velocity so that the energy is partitioned in proportion to the mass of each fragment. These fragments then have less E/q than the initial molecular value and will not travel as deeply into the LEF region of the device as would directly analyzed atomic ions of the same nominal E/q. Because of small E-field nonlinearities in an appropriately detuned LEF3D device, especially at the low-potential entrance end of the device, the times of flight of the fragments can be made shorter than those of atomic ions, an effect that allows separation of molecular and atomic interferences.

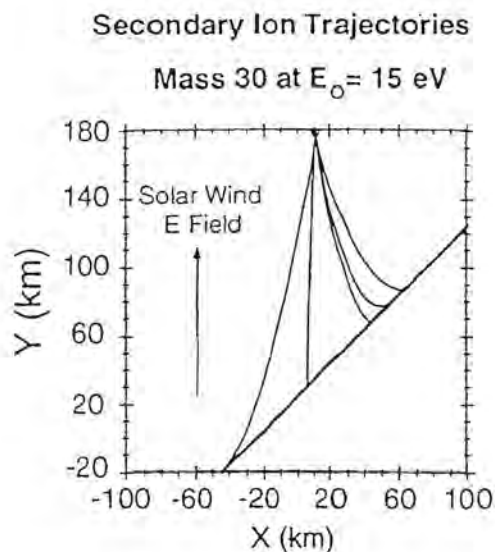## Secondary Ion Trajectories

Mass 30 at E_o= 15 eV

Fig. 2. Trajectories of sputtered secondary ions for typical solar wind conditions. Two representative paths illustrate how ions originating at different locations pass through a 100-km lunar orbit; the two ions are distinct in their arrival directions and their energies.

Finally, in addition to its orbital reconnaissance role, an LEF3D instrument can also perform surface composition measurements in conjunction with an active sounding technique. For example, ions produced by laser-induced breakdown of lunar materials would facilitate remote assessment of exposed materials not accessible to direct rover sampling, for example. An LEF3D instrument on a stationary landed platform would also provide synoptic monitoring of the atmosphere and volatile environment in conjunction with a geophysical station.

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LUNAR RESOURCE ASSESSMENT: AN INDUSTRY PERSPECTIVE.
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Introduction: The goals of the U.S. space program are to return to the Moon, establish a base, and continue onward to Mars. To accomplish this in a relatively short time frame and to avoid the high costs of transporting materials from the Earth, we will need to mine resources on the Moon. Oxygen will be one of the most important resources, to be used as a rocket propellant and for life support. Ilmenite and lunar regolith have both been considered as ores for the production of oxygen.

Resource production on the Moon will be a very important part of the U.S. space program. To produce resources we must explore to identify the location of ore or feedstock and calculate the surface and underground reserves. Preliminary resource production tests will provide the information that can be used in final plant design. Bechtel Corporation's experience in terrestrial engineering and construction has led to an interest in lunar resource assessment leading to the construction of production facilities on the Moon.

There is an intimate link between adequate resource assessment to define feedstock quantity and quality, material processing requirements, and the successful production of lunar oxygen. Although lunar resource assessment is often viewed as a research process, the engineering and production aspects are very important to consider. Resource production often requires the acquisition of different types, scales, or resolutions of data than that needed for research, and it is needed early in the exploration process. An adequate assessment of the grade, areal extent, and depth distribution of the resources is a prerequisite to mining. This paper emphasizes the need for a satisfactory resource exploration program using remote sensing techniques, field sampling, and chemical and physical analysis. These data can be used to define the ore for oxygen production and the mining, processing facilities, and equipment required.

Background: The lunar environment is harsh and the emplacement of production facilities and mining will not be simple. Adequate data gathered now will prevent costly errors later. There are special problems associated with the lunar environment and mining operations. Temperature fluctuations will cause materials to become brittle. Reduced gravity will affect material handling

and transport. The near-vacuum conditions will result in outgassing of materials and difficulties with lubrication around bearings and seals.

Some extreme conditions that provide construction challenges are also found on Earth. Bechtel Corporation has successfully designed, engineered, and constructed the Polaris mine, processing plant, and support facilities for COMINCO of Canada. The Polaris lead and zinc mine is located 90 miles north of the Arctic Circle and 600 miles from the North Pole. The entire processing plant was built on a single barge and delivered to the site during the last high tide, before the end of the six-week-long ice-free shipping season. It was docked in a dredged area, frozen in place, and has operated year round.

We can take advantage of our resource processing experience in the terrestrial environment in planning for lunar oxygen production. However, the Moon presents unique processing challenges. One of the unique problems on the Moon is that the ore or feedstock is being characterized at the same time that processing design decisions need to be made. Various authors have rated the favorability of different oxygen production processes. There is no general agreement on the best process or the most desirable feedstock [1]. Processes such as pyrolysis, electrolysis, and hydrogen reduction have been cited as being the most feasible. The process finally chosen will depend on the type of feedstock and will dictate the number of operating units, the reagents, and the power supply required. Since the required facilities and some materials will need to be transported from the Earth at great expense, at least initially, careful decisions must be made for process selection and plant design.

The feedstocks most often cited as resource material are bulk soil and ilmenite. However, we cannot choose a process that requires ilmenite unless we know that there are sufficient reserves at and below the surface. The consistency of the bulk soil composition, the impurities, and the grain size of the bulk soil at proposed mining sites also need to be determined if lunar regolith is to be used as the feedstock.

The ore or feedstock grade and the areal and depth distribution of the ore will control the amount and type of mining equipment needed to supply the process plant. Hypothetically, an ore with 5% ilmenite might require 20 mining and transport vehicles, while an ore with 20% ilmenite might require 5 vehicles.

Remote Sensing of Lunar Resources: Various remote sensing methods have been devised to assess lunar resources, specifically ilmenite. Telescopic measurements from Earth with spatial resolutions of between 1 and 20 km have been our greatest source of mineralogical data. The telescopic measurements have been used in conjunction with chemical analyses of a very limited number of lunar samples. The information that will be needed for material processing will require even higher resolution.

Based on earlier work by Charette and others [2], Pieters [3] has graphed the TiO_2 content of lunar samples from Apollo and Luna missions against the telescopic reflectance of those sample sites. These authors have found a distinctive relationship between the weight percent of TiO_2 and the ratio of the spectral bands at 0.40- and 0.56-μm wavelength. This relationship is only applicable to sites with mature regolith that contain abundant agglutinate and other glass. A linear relationship was found at higher concentrations of TiO_2. Johnson and others [4] have mapped surface ilmenite concentrations from telescopic reflectance measurements and have identified two regions with greater than 8 wt% TiO_2. The projected concentrations are based on concentrations

in returned lunar samples. Most of our knowledge of the chemical and mineralogical composition of the Moon has come from the 832 kg of samples returned during the Apollo missions from six sites.

To examine the lunar resource assessment process, a known mining area in northern California was selected as a lunar analogue. Bechtel contracted for a flight line of remote sensing data over the New Almaden mercury mine, south of San Francisco, near San Jose. This mine has produced 40% of the mercury mined in the U.S. The site was chosen because the area contains some rocks and minerals that are analogous to lunar rocks, including iron oxide minerals. The data were acquired with the Geoscan MkII Airborne Multispectral Scanner. The sensor has 24 spectral bands in the visible, near infrared, shortwave infrared, and thermal infrared parts of the spectrum. The spatial resolution on the New Almaden flight was about 5 m. Existing topographic and geologic maps were used in the resource assessment in conjunction with the remote sensing data.

By examining the spectral curves of minerals associated with the mercury ore, processing strategies were defined to map iron-stained silica carbonate rock and serpentinite. Two separate mappings were produced. The first indicated a conservative estimate of mineral distribution, and the second a less conservative estimate. From indications in the field, the true mineral distribution is somewhere between the two estimates. The remote sensing data are most effective when used together with field sampling and chemical and mineralogical testing. This will be especially important in the lunar resource assessment program.

Conclusions: It is essential to define the lunar ore material and assess its grade and areal and depth distribution. Experience with Canadian gold mines shows that two to three times as many mines fail as succeed. We cannot afford a failure on the Moon, and accurate resource assessment is a key part of the success strategy. The keys to the success of lunar mining operations are caution with new processes, the collecting and testing of bulk samples, and adequate ore reserve calculations.

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LUNAR RESOURCES USING MODERATE SPECTRAL RESOLUTION VISIBLE AND NEAR-INFRARED SPECTROSCOPY: Al/Si AND SOIL MATURITY. Erich M. Fischer, Carlé M. Pieters, and James W. Head, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

Introduction: Modern visible and near-infrared detectors are critically important for the accurate identification and relative abundance measurement of lunar minerals; however, even a very small number of well-placed visible and near-infrared bandpass channels provide a significant amount of general information about crucial lunar resources. The Galileo Solid State Imaging system (SSI) multispectral data are an important example of this. Al/Si and soil maturity will be discussed below as examples of significant general lunar resource information that can be gleaned from moderate spectral resolution visible and near-infrared data with
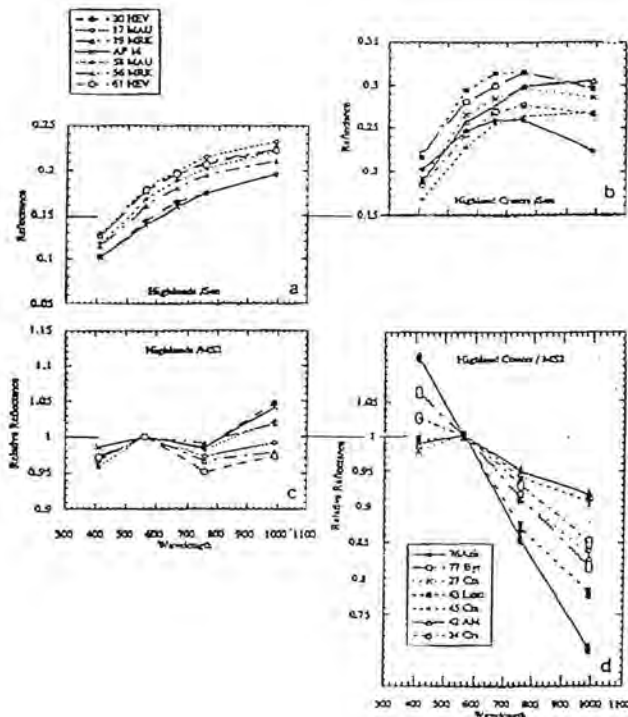
Fig. 1.   Representative SSI spectra of mature ("highlands") and immature ("highland craters") highland materials. (a) and (b) are scaled to "Sun," thus preserving albedo information. (c) and (d) are scaled to the Mare Serenitatis standard area MS2 and 0.56 μm, accentuating color differences. Figure adapted from [10].

relative ease. Because quantitative albedo data are necessary for these kinds of analyses, data such as those obtained by Galileo SSI are critical.

SSI obtained synoptic digital multispectral image data for both the nearside and farside of the Moon during the first Galileo Earth-Moon encounter in December 1990 [1]. The data consist of images through seven filters with bandpasses ranging from 0.40 μm in the ultraviolet to 0.99 μm in the near-infrared. Although these data are of moderate spectral resolution, they still provide information for the following lunar resources: (1) titanium content of mature mare soils based upon the 0.40/0.56-μm (UV/VIS) ratio, (2) mafic mineral abundance based upon the 0.76/0.99-μm ratio, and (3) the maturity or exposure age of the soils based upon the 0.56–0.76-μm continuum and the 0.76/0.99-μm ratio. Within constraints discussed below, these moderate spectral resolution visible and near-infrared reflectance data can also provide elemental information such as Al/Si for mature highland soils.

Soil Maturity from the SSI Data: Immature soils, relatively unweathered in the lunar environment due to their young exposure age, are fundamentally different from mature soils. For example, immature soils are coarser and contain fewer aging products such as agglutinates (derived from micrometeorite impact) and solar-wind-implanted components such as hydrogen and helium. These fundamental differences cause immature lunar materials to be optically different from their mature counterparts. Immature soils associated with fresh impact craters are particularly useful for the study of vertical and horizontal crustal heterogeneity since they have much higher spectral contrast and thus provide excellent information on mineralogical composition. On the other hand,

immature materials would be a very poor source of solar-wind-implanted components and iron-rich agglutinates. Moderate spectral resolution visible and near-infrared spectroscopy can be used for distinguishing between mature and immature soils.

Illustrated in Figs. 1a through 1d are representative SSI spectra of mature highland soils and immature highland materials. The spectra in Figs. 1a and 1b have been scaled to "Sun," thus keeping the albedo information, while those in Figs. 1c and 1d have been scaled to the Mare Serenitatis standard area MS2 and also to 0.56 μm, allowing color differences to be discerned more easily. These figures illustrate three critical optical/spectral properties that differ between immature and mature highland soils; these are (1) albedo, (2) the 0.56–0.76-μm continuum, and (3) the 0.76/0.99-μm ratio. Immature highland materials are characterized by higher albedos, lower 0.76/0.56-μm ratios, and higher 0.76/0.99-μm ratios relative to their mature counterparts. Because the albedos of mature and immature highland materials overlap to some extent, we have decided to use only the 0.76/0.56-μm and 0.76/0.99-μm ratios to distinguish immature and mature highland materials in this study. Figure 2 illustrates the relationship between the 0.76/0.56-μm and 0.76/0.99-μm ratios for the Galileo SSI lunar coverage. Although not obvious from this figure, there are very useful and systematic relationships between these two ratios. As described above, most immature highland materials can be characterized well as having 0.76/0.56-μm ratios lower than a certain value and 0.76/0.99-μm ratios higher than a certain value; thus they plot in the upper lefthand portion of the scatterplot. Using these two criteria, the immature highland materials observed by SSI can be identified.

Al/Si Calculated from the SSI Data: While the mineralogical information normally associated with visible and near-infrared multispectral data is clearly pertinent to the assessment of lunar resources, this type of data can provide additional compositional information with which it is not usually associated. An example is derived from the important positive relationship that was observed between Al/Si measured by the Apollo X-ray spectrometer, and normal albedo [2,3]. The linear portion of the relationship between albedo and Al/Si, shown by the line in Fig. 3, appears to be dominated by mature lunar highland soils. Near the low albedo values of the mare, the linearity may to some extent be affected by mare/highland mixing. This linear relationship for mature highland soils is intuitively expected because, for a steady-
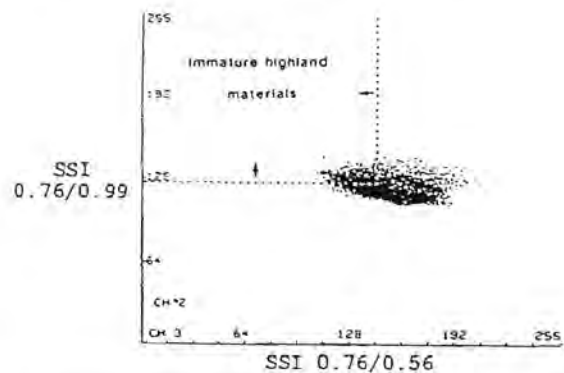

Fig. 2.   Scatterplot of the 0.76/0.56-μm continuum ratio vs. the 0.76/0.99-μm ratio for the Galileo SSI lunar coverage. Immature highland materials systematically lie in the upper lefthand quadrant of this plot. Axis values are in DNs.
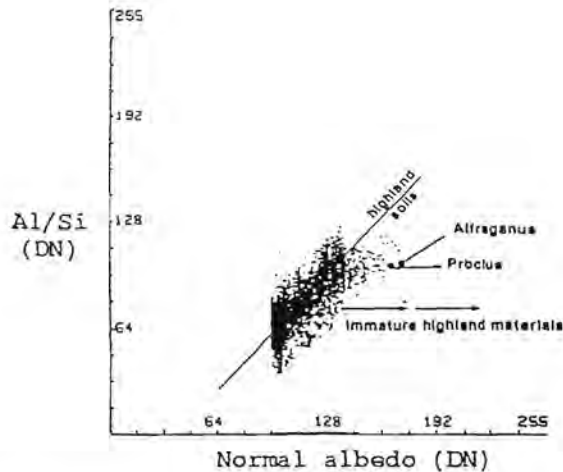
Fig. 3. Scatterplot of Al/Si from the Apollo X-ray spectrometer [6] vs. lunar normal albedo [7]. DN values are from the La Jolla Consortium data. The line marked "highland soils" illustrates the linear trend of the mature highland soils. Points marked "Proclus" and "Alfraganus" are fresh impact craters. Direction of immature highland materials is indicated by the arrow.

Fig. 4. Three-slice map of relative Al concentration for the highland soils observed by SSI (overlain by the La Jolla Consortium grid). Black corresponds to regions (mare and immature soils) for which Al concentrations cannot be calculated using the procedure described in the text. Brighter grey levels correspond to higher relative Al concentrations. o = Orientale Basin, h = Hertzsprung Basin, sp = South Pole-Aitken Basin, and ss = Schiller-Schickard.

state (mature soil) abundance of absorbing soil alteration (aging) products and grain-size distribution, the albedo of anorthositic highland material would be expected to be controlled by the abundance of feldspar, which in turn also controls the Al/Si value due to its Al-rich nature. On the other hand, two types of lunar material do not follow a simple direct relationship between albedo and Al/Si. One of these materials is mare soil. These soils, plotting at normal albedos of less than approximately 106 DN in Fig. 3, are not expected to follow such a direct relationship since the range of plagioclase abundance is limited while the amount of albedo-controlling opaques varies extensively. The other type of lunar material that diverges from the linear relationship is material excavated by recent highland impact events (points lying to the right of the linear trend). The points labeled "Proclus" and "Alfraganus" in Fig. 3 are fresh highland impact craters. The high albedo of most types of recently excavated feldspathic material is normally not due to extremely high aluminum content, but rather due to the fact that the material has not been exposed long enough to have appreciably darkened by accumulation of agglutinates and other processes (i.e., [4,5]). If the correlation between albedo and Al/Si is corrected for the mare soils and immature material, then the linear relation can be utilized to calculate Al/Si. The mare soils can easily be excluded simply on the basis of albedo. The immature highland materials are identified and removed using the 0.76/0.56-μm and 0.76/0.99-μm ratios, as discussed above. Although the Apollo X-ray spectrometer data cover only 9% of the lunar surface, if the same correlation between albedo and Al/Si is valid for the mature highland soils of the rest of the Moon, then Al/Si can be estimated for other areas by using quantitative albedo information. Quantitative albedo can be derived from SSI or other radiometrically calibrated visible or near-infrared data. The distinct advantage of the SSI data in this case is their extensive spatial coverage.

Since the Apollo X-ray and current SSI data do not overlap to a great extent, in order to compute Al/Si for regions observed by SSI, a three-step process is used to relate the two datasets. The first step is to quantify the linear relationship between Al/

Si [6] and normal albedo [7] for the mature highland soils for which the two types of data exist (portions of the eastern nearside and limb). This relationship is illustrated by the straight line in Fig. 3. The values on the axes are in DNs as per the La Jolla Lunar Consortium data. Conversion to actual Al/Si and other values will be undertaken in the future. Then, normal albedo is calculated for the SSI data from an empirical relationship between normal albedo and SSI reflectance at 0.56 μm for the areas where the two types of data overlap (most of the western nearside). Finally, using the normal albedo of the SSI data, Al/Si is estimated for the mature highland soils observed by SSI by employing the relationship quantified in step 1.

From this analysis we find that large-scale variations in aluminum content occur throughout the highlands observed by SSI (Fig. 4). Relative depletions of aluminum occur in the South Pole-Aitken region and the Schiller-Schickard cryptomare region. This is expected for Schiller-Schickard if less aluminous mare soils were indeed mixed with more aluminous highland soils in this area. Relative concentrations of aluminum occur in the Bailly, Korolev-Hertzsprung, and Orientale regions. The finding of high concentrations of aluminum in the Orientale region is supported by the discovery of anorthosite-rich massifs in the Inner Rook Mountains [8,9].

Conclusion: The simple techniques described above can be used to derive a surprising wealth of general information about a number of critical lunar resources. Although simple in nature, the importance of these techniques should not be underestimated as they rely only upon existing technology and very spectrally limited data. The proposed lunar Discovery/Scout-class missions to the Moon may provide a mechanism for quickly obtaining global basic lunar resource information with a moderate spectral resolution, high-spatial-resolution visible, and near-infrared imaging system.

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RADON AS A TRACER FOR LUNAR VOLATILES.

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Introduction: Radon and its decay product polonium can be used as tracers to search for lunar volatiles. One effective technique to look for them would be by using alpha-particle spectrometers from lunar orbit.

Alpha spectrometers were flown in the Apollo Service Modules during the Apollo 15 and 16 missions, and did observe ^{222}Rn and its decay product ^{210}Po on the lunar surface from orbit [1,2]. This demonstrates that radon and polonium can be observed from orbit; what must next be shown is that such observations can reveal something about the locations of volatiles on the Moon.

How Radon and Polonium Can Act as Tracers for Volatiles: What must first be understood is that radon released in the lunar regolith has a very low probability of reaching the surface before it decays, if it must do so under its own power, by random walk. Under the extreme vacuum of the Moon, the mean free path of a radon atom's random walk is not determined by collisions with other gas molecules, but rather by collisions with soil grain surfaces. The problem the atom faces is that it has such a high heat of adsorption that when it collides with a soil grain surface, it tends to stick very tightly to that surface, and thus remain there for a comparatively long time before it takes the next hop. This slows down the diffusion process so much that almost all of the radon atoms random walking in this way will decay before they reach the lunar surface [3]. On top of that, radon atoms may have difficulty getting "unstuck" from their production sites into the intergrain volume for even the first hop [2].

For these reasons, if radon or its decay product polonium are seen on the lunar surface in significant amounts, the radon was almost certainly swept out by some other outflowing gas or gases. The Apollo 15 and 16 orbital alpha spectrometer results indicate another reason to suspect that radon is brought to the surface by sweeping rather than by random diffusion: the radon and polonium decay rates observed were not in equilibrium with each other [1,2]. At Aristarchus Crater during Apollo 15, the decay rate of ^{222}Rn was in excess of what would be in equilibrium with ^{210}Po [1]. At other locations, such as Grimaldi Crater and the edges of circular maria, the decay rate of ^{210}Po was in excess.

The half-life of ^{222}Rn is 3.8 days. The time to reach decay equilibrium between ^{222}Rn and ^{210}Po is largely controlled by the 22.3-year half-life of the intermediate isotope ^{210}Pb. Thus the disequilibria between decay rates of radon and polonium indicate that outflow rates of radon at these locations on the Moon have varied on timescales of days to years. Indeed, given the short half-

life of ^{222}Rn, the radon observed at Aristarchus during Apollo 15 must have been coming out of the Moon during the time of the mission, or within a few days before. This is a further argument in favor of a sweeping mechanism for bringing the radon to the surface, rather than a steady diffusion. In this connection, it is worth noting that the sites where higher-than-average radon and polonium decay rates were observed—Aristarchus, Grimaldi, and edges of circular maria—are among those most frequently cited as locations for lunar transient events (LTE), as summarized by Middlehurst and Moore [4,5]. For these reasons, it has previously been suggested [6] that radon and polonium can act as a tracer system for recent geologic activity on airless planetary bodies.

But radon and polonium activity can trace not only where activity is taking place, but where volatile deposits are. For in order for a "sweeping" mechanism to bring radon to the surface, there must be volatile reservoirs as well as activity to bring it up. So observing major amounts of radon and/or polonium at some location on the surface would be a strong indicator of a source of volatiles beneath that location.

Where might such sources of volatile materials lie, and how might they have gotten there? One possibility is that, even though analysis of returned samples indicates that the near-surface layers of the Moon are extremely depleted in water and other volatiles, deposits of volatiles may exist at greater depths. Our present understanding of the Moon's formation and history is not yet complete enough to rule this out. Another concept, mentioned by Smith [7] and Feldman et al. [8], is that some fraction of the water from comets impacting the Moon may be driven down into the regolith and megaregolith by the impact process, to be trapped in pores and fractures or to form hydrated minerals, and remain buried for geologically significant periods of time.

The latter idea, if correct, would make understandable the association of many LTE with young bright ray craters, such as Aristarchus.

Such potential pockets of buried cometary volatiles represent another place to search for useful volatile materials, in addition to the frequently mentioned idea of ice deposits in permanently shadowed craters at the lunar poles [9]. We should keep in mind that no one presently knows for certain that such polar ice deposits exist.

We don't know, of course, whether any pockets of cometary volatiles exist elsewhere, either. And in fact, Smith's suggestion runs counter to estimates by Chyba [10] and others that volatiles from objects impacting the Moon would be almost completely lost. The point is that any significant lunar source of, for example, water or carbon dioxide or nitrogen would have enormous value for life support at a manned lunar settlement, so much value that we should use every reasonable search technique, and look everywhere we can think of, in our efforts to find sources of useful volatiles on the Moon. Even if the likelihood of success is small, the potential payoff justifies a significant search effort.

One attraction of using radon as a tracer is that it doesn't matter if the idea of cometary implantation of volatiles is wrong. This technique does not depend on any assumptions about how volatiles got into place. If volatiles are present, and if they are coming to the surface, they will bring radon with them. The radon—or its polonium descendant—can then be observed from lunar orbit.

The Apollo 15 and 16 alpha spectrometer results already give us strong reason to suspect that deposits of volatiles do exist at some locations within the Moon, from which "burps" occasionally come to the surface in an episodic fashion.

One caution: Detecting radon or polonium from lunar orbit can reveal the existence and selenographic locations of volatile reservoirs within the Moon; however, such detections will not reveal the amount of volatile material within a reservoir, its composition, how deeply it is buried, nor how difficult it will be to gain access to the material. Thus this search technique may be of more value for the long term, for permanent human settlement of the Moon, than for an initial base.

Proposed Method of Search: It will surprise no one who has read this far that I am proposing to look for radon and polonium with an alpha spectrometer from lunar orbit, just as was done on Apollo 15 and 16. One important difference is that this time it should be done from lunar polar orbit in order to get a complete global survey of any significant radon sources.

It would be useful to narrow the selenographic resolution of detection, if feasible. The maps of ^{210}Po distribution produced from Apollo 15 and 16 data show ^{210}Po activity variations for blocks of the lunar surface 10° wide [11]. It would be very helpful to be able to locate volatile flows more precisely. By integrating over several orbits, it should be possible to improve the signal-to-noise ratio enough to do this [12].

Information of the sort I am proposing may be provided by the proposed Lunar Prospector mission [12], if and when it flies. That mission has an alpha spectrometer among its planned suite of instruments.

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ECONOMIC GEOLOGY OF THE MOON: SOME CONSIDERATIONS.

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Supporting any but the smallest lunar facility will require indigenous resources due to the extremely high cost of bringing material from Earth [1]. The Moon has also attracted interest as a resource base to help support near-Earth space activities, because of the potential lower cost once the necessary infrastructure has been amortized. Obviously, initial lunar products will be high-volume, bulk commodities, as they are the only ones for which the economics of lunar production are conceivably attractive. Certain rarer elements, such as the halogens, C, and H, would also be extremely useful (for propellant, life support, and/or reagents), and indeed local sources of such elements would vastly improve the economics of lunar resource extraction.

However, early scenarios for lunar resources, based on extracting many common elements from ordinary regolith [2], are probably unworkable. A survey of terrestrial mining experience indicates that the overwhelming criterion of a potentially economic deposit is its recoverable concentration of the desired element [3]. This results because separating elements is difficult and costly, and is indeed why "ores"—i.e., anomalous concentrations of the desired element—are worth seeking in the first place. In fact (and somewhat paradoxically), a high-grade ore is most critical for large-volume commodities, as those would be prohibitive to purify on the scale required. Hence, identifying the most concentrated sources of desired element(s) for local resource extraction should be an element of future lunar missions, and certainly should be a factor in siting a lunar base.

Few lunar geologic studies to this point, however, are directly relevant to exploration for potential ores, as they have been concerned with identifying large-scale, global processes. This focus has been appropriate, of course, given our a priori ignorance of the Moon. Moreover, quite apart from the Moon's scientific interest, serious concern about its resource value would also have been highly premature, for at least two reasons: (1) Useful constraints would be impossible without first knowing the basic geologic framework and (2) potential resources cannot be evaluated in a vacuum; their value depends on their possible uses. However, the broad-brush approach of planetological studies is opposite that of economic geology, because economic geology deals with the products of rare events. Ore deposits typically occur where by happenstance a rare process, or a fortuitous combination of processes, has run to an extreme. Such deposits are rare by their very nature; indeed, almost by their very definition. Nonetheless, they are worth seeking because of the extreme expense of separating elements, so that it is highly cost effective to let natural processes carry out as much separation as possible first. Hence, global characterizations such as typify traditional lunar studies are not immediately relevant for economic geology investigations. They merely set the geologic context, whereas economic geology lies in the unusual—and extremely local—variations from the norm.

It has been argued, especially in the popular literature, that the anhydrous nature of lunar materials precludes any ore deposits like those on the Earth. This is overstated. For one thing, the Moon is vastly more heterogeneous than had been thought even until relatively recently, as has been demonstrated by both ongoing studies of lunar petrology [4] and by remote sensing [5]. The Moon underwent protracted igneous activity, spanning hundreds of millions of years, during its early history, and this led to varied and large-scale differentiation and fractionation.

Second, the mere waterlessness of the lunar environment does not preclude all ore-forming processes. Although it is true that water is vital in forming many terrestrial ores, anhydrous magmatic differentiation is also capable of generating substantial element concentrations, and indeed has formed some terrestrial ore deposits. Such purely magmatic processes include partial melting, fractional crystallization, and phase separation (liquid unmixing or crystal settling). Examples of such magmatic ores on Earth include Cu-Ni sulfide ores from sulfide liquid immiscibility, chromite from cumulate settling, and magnetite ores crystallized from late-stage magmatic fluids extremely enriched in Fe [6]. Similar processes may occur on the Moon [7]. Yet other potential lunar processes may have no terrestrial analogues, as with the possibility of cold-trapped volatiles in permanently shadowed regions at the lunar poles [8].

To be sure, the lunar geologic environment is very different from the terrestrial, and the possible consequences of the Moon's low oxidation state and waterlessness for generating useful concentrations of elements must be addressed. For example, considering the behavior of the rarer elements under lunar conditions with a view to how (or whether!) they can become concentrated

locally would be valuable. Many industrially important elements are highly incompatible and in a magma will tend to become concentrated in the residual melt, so that useful concentrations may form [7]. However, the enormous literature on lunar rare elements is focused instead on their use as tracers of large-scale geologic processes (e.g., partitioning of REE) and thus is not directly applicable to economic geology.

For example, much lunar Cr is present as Cr^{++}, due to the reduced character of lunar rocks [9], and Cr is enriched in the lunar crust relative to Earth. The mechanism of this enrichment seems somewhat obscure, however. Presumably, Cr^{++} is excluded from compact Fe-Mg silicates in the lunar mantle, as it is a large ion [10]; moreover, Cr^{++} has large Jahn-Teller effects and hence prefers distorted crystal sites. Hence the Cr on the surface probably arrived as Cr^{++} in residual melts originally fractionated out of the mantle. However, surface Cr commonly exists as Cr^{+++}, especially in chromite [11]. Data from reduced chromian slags indicate that at low temperatures CrO is unstable and will disproportionate into Cr metal and Cr_2O_3 [12]. As Cr metal is more electropositive than Fe, this suggests that some of the native Fe on the Moon may result from reduction by Cr^{++} oxidation, and textural relations support this interpretation [13]. In any case, understanding Cr mobility due to its varying redox behavior may allow finding areas enriched in it, and may also have implications for deposits of native Fe.

Moreover, as this example suggests, the slag literature seems to be a largely overlooked source of possible insights about the behavior of silicate melts under extremely reducing conditions. They may provide information on rare elements in particular. Many slags contain not only Cr^{++}, but Ti^{+++} or even Ti^{++} [12]. The ceramic literature may also be useful as many high-performance ceramics are anhydrous. Indeed, industrial experience has already provided extremely useful analogues for some non-terrestrial processes, e.g., Sill's [14] modeling of the role of sulfur in Venus cloud processes, using observations from Lunge's [15] industrial treatise on the obsolete lead-chamber process for commercially producing sulfuric acid, and Lee et al.'s [16] observations of molten sulfur flows in commercial mining operations to infer behavior of natural flows on Io. Such literature also seems an underused source for potential insights into lunar conditions.

Surface Signatures: It is not enough to predict mechanisms by which ores may be formed; they must also be found. Seeking a distinctive signature from orbital sensors is an obvious and relatively cheap approach; e.g., it has been commonly advocated for detecting whether cold-trapped polar volatiles exist. Many if not most ore deposits will be too small, however, to show up with the resolution proposed for probes such as the Lunar Observer. For example, a deposit of pure ilmenite 100 m on a side, which would be more than enough to support an initial lunar installation, would not be seen.

Detection of such small deposits must be more subtle, especially as global increases in resolution are not practical. Instead, the signature of potentially favorable geologic settings for concentration of the desired element must be sought; once such areas have been identified, they can be targeted for further investigation.

It seems underappreciated that this is how mineral exploration is carried out on Earth. For example, an explorationist seeking Au mineralization in Nevada does not begin by mapping the entire state at 1-m resolution. Instead, he ,or she focuses attention on promising areas identified on the basis of their general geologic setting, and maps them in detail. Similarly, small but promising areas on the Moon, initially found by remote sensing, can be later focused on in detail with high-resolution sensing, and in the case of the most favorable areas, actual samples can be collected.

Conclusion: In summary, a viable ore resource contains as high a concentration of the desired element as possible in a form that is as easy to recover as possible, and such deposits moreover are unusual, resulting from rare processes or unusual extremes of common processes. This will be true of lunar resources as much as terrestrial ones. To explore for lunar resources, therefore, the lunar geologic literature must be reevaluated with this perspective, using our knowledge of global lunar processes to establish geologic contexts, and then determining what element-concentration processes might occur locally in such contexts. Terrestrial analogues, such as magmatic ore formation, as well as lunar samples that seem to reflect unusual processes, should help identify such possibilities. Industrial experience with possibly relevant systems such as reducing slags or anhydrous ceramics may also provide insight on possible ore-forming processes. Once possibilities are established, then attention can be focused on promising lunar localities.

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THE TARGET: H_2O ON THE MOON. J. Green[1], J. Negus-de Wys[2], and A. Zuppero[2], [1]California State University, CA, USA, [2]EG&G Idaho, Inc., ID, USA.

The importance of H_2O on the lunar surface has long been identified as a high priority for the existence of a human colony for mining activities and, more recently, for space fuel. Using the Earth as an analogue, volcanic activity would suggest the generation of water during lunar history. Evidence of volcanism is found not only in present lunar morphology, but in over 400 locations of lunar transient events catalogued by Middlehurst and Kuiper in the 1960s. These events consisted of sightings since early history of vapor emissions and bright spots or flares. Later infrared scan-

ning by Saari and Shorthill showed "hot spots," many of which coincided with transient event sites. Many of the locations of Middlehurst and Kuiper were the sites of repeat events, leading to the conclusion that these were possibly volcanic in nature.

If water were formed on the lunar surface in the past through volcanic activity, remnants of frozen H_2O could be expected to survive in the polar regions and in crater rims, protected by meters of fine ($15\text{-}\mu$m) lunar regolith from the high-vacuum, high-escape velocity, and the long, hot lunar day.

More lunar volcanic resources may possibly be present on the highlands than heretofore believed, a belief based in part on remote sensing of the lunar limb and farside by the Galileo spacecraft in 1990. The probe discovered probable volcanic "cryptomare" provinces on the highlands. Highland volcanism enhances the probability of endogenic water resources on the floors of shadowed polar craters in addition to possible cometary ice input. Modification of Strategic Defense Initiative weaponry for use as orbiting cislunar remote sensors could be useful in detecting ice or ice clathrate within polar craters especially in the vicinity of lunar transient sites. Focused neutron beams from a linear accelerator in polar orbit could be directed onto the floors of eternally shadowed crater floors to detect possible water ice by the 2.22-meV gamma backscatter of hydrogen. Prior to renewed manned exploration of the Moon, many modified SDI systems could be used in active remote sensing exploration for both volcanic and impact-derived volatiles in lunar shadow.

The exploration system seeks to find a surprisingly small amount of water ice. The H_2O would be used for massive cargo propulsion, life support, and material processing. Direct use of the water as propellant in nuclear thermal steam rockets provides nearly the optimum ratio of payload mass per tanker ship mass for lunar ascent and escape missions. The simplicity is of very high practical value to lunar operations. Converting the water into cryofuels provides the most resource-efficient propulsion. To supply 10,000 tons of propellant or rocket fuel to lunar escape would require finding a block of permafrost less than 35 m across. This 10 ktons of fuel is about as much as has been launched during the entire history of space. It would provide the fuel to take 50 payloads of 100 tons each from the lunar surface to an Earth orbit, or to take 25 payloads of 100 tons each to the Moon from low Earth orbit. To deliver 10,000 tons of lunar mass to each of 100 solar power stations of multigigawatt capacity would require finding a mere 160-cubic-meter block of ice.

LUNAR MAGNETIC FIELDS: IMPLICATIONS FOR RESOURCE UTILIZATION. L. L. Hood, Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, USA.

It is well known that solar-wind-implanted hydrogen and helium-3 in lunar soils are potentially usable resources for future manned activities. Hydrogen applications include manufacture of propulsion fuel and combination with oxygen (extracted from minerals such as ilmenite) to produce water. More speculatively, helium-3 may ultimately be returned to Earth as a fuel for future terrestrial fusion reactors. For economical mining of these implanted gases, it is desirable that relative concentrations exceed that of typical soils (e.g., [1]). It has previously been noted that the monthly variation of solar wind flux on the surface due to lunar immersion in the geomagnetic tail may have measurable consequences for resource utilization [2]. In this paper, it is pointed out that, for a constant external flux, locally strong lunar crustal magnetic fields will exert the dominant influence on solar wind volatile implantation rates. In particular, the strongest lunar crustal magnetic fields will both deflect and focus incident ions in local regions leading to local enhancements of the incident ion flux. Thus, the most economical sites for extraction of solar-wind-implanted volatiles may be within or adjacent to strong crustal magnetic fields. In addition, solar wind ion deflection by crustal magnetic fields must be considered in evaluating the issue of whether remnant cometary ice or water-bearing minerals have survived in permanently shadowed regions near the lunar poles [3]. This is because sputter erosion of water ice by solar wind ions has been suggested to be an important ice loss mechanism within permanently shadowed regions [4]. Thus, permanently shadowed regions that are also shielded from the solar wind by locally strong crustal fields could be the most promising locations for the survival of cometary ice.

Although the largest directly measured surface magnetic field was 327 nT at the Apollo 16 site [5], it is likely that much larger surface fields exist elsewhere in regions of strong magnetic anomalies detected from orbit. Modeling of the latter suggests surface fields as large as several thousand nT (several hundredths of a gauss) in restricted regions. Direct surface measurements of incident solar wind ions were obtained at the Apollo 12 and 15 landing sites where surface field amplitudes were only ~38 and ~3 nT respectively. Nevertheless, at the Apollo 12 site, incident ions were observed to be decelerated by as much as 70 km/s and to be deflected in direction by ≤10° [6]. We have previously calculated the deflection of solar wind ions by simulated lunar crustal magnetic fields for the purpose of investigating the origin of swirl-like albedo markings that are associated with many of the strongest lunar magnetic anomalies [7]. It was found that significant deflections do occur and that local plasma voids are produced at the lunar surface.
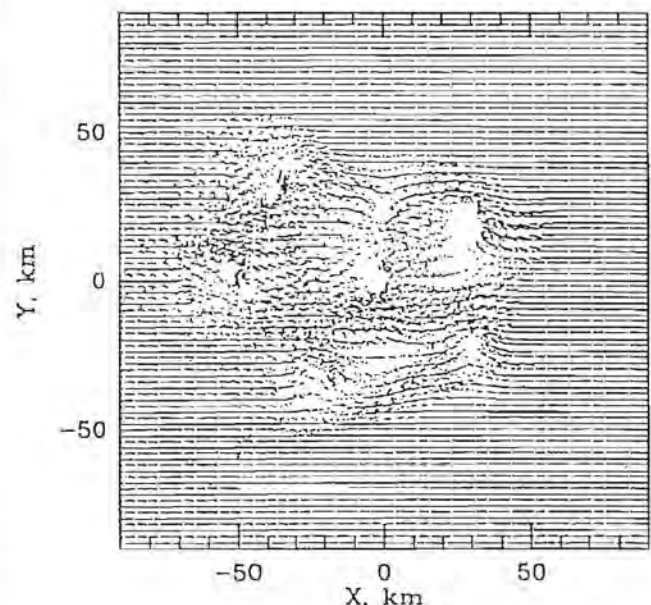

Fig. 1.

In this paper, additional numerical simulations are employed to show that solar wind ion deflection by strong lunar magnetic anomalies can produce local increases in the implantation rate of solar wind gases such as hydrogen. This may increase the resource potential of these volatiles. An example of the surface "shot pattern" produced in one such simulation is shown in the figure. The calculation includes a first-order accounting for the compression (and consequent local amplification) of crustal magnetic fields by the incident solar wind. The net effect is a slight increase in the deflection of ions as compared to that which would occur in the absence of field compression. As a nominal model of a large-amplitude, complex magnetic anomaly source region, we consider a magnetization source distribution represented by a series of dipoles with locations, orientations, and magnetic moments similar to those tabulated in [7]. The resulting magnetic anomaly fields are comparable to those measured over large anomaly sources with the Apollo subsatellite magnetometers. Surface fields are a maximum of ~3000 nT, or about 1 order of magnitude larger than that measured at the Apollo 16 landing site.

Additional simulations indicate that if water ice exists in permanently shadowed regions of the lunar poles together with locally strong magnetic fields, these fields would be capable of preventing sputter erosion losses by interplanetary and magnetospheric ion fluxes. In particular, model simulations indicate that the ability of magnetic anomalies to shield the surface from incident ions increases with the angle of incidence and, hence, for most particle sources, with selenographic latitude.

The possibility that relatively strong anomalies are capable of providing significant protection of humans and materials against major solar flare particle events has also been examined and found to be unlikely.

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MAPPING THE MOON IN SOFT X-RAYS: PROMISES AND CHALLENGES. R. M. Housley, Rockwell International Sciences Center, P.O. Box 1085, Thousand Oaks CA 91360, USA.

Recent ROSAT images reported by Schmitt et al. [1] show that the sunlit part of the Moon is a significant source of very soft X-rays. Stimulated by these observations, Edwards et al. [2] have made an analysis of the response of the Moon to the solar soft X-ray and EUV spectrum. They argue that much of the observed emission is in the form of discrete fluorescence lines in the energy range 25 to 100 eV, and that these lines are generally much stronger than the adjacent directly scattered solar background. On this basis they suggest that soft X-ray fluorescence can be used to remotely obtain high-precision elemental maps of the lunar surface. Edwards et al. have continued to develop this idea and have suggested a system using soft X-ray telescopes in lunar orbit, which could also obtain very good spatial resolution (personal communication, 1992). This combination could be extremely valuable in

furthering our understanding of lunar chemistry and potential resource distributions.

The fluorescence X-rays considered by Edwards et al. [2] all necessarily involve transitions between the valence band and very shallow core vacancies. Their energies, structures, and overall widths hence reflect the characteristics of the host matrices, and vary with valence state and coordination. In determining line structures, valence electrons derived from the fluorescing atoms' atomic states generally contribute most heavily and their weighting depends on dipole selection rules. Thus even two elements in the same compound are expected to have significantly different line shapes.

In light of the above it is clear that lunar mapping missions could best be planned using actual soft X-ray fluorescence spectra of representative lunar regolith samples, and the component minerals and glasses that make them up. Since such data are not currently available we here use our published XPS data on lunar samples [3] along with unpublished data on minerals to estimate most probable X-ray energies and allowed ranges. This is possible since both the core levels and the valence band levels are seen in the XPS data. The results are presented in Table 1.

TABLE 1.　X-ray fluorescence energies and linewidths.

Element	Fluorescence Transition	Predicted Energy (eV)	Allowed Range (eV)	Reference	Samples Used
Na	$L_{23}V$	22	±6	u	Labradorite
Mg	$L_{23}V$	42	±4	u	Forsterite
		42	±7	3	Synthetic lunar glass
		42	±7	3	Lunar regolith 10084
Al	$L_{23}V$	66	±6	u	Labradorite
		67	±6	u	Synthetic lunar glass
		67	±6	u	Lunar regolith 10084
Si	$L_{23}V$	94	±6	u	Labradorite
		95	±4	u	Forsterite
		94	±7	u	Synthetic lunar glass
		96	±7	u	Lunar regolith 10084
S	$L_{23}V$	156	±8	u	FeS
		154	±7	u	ZnS
Ca	$M_{23}V$	18	±6	u	Labradorite
		19	±7	3	Synthetic lunar glass
		18	±7	3	Lunar regolith 10084
Ti	$M_{23}V$	32	±7	u	Ilmenite
		31	±7	3	Synthetic lunar glass
		30	±7	3	Lunar regolith 10084
Fe	$M_{23}V$	49	±7	u	Ilmenite
		49	±7	3	Synthetic lunar glass
		49	±7	3	Lunar regolith 10084
Zn	$M_{23}V$	80	±6	u	ZnS
		80	±6	u	ZnO

TABLE 2. Selected X-ray escape depths (Å).

Material	Energies (eV)			
	30.5	72.4	91.5	151.1
10084 glass	190	430	530	670
67701 glass	180	470	510	630
ZnS		380	420	660

It is also useful to know how thick a region of the lunar surface will be sampled by these soft X-rays. We have estimated mean escape depths for several energies and compositions corresponding to a mare glass, a highland glass, and ZnS using the mass attenuation coefficients of Henke et al. [4], and present them in Table 2.

High spatial resolution combined with the thin surface layer from which these soft X-rays arise suggests the exciting possibility that X-ray telescopes could map lunar volcanic volatiles from orbit. The most characteristic feature of known lunar volcanic volatile deposits is a conspicuous enrichment in sulfur and zinc on grain surfaces [5,6]. These Zn,S-rich surface films can be seen in SEM images. In XPS studies [7] we have found surface Zn concentrations higher than 5 atomic percent and have estimated a depth of at least 100 Å. Thus Apollo 17 orange glass appears to have enough Zn and S to be seen from orbit, and it would be very surprising if there are not other lunar regions much richer in volcanic volatiles.

In our XPS studies of lunar regolith fines [8] we found that a significant fraction of the iron in the outer few hundred angstroms of grain surfaces was reduced to the metallic form, presumably as a result of micrometeorite vaporization and solar wind effects. Because of the strong possibility of substantial reoxidation of lunar material during storage, sample preparation, and analysis, we cannot know what the reduced fraction was on the lunar surface, but it may have been large. The M_{23} XPS lines and $M_{23}VV$ Auger lines of Fe^{++} and $Fe°$ have different shapes and energies, allowing them to be easily distinguished. It seems likely that the $M_{23}V$ X-ray line will also, so the oxidation state of Fe in the regolith might be mapped with properly chosen telescopes.

We thus suggest that, in addition to major-element mapping, consideration be given to volcanic volatile mapping and regolith oxidation state mapping.

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ASSESSMENT OF THE LUNAR SURFACE LAYER AND *IN SITU* MATERIALS TO SUSTAIN CONSTRUCTION-RELATED APPLICATIONS.

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In this paper we focus on present and future technologies to facilitate lunar composition and resource assessment with applications to lunar surface construction. We are particularly interested in the construction activity associated with lunar-based astronomy. We address, as an example, the use of ground-probing radar to help assess subsurface conditions at sites for observatories and other facilities.

We feel that a multidisciplinary effort is desirable to identify what engineering data on the lunar environment and on the lunar soil and rock should be collected and how it should be obtained. Johnson and Burns [1] have urged action to acquire the following information and resolve issues indicated: (1) topographic maps of potential observatory sites (e.g., 10-cm contours over an area 1 km in radius); (2) detailed boulder sizes and counts over the same area; (3) surveys (e.g., by radar, microwave, or other means) for subsurface boulders over critical areas where foundations and excavation are desired; (4) surveys of depth-to-bedrock (with suitable definition and characterization of bedrock); (5) trenching and bulldozing experiments to establish energy requirements and depth limitations of these operations; (6) drilling and coring experiments (with energy consumption and depth limitations clarified); (7) force-vs.-depth cone penetrometer measurements to be used for siting settlement-sensitive telescope structures; (8) trafficability measurements including establishing energy consumption, slope-climbing capabilities, and formation of ruts or depressed surfaces by repeated traverses of unprepared surfaces; and (9) electrostatic charge measurements.

This listing has grown out of discussions with Dr. W. David Carrier III of the Lunar Geotechnical Institute and others. The list will vary somewhat depending on requirements for lunar-based facilities and operations. Johnson et al. [2] have noted that it is necessary to start now to develop the concepts and technologies for the next generation of space-based telescopes. A successor for the Hubble Space Telescope could be either in high Earth orbit (HEO) or on the Moon. To properly assess the merits of these suggested future telescopes, technology development for lunar as well as HEO telescopes should now be pursued so that properly informed decisions may be made. Part of the technology development requires improved understanding of engineering properties of lunar surface and subsurface materials and dust behavior. Johnson and Wetzel [3] note that the success of a large lunar-based telescope will depend on an appropriately engineered structure, a suitable interface (foundation) with the lunar regolith, and a carefully thought-out construction process. Johnson and Burns [1] have discussed the technology development required for large lunar telescopes and lunar optical/UV/IR synthesis arrays. They encourage the community to plan early lunar-bound payloads and surface operations to advance the knowledge and understanding required for building large telescopes on the Moon after the year 2000. Examples of key technologies for large lunar observatories that we feel deserve attention early in the program to return to the Moon are

1. Geotechnical (e.g., soils, excavation, foundations, and use of in situ materials for shielding).

2. Mitigation of detrimental effects of the environment (e.g., dust, thermal, primary and secondary impacts of micrometeoroids, radiation, and vacuum). This area includes obtaining a better understanding of the dust and debris environments above and on the surface of the Moon.

3. Approaches to use in construction on the Moon (e.g., extravehicular activity, robotics, telepresence, assembly aids, connectors). The appropriate choices can be made only with adequate knowledge of the surface conditions and variability.

4. Contamination/interference control and restoration processes. May vary with chemistry and mineralogy.

5. Performance of optical and related systems and charge-coupled devices (CCDs) on the Moon. CCDs deserve particular attention with respect to shielding requirements against cosmic and solar flare radiation. Shielding will probably be with in situ materials requiring excavation and placement at desired densities.

6. Test and evaluation techniques for lunar observatory systems and construction approaches to validate approaches before returning to the Moon. Depends on devising appropriate simulation of lunar conditions.

We anticipate that the initial telescopes on the Moon will be small automated instruments that have already been shown to be feasible by existing Earth-based robotic telescopes. These early telescopes will not only establish the viability of telescopes on the lunar surface, but will also perform excellent extended observations during the long lunar night to test models of active stars and galaxies, and do all-sky CCD surveys in the ultraviolet and infrared using a Schmidt wide-field telescope to complement the important sky survey done at Mount Palomar. We conclude that attention must be given to instrumenting these small telescopes in innovative ways to obtain information that will help find answers to unknowns in the areas listed above. We suggest that there are excellent opportunities to use the early landers to investigate the behavior of the soil under load, determine the extent of dust movement (e.g., levitation) associated with the passage of the lunar terminator, and place bounds on disturbances associated with vehicle operations on the Moon. Creative uses of information obtained from many innovative approaches may be used to help make lunar-based telescopes a reality.

For example, ground-probing radar has many terrestrial applications (e.g., in assessing pavement layer thicknesses in highway engineering applications, in determining the location of fissures in the dry lake bed at the Edwards Air Force Base shuttle landing site, and at Meteor Crater, Arizona, in investigations of the ejecta blanket). We propose to use this technology on the Moon in conjunction with other techniques such as penetrometers, borings, and core recovery to ascertain needed subsurface soil and rock properties. The goal is to minimize the use of labor-intensive subsurface sampling required during site investigations on the Moon and to improve approaches to assessing in situ lunar construction materials.

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AN IN SITU TECHNIQUE FOR ELEMENTAL ANALYSIS OF LUNAR SURFACES.   K. Y. Kane and D. A. Cremers, CLS-4, Mail Stop J567, Los Alamos National Laboratory, Los Alamos NM 87545, USA.

An in situ analytical technique that can remotely determine the elemental constituents of solids has been demonstrated. Laser-Induced Breakdown Spectroscopy (LIBS) is a form of atomic emission spectroscopy in which a powerful laser pulse is focused on a solid to generate a laser spark, or microplasma. Material in the plasma is vaporized, and the resulting atoms are excited to emit light. The light is spectrally resolved to identify the emitting species.

LIBS is a simple technique that can be automated for inclusion aboard a remotely operated vehicle. Since only optical access to a sample is required, areas inaccessible to a rover can be analyzed remotely. A single laser spark both vaporizes and excites the sample so that near real-time analysis (a few minutes) is possible. This technique provides simultaneous multielement detection and has good sensitivity for many elements. LIBS also eliminates the need for sample retrieval and preparation preventing possible sample contamination. These qualities make the LIBS technique uniquely suited for use in the lunar environment.

LIBS has been demonstrated using several different types of samples at distances between 4 and 18 m. Analyzed samples include simulants of Apollo mission Moon rocks, Mauna Loa basalt samples, and rock powder reference standards. An example of the spectra obtained with this technique using an Apollo Moon rock simulant is presented in Fig. 1. The presence of several elements such as aluminum, calcium, iron, magnesium, silicon, and titanium is clearly evident.

A portable LIBS instrument has been field tested with good preliminary results. An exposed tuff face was interrogated by the laser spark at a distance of approximately 18 m in bright sunlight. Spectra obtained at this distance displayed very strong emission
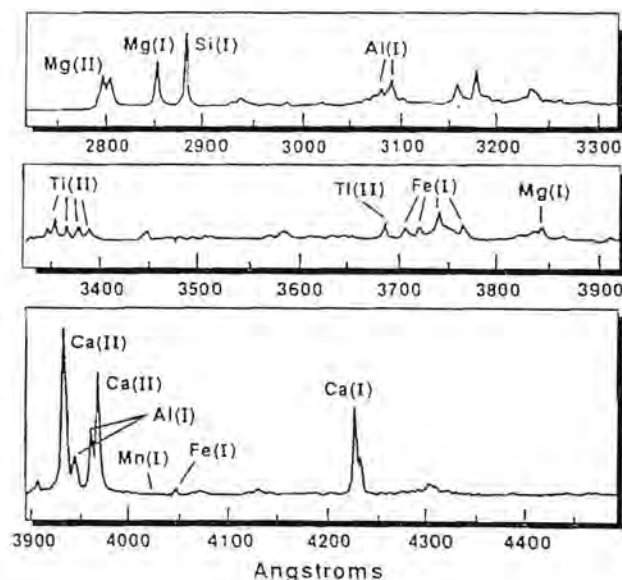

Fig. 1.   Laser spark spectra of an Apollo Moon rock simulant in a vacuum chamber at a distance of approximately 10 m.
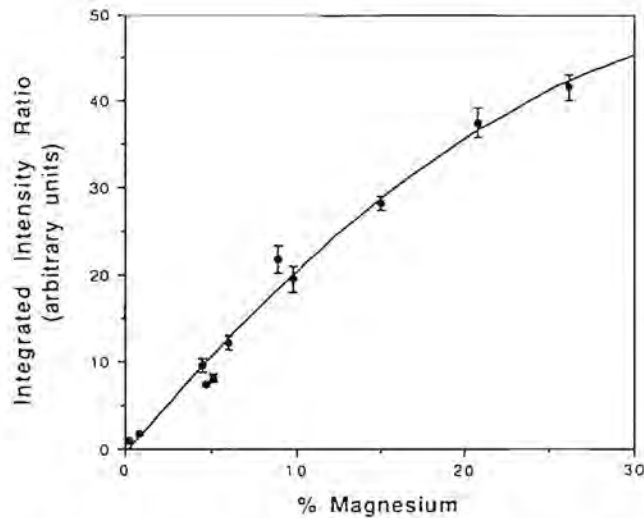
Fig. 2. Calibration curve for magnesium generated by monitoring the Mg I (285.2 nm) emission line.

intensities with negligible background interference indicating the feasibility of extending the analysis distance significantly beyond 18 m. This would require optimization of the focusing optics and an automated alignment capability to optimize light collection.

Experiments to date have proven the qualitative analysis capabilities of this technique. Preliminary calibration curves have been generated using rock powder standards to provide a quantitative measure of the technique. These curves were generated by monitoring the emission intensity of specific elemental lines. The calibration curve for magnesium is shown in Fig. 2. Similar curves have also been obtained for calcium and aluminum. Further experiments are needed to verify the quantitative capabilities of LIBS and to determine a set of optimum operating parameters.

ROBOTIC LUNAR ROVER TECHNOLOGIES AND SEI SUPPORTING TECHNOLOGIES AT SANDIA NATIONAL LABORATORIES.

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Robotic Rovers: Existing robotic rover technologies at Sandia National Laboratories (SNL) can be applied toward the realization of a robotic lunar rover mission in the near term. The facilities and robotic vehicle fleet at SNL's Robotic Vehicle Range (SNL-RVR) have been used to support technology base development in the mobile robotics field since 1984. Applications ranging from DOD battlefield and security missions to multiagency nuclear emergency response team exercises have utilized various elements of that technology base. Recent activities at the SNL-RVR have demonstrated the utility of existing rover technologies for performing remote field geology tasks similar to those envisioned on a robotic lunar rover mission. Specific technologies demonstrated include low-data-rate teleoperation, multivehicle control, remote site and sample inspection, standard bandwidth stereo vision, and autonomous path following based on both internal dead reckoning and an external position location update system. These activities serve to support the use of robotic rovers for an early return to the lunar surface by demonstrating capabilities that are attainable with off-the-shelf technology and existing control techniques. Sandia National Laboratories' Advanced Vehicle Technologies Department's extensive experience in designing and producing fieldable robotic rover systems provides a practical, realistic basis for integrating this technology within a multiagency team's scenario for a near-term robotic lunar rover mission.

SEI Supporting Technologies: The breadth of technical activities at SNL provides many supporting technology areas for robotic rover development. These range from core competency areas and microsensor fabrication facilities, to actual space qualification of flight components that are designed and fabricated in-house. These capabilities have been developed over the years to serve SNL's role in missions for a variety of customers, including U.S. industry, the U.S. Department of Defense, the U.S. Department of Energy, and elements of the nation's intelligence community.

LUNAR PROSPECTOR: A PRELIMINARY SURFACE REMOTE SENSING RESOURCE ASSESSMENT FOR THE MOON.

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The potential existence of lunar volatiles is a scientific discovery that could distinctly change the direction of pathways of inner solar system human expansion. With a dedicated germanium gamma ray spectrometer launched in the early 1990s, surface water concentrations of 0.7% could be detected immediately upon full lunar polar orbit operations. The expense of lunar base construction and operation would be dramatically reduced over a scenario with no lunar volatile resources. Global surface mineral distribution could be mapped out and integrated into a GIS database for lunar base site selection. Extensive surface lunar mapping would also result in the utilization of archived Apollo images.

The presence or lack of solid water and other frozen volatiles at or near the surface of the Earth's nearest celestial neighbor, the Moon, will dramatically affect the way in which we will approach the surface exploration of the Moon. For almost three decades, various scholars have debated the existence of water ice at the lunar poles. A variety of remote sensing systems and their parameters have been proposed for use in the detection of these lunar ice masses. The detection or nondetection of subsurface and surface ice masses in lunar polar crater floors could dramatically direct the development pathways that the human race might follow in its radiation from the Earth to habitable locales in the inner terran solar system.

Over time, the lunar surface soil is turned over in a process called gardening, which results in lunar regolith. It has been proposed that this process involves lunar material overlying cometary, asteroidal frozen, and condensed volatiles that would have impacted over the entire lunar surface. The three potential sources of lunar volatiles, especially water, are in lunar polar crater bottoms, transient lunar phenomena (TLP), and a thin layer of ice distributed broadly over the lunar globe at a depth of 200 m. The proposed lunar sensing devices could only detect the first two volatile deposit regimes. The depth of surface penetration of the gamma ray spectrometer is 1 m with a sodium iodine scintillator and up to several meters with a germanium solid-state detector. This will mean that lower deposits cannot be detected until there has been on-site base development. The polar ice would form at the base of small lunar polar craters where the measured ambient

temperatures are 120 K. With a thin covering of native lunar material, it would be possible for the cometary source volatiles to remain continuously in the shade for several million to several billion years if the models of planetary stability are correct. The second lunar ice potential, TLP, has been postulated as an out-gassing process of near-surface volatiles. If the spectrometer were pointed to a lunar event, which was previously detected by an Earth telescope, it would be possible to determine if this is an outgassing. If an outgassing event occurred, it might indicate recoverable volatile concentrations in liquid form near the surface. The TLP might be an outgassing of existing deep subsurface ice or liquid deposits. However, there have been no distinct references to this potential correlation of source and event of TLP. The third potential volatile source deposit cannot be investigated nor developed at present without direct contact with the planet's surface.

In all remote sensing, a major factor that the field scientist has to face is the logistical tether and how this directly affects the payload capability. The Space Studies Institute (SSI) did a comparative study of various probe designs that showed that many transorbit vehicles already are available to place a remote sensing platform in lunar polar orbit.

The first distinctions that digital remote sensing made was between solid rock and liquid water on Earth. The spectral signatures of various elements are distinct from one another, having distinct signatures when they are combined in various molecular chains. In the neutron spectral mapping mode, the germanium gamma ray spectrometer detector will be able to detect the presence of water in surface material to a ratio of 0.7%. The Apollo spectral mapping around the equator was a gamma ray sodium iodine scintillator detector. The neutron mode mapping of lunar cold sink volatiles will occur at a faster rate with a germanium gamma ray spectrometer detector than with an sodium iodine scintillator detector 30X the rate.

The secondary surface mineral features that are targeted for mapping are iron, titanium, uranium, thorium, and potassium. Out of the 20 mapping experiments proposed for the lunar prospector, the most public mission is the mapping of hydrogen and oxygen distribution. Yet, with the additional 19 experiments, it will be possible to map out surface minerals for a nonlunar ice development scenario. The germanium gamma ray spectrometer has distinct advantages in resolution and spectral definition over the Apollo-era sodium iodine scintillator detector. With a germanium gamma ray spectrometer, detection time for valid distinction of surface composition will decrease by several orders of magnitude. In no reference was any note made of the pixel size from the proposed 100-km orbital altitude.

The lunar surface has been systematically mapped for the last four centuries. The various images have not been integrated into a digitized GIS. The detailed mapping during the selection of the lunar landing sites in the 1960s, along with the satellite flybys that produced a wealth of surface images, have been underutilized and have not been integrated into one digital database. Any new surface digital images should be preserved in an archive that integrates existing images with two-decade-old images. While many of these older images did not contain any spectral information, they were extremely detailed and would be useful to overlay in a GIS context with new gamma ray spectrometer information from the Moon. This would allow a combination of the high-resolution characteristics of the early missions and the spectral information from a lunar polar orbiting imaging platform. The current focus of funded astronomical projects has moved away from the tax-

onomic cataloging of asteroids and other small bodies within the solar system. These small bodies are not seen as solving some of the basic puzzles of our solar system's genesis. Like the sensing exploration and mapping of the Moon, this kind of detailed cataloging is very boring science. Rather than discovering new vistas, it is filling in ultimately predictable blanks in already outlined scientific structures. The purpose of remote sensing capabilities over the lunar surface is the preliminary step in the mapping of future landing sites. While a lunar remote sensing platform will not solve many, if any, great questions of the solar system, it will lead to a greater understanding of our next home: the Moon's surface.

With the increasing number of countries that can launch small payloads into LEO, options exist beyond the conventionally perceived launch systems such as the U.S. space shuttle or an unmanned rocket system. Different systems have been compared as they directly relate to the science payload with the Shuttle Lunar Getaway Special proving to be the cheapest and most deployable under a wide variety of political and financial considerations. This would only require a 150-kg spacecraft as compared to an unmanned launch system that weighs 570 kg. The Getaway Special spacecraft could be launched on a wide variety of rockets including those of the Chinese. Their agency, the China Great Wall Industry Corporation, is interested in the concept of launching a lunar-bound vehicle, although they wish to concentrate on commercial launches. SSI has not investigated the possibility of a communist Chinese launch of a lunar reconnaissance probe. However, as of late April 1990, the SSI was of the opinion that they would launch with a U.S.S.R. unmanned rocket to LEO for a transorbital flight to a lunar polar orbit.

The initially proposed scenario of deployment was a Shuttle Garbage Can special launch with an ion propulsion engine that would inject the probe into a lunar orbit within two years. While the launch vehicle has still not been decided, the structure and performance characteristics of a prospector have been discussed at some length. Up to the 1990s, ion propulsion systems have not been used in any lunar probes. The trajectory of the slower shuttle launch would follow a similar telemetry as that of a faster chemical propulsion system, except in the LEO-to-transfer-orbit section of the trip. The mass of a launched prospector platform would be approximately 150 kg. The current NASA plan for a lunar remote sensing probe is an observer-class polar orbiter that would be ready for launch tentatively in the late 1990s. The observer platform is quite complex and expensive and would be ready in 8 to 10 years. The observer-class vehicle would not be compromised by a dedicated one-instrument germanium gamma ray spectrometer mission to a lunar orbit, since an observer mission to the Moon would be substantially more comprehensive than a prospector mission. A late 1990s observer mission could build on the images that were received by the prospector and would be substantially more comprehensive than the precursor mission.

The majority of the outer solar system science probes that have been launched are not in any way tied directly to the process of human expansion off the Earth. Scientific data are creating new paradigms but not directly contributing to the radiation of the species into space. The NASA lunar observer class probe has been proposed for launch in the later part of the decade. At the point when the information from this observer class probe is analyzed, a direction will appear. The immediate launch of a lunar orbiting platform carrying a germanium gamma ray spectrometer could expect a data return by late 1992, which could set science

on a determined course toward colonization. With on-site surface exploitable volatiles, a lunar base could "live off the land" to a greater extent than expected than under a scenario without any lunar frozen water or other volatiles. With a joint surveying and mapping mission of the Moon with American instrumentation and an immediate Soviet launch to lunar polar orbit, globally redundant projects such as the U.S. space station *Freedom* and the Soviet station *Mir* could be replaced with a more culturally and politically diverse lunar base. With marginal modification, modules built for LEO could be placed on the lunar surface and/or attached to *Mir*. While much has been written on the utilization of lunar volatiles as a source of propellant fuel for a LEO, inner solar system, transportation node, the potential of the discovery of lunar ice will enable human outposts to "live off the land" on the Moon.

The development of strategies focusing on the utilization of existing, nonterrestrial resources on-site is of primary concern. This would not be a departure from the ideology of exploration of the solar system, but would merely be wisely following the Punjabi proverb "Grasp all, lose all." It does not function in a pattern of evolutionary development and growth. Currently, the Western program is not focused in a specific direction. The assessment of these mineralogical maps of the Moon could lead to an evolution of direct launching to the Moon without an expensive station around the Earth. Previously, the U.S. had an existing operational space station, but abandoned it to the elements and its ultimate fiery fate. A lunar base would involve less ultimate short-term and long-term expenditure than would space station development. The primary justification made for the lunar base is the ultimate export of volatiles to LEO.

With the recent offer by the U.S.S.R. to launch a germanium gamma ray spectrometer instrumented platform to the Moon, the direction of the planet for the next 25 years will become clearer. Comparing the Ride Report and The National Commission on Space Report, Hempsell found that each of these pathways of solar system expansion could be developed in the twenty-first century. His conclusion was that immediate investment in an extensive lunar infrastructure would offset its initial costs.

Current human decisions will have an impact on global development over the next thousand years. These decisions include proposals and data that will reinforce our commitment to expansion off the planet. The previous lunar mission and telescope images that have been compiled over a 30-year period should be digitized in a standardized format and integrated into a GIS computer database. The gamma ray spectrometer data would then be only one level of the overlaid cartographic information. This same technique could then be duplicated on other terrestrial and nonterrestrial site locations. Currently, the only portions of the Moon that have been mapped with spectrographic analysis are those around the lunar equator from the Apollo exploration period. One example of lunar surface features that have not been mapped totally is the lunar lava tubes, which could supply excellent first-stage radiation shield structures.

A dedicated, one-instrument, gamma ray spectrometer that is being developed for the lunar prospector probe could be used in an identical format to map surface resources on other inner solar system bodies. The resulting maps would also give us definite information on those resource nodes that should be targeted for development and human settlement. With limited monies, hard decisions must be made whether to fund projects that, while of immense scientific merit, have little utility to the potential expansion of our species off the planet. Any expansion off the Earth

will involve lunar resource development in some manner. The discovery of lunar ice at the poles would influence the immediacy of a lunar polar station.

Spectral surface characteristics of the Moon have been an ignored area of scientific inquiry. The sensing systems and launching platforms are available, and a prospector mission would cost about $30 million in a shuttle launch configuration through to a $75 million cost. While it is not a flashy area of study, it will pave the way for permanent habitation of our nearest celestial body. Politicians should be supplied with maps and information, rather than fantasian utopian images, to base decisions of funding and political directions of scientific research.

When the U.S. President Thomas Jefferson sent Lewis and Clark westward, he expected and received detailed reconnaissance maps. These maps were the basis of all later discussions of how the U.S. should expand. Many expensive interplanetary probes have been launched without any discussion as to whether they will impact on the expansion of the human solar system ecumene.

The germanium gamma ray spectrometer is an inexpensive, already extant instrument that, while not necessarily answering many scientific questions, will tell human beings where and how to direct their expansion of the mineral exploitation of the Moon.

UTILIZATION OF GEOGRAPHIC INFORMATION SYSTEM IN LUNAR MAPPING.   A. A. Mardon, Department of Space Studies, University of North Dakota, Grand Forks ND 58202, USA.

Substantial digital remote sensing, lunar orbital photography, Earth-based remote sensing, and mapping of a variety of surficial lunar phenomena have occurred since the advent of the Space Age. This has led to a bewildering and quite disparate collection of archival sources insofar as this digital data and its cartographic representation can be found within many countries of the world. The importance of this mapping program in support of human expansion onto our nearest planetary neighbor has been recognized since the advent of the Space Age [1]. This is still as true as when it was stated in 1964 that, "The program for landing men on the lunar surface requires that suitable and safe sites be defined and verified before the actual landings" [2].

In 1991 only the U.S.A. has landed humans on the Moon. If during the preceding decade efforts had been dedicated to developing inexpensive labor-intensive tasks such as the detailed mapping of the Moon [3], we would be further ahead today in lunar exploration. A series of small-scale maps of the Moon at 1 km to 1 cm, done with the support of Geographic Information System (GIS), would serve decision makers well in the process of accessing the development of manned occupance of the Moon. Nothing has been published to this date on the use of GIS in a lunar mapping context [4].

Maps and the data that they are derived from are the primary way in which people explore new environments and use previously discovered data to increase the bounties of any exploration. The inherent advantage of GIS is that it would allow immediate online access on the Moon of topographically represented data [5,6], with analysis either on site or from Earth. This would mean that astronauts in the field would be able to get instantaneous cartographic data representations on any of the suited visual monitors that would be part of an astronaut's extravehicular suit.

Any vehicles or shelters that would be used on the Moon would have internal video monitors. The multiple database maps could be instantaneously represented on the screens of those persons using transmitted data in order that decisions on the direction of a route of traverse or assistance in the selection of a site to use could be worked out on the spot in the field. A similar proposal was presented to the National Science Foundation on the mounting of video map monitors on the dashboard of snowmobiles used in the field in Antarctic traverses. These monitors could be viewed while riding along on the snowmobile. Personal experience in the Antarctic shows that other members of the Plateau-based field team were continually referring to our maps for a variety of purposes. An inertial guidance system could be used in conjunction with lunar satellite telemetry to give onboard GIS exact, continuous coordinates on the entire lunar surface. It would be rather difficult to handle a conventional two-dimensional cloth or paper map from inside a spacesuit. Orbital photography could be directly portrayed or portrayed with graphic enhancements in the lunar environment.

Further developments in GIS cartographic representation make it now possible for it to be used in the form of a video monitor, and apropos the GIS this would be well suited to the medium of maps that will be used in space.

A GIS would be operationally actualized in a lunar field environment by becoming a standard part of the astronaut's lunar surface suit. A variety of configurations could be envisaged for use in the field. The first proposed configuration of GIS that the author proposes is that a small 10–15-cm full-color monitor be installed on the side of the interior of the spacesuit helmet. This screen could display the entire range of topographic features and would have the resolution of the current high-resolution television screens. The astronaut would swivel his head to either the right or the left to see this screen. The second proposed configuration is a Heads-Up Display (HUD) on the faceplate of the helmet. This would be similiar to the HUD that is seen in fighter aircraft allowing target acquisition and data displayed in a manner that can be seen through [7]. Thus monochromatic lines or a full-color display could portray multiple datasets in a see-through monitor; in very simple terms the helmet face plate would become the monitor. The graphic information could be switched on and off and different densities of graphic and digital information could be displayed on a HUD system. The third configuration in which GIS could be displayed is in the form of a chest-mounted screen that would swing out and could be viewed when looking directly downward. The fourth configuration is a screen in a portable carrying case that could be held up by one hand to view. The fifth configuration is the faceplate could be replaced by a monitor close to the eyes with no translucent properties [8].

The utilization of screens for display purposes would be very easy, for vehicles would probably have monitors for other assigned purposes, namely the secondary purpose of displaying any required maps. Out of all the variety of ways to display cartographic information, the one that is most likely to be developed and utilized is the HUD on the spacesuit helmet faceplate. All internal video monitors could be used in a similar manner to that used by pilots, for example a HUD, either in the form of a direct voice command or through focusing one's eye on a certain area of the screen and blinking. This technology is rumored to have been developed to a high degree in the USAF Apache helicopter and F-18 [7]. This would allow the astronaut to move smoothly on the display screen from different databases and from different scale-map displays. The

monitor display could go from a 1-cm- to 1-km-scale topographic display to a 1-cm to 1-m topographic display with a blink of the eye and/or a vocal command. Other suit status information could be displayed or overlayed onto this information.

Historically, maps were created before an expedition began, based on all accessible information about an area that was relevant. A lunar utilization of the available GIS would allow the modern and future lunar explorer the opportunity to have immediately updated maps that use several Earth nations' archival resources. Thus, ironically, this could be its most impressive contribution manifested by its inherent speed and agility to address new problems.

The author proposes that the new cartographic techniques that have been developed within the GIS could be applied to the methods of archival storage, retrieval, and representation of the bewildering array of lunar surficial phenomena data sources [9]. GIS cartographic technology allows the multiple overlaying of disparate digital and cartographic data in order to correlate and substantiate new patterns. Then contemporary and historical lunar data compiled by a variety of nations could be referenced for retrieval. These sources would in some cases be damaged with the passage of time [10]. GIS could be used to archive and allow new and novel utilization of any old unused data.

An examination of the references in *NASA Technical Abstracts* from 1958 to 1989 suggests that there is first of all a correlation with exploration activity and the publication of maps. After the funding cuts of the 1970s, on average the ratio of entries under lunar mapping and lunar photography has been less than it was before and during the active exploration stage of the Moon by the U.S. This also means that it does support an active mission of exploration of the Moon. One problem with this form of analysis is that it relies heavily upon the abstracting heading system. Many articles that directly relate to the topic of mapping are not covered in the abstract headings. The author proposes that over a 30-year period abstract publication rates can indicate interest in the space program and specifically lunar mapping. Future increases in the appearance of mapping heading abstracts might indicate an increased serious interest in lunar exploration by the U.S.A. At the current time the mapping headings do not correspond to the numbers that appeared in the 1960s before the manned lunar landings.

A future area of research that could be developed upon the integration and data entry of all the lunar maps and orbital and surface photography is the comparison of photographs to measure the small meteorite impact rate on the Moon. This would involve the superimposition of future images over preserved past images. This would be another means, that we currently do not have, to measure temporal differences in small-body meteor impact rates. Evidence of mass slope slippages along crater walls that might also occur could be seen in compared images. These observations could be seen when comparing 1960s and 1970s images with future lunar images. Using archived historical aerial photography to compare changes over time in the cultural and physical landscape has been quite common on Earth, and on the Moon archived images in an internationally standardized computer medium might provide us with valuable insights into planetary processes.

A robust lunar planetary-scale mapping program is a primary prerequisite to a well-informed decision-making process in the site selection of permanent lunar facilities [1]. The utilization of GIS in support of this goal would be timely and has precedents in site selection procedures on Earth [11]. Historically, mapping has been

the major tool in exploration over the past half millenium. This newest powerful tool for the modern cartographer could be cost-effectively used to accelerate and correctly discern optimal lunar sites for utilization.

We went to our Moon over 20 years ago with technology that makes our current general technological level seem extremely advanced. Our movement to our nearest planetary neighbor is not a matter of needing superior technology but is one of organizing what we currently know in a superior manner. Using technology that has already been proven and is inexpensive to support, our drive out from Earth has greater potential for success than in developing unproven technology. A universal cartographic database founded on the principles at the center of GIS would become the same helpful tool for exploration that the ancient maps of Herodotos, Ptolemy, and Strabo were to Columbus in his discovery of the "New World" in 1492.

"Discovery is documentation" [12] and, simply, the most useful form of documentation for exploration is the map. This still applies to our future exploration of the Moon as it is applied to historic exploration on Earth. This use of historic maps in exploration has been shown in Henry the Navigator's use of Necho's African map. This map, as described in Herodotos' History, was made in the sixth century B.C. The map described the legendary circumnavigation of Africa sponsored by the Egyptian Necho. This was then used in the fifteenth century A.D. by Henry the Navigator to justify the Portuguese southward exploration in their attempt to follow Necho's described legendary circumnavigation of Africa 2100 years previously.

Our maps of the Moon, whether they be represented on paper or computer screen, will be the human race's most valuable and inexpensive tool in the exploration and conquest of the Moon.

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MÖSSBAUER SPECTROSCOPY FOR LUNAR RESOURCE ASSESSMENT: MEASUREMENT OF MINERALOGY AND SOIL MATURITY.

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Introduction: First-order assessment of lunar soil as a resource includes measurement of its mineralogy and maturity. Soils in which the mineral ilmenite is present in high concentrations are desirable feedstock for the production of oxygen at a lunar base.

Fig. 1.

Fig. 2.

The maturity of lunar soils is a measure of their relative residence time in the upper 1 mm of the lunar surface. Increasing maturity implies increasing load of solar wind species (e.g., N, H, and ^{3}He), decreasing mean grain size, and increasing glass content. All these physicochemical properties that vary in a regular way with maturity are important parameters for assessing lunar soil as a resource. For example, ^{3}He can be extracted and potentially used for nuclear fusion. A commonly used index for lunar soil maturity is I_s/FeO,

Fig. 3.

which is the concentration of fine-grained metal determined by ferromagnetic resonance (I_s) normalized to the total iron content (as FeO) [1]. I_s/FeO has been measured for virtually every soil returned by the Apollo and Luna missions to the Moon; values for surface soils are compiled by [2].

Because the technique is sensitive to both oxidation state and mineralogy, iron Mössbauer spectroscopy (FeMS) is a viable technique for *in situ* lunar resource assessment. Its utility for mineralogy is apparent from examination of published FeMS data for lunar samples [e.g., 3–5]. From the data published by [5], we can infer that FeMS data can also be used to determine soil maturity. We discuss here (1) the use of FeMS to determine mineralogy and maturity and (2) progress on development of a FeMS instrument for lunar surface use.

Mineralogy and Maturity: Figure 1 shows FeMS spectra for two Apollo 17 soils, 72131 and 73131. Even by visual inspection, the two soils have very different proportions of the ferrous-bearing minerals pyr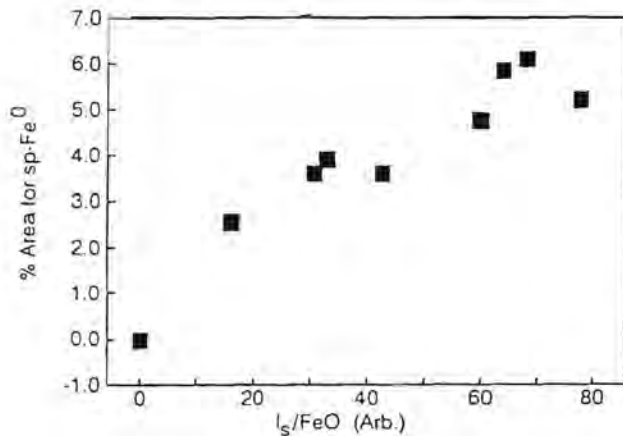oxene, olivine, and ilmenite. From peak areas, the percentages of total iron associated with each of those mineralogies are 66, 15, and 16 for 72131 and 57, 39, and 4 for 73131. Thus, a Mössbauer spectrometer on a lunar rover could be used to prospect for ilmenite-rich soil horizons (deposits).
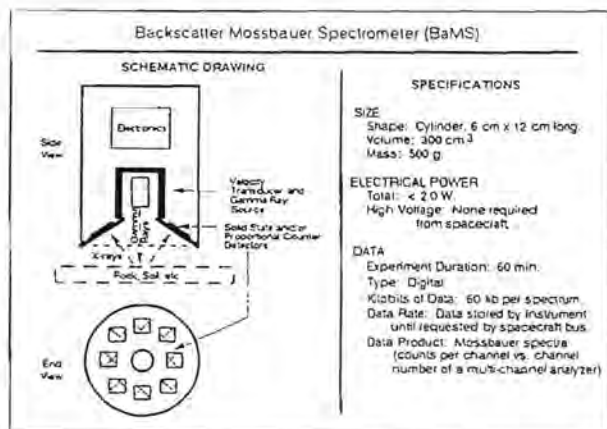

Fig. 4.

A reason for finding ilmenite deposits is shown in Fig. 2, which presents FeMS spectra for a crushed lunar rock (70035) both before and after reduction by hydrogen. The only two iron-bearing mineralogies present in the untreated rock are ilmenite and pyroxene, with 23% of the total Fe in the ilmenite. After H_2 reduction, there is no evidence in the FeMS spectra for ilmenite. Only metallic iron and pyroxene are present, which implies that reduction of ferrous iron in ilmenite is kinetically favored over that in pyroxene. The 36% area for Fe metal does indicate, however, that some of the ferrous iron in pyroxene has been reduced to metal.

In Fig. 3, we plot the excess area near zero velocity, which is a measure of the concentration of superparamagnetic Fe metal (sp-Fe^0), as a function of the maturity index I_s/FeO for nine lunar samples. The area for sp-Fe^0 was calculated using the procedure of [5] except that no attempt was made to correct for saturation effects. A linear correlation is present, which demonstrates that maturity data can be derived from Mössbauer measurements.

Instrument Development: The current status of development of our backscatter Mössbauer spectrometer (BaMS) is described by [6]. A schematic of the instrument, together with specifications, is given in Fig. 4. The instrument has low mass, low volume, low power consumption, and low data transfer rate. We have built and fully tested the velocity drive. Operation in backscatter mode means that no sample preparation is required. The instrument can be placed on a lander or rover or used at a lunar base.

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GAMMA RAY AND NEUTRON SPECTROMETER FOR THE LUNAR RESOURCE MAPPER.

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One of the early Space Exploration Initiatives will be a lunar orbiter to map the elemental composition of the Moon. This mission will support further lunar exploration and habitation and will provide a valuable dataset for understanding lunar geological processes. The proposed payload will consist of the gamma ray and neutron spectrometer discussed here, an X-ray fluorescence imager [1], and possibly one or two other instruments. The spacecraft will have a mass of about 1000 kg including fuel, be built on a fast schedule (about three years), and have a low cost (about $100 M including launch). Launch is tentatively scheduled for April 1995.

Most gamma rays used to map lunar elements are in the energy range of 0.2–8 MeV. The proposed gamma ray detector will contain an n-type germanium crystal that is ≈70% efficient [relative to a 7.62-cm-diameter × 7.62-cm-length NaI(Tl) scintillator]. N-type is used because it is much less susceptible to radiation damage than p-type germanium. Because a Stirling cycle cooler will be used, the crystal will be mounted using techniques commercially developed in recent years for operating germanium detectors on vibrating platforms. A segmented cesium iodide (CsI(Na)) anti-coincidence shield on the sides and back of the germanium crystal

GERMANIUM GAMMA-RAY SENSOR
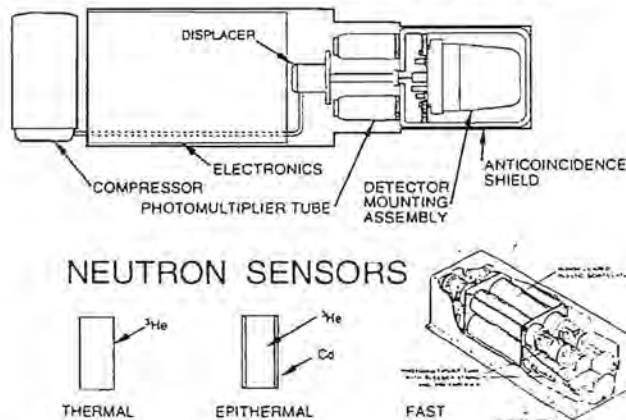

NEUTRON SENSORS

Fig. 1. Schematics of a generic germanium detector with a split-cycle Stirling cooler (adopted from [5]) and the neutron sensors for thermal, epithermal, and fast neutrons.

will eliminate most events due to charged particles, gamma rays produced by cosmic rays incident on the spacecraft, and Compton-scattered events in the crystal. A plastic scintillator over the nadir-pointing surface of the germanium crystal will provide a similar capability in the forward direction without significantly attenuating the gamma ray flux from the Moon. The gamma ray detector will be on a short cantilever to further reduce the background from the spacecraft. One side segment of the cesium iodide shield will serve as a back-up for the germanium crystal.

The critical issue for operating a germanium detector in space is the method of cooling. For short missions, stored cryogens such as liquid nitrogen, solid methane, or solid argon have been proposed. For longer missions a passive radiator, such as used on the Mars Observer, or an active device, such as a Stirling cycle cooler, is required. We propose not to use a passive radiator because of complications in shielding the radiator from the Sun, Earth, and Moon when the spacecraft is in a polar orbit and, instead, propose to use the British Aerospace Stirling cycle cooler based on the Oxford design. This closed-cycle mechanical cooler is designed for a 10-year lifetime and has operated successfully in the laboratory without maintenance for over 2½ years. Two of these miniature cryocoolers were launched on 12 September 1991 as part of the Improved Stratospheric and Mesospheric Sounder (ISAMS) multichannel infrared radiometer on the Upper Atmosphere Research Satellite and are still operating successfully. Because the germanium detector energy resolution can be degraded by vibration, we plan to use a pair of these coolers with two compressors and two expanders mounted back to back to minimize vibration. In addition, we will use a flexible vibration decoupler between the expander cold tips and the germanium crystal. Microphonics should not be a problem because a germanium detector cooled by a cryocooler with a higher vibration level gave 3.6-keV resolution at 1332 keV, which is ~2 times worse than with a good laboratory Ge detector, but is more than adequate for planetary elemental mapping.

A neutron detector is required because it provides maximum sensitivity for hydrogen and hence water. Data from the gamma ray detector and the neutron detector are complementary because the neutron flux, which produces most gamma rays, can be used

to normalize the gamma ray line intensities; in turn, the gamma ray data are needed to determine the composition of the lunar surface and hence the moderation of neutrons by elements other than hydrogen [2]. Three different sensors are used to measure the neutrons in three energy ranges. Thermal neutrons ($E_n \sim$ 0.010.4 eV) are measured with a bare ^{3}He proportional counter, epithermal neutrons ($E_n \sim 0.4$–10^3 eV) with a ^{3}He proportional counter wrapped with cadmium (which strongly absorbs thermal neutrons), and fast neutrons ($E_n \sim 0.5$–10 MeV) with the backup Army Background Experiment (ABE) instrument, which contains four boron-loaded plastic scintillators [3]. Thermal/epithermal and fast/epithermal counting ratios are very sensitive to the amount of hydrogen in the lunar surface [4].

The gamma ray and neutron spectrometer will provide data on many elements over the entire lunar surface. Published estimates of the detection limits for similar detectors range from 0.016 ppm for uranium to 1.3% for calcium [5]. We estimate a hydrogen detection limit of 100 ppm based on this neutron detector system [4]. The spatial resolution is about 140 km × 140 km, which is determined by the orbit altitude of 100 km [6]. Both gamma rays and neutrons sense the elemental composition of the lunar surface to depths of tens of centimeters. The results from this instrument will complement the measurements from elemental and/or mineralogical remote sensing instruments with higher spatial resolution.

This work was supported by NASA and done under the auspices of the U.S. DOE.

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MAGNETIC SUSCEPTIBILITY MEASUREMENTS FOR *IN SITU* CHARACTERIZATION OF LUNAR SOIL. R. R. Oder, EXPORTech Company, Inc., New Kensington PA, USA.

Magnetic separation is a viable method for concentration of components of lunar soils and rocks for use as feedstocks for manufacture of metals, oxygen, and for recovery of volatiles such as ^{3}He [1].

Work with lunar materials indicates that immature soils are the best candidates for magnetic beneficiation [2]. The magnetic susceptibility at which selected soil components such as anorthite, ilmenite, or metallic iron are separated is not affected by soil maturity, but the recovery of the concentrated components is. Increasing soil maturity lowers recovery [3]. This is illustrated in Fig. 1.

Mature soils contain significant amounts of glass-encased metallic iron. Magnetic susceptibility, which is sensitive to metallic iron content, can be used to measure soil maturity. The relationship between the ratio of magnetic susceptibility and iron oxide and the conventional maturity parameter, I_s/FeO, ferromagnetic resonant intensity divided by iron oxide content, is given in Fig. 2. The magnetic susceptibilities were determined using apparatus designed for magnetic separation of the lunar soils.

Magnetic susceptibility should be incorporated in the instrumentation packages carried by lunar landers and rovers for *in situ* identification of candidate soils best suited for magnetic benefi-
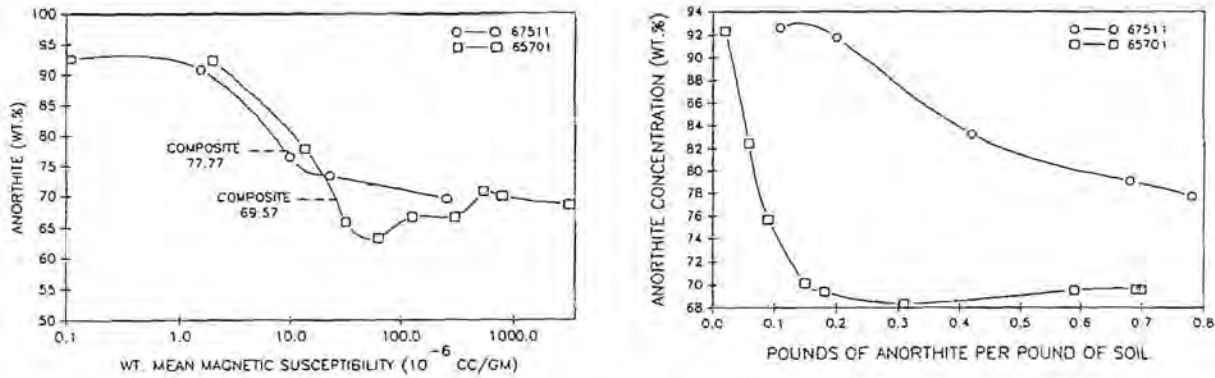
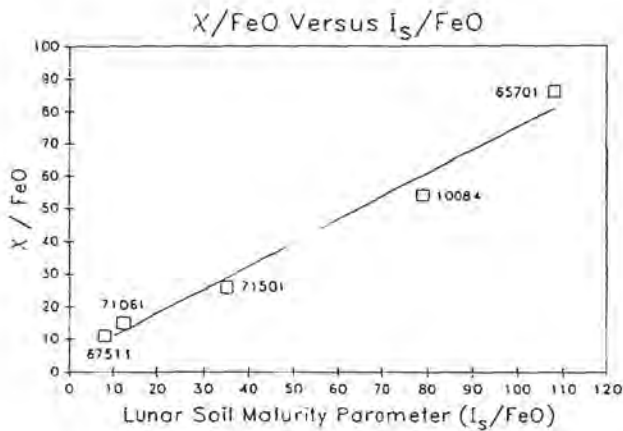Fig. 1. Anorthite separation from highland soils.

Fig. 2. X/FeO vs. soil maturity.

ciation. The measurement is more amenable to *in situ* measurement than is ferromagnetic resonance.

There are many ways to measure magnetic susceptibility that could be incorporated in mobile soil characterization packages. Instrumentation to detect separable ilmenite might combine magnetic susceptibility and X-ray methods to measure iron and titanium. Measurements could be made on soil samples or on core samples for rapid determination of maturity. This would permit a quick assessment of the potential for magnetic separation of selected mineral components.

References: [1] Oder R. R. et al. (1989) *LPSC XX*, 804–805; Oder R. R. and Taylor L. A. (1990) In *Engineering, Construction and Operations in Space II* (S. W. Johnson and J. P. Wetzel, eds.), 143–152, American Society of Civil Engineers, New York. [2] Oder R. R. and Jamison R. E. (1989) *Final Report, Phase I SBIR Program*, NASA Contract NAS 9-18092. [3] Oder R. R. (1991) *IEEE Transactions on Magnetics*; Oder R. R. (1991) AIME-SME Annual Meeting, Denver.

THE QUICKEST, LOWEST-COST LUNAR RESOURCE ASSESSMENT PROGRAM: INTEGRATED HIGH-TECH EARTH-BASED ASTRONOMY. Carlé M. Pieters and the PRELUDES Consortium, Brown University, Providence RI 02912, USA.

Introduction and Recommendations: Science and technology applications for the Moon have not fully kept pace with technical advancements in sensor development and analytical information extraction capabilities. Appropriate unanswered questions for the Moon abound, but until recently there has been little motivation (funding) to link sophisticated technical capabilities with specific measurement and analysis projects. Over the last decade enormous technical progress has been made in the development of (1) CCD photometric array detectors, (2) visible to near-infrared imaging spectrometers, (3) infrared spectroscopy, (4) high-resolution dual-polarization radar imaging at 3.5, 12, and 70 cm, and equally important, (5) data analysis and information extraction techniques using compact powerful computers. Parts of each of these have been tested separately, but there has been no programmatic effort to develop and optimize instruments to meet lunar science and resource assessment needs (e.g., specific wavelength range, resolution, etc.) nor to coordinate activities so that the symbiotic relation between different kinds of data can be fully realized. No single type of remotely acquired data completely characterizes the lunar environment, but there has been little opportunity for integration of diverse advanced sensor data for the Moon.

Recommendation. A research and analysis program to survey potential resource sites on the lunar nearside is recommended that would include aggressive instrument development and acquisition and analysis of advanced sensor data obtained for the Moon with optical, infrared, and radar telescopes. Coordinated acquisition and integration of advanced sensor data can provide synoptic information necessary to assess regional compositional diversity, local regolith character, and geologic context of sites on the lunar nearside that have high potential for lunar resources. The cost of such an R&A program is estimated to be about $5 million per year. This program includes an instrument development and upgrade program during the first year, and calibration and initial data products by the second year. The broad nature of the program exercises expertise gained during and since Apollo and provides

TABLE 1.   Evolution of VIS/near-IR spectroscopy of the Moon.

Date[*]	Person/Group	Capability	Range	Min. Resol.	~Coverage
1912	R. W. Wood	Photographic color	V	~30 km	Nearside
1968	T. B. McCord	PMT <25-color spot	xV	20 km	>100 areas
1970	L. A. Soderblom	3-color image scan	V	20 km	M. Tranquillitatis
1970	McCord/Johnson	~50-color spot	xV + nIR	20 km	<10 areas
1976	McCord et al.	3-color vidicon	xV	2 km	Nearside mare
1977	McCord/Pieters	Vidicon spectrometer/	xV	2 km	100 km linear
		polarimeter	xV	5 km	<20 areas
1980	McCord et al.	128-color single spot	nIR	5 km	>100 areas
1989	French/Germans	3–10-color CCD	xV	1 km	100 × 100 areas
1990	Lucey et al.	CCD spectrometer	xV	2 km	100 km linear
1990	Galileo SSI team	CCD imaging (spacecraft)	xV	5 km	1/2 Moon
1990	Galileo NIMS team	Stepped I³ spectrometer	nIR+	100 km	1/2 Moon

[*] First publication/presentation.
Spectral range: V = visible (0.4–0.7 μm); xV = extended visible (0.32–1.1 μm); nIR = near infrared (0.6–2.6 μm).

young scientists the experience necessary to carry out the proposed more complete global assessment of the Moon to be acquired from orbital spacecraft.

Reasons for implementation of an aggressive R&A lunar astronomy program in the current environment. (1) SEI. The information produced has immediate and direct input into the Space Exploration Initiative (SEI). It provides an early broad assessment of potential lunar sites that cannot be easily achieved by other means on a timescale that is immensely valuable to the decision-making process. It is visible activity showing immediate results for the SEI program and is excellent preparation for the important, more detailed program of orbital measurements. (2) Technology Development. The proposed R&A program drives U.S. advanced sensor development and use with significant real applications. Integration and analysis of complex advanced sensor data are essential capabilities that need to be developed and tested. Experience gained from the project will give a head start to the technical needs for later detailed analysis of global systems (Earth, Moon, Mars). (3) Science Education. The program will contain heavy university involvement and provide an active research environment essential for the training of new lunar scientists. Highly technical activities with a focus on lunar science will significantly expand the number of young scientists appropriately trained for lunar science and exploration by the turn of the century.

Two Examples of Technology Concepts for **Lunar Measurements:** *VIS/near-IR spectroscopy.* The mineral composition of surface material can be derived from visible and near-infrared radiation reflected from the surface. The source of radiation is the Sun and the capabilities of the detector system determine the type of information derived. Solar radiation interacts with the first few millimeters of material and is altered by the absorption properties inherent to the surface material. When the reflected radiation is analyzed with high spectral resolution, broad absorption bands are detected that are highly diagnostic of the minerals present on the surface. For lunar materials, most major rock types can be readily distinguished based on the mineral absorption bands present in their spectra.

As summarized in Table 1, the color of the Moon has been under study since the early part of this century. When photoelectric detectors became available in the late 1960s and 1970s the spectral properties of different areas on the Moon were measured quantitatively. Until infrared detectors were available in the late 1970s and early 1980s, spectral analyses were limited largely to distinguishing different units on the surface based on color differences in the extended visible range of the spectrum. Framing cameras using two-dimensional silicon detectors (vidicons and CCDs) allowed the extent of distinct surface units to be mapped. With the development of high-spectral-resolution near-infrared spectrometers, the diagnostic mineral absorption bands could be identified and the composition of the surface characterized. Such studies flourished in the 1980s, with significant science return using point spectrometers, with which the spectrum of an individual lunar area 3–20 km in diameter is measured and surface composition of that location analyzed.

Current technology allows both the spatial extent of surface units and the compositional character of surface material to be analyzed with an advanced sensor called an imaging spectrometer. Such instruments have been developed and successfully flown on aircraft for terrestrial applications, but none have been designed and built to specifically meet lunar exploration needs. An imaging spectrometer utilizes recent advancements in detector development and optical design to obtain an "image cube" of data (two dimensions of spatial information and one dimension of spectral information). For lunar applications the design should include high-spatial (1–2 km) and high-spectral (10 nm) resolution from the visible through the near-infrared, where most diagnostic absorption bands occur.

TABLE 2.   Evolution of radar measurements for the Moon.

Dates	Capability	Resolution	Nearside Coverage
1946	First detection	Bulk Moon	—
1962	Crater Tycho detected	10 km	—
1964–1972	Backscatter, imaging 7.5 m	40 km	Near global
	Backscatter imaging 70 cm	10 km	Global
	Backscatter imaging 3.8 cm	2 km	Global
	Topography imaging 3.8 cm	2 km	Local targets
1980–1983	Backscatter imaging 70 cm	2 km	Global
1985–1991	Backscatter imaging 70 cm	500 m	Local targets
	Backscatter imaging 12.6 cm	300 m	Local targets
	Backscatter imaging 3.8 cm	50 m	(In progress)

Radar backscatter. The surface and subsurface scattering properties of the Moon can be analyzed using radar backscatter imaging. The radiation is both transmitted and received by Earth-based radar antennae. Two-dimensional backscatter images are derived using a delay-doppler technique developed in the 1960s and 1970s. The returned signal is directly related to the geometry of the measurements, the number of scatterers encountered on the scale of the wavelength, and the dielectric properties of surface materials. Surfaces that are smooth on the scale of the wavelength reflect the radiation in a specular manner. Surfaces containing abundant scattering elements on the scale of the wavelength return a higher signal. Since the lunar surface is anhydrous, subsurface block population can also be detected with longer wavelengths.

As summarized in Table 2, radar measurements of the Moon have also had a long history with several important milestones. First was simply the detection of the Moon with Earth-based instruments. As technology advanced during the 1960s and 1970s, the techniques for measurement of radar backscatter of the Moon were perfected and two-dimensional images of the radar backscatter properties were produced at relatively low spatial resolution. Analyses of dual-polarization radar data confirmed the sensitivity to block population on the surface. The last several years have seen dramatic improvement of radar measurements possible. These include an improvement in both sensitivity and, more important for lunar measurements, an improvement in the spatial resolution that can be obtained with Earth-based telescopes.

Current technical capabilities indicate that a spatial resolution of 30–300 m is possible for lunar nearside targets (optical telescopes can achieve 1-km resolution; Lunar Orbiter IV obtained ~100-m resolution for the lunar nearside from orbit). Several tests of these new radar capabilities have already been made. In order to achieve the desired resolution and science analysis return, a modest upgrade to current radar telescopes is required to allow dual polarization at three wavelengths and more extensive data analyses (information extraction) capabilities need to be developed for lunar specific applications.

LUNAR SURFACE ROVERS.

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Despite the Ranger, Lunar Orbiter, Surveyor, Apollo, Luna, and Lunokhod programs, many questions of lunar science remain unanswered because of a lack of specific data. With the potential for returning humans to the Moon and establishing a long-term presence there, a new realm of exploration is possible. Numerous plans have been outlined for orbital and surface missions. Here we describe the capabilities and objectives of a small class of rovers to be deployed on the lunar surface. The objective of these small rovers is to collect detailed *in situ* information about the composition and distribution of materials on the lunar surface. Those data, in turn, would be applied to a variety of lunar geoscience questions and form a basis for planning human activities on the lunar surface.

The initial rover design has been scoped for a small Artemis lander payload (about 60 kg). It consists of a four- or six-wheeled, solar-powered rover with a mass of 28 kg. Two rovers would be deployed from a single Artemis lander. Rover lifetime would be at least 3 lunar days and hopefully 7–10; at least tens of kilometers of range are possible (depending upon the amount of time devoted to moving vs. sampling and analysis). During the lunar night, the rover would hibernate. About 11 kg of the total 28 kg is available for science payload and sampling equipment, which allows for a variety of capabilities that capitalize on microtechnology. Rover speed would be 0.5–1.0 km/hr depending upon the terrain. Power (60–200 W) is provided by solar panels (0.3 m^2) that also serve to shield the rover from high thermal loads during the day. 120 Whr of AgZn batteries provide capability for short-period, high-load demands; these batteries are capable of withstanding the lunar night. Nominal data rate would be about 30 kbps at 20 W RF; rates as high as 150 kbps would be possible for limited periods. Control of the rover mobility would be in two modes: behavioral control driving and teleoperation driving. In the behavior control mode, a series of way points would be selected and the rover would navigate along the predetermined path to a site, invoking autonomous obstacle avoidance if necessary. In the teleoperation driving mode, mobility would be controlled in a real-time sense from the Earth using slow-scan video for viewing. Sampling and deployment would all be done autonomously once a specific action and position had been selected from the ground. The system would not make autonomous decisions about measurement or sampling.

Two types of payloads are envisioned for such a small rover: a geoscience payload and a physical properties payload. The nominal geoscience payload is aimed at addressing the chemical and mineralogic properties of the regolith and rocks, the composition of absorbed and adsorbed gases in the regolith, and the morphology of the surface to millimeter scale. The payload includes stereo imaging, field lens camera, infrared imaging spectrometer, evolved gas analysis, and alpha/proton/X-ray fluorescence instruments, as well as a scoop and an auger drill to obtain samples of the upper meter of regolith. Using these data, several questions can be addressed: geochemical and petrological processes; regolith stratigraphy and development; history of the solar-wind-implanted gases; lunar resources; small-scale surface morphology; and site evaluation.

Stereo imaging is achieved through two mast-mounted CCD framing cameras (800 × 1000 pixels) with a separation of about 25 cm. Mast mounting allows 360° horizontal viewing and 120° of vertical viewing. The field lens camera is the same type of camera but mounted on the rover body with optics that allow imaging at a resolution of a few millimeters in the near field. The infrared imaging spectrometer covers the spectral range of 0.7 to 2.5 μm and focuses on the portion of the spectrum sensitive to pyroxenes, olivines, FeO content, and soil composition. A spatial resolution of <2 mm at 30 cm is possible. The alpha/proton/X-ray fluorescence instrument is aimed at obtaining elemental composition. The alpha/proton mode measures low Z elements, whereas the X-ray fluorescence mode is sensitive to higher Z elements. Curium-244 is used as the source for the alpha particles; [109]Cd or [244]Cm would be used for the X-ray excitation. The evolved gas analysis system would be used to heat the samples to drive off gases that would then be analyzed by a mass spectrometer or other system. Target gases include H_2, ^{3}He, SO_2, CO, CO_2, H_2S, H_2O, and N_2. Two types of sample acquistion equipment are planned: a scoop and a drill. The scoop is a clamshell mounted on a 4 degree-of-freedom arm and would collect samples for analysis to depths of a few centimeters with a sample volume of a few cubic centimeters; it could also be used for shallow trenching. This same arm would also deploy the alpha/proton/X-ray device to the surface. The drill is an auger drill mounted to the rover body that

could penetrate to depths of about 1 m. Sample volume of a few cubic centimeters from depth intervals of a few centimeters would be obtained. The auger would be housed in a tube such that samples from a given depth remain isolated from regolith material at other depths.

A physical properties payload would be intended to study the geotechnical properties of the surface and subsurface. Those data would be aimed primarily at engineering objectives but would also be applicable to geoscience problems. Parameters of interest include particle size and shape, density and porosity, compressibility, shear strength, bearing capacity, trafficability, electrical conductivity, and charging/discharging of the surface. The complete payload is under study and has not yet been determined. However, it is anticipated that an electron-magnetic sounding system would be used to determine the thickness, stratigraphy, and boulder content of the regolith. This system would be mounted on the rover body such that long distance or areally extensive traverses could be obtained.

Later Artemis landers have a larger payload capability, about 200 kg or larger. Additional studies are underway that consider the possibility of building larger rovers that have more capability, particularly with respect to lifetime, range, and drilling. Alternatively, the larger payload capacity could be used to deploy more of the small rovers outlined above.

COMBINED GAMMA RAY/NEUTRON SPECTROSCOPY FOR MAPPING LUNAR RESOURCES. R. C. Reedy, R. C. Byrd, D. M. Drake, W. C. Feldman, J. Masarik, and C. E. Moss, Space Science and Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545.

Some elements in the Moon can be resources, such as hydrogen and oxygen. Other elements, like Ti or the minerals in which they occur, such as ilmenite, could be used in processing lunar materials. Certain elements can also be used as tracers for other elements or lunar processes, such as hydrogen for mature regoliths with other solar-wind-implanted elements like helium, carbon, and nitrogen. A complete knowledge of the elemental composition of a lunar region is desirable both in identifying lunar resources and in lunar geochemical studies, which also helps in identifying and using lunar resources. Discussed here is the use of gamma ray and neutron spectroscopy together to determine abundances of many elements in the top few tens of centimeters of the lunar surface. To date, very few discussions of elemental mapping of planetary surfaces considered measurements of both gamma rays and the full range of neutron energies.

The concepts of using gamma rays or neutrons escaping from the Moon to determine lunar elemental composition date back over 30 years (e.g., [1]). In 1971 and 1972, gamma ray spectrometers (GRS) on Apollos 15 and 16 mapped ≈22% of the lunar surface but only could determine the abundances of several elements (Th, Fe, Ti, K, and Mg) because of the use of low-resolution NaI(Tl) scintillator detectors and the short durations of the missions. A high-resolution germanium GRS is on the Mars Observer scheduled to be launched in late September 1992 [2]. Such a spectrometer is much more sensitive for determining lunar elemental abundances and for identifying surface components than was the Apollo GRS [3]. Neutron spectroscopy of another planet has not been done yet, although the Mars Observer GRS is capable of detecting thermal and epithermal neutrons [2]. A germanium GRS

can also detect neutrons ≥0.6 MeV by triangular-shaped peaks in the spectrum made by neutron-induced inelastic-scattering reactions in the detector [4]. The inclusion of a detector specifically designed to measure fast ($E_n \sim 0.1$–10 MeV) neutrons improves the sensitivity of detecting hydrogen in the lunar surface [5]. Spectrometers to measure the fluxes of gamma rays and neutrons escaping from the Moon are discussed elsewhere in this volume [6]. A gamma ray spectrometer can also be used to detect thermal and epithermal neutrons using coatings of thermal-neutron-absorbing materials [3], although not with the sensitivity of detectors designed specifically for such neutrons. The theories for gamma ray and neutron spectroscopy of the Moon and calculations of leakage fluxes are presented here with emphasis on why combined gamma ray/neutron spectroscopy is much more powerful than measuring either radiation alone.

Sources of Neutrons and Gamma Rays: Most gamma ray lines made by the decay of excited states in nuclei are produced by several types of nuclear reactions, mainly neutron nonelastic scattering and neutron capture [7–9]. The main exceptions are the gamma rays made by the decay of the naturally radioactive elements (K, Th, and U). The neutrons are made by the interaction of the energetic particles in the galactic cosmic rays (GCR) with the lunar surface [10]. Neutrons are produced mainly with energies of ~0.1–10 MeV, with some made with higher energies. The rates for the production of these fast neutrons depends on the intensity of the GCR particles, which can vary by a factor of ≈3 over an 11-year solar cycle [11], and is slightly (~5%) dependent on the surface composition [12]. The transport and interactions of these fast neutrons are also dependent on the surface composition. Neutrons in the Moon can be slowed by scattering reactions to epithermal ($E_n \sim 0.5$–10^3 eV) and thermal ($E_n \sim 0.01$–0.5 eV) energies. The flux of epithermal neutrons is mainly dependent on the hydrogen content of the surface, while the flux of thermal neutrons depends both on the amounts of neutron moderators like H and of thermal-neutron absorbers like Fe, Ti, Sm, and Gd [1,5,12,13]. Many neutrons escape from the lunar surface and can be detected in orbit. The gravitational field of the Moon affects slightly the flux at orbit of the lowest-energy neutrons [14].

The reaction of these neutrons with atomic nuclei in the lunar surface produces most of the gamma rays used for elemental mapping. Fast neutrons make gamma rays by a large variety of nonelastic-scattering reactions. Many elements (e.g., O, Mg, Si, and Fe) are mapped by neutron inelastic-scattering reactions making excited states in the target nucleus, such as $^{24}Mg(n,n\,\gamma)^{24}Mg$ exciting the 1.369-MeV state of ^{24}Mg (which almost immediately, ≤1 ps, decays to the ground state). Neutrons with energies of ~0.5–10 MeV make most of these inelastic-scattering gamma rays. Neutrons with higher energies can induce many types of reactions, such as the $^{28}Si(n,n\,\alpha\,\gamma)^{24}Mg$ reaction, which also can make the 1.369-MeV gamma ray. Many thermal and some epithermal neutrons produce gamma rays by neutron-capture reactions, such as the $^{28}Si(n,\gamma)^{29}Si$ reaction, which makes a cascade of gamma rays. The cross sections for neutron-capture reactions vary by orders of magnitude, and the elements mapped by gamma rays made by such reactions (e.g., Ti, Fe, and possibly Cl, Sm, and Gd) are those with high cross sections for (n,γ) reactions and that emit one or more gamma ray with a high yield per captured neutron.

Calculations of Neutron and Gamma Ray Fluxes: The ultimate sources of lunar neutrons and most lunar gamma rays are from interactions of the high-energy ($E \sim 0.1$–10 GeV) particles in the galactic cosmic rays. The Los Alamos high-energy transport

code LAHET is used to calculate the transport and interactions of the GCR particles and the production of secondary particles, especially neutrons. The LAHET code is based on the HETC code used by [12] but with additional physics included in the code, such as the production of neutrons by preequilibrium processes in excited nuclei. Neutrons with energies below 20 MeV are transported with the MCNP or ONEDANT codes. The ONEDANT code has been modified [14] to transport low-energy neutrons to orbital altitudes with consideration of gravity and the neutron's half-life. This series of codes is used to calculate the fluxes of neutrons escaping from the Moon. Preliminary results for neutrons escaping from the Moon were calculated by [5] using the ONEDANT code. As in [5], a range of lunar compositions and hydrogen contents has been examined with the LAHET/MCNP codes. The results of our calculations are consistent with those in [5] and show that taking ratios of the fast/epithermal and thermal/epithermal neutron fluxes is the best for determining both lunar hydrogen contents and the effective $1/v$ macroscopic cross section for the absorption of thermal neutrons in a lunar region.

To date, most studies of lunar gamma ray fluxes have used the values in [7,8]. In these works, the gamma ray fluxes from nonelastic-scattering reactions were calculated using the fast neutron fluxes of [10] and cross sections for producing specific gamma rays as a function of energy. The gamma ray fluxes from neutron-capture reactions were calculated with neutron-capture rates derived from [13] and evaluated nuclear data for gamma ray yields. Elemental detection sensitivities for a number of elements using both the Apollo Gamma Ray Spectrometer system and a high-resolution germanium spectrometer are given in [3]. Hydrogen is best measured using thermal, epithermal, and fast neutron spectrometers together with elemental abundances determined from a gamma ray spectrometer [5]. We are now in the process of coupling the neutron fluxes calculated with the codes discussed above with codes for the production and transport of gamma rays and will soon have new sets of elemental detection sensitivities using gamma ray and neutron spectrometers. For now, the calculated gamma ray fluxes of [8] are being used, as in the recent study by [3], which showed the great superiority of using high-resolution gamma ray spectrometers for lunar mapping.

Conclusions: The calculations for fluxes of neutrons escaping from the Moon have been extended and support the conclusions of [5] for using ratios of thermal, epithermal, and fast neutrons for lunar elemental studies. The fluxes of fast neutrons can vary by ~10% depending on the surface composition independent of the major variations expected from GCR-flux changes over a solar cycle. The direct measurement of the fluxes of fast neutrons can be used to help determine elemental abundances from nonelastic-scattering gamma rays, and the use of ground truths (as with the Apollo gamma ray spectra) or normalizing the sum of all abundances to unity may not be needed. Similarly, direct measurements of the fluxes of thermal (and epithermal) neutrons can be used to determine abundances from fluxes of neutron-capture gamma rays. The elemental abundances derived from the gamma ray data are needed in interpreting the neutron measurements. The thermal/epithermal ratio can be used to get an independent measure of the effective $1/v$ macroscopic cross section for thermal neutrons. Differences of this macroscopic cross section determined from the major elements mapped with gamma rays from that inferred from low-energy neutrons could indicate the presence of other elements

that strongly absorb thermal neutrons, such as Sm and Gd. Thus in many ways the complementary nature of gamma rays and neutrons make a combined gamma ray/neutron spectrometer more powerful than each technique by itself.

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COMPAS: COMPOSITIONAL MINERALOGY WITH A PHOTOACOUSTIC SPECTROMETER.   W. Hayden Smith, Washington University, St. Louis MO 63130, USA.

There is an important need for an *in situ* method of mineral and rock identification and quantification that provides true absorption spectra for a wide spectral range for lunar lander/rover missions.

Many common minerals, e.g., some feldspars, magnetite, ilmenite, and amorphous fine solids or glasses, can exhibit flat spectral reflectances in the 400–2500-nm spectral region that render inaccurate or difficult their spectral detection and quantitative analysis. Ideal rock and mineral spectra are, of course, pure absorption spectra that are independent of the spectral effects of scattering, particle size, and distribution that can result in a suppression or distortion of their spectral features. This ideal seldom pertains to real samples. Since sample preparation is difficult and may fundamentally alter the observed diffuse spectral reflectance, an *in situ* spectral measurement method for rocks and minerals on the Moon, insensitive to the sample morphology, would be invaluable.

Photoacoustic spectroscopy is a well-established technique appropriate for this task that has been widely applied in condensed-phase spectral studies of complex, highly light scattering, unprepared samples of everything from coal to whole blood, including rock and mineral characterization.

A Compositional Mineralogy Photoacoustic Spectrometer, or COMPAS, can enable *in situ* spectral measurement of rocks and minerals, bypassing the major limitations of diffuse reflectance spectroscopy. COMPAS has the following features: (1) it is designed for *in situ* spectral characterization of rocks and minerals and their surface weathering species; (2) it does not require modifying or altering the sample or its surroundings; (3) it provides spatial resolution on a submillimeter scale, functions at the ambient (high or low) temperature, and requires no coolants; (4) spatial and spectral data are acquired in a serial mode at a modest data rate; (5) it has no internal moving components, which gives it high reliability; and (6) it is physically very small with low weight and power requirements.

COMPAS spectral capabilities for rock and mineral samples will be incorporated into an instrument prototype specifically for lunar measurements, compatible with rover capabilites.

LUNAR UV-VISIBLE-IR MAPPING INTERFEROMETRIC SPECTROMETER.

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We have developed ultraviolet-visible-infrared mapping digital array scanned interferometers [1] for lunar compositional surveys. The research has defined a no-moving-parts, low-weight and low-power, high-throughput, and electronically adaptable digital array scanned interferometer that achieves measurement objectives encompassing and improving upon all the requirements defined by the LEXSWIG for lunar mineralogical investigation. In addition, LUMIS provides a new, important, ultraviolet spectral mapping, high-spatial-resolution line scan camera, and multispectral camera capabilities. We describe an instrument configuration optimized for spectral mapping and imaging of the lunar surface and provide spectral results in support of the instrument design.

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LUNAR RESOURCE ASSESSMENT: STRATEGIES FOR SURFACE EXPLORATION.

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Use of the indigenous resources of space to support long-term human presence is an essential element of the settlement of other planetary bodies. We are in a very early stage of understanding exactly how and under what circumstances space resources will become important. The materials and processes to recover them that we now think are critical may not ultimately be the raison d'etre for a resource utilization program. However, the need for strategic thinking proceeds in parallel with efforts to implement such plans and it is not too soon to begin thinking how we could and should use the abundant resources of materials and energy available from the Moon.

A plan to assess the resources of the Moon (or any extraterrestrial body) must be based on at least a rudimentary understanding of the following questions: (1) What materials and energies are likely to be needed by the envisioned space-faring infrastructure? (2) Where are these commodities on the Moon and what are their physical states and concentrations? (3) What types of processing are required to produce the desired products and how can such processing yield the maximum possible return? Once the first question has been addressed, resource assessment concerns itself primarily with question 2. However, the realities of question 3 must always be kept in mind during resource assessment; the distinction between ore and gangue is economic, not geologic.

My supposition is that at a minimum, we will want the following commodities: (1) bulk regolith, for shielding and construction on the lunar surface (ultimately for export to human-tended stations in Earth-Moon space), and (2) oxygen and hydrogen, for propellant and life support. I confine my attention to these essential products.

Synergy with Orbital Missions: Resource assessment requires both orbital and landed prospecting. Moreover, landed missions can be more effectively planned and conducted if some orbital reconnaissance is carried out before the landed payloads are sent. The issues associated with orbital prospecting are ably summarized by Taylor [1] and I touch on them here only from the perspective of the need to carry out a successful series of lander missions.

The lunar surface composition should be surveyed globally. This survey is the number one priority and should be carried out as soon as possible. From these data, a set of potential prospects can be selected and characterized to a first order. It will then become the task for a follow-up lander mission to obtain the data of quality sufficient to make judgments on the type of processing to be done, availability of feedstocks, and estimated product yields.

Bulk Regolith—The First Lunar Resource: Although the initial return to the Moon requires no *In Situ* Resource Utilization (ISRU), the long-term presence of people on the Moon compels us to consider the likely first needs of these lunar inhabitants. One can envision bringing along enough consumables (oxygen, water, food) to support the crew members for significant lengths of time, but shielding from the harsh radiation environment at the lunar surface requires mass, and lots of it. Several scenarios envision the use of bulk regolith piled over habitation modules. Bulk regolith is available in virtually unlimited quantities nearly anywhere on the Moon (it is hard to come by only at very fresh, large crater melt sheets, such as King). I believe that we understand the nature, formation, and evolution of the regolith well enough from Apollo to begin using regolith immediately for shielding purposes. If terrain-moving and construction equipment is built robustly enough, there is little need for precursor characterization of the site regolith. However, for completeness, Table 1 lists the desired knowledge of regolith properties and an estimate of the required fidelity of information.

Oxygen for Fuel and Life Support: After bulk regolith, lunar oxygen seems to be the most important resource for human use on the Moon. The amounts of oxygen required to support human life are trivial; in the following, I am assuming that oxygen is being produced primarily for use as propellant to support the Earth-Moon transportation infrastructure. If so, abundant oxygen will also be available to support life at the lunar outpost.

There is no shortage of this commodity: Lunar soils are at least 45% by weight oxygen. However, a strategy to assess oxygen resource potential must assume some type of processing scheme. Both high-yield and low-yield processes have been proposed to extract lunar oxygen. High-yield processes (e.g., magma electrolysis [2]) can effectively use any lunar material as feedstock and thus have no real assessment requirements for potential prospects. One low-yield process has received considerable attention: reduction of lunar ilmenite by hydrogen (e.g., [3]). This technique has been validated, at least at the workbench level, and produces oxygen at roughly 3% efficiency. The ilmenite reduction method requires a specific feedstock: lunar ilmenite grains or, at least, ilmenite-rich lunar soils. This requirement drives prospecting to high-Ti-composition maria; the ore should be as rich as possible in modal ilmenite (Table 1).

Given low-yield ilmenite reduction, the resource assessment task is simplified to identifying the highest ilmenite concentrations on the Moon and at specific sites, characterizing ilmenite gross abundances and their lateral and vertical variability (on a scale of a few meters). The location of ilmenite-rich regions is well suited to orbital prospecting [1]. Once such areas have been identified,

TABLE 1.   Resource assessment needs: Initial surface missions.

Knowledge Needed	Obtained By	Precision Required
Regolith thickness	Lander imaging	0.5 m
Regolith fragment size distribution	Lander imaging	±10 cm
Bulk chemistry/ mineralogy	XRF/XRD/Mössbauer	± few %
Solar wind gas concentration	Lander GRS/NS	10s of ppm
Bulk	Lander EGA	1 ppm
Variability (10-m scale)	Rover EGA	1 ppm

promising sites should be investigated by selected *in situ* measurements. The heterogeneity of the ilmenite concentrations should be measured at scales commensurate with the those of the expected mining operations; nominally, this is likely to be on scales of a few meters. Concurrent documentation of regolith physical properties is also required, as the presence and abundance of large blocks, for example, might significantly influence mining operations. The data needs, some selected techniques for their acquisition, and precision required are estimated in Table 1.

Hydrogen for Fuel and Life Support: In contrast to oxygen, hydrogen is rare on the Moon. Hydrogen is important both as a fuel to support the transportation infrastructure, but it is also an essential resource to make water for life support, thermal control, and agriculture.

As far as we know, lunar hydrogen predominantly takes the form of molecules of solar hydrogen, adsorbed onto fine grains of lunar dust [4]. About 90% of the solar-wind-implanted hydrogen can be extracted by heating the lunar soil to about 700°C. Typical concentrations of hydrogen in Apollo soil samples are between 20 and 50 ppm [4]; there seem to be positive correlations between Ti content of mare soils and total hydrogen abundance and between soil maturity and hydrogen abundance. However, we have never made *in situ* measurements of lunar hydrogen and we do not know how it varies laterally or vertically in the regolith on a scale of meters. We also do not know how these supposed correlations hold up over the entire Moon or whether they exist at scales appropriate for resource extraction.

If hydrogen extraction from the Moon's surface is to become a reality, we must characterize its presence, abundance, and distribution in detail. I would give initial attention to high-Ti areas, including regional pyroclastic deposits [5]. A surface rover mission should simultaneously analyze soil chemistry, maturity, and adsorbed gas concentration; such a prospect should be carried out within a small area (e.g., a few kilometers square). Measurements of hydrogen concentration measured *in situ* on the Moon could then be correlated with both chemistry and maturity, two properties easily measured remotely from orbit at scales of meters to kilometers. In this case, a detailed site survey would have implications for estimates of the global reserves of lunar hydrogen.

Conclusion: This work is an attempt to understand what resource assessment means for an initiative that attempts to utilize indigenous lunar resources, quite probably on an experimental basis. I have discussed what I consider to be top-priority commodities and the knowledge needed to efficiently extract these products. As our knowledge improves on what space resource utilization requires and entails, we should develop a flexible strategy that will ensure we obtain the information we need in a timely manner.

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HIGH-RESOLUTION EARTH-BASED LUNAR RADAR STUDIES: APPLICATIONS TO LUNAR RESOURCE ASSESSMENT.

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The lunar regolith will most likely be a primary raw material for lunar base construction and resource extraction. High-resolution radar observations of the Moon provide maps of radar backscatter that have intensity variations generally controlled by the local slope, material, and structural properties of the regolith. The properties that can be measured by the radar system include the dielectric constant, density, loss tangent, and wavelength scale roughness.

The radar systems currently in operation at several astronomical observatories provide the ability to image the lunar surface at spatial resolutions approaching 30 m at 3.8-cm and 12.6-cm wavelengths and approximately 500 m at 70-cm wavelength. The radar signal penetrates the lunar regolith to a depth of 10–20 wavelengths so the measured backscatter contains contributions from the vacuum-regolith interface and from wavelength-scale heterogeneities in the electrical properties of the subsurface material. The three wavelengths, which are sensitive to different scale structures and scattering volumes, provide complementary infor-
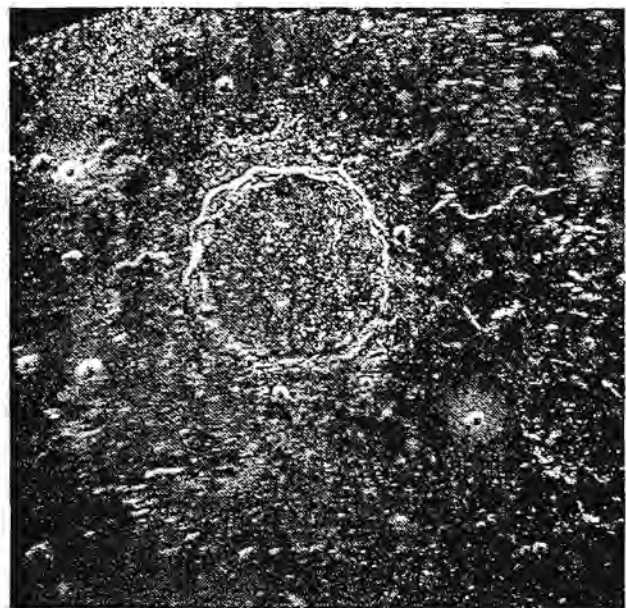

Fig. 1.   Averaged 12.6-cm radar image of the depolarized relative backscatter cross section of the 100-km-diameter crater Plato (52°N, 9°W) and surrounding terrain. The incidence angle is 56° in the center of the image, north is to the top, and illumination is from the south-southeast.

mation on the regolith properties. For example, the longer wavelength observations can be used to estimate the depth of pyroclastic mantled deposits [1], which usually have low surface roughness and block content and can be identified by very low radar backscatter at the shorter wavelengths [2,3].

In general, a circularly polarized signal is transmitted and both senses of circular polarization are received containing the polarized and depolarized components of the backscattered signal (though the capability exists to transmit and receive linear polarizations). These polarization components correspond to the opposite sense of circular polarization to the transmitted signal (that polarization sense expected from a single reflection with a plane interface) and the orthogonal circular polarization respectively. The backscattered signal has contributions from quasispecular and diffuse scattering. The first, due to reflection from small facets, contributes to the polarized signal and the second, due to wavelength-size surface and near-surface structures, contributes to both receive polarizations [4]. The relative power in the two polarizations provides useful information on properties of the surface, in particular, wavelength-scale roughness that is usually attributed to large angular rocks. The ejecta of fresh impact craters resulting from an impact sufficient in size to excavate relatively blocky material are readily evident by an enhanced radar signature [5], especially in the depolarized signal.

The density of the lunar regolith can be related to the dielectric constant using results from analysis of the electrical properties of lunar rocks returned to the Earth [6]. The dielectric constant of the lunar regolith can potentially be estimated from the ratio of the backscatter in the local vertical and horizontal directions for areas where the radar signal is dominated by volume scattering. High-incidence-angle observations of the lunar mare are possibly most suitable because of the assumed low surface backscatter and good coupling of the vertical polarization to the surface when imaged near the Brewster's angle (incidence angle ~60°).

Lunar topography has been measured using a two-element radar interferometer achieving elevation accuracy better than 500 m at a spatial resolution of 1 km to 2 km [7,8]. An alternative interferometric technique that can be applied to lunar mapping requires two images of the same area observed with very similar viewing geometries that are compared to generate interference fringes that can be unwrapped to derive local topography [9]. The present ability to image the lunar surface at 30-m to 40-m spatial resolution potentially provides an order of magnitude better topographic resolution and accuracy over the previous results.

Several lunar sites were observed using the 12.6-cm wavelength radar system at Arecibo Observatory in 1990 and further observations are planned for later this year (Fig. 1). The raw data collected for each site cover an area approximately 100–300 km by 400 km and are processed into images of relative backscatter cross section. Five of the sites were observed with a spatial resolution potentially better than 50 m and the remaining sites were observed with spatial resolutions varying up to 220 m. Aims of the previous and future observations include (1) analysis of the scattering properties associated with fresh impact craters, impact crater rays, and mantled deposits; (2) analysis of high-incidence-angle observations of the lunar mare to investigate measurement of the regolith dielectric constant and hence porosity; (3) investigation of interferometric techniques using two time-delayed observations of the same site, observations that require a difference in viewing geometry <0.05° and, hence, fortuitous alignment of the Earth-Moon system when visible from Arecibo Observatory.

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REMOTE ASSESSMENT OF LUNAR RESOURCE POTENTIAL. G. Jeffrey Taylor, Planetary Geosciences, University of Hawaii, 2525 Correa Road, Honolulu HI 96822, USA.

Assessing the resource potential of the lunar surface requires a well-planned program to determine the chemical and mineralogical composition of the Moon's surface at a range of scales. The exploration program must include remote sensing measurements (from both Earth's surface and lunar orbit), robotic in situ analysis of specific places, and, eventually, human field work by trained geologists (Fig. 1). This paper focuses on remote sensing data; strategies for in situ observations are discussed ably by P. Spudis [1].

Resource assessment requires some idea of what resources will be needed. Studies thus far have concentrated on oxygen and hydrogen production for propellant and life support, [3]He for export as fuel for nuclear fusion reactors, and use of bulk regolith for shielding and construction materials. On the other hand, igneous processes might have provided caches of useful materials, so one ought to search for likely possibilities. The measurement requirements for assessing these resources are given in Table 1 and discussed briefly below. The overriding need, however, is to obtain a global chemical and mineralogical database. This will provide a first-order global characterization of the Moon, create a framework in which to assess resources, and keep options open as we begin to understand what resources will be needed on the Moon. Spatial resolutions suggested in Table 1 are based partly on known instrument capabilities and partly on the desire for orbital missions to provide sound information to plan future landed missions. Thus, resolution needs to be better than the scale of early robotic roving missions, about 10 km.

Ilmenite—Source for Oxygen, Hydrogen, and Helium: Numerous techniques have been proposed to produce oxygen. Some can use any feedstock, including bulk regolith. In those cases, the key information needed is the properties of the regolith. However, some processes, including the most mature ones, center
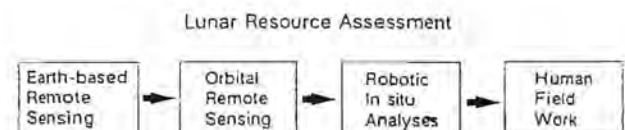
Lunar Resource Assessment

Fig. 1.   Lunar resource assessment needs to be a phased activity, beginning with observations from Earth (which my colleagues refer to as a selenocentric orbiter), followed by global remote sensing measurements. These programs allow rational choice of landing sites for in situ measurements and eventual field work by astronaut geologists. Although orbital remote sensing missions logically precede landed robotic missions, they need not cease once landed missions begin. Similarly, once humans begin to do field studies, robotic landed missions can and should continue.

TABLE 1. Orbital remote sensing for lunar resources.

Objective	Measurement	Technique	Precision and Resolution
Ilmenite abundance and distribution (relates to H, He, and O_2 potential; also to Ti and Fe production)	1. TiO_2 concentration 2. Concentration of other major elements (Si, Al, Mg, Fe, Ca) 3. Modal abundance of ilmenite 4. Regolith maturity	1,2. X-ray fluorescence or gamma ray 3a. Albedo 3b. UV spectroscopy 4. Reflectance spectra	1. ±5%; 10s km spatial 2. ±5%; 10s km spatial 3a. ±10%; 100 m spatial 3b. 0.1 to 0.7 μm; 100 m spatial 4. Broad characterization; 5 narrow bands at 0.7, 0.9, 0.95, 1.0, and 1.5 μm (or imaging spectrometer); 100 m spatial
Regolith properties (relates to plans for mining, base construction, and ilmenite abundance)	4. Regolith maturity 5. Regolith thickness 6. Block distribution	4. Same as above 5. Imaging 6. Imaging	4. Same as above 5. 2 m spatial 6. 1 m spatial
Unexpected enrichments of elements or minerals	6. Concentrations of major elements (Si, Al, Mg, Fe, Ca, Ti) 7. Concentrations of incompatible trace elements (U, Th, K) 8. Presence of unusual minerals (e.g., quartz)	6. X-ray fluorescence 7. Gamma ray spectrometry 8. Imaging reflectance and emission spectroscopy	6. ±5%; 1 km spatial 7. ±5% (in 1–100-ppm range); 10 km spatial 8. Full spectral coverage, 0.1 to 50 μm

around ilmenite reduction. In these cases, the key information is the abundance and physical state of ilmenite in the regolith. The ideal regolith contains a high abundance of ilmenite and has been reworked by impacts sufficiently to break up rocks, but not so much as to convert much of the regolith (including ilmenite) to glassy agglutinates. Thus, we need to know (1) the Ti concentration, which gives us the potential ilmenite concentration; (2) concentrations of other major elements for completeness and to help assess modal ilmenite by calculating normative ilmenite; (3) the modal abundance of ilmenite, which can be obtained directly, in principle, by spectral measurements in the UV and by albedo measurements; and (4) regolith maturity, to choose areas richest in ilmenite fragments. Hydrogen and helium concentrate in ilmenite. This effect overwhelms the effect of soil maturity, though both are important. Thus, the highest concentration of H and He are in high-ilmenite soils that have long exposure histories. So, in this case, the optimum soil would have high maturity, rather than the intermediate soil preferred for oxygen production by ilmenite reduction.

Regolith—Shielding and Construction Material: We probably already know enough about the lunar regolith to design equipment to excavate and transport it. However, for completeness, I list the properties that can be assessed from orbit (Table 1). Maturity was discussed above. Regolith thickness can be deduced from crater morphologies; thus high-resolution imaging is needed. Clearly, this cannot be done globally. Determining the abundance and distribution of blocks of rock also requires high-resolution imaging. How good the resolution needs to be is problematic; since block distributions tend to follow a power law (i.e., the size distribution is fractal), one can measure blocks larger than 1 m and deduce the distribution at smaller sizes.

The Unexpected: The absence of water on the Moon limits the potential for elemental concentrations and the production of unusual minerals. However, extreme igneous fractionation might have produced some materials rich in incompatible elements (U, Th, K, rare earths) and perhaps even certain volatiles such as halogens and the elements that might have formed complexes

with them (e.g., Ge). The trick is to search for evidence for extensive igneous evolution: high Fe/Mg; enrichments in elements such as U, Th, and K; and the presence in moderate to high amounts of minerals such as quartz and alkali feldspar.

Reference: [1] Spudis P. D., this volume.

A COMBINED XRD/XRF INSTRUMENT FOR LUNAR RESOURCE ASSESSMENT.

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Robotic surface missions to the Moon should be capable of measuring mineral as well as chemical abundances in regolith samples. Although much is already known about the lunar regolith, our data are far from comprehensive. Most of the regolith samples returned to Earth for analysis had lost the upper surface, or it was intermixed with deeper regolith. This upper surface is the part of the regolith most recently exposed to the solar wind; as such it will be important to resource assessment. In addition, it may be far easier to mine and process the uppermost few centimeters of regolith over a broad area than to engage in deep excavation of a smaller area. The most direct means of analyzing the regolith surface will be by studies in situ. In addition, the analysis of the impact-origin regolith surfaces, the Fe-rich glasses of mare pyroclastic deposits, are of resource interest [1,2], but are inadequately known; none of the extensive surface-exposed pyroclastic deposits of the Moon have been systematically sampled, although we know something about such deposits from the Apollo 17 site. Because of the potential importance of pyroclastic deposits, methods to quantify glass as well as mineral abundances will be important to resource evaluation.

Combined X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis will address many resource characterization problems on the Moon. Other means of chemical analysis (e.g., instrumental neutron activation analysis or laser-induced breakdown spectroscopy) would extend the suite of elements measured beyond
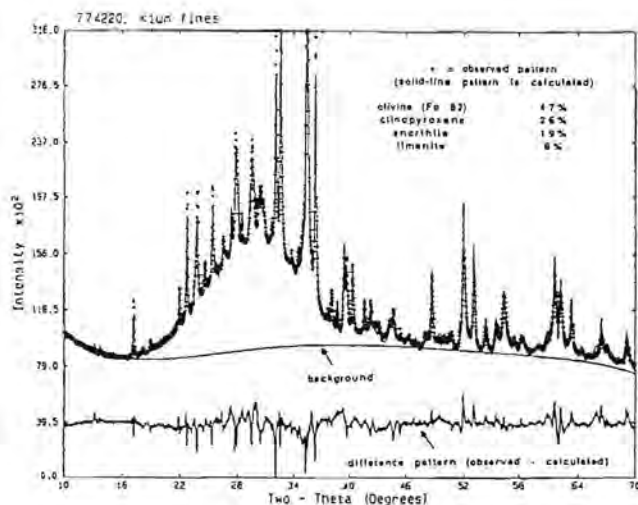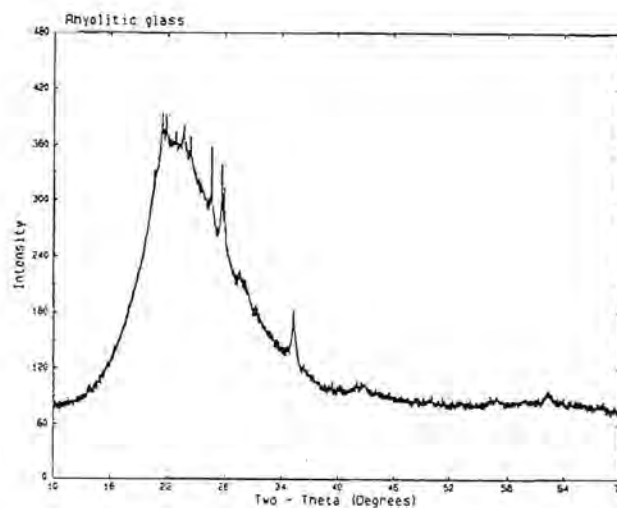
Fig. 1.

Fig. 2.

those detectable by XRF, particularly for elements lighter than Mg. However, XRF methods are valuable for obtaining full major-element abundances with high precision. Such data, collected in parallel with quantitative mineralogy, permit unambiguous determination of both mineral and chemical abundances where concentrations are high enough to be of resource grade.

Collection of both XRD and XRF data from a single sample provides simultaneous chemical and mineralogic information. These data can be used to correlate quantitative chemistry and mineralogy as a set of simultaneous linear equations, the solution of which can lead to full characterization of the sample. The use of Rietveld methods for XRD data analysis can provide a powerful tool for quantitative mineralogy [3] and for obtaining crystallographic data on complex minerals [4]. Rietveld methods applied to the XRD data will provide (1) enhanced accuracy for quantitative mineralogy, (2) a capability for crystal-chemical characterization of unstable minerals (e.g., the questionable lunar occurrences of lawrencite, $FeCl_2$ [5]) in their natural environment, and (3) a capability to recognize and characterize previously unknown minerals.

Ultimately, Rietveld methods can be used to determine glass abundances where the sample contains a particular type of glass. This approach will be most useful in the exploration of pyroclastic glass deposits. Figure 1 shows an XRD pattern obtained from the <1-μm fraction of pyroclastic sample 74220,19, obtained by settling in Freon. This pattern was collected from 17 mg of material. Rietveld analysis was used to obtain the abundances of crystalline constituents (normalized to 100%) as well as the olivine Mg/Fe ratio. When similar data are obtained on pure splits of the pyroclastic glass, then abundances of this glass (represented by the amorphous bulge between 17° and 46° 2Θ) can be determined. Other glasses, either known or exotic, can be modeled from diffraction data. Figure 2 illustrates the very different amorphous diffraction character of terrestrial rhyolitic glass in comparison with the basaltic pyroclastic glass of 74220 in Fig. 1. With appropriate library diffraction data, a wide variety of glasses and minerals can be determined quantitatively in lunar materials.
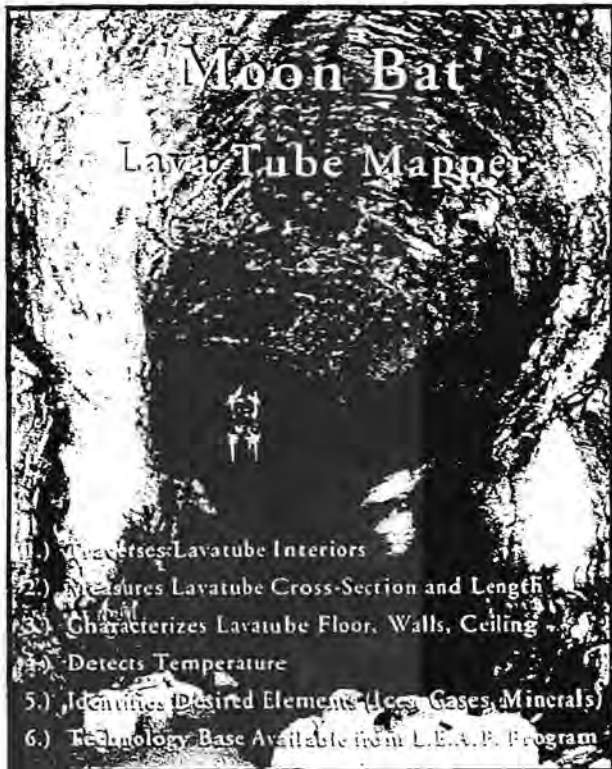
References: [1] McKay D. S. et al. (1991) LPSC XXII, 881–882. [2] Hawke B. R. et al. (1989) LPSC XX, 389–390. [3] Vaniman D. T. (1991) LPSC XXII, 1429–1430. [4] Vaniman D. et al. (1991) Clay Min. Soc. 28th Ann. Mtg., 157; [5] Taylor L. A. et al. (1973) Proc. LSC 4th, 829–839.

LUNAR LAVA TUBE SENSING. Cheryl Lynn York, Bryce Walden, Thomas L. Billings, and P. Douglas Reeder, Lunar Base Research Team, Oregon L^5 Society, P.O. Box 86, Oregon City OR 97045-0007, USA.

Large (≥300-m-diameter) lava-tube caverns appear to exist on the Moon and could provide substantial safety and cost benefits for lunar bases. Over 40 m of basalt and regolith constitute the lava tube roof and would protect both construction and operations. Constant temperatures of –20°C reduce thermal stress on structures and machines. Base designs need not incorporate heavy shielding, so lightweight materials can be used and construction can be expedited [1,2]. Identification and characterization of lava tube caverns can be incorporated into current precursor lunar mission plans. Some searches can even be done from Earth.

Earth-based sensing of major near-surface (200-m-deep) lunar lava tubes and their entrances at 25-m resolution may be possible using Earth-penetrating radar (EPR) interferometry [3]. From lunar orbit 1-m EPR resolution should be achievable. Radar, lidar, and optical and infrared imaging might spot an entrance candidate from lunar orbit without using power-intensive EPR. Lava tube entrances can also be found directly by surface explorers (human or machine). Multifunctional kinetic penetrators and high-resolution seismic arrays may detail likely sites. Any search for lunar ice or other captured volatiles should include sheltered lava tube entrances and skylights (spot roof collapses).

Interior volume mapping to 10-cm resolution should be possible using lidar, microwave, or optical imaging from a platform moving along the length of the cavern. Floor and ceiling detail in optical or lidar data could be evaluated for lunar geoscience and possible

Fig. 1.

lunar base engineering use. Dust and other deposits in a lunar cave may be identified and mapped in a variety of ways although lunar lava tube caverns may be relatively dust free. Sensors used for surface exploration are suitable in lava tubes, including IR and UV spectrometers, lasers, vapor detectors, probes, optical spectrometers and imagers, and neutron activation analysis, although some of these sensors require a "light" source. A hovering rover, which we have christened a "Moon Bat," could lift off from a surface lander and fly into and through a lava tube cave. Based on present and near-future SDIO Light Exo-Atmospheric Projectile (L.E.A.P.) technology, the "Moon Bat" could gather data rapidly while "on the fly" and its rockets could provide a light source.

Specific recommendations for lunar lava tube search and exploration are (1) an Earth-based radar interferometer, (2) an EPR orbiter, (3) kinetic penetrators for lunar lava tube confirmation, (4) a "Moon Bat" hovering rocket vehicle, and (5) the use of other proposed landers and orbiters to help find lunar lava tubes.

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