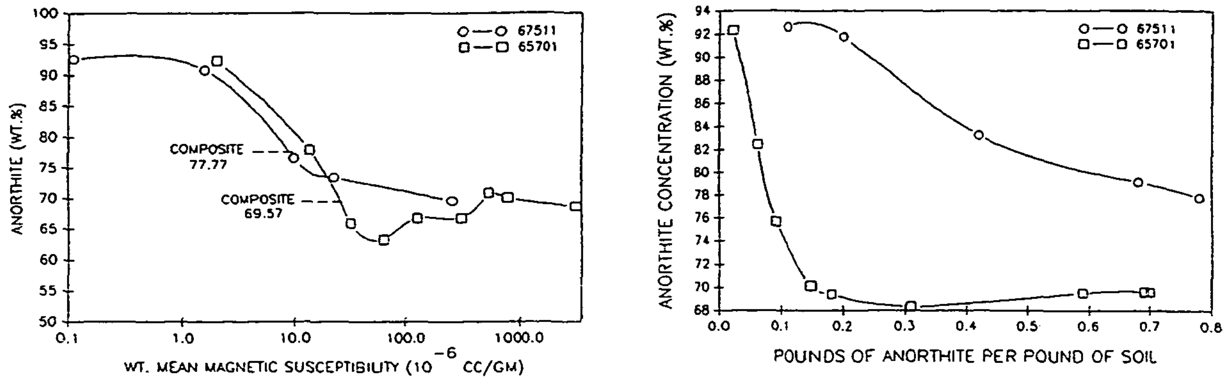

Fig. 1. Anorthite separation from highland soils.

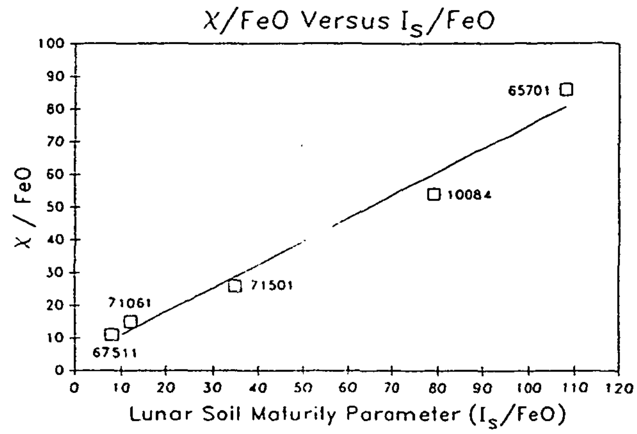

Fig. 2. X/FeO vs. soil maturity.

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.

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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 I^3 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. J. B. Plescia, A. L. Lane, and D. Miller, Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA.

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, ^3He, 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