

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 $\sim 60^\circ$).

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 $< 0.05^\circ$ 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, ^3He 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

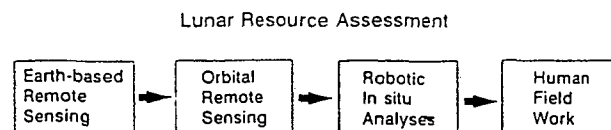


Fig. 1. Lunar resource assessment needs to be a phased activity, beginning with observations from Earth (which my colleagues refer to as a selenocentric orbiter), followed by global remote sensing measurements. These programs allow rational choice of landing sites for *in situ* measurements and eventual 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	1,2. X-ray fluorescence or gamma ray	1. ±5%; 10s km spatial
	2. Concentration of other major elements (Si, Al, Mg, Fe, Ca)		2. ±5%; 10s km spatial
	3. Modal abundance of ilmenite	3a. Albedo	3a. ±10%; 100 m spatial
	4. Regolith maturity	3b. UV spectroscopy 4. Reflectance spectra	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	4. Same as above	4. Same as above
	5. Regolith thickness	5. Imaging	5. 2 m spatial
	6. Block distribution	6. Imaging	6. 1 m spatial
Unexpected enrichments of elements or minerals	6. Concentrations of major elements (Si, Al, Mg, Fe, Ca, Ti)	6. X-ray fluorescence	6. ±5%; 1 km spatial
	7. Concentrations of incompatible trace elements (U, Th, K)	7. Gamma ray spectrometry	7. ±5% (in 1-100-ppm range); 10 km spatial
	8. Presence of unusual minerals (e.g., quartz)	8. Imaging reflectance and emission spectroscopy	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.

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A COMBINED XRD/XRF INSTRUMENT FOR LUNAR RESOURCE ASSESSMENT. D. T. Vaniman, D. L. Bish, S. J. Chipera, and J. D. Blacic, Los Alamos National Laboratory, Los Alamos NM 87545, USA.

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