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-

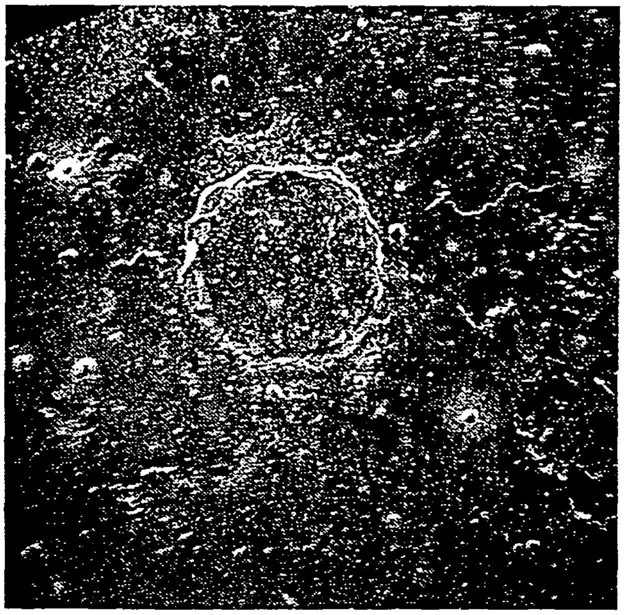

Fig. 1. Averaged 12.6-cm radar image of the depolarized relative backscatter cross section of the 100-km-diameter crater Plato (52°N, 9°W) and surrounding terrain. The incidence angle is 56° in the center of the image, north is to the top, and illumination is from the south-southeast.

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.

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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

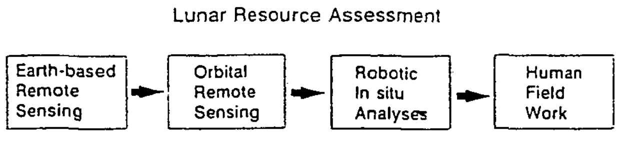

Fig. 1. Lunar resource assessment needs to be a phased activity, beginning with observations from Earth (which my colleagues refer to as a selenocentric orbiter), followed by global remote sensing measurements. These programs allow rational choice of landing sites for *in situ* measurements and eventual 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.