mation on the regolith properties. For example, the longer wave-
length 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 back-
scatter 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 back-
scattered signal has contributions from quasipunctual and diffuse
scattering. The first, due to reflection from small facets, contrib-
utes to the polarized signal and the second, due to wavelength-
site surface and near-surface structures, contributes to both
receive polarizations [4]. The relative power in the two polar-
izations 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 topo-
graphic 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 obser-
vations 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 reso-
lution 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) inves-
tigation 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.

Assessing the resource potential of the lunar surface requires
a well-planned program to determine the chemical and mineral-
ological composition of the Moon’s surface at a range of scales.
The exploration program must include remote sensing measure-
ments (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, for ex-
port 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 require-
ments 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 frame-
work 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 seleno-
centric 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>
<thead>
<tr>
<th>Lunar Resource Assessment</th>
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<tbody>
<tr>
<td>Earth-based Remote Sensing</td>
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</table>

TABLE 1. Orbital remote sensing for lunar resources.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Measurement</th>
<th>Technique</th>
<th>Precision and Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ilmenite abundance and distribution</td>
<td>1. TiO₂ concentration</td>
<td>1. X-ray fluorescence or gamma ray</td>
<td>1. ±5%; 10 km spatial</td>
</tr>
<tr>
<td>(relates to H, He, and O₂ potential; also to Ti and Fe production)</td>
<td>2. Concentration of other major elements (Si, Al, Mg, Fe, Ca)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>3. Modal abundance of ilmenite</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>4. Regolith maturity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regolith properties</td>
<td>4. Regolith maturity</td>
<td>4. Same as above</td>
<td></td>
</tr>
<tr>
<td>(relates to plans for mining, base construction, and ilmenite abundance)</td>
<td>5. Regolith thickness</td>
<td>5. Imaging</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6. Block distribution</td>
<td>6. Imaging</td>
<td></td>
</tr>
<tr>
<td>Unexpected enrichments of elements or minerals</td>
<td>6. Concentrations of major elements (Si, Al, Mg, Fe, Ca, Ti)</td>
<td>6. X-ray fluorescence</td>
<td>6. ±5%; 1 km spatial</td>
</tr>
<tr>
<td></td>
<td>7. Concentrations of incompatible trace elements (U, Th, K)</td>
<td>7. Gamma ray spectrometry</td>
<td>7. ±5% (in 1-100-ppm range); 10 km spatial</td>
</tr>
<tr>
<td></td>
<td>8. Presence of unusual minerals (e.g., quartz)</td>
<td>8. Imaging reflectance and emission spectrometry</td>
<td></td>
</tr>
</tbody>
</table>

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 the current capabilities.