# Lunar Surface Exploration Strategy
## Lunar Exploration Science Working Group (LExSWG)

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# 1. INTRODUCTION: WHY THE MOON?

The Moon is a compelling object for study. Its scientific value stems from the relationship to Earth, its proximity, its diverse geologic history, and its role as natural laboratory. Missions to the Moon have enormous value in the development of new technologies ranging from robotics to resource utilization to human life support and habitation. Lunar missions also provide exciting opportunities for educating and inspiring our children and for cooperation among nations. We outline below the reasons why the Moon is such an irresistible object for study and destination for spacecraft.

**Cornerstone for planetary science.** The Moon's geological engine shut down long ago, but not before it provided a rich record of planetary differentiation and early evolution. Such a detailed record does not exist on Earth because it is geologically hyperactive. The Moon contains information about its initial differentiation and crustal formation, subsequent magmatic activity, and impact bombardment history. The idea of the lunar magma ocean has been extended by many investigators to the Earth and other terrestrial planets, and even to asteroids. The surface chronology of the Moon has been at least partially calibrated by age dating rocks returned from specific localities, thus providing a useful correlation between the number of craters and the absolute age of planetary surfaces. This forms the basis of calibration of crater counts and the ages of the surfaces of other planets.

**Natural laboratory for planetary processes.** The study of fundamental processes, such as impact or volcanism, in a different gravitational environment and in virtually no atmosphere is uniquely possible on the Moon. Understanding the processes that shape the planets is a primary goal of planetary research. For example, the Moon, Mars, Venus, and Earth have diverse volcanic features. Mercury apparently has ancient lava plains. Vesta and possibly other asteroids went through a stage of intense volcanism, recorded in part by the eucrite meteorites. Io is the most volcanically active body in the Solar System, erupting both pyroclastic materials and lava flows. Even the icy satellites of the outer planets have experienced or are experiencing nonsilicate volcanism. Missions to the Moon can focus on understanding the physical and chemical processes that drive volcanism. The Moon offers several areas where the products of volcanism can be studied in detail, including those with both pyroclastic and effusive flows and vents. Most volcanological studies are best conducted on the Earth, of course, but terrestrial studies are restricted to only one set of environmental conditions. To better understand the full range of planetary volcanism, we must study volcanic processes operating in very different conditions. Volcanic processes vary with the abundances of volatiles, atmospheric density and composition, gravity, and crustal composition, density, and thickness. We need to examine them closely—field studies, not just orbital surveys, are essential. The Moon, while close to us in distance, offers gravitational and atmospheric conditions as far removed from the Earth as possible on a large terrestrial body in our Solar System. The Moon is also exceptionally suited to studies of the impact process, especially because so many features are well preserved.

**Origin of the Earth-Moon system.** Whether the Moon formed as the result of a giant impact, fissioned from the Earth, or formed as a binary system, its origin is inexorably linked to the origin of the Earth. The precise mode of formation affected the early thermal state of both bodies and, therefore, affected the subsequent geological evolution. How the planets formed also affects our views of planetary accretion in general—were there a large number of moon-sized or larger bodies with large eccentricities so that giant impacts were common, or were bodies mostly in circular orbits, with intermediate-sized bodies and giant impacts uncommon.? The nature of this dynamical environment has great implications for determining when the impact rate on Earth was gentle enough to allow life to develop.

**Exploration legacy of Apollo.** We have enough experience in exploring the Moon to know how to explore it, but not so much that exploration is even close to being complete. Apollo experience and 25 years of lunar sample study have produced a series of sophisticated questions to ask. Lunar missions are problem oriented explorations, not essentially random studies geared to finding out the general features of a planet. Previous lunar exploration has revealed what capabilities we will need to explore its surface robotically and what analytical capabilities will be needed by remote instruments to make significant advances.

**Lunar resources: making exploration less expensive and more capable.** Using the resources on other planets will greatly enhance operations on future missions and decrease their cost. The lunar surface contains the ingredients for fuels and life support. It is possible that the utilization of lunar materials and the lunar environment can remedy fundamental resource limitations of the Earth, particularly our access to large scale, non-polluting and essentially unlimited supplies of energy.

**The Moon as a solar telescope.** The weak magnetic field and absence of a thick atmosphere allows the solar wind to strike the surface of the Moon, where it is implanted into mineral grains. In principle, the history of the Sun for the past four billion years can be obtained from studies of these grains, especially if careful sampling can allow dating of the time implantation took place. Such studies constitute basic solar physics and have implications for climate change on Earth.

**The Moon as site for astronomical observatories.** The lunar surface is the best place in the Solar System for making astronomical observations. Its thin atmosphere allows for observations not affected by atmospheric distortion or absorption. Its low seismicity allows for development of optical arrays with exceptional baselines (10 km is relatively straight forward). Its low gravity allows construction of larger, lower mass telescopes; for example, steerable radio telescope antennae up to 1 km could be constructed. Its slow rotation makes pointing easy and permits long-duration observations. The Moon's location also makes it ideal for synoptic views of the Earth, especially of its magnetosphere. The lunar surface may be the ideal place for advanced space-watch systems for tracking asteroids and comets on courses dangerously close to Earth's orbit.

**Testbed for new technologies and human adaptation to the space environment.** The Moon can be used as a functional testbed and development laboratory for technical capabilities that will be required for future exploration by robots and people. Its proximity to Earth allows for rapid transit, so results are known quickly, allowing for rapid development of new technologies. The short light travel-time allows direct control of experimental robotic systems, such as rovers, leading to more rapid development of autonomous systems. Development of habitation, life support, use of indigenous materials, long-lived power systems, operational autonomy, and surface mobility systems will aid future human exploration of the planets. The Moon can be an important location for studying the long-term effects on humans in less than 1-g environments. Astronauts on the Moon can be protected from the harsh radiation environment of space by shielding with lunar materials, and can perform useful technical work at the same time they are demonstrating the consequences of long-term exposure to 1/6-g and exploring ways to counteract the detrimental effects. This understanding is crucial to the safety of the first astronauts to spend extended times on the surface of Mars.

**Lunar missions and international cooperation.** The Moon can be an outstanding venue for international cooperation. Technical capability for exploring the Moon has been demonstrated by several nations, and some are beginning to plan long-term exploration programs. The fact that the location of a lunar outpost or complex robotic installation such as an observatory can be viewed from practically anywhere on Earth could create a strong emotional linkage among people of all nationalities on Earth.

**Unsurpassed educational opportunities.** The short distance between the Earth and Moon provides a unique environment for exciting our youth, because it is possible to create complex interactive exploration activities in conjunction with either human or robotic exploration missions. For example, because the round trip communications time is so short, students could actually operate systems on the Moon from their classrooms or perform experiments in the lunar environment, using teleoperations/telepresence systems. When combined with innovative curricula, the educational opportunities afforded by missions to the Moon are unprecedented. Most important, exploring and developing the Moon can provide a hopeful dream of a positive future for our children and grandchildren. It can vividly illuminate American discipline, imagination, skill, and sense of adventure, while demonstrating our willingness to share our future with the rest of humanity. It can become a demonstration of the positive benefits of advanced technology and can make real the possibility that people who are young today, anywhere in the world, can aspire to travel to the Moon and beyond, and participate in a major evolutionary step for the human race.

**Permanent human habitation possible now.** A self-sustaining settlement on the Moon could be created now using existing technology. An economic basis for sustaining such a colony is not yet demonstrated, but a role in future energy systems could provide such a basis.

This report highlights the key elements of a strategy for the exploration of the lunar surface by robotic spacecraft, which will address fundamental problems in planetary science and begin to develop new technologies. The Lunar Exploration Science Working Group (LExSWG) developed it during 1992-1995, with the invaluable assistance of many other experts in lunar science and resource extraction and utilization. Although the strategy emphasizes inexpensive robotic missions, it sets the stage for intense human exploration. The eight-part report begins by summarizing the science themes and mission elements LExSWG has developed (published in LExSWG, 1992), and briefly outlines the priorities for orbital exploration. It then discusses strategies for robotic surface exploration, sample return missions, and the use of the Moon as a testbed for technology development, including resource utilization.

# 2. SCIENCE THEMES AND MISSION ELEMENTS

LExSWG (1992) has established and described in detail broad science themes to advance our understanding of the Moon's origin and subsequent geological evolution. We summarize these themes here and also present a different kind of theme, that of using the Moon to better understand fundamental planetary processes such as volcanism. This section begins by describing an updated list of the types of missions needed to address the central science themes and to use the Moon as a natural laboratory.

## SCIENCE THEMES

### Formation of the Earth-Moon system

The origin of the Moon is intimately connected to the dynamic environment in the inner Solar System and to the origin of the Earth. The leading hypothesis at present is that the Moon formed as the result of the impact of a Mars-sized object with the growing Earth. This hypothesis is not proven, however, and even if correct, the details of the process are not clear. Whatever the process of lunar formation, it is likely to have strongly affected the early thermal state of the Earth.

One way of testing models of lunar origin is to determine the bulk chemical composition of the Moon. This requires measuring the abundances of key elements or groups of elements. Of central importance are the abundance of iron, the ratio of FeO to MgO, and the concentrations of refractory elements such as Al, U, and Th. These and other chemical parameters can constrain the processes by which different elements were partitioned between the Earth and the Moon, which in turn can limit or eliminate some models for formation of the Earth-Moon system. At present, the composition of the Moon's crust is poorly known, that of the upper mantle even less well known, and the composition of the lower mantle is only vaguely estimated. Furthermore, the size and composition of a metallic core is unknown, except to constrain it to be between 100 and 500 km in diameter. These fundamental questions can be addressed by pursuit of the following science objectives.

*Chemical bulk composition*, of the lunar crust, mantle and (if present) the lunar core, is the primary science objective. Data for global lunar crustal composition can be obtained from orbit; distributions of U and Th with depth can be constrained by heat-flow experiments on the surface. The *compositions of unfractionated basalts*, identified from sample returns, can be used to probe the composition of the lunar mantle. Geophysical measurements can help to constrain the *thickness and mineralogic composition of the crust and mantle* as well as the possible presence of a lunar core.

### Thermal and magmatic evolution of the Moon

Understanding the Moon's thermal and magmatic evolution entails understanding the origin of the earliest crust (and if it formed from a magma ocean), the duration of primary differentiation, mechanisms for core formation, processes in large bodies of magma (magma oceans?), the thermal and dynamic evolution of the lunar mantle, the source of the ancient lunar magnetic field, how magma production rates changed with time, and the processes that formed highland igneous rocks and mare basalts. Extracting all this information from the Moon is not a simple task, and many questions remain. A central idea in lunar science is that the outer part of the Moon melted to a depth of several hundred kilometers soon after accretion, forming a global magma ocean. While this concept is widely accepted, it must be tested by determining (1) the amount of anorthosite (measurable by the amount of Al relative to other elements) in the crust and (2) the nature of the oldest lunar rocks (do they represent compositions that are likely to segregate from a vast magma ocean?). The full range of rock types in either the highlands or maria is not known and the age of the youngest igneous event is uncertain to ± 1 Gy. The variation in the magma production rate vs. time is not known, hindering our assessment of lunar thermal evolution. These questions are addressed in the following science objectives.

The *bulk composition of the crust and mantle* must be known to determine the extent to which chemical segregation operated within the primitive Moon. In addition, the *lateral and vertical chemical variability of the crust* can be used to determine whether a single uniform magma system was involved. Much of this data can be obtained by orbital geochemical mapping. However, landed missions and some sample returns will be necessary to determine the *compositions and ages of the oldest lunar rocks*, the full *range of both highland and mare rock types*, and the *ages of the youngest lunar igneous rocks*.

### Bombardment history of the Earth-Moon system

The bombardment history of the Moon has enormous implications for the accretion of the Earth-Moon system, the evolution of the planetesimal flux early in Solar System history, the development of crusts on the terrestrial planets, and the evolution of life on Earth. One of the most hotly contested ideas in lunar science is the nature of the variation of the impact flux with time in the period before 3.8 Gy ago. A substantial increase in the bombardment rate in the interval 3.85 to 3.95 Gy has been proposed, but not proven. If it happened, then a large fraction of landforms visible in the lunar highlands formed in this narrow interval. Determining whether such a “cataclysm” occurred will require obtaining samples for radiometric dating; the cumulative experience gained from past studies of rocks from terrestrial craters, lunar impact breccias, and shocked and shock-melted meteorites indicate that craters are best dated by analyzing the impact melt rocks produced when the craters formed. Our need for information on these topics can be addressed by the following science objectives.

The most critical science objective is to obtain a representative set of *radiometric ages on impact melts* from several large pre-Imbrium craters. To test the differing hypotheses of prolonged versus brief, cataclysmic impact history, radiometric ages must be obtained from samples returned to Earth. In addition to these age data, it will be important to determine the *compositions of the dated impact melts* to link major impacts with temporal variations in crustal targets.

### Regolith formation

The Moon is covered by a blanket of impact-generated debris called the regolith. Studies of the lunar regolith have been informative about regolith formation processes on other airless bodies such as Mercury and asteroids. The regolith is what all our remote sensing measurements observe, so it is imperative that we understand the relation between regolith and the rocks beneath it. Regolith is where virtually all lunar samples were collected, and it records part of the lunar bombardment history. The regolith is so complicated that understanding it will require a major effort in remote sensing from orbit, detailed field observations and *in situ* chemical analyses, determinations of solar-wind gas concentrations, and geophysical studies to measure regolith depths. The following science objectives address the problems of regolith formation.

*Regolith thickness variations*, determined by radar studies or by crater excavation data, will provide information on the formation of regolith in different terranes of different ages. *Regolith compositions compared with rocks beneath or nearby* will address the role of distant versus proximal source regions, in a variety of cratering regimes.

### Regolith record of solar history

The regolith contains unique information about the history of solar and galactic radiation. Lunar sample studies have shown that there are secular changes in the isotopic composition of solar gases. For example, $^{15}N/^{14}N$ has increased by 50% during the past 3 Gy. The cause is unknown, but almost certainly reflect changes in processes operating inside the Sun. Science objectives for study of the ancient sun are listed below.

The *analysis of carefully selected regolith layers* can provide data on gas abundances, on solar-wind gas isotopic ratios, and perhaps on solar-flare track abundances from the distant past. In particular, the collection of *samples of paleoregolith beneath datable layers* (such as basalt flows) can allow precise dating of the solar record. Luck may be required to obtain such samples for return to Earth by robotic missions; some of these problems may require a human presence.

### Nature of the lunar atmosphere

The tenuous lunar atmosphere provides a baseline for studies of other bodies with similar atmospheres, including Mercury, Io, and asteroids. The Moon has a type of atmosphere known as a surface-boundary exosphere in which atoms and molecules removed from the surface (by sputtering, for example) can escape directly to space. Such atmospheres have an intimate connection to the surface, so atmospheric measurements provide chemical data about surface compositions. The proximity to Earth can allow for active experiments to study the energetics, solar-wind interactions, sources, and sinks in the lunar atmosphere. At present, we understand the sources and sinks of atmospheric gases but have not quantified them or even determined their relative importance. The details of chemical interactions between the atmosphere and the surface are not understood. Intriguing observations of radon and argon releases have been only tentatively related to specific features on the Moon or to tectonic events. The following science objectives will provide the basic information for sorting out the roles of space and the planetary host in defining tenuous atmospheres.

Combined studies using surface instruments and orbital instruments can provide determinations of *bulk atmosphere composition* and the *variation of composition, pressure, and temperature with height*. Combined studies of regolith gases, transient lunar sources, and day/night compositional cycles will provide the quantitative measures to determine the *relative importance of sources and sinks* and the *spatial correlation between atmospheric and surface compositions*. Further inclusion of data on inputs from the solar wind and on interactions between the terrestrial magnetosphere and ionic species can be used to *quantify extra-lunar sources and influences*.

### The Moon as a natural laboratory for studying planetary processes

The proximity of the Moon and the well-preserved nature of ancient geologic features on its surface provide a museum of planetary processes in the near neighborhood of the Earth. One of the tenets of comparative planetology is that certain geologic processes can be best understood by observing their operation on different planets, where overriding similarities can be separated from planet-specific influences. Of these processes, we emphasize *impact cratering* and *volcanism*.

Impact is the fundamental process by which planets are assembled and all terrestrial planets display the effects of bombardment on their surfaces. The Moon is an ideal natural laboratory in which to study impact processes because so many craters, including large impact basins, are so well preserved. This contrasts sharply with Earth, where erosion and mountain building have erased a large part of the cratering record. The craters of the Moon provide an opportunity to delve into the physics of impact processes. First order questions remain unsolved. We do not know the shape and relative dimensions of the cavity of excavation in large cratering events, or how the system of concentric rings around large basins form. By combining both orbital and lander geochemical and mineralogic data, we can gain a knowledge of the composition and morphology of large crater and basin ejecta deposits, of the nature of the crust beneath ring systems, and of the mechanisms of crater formation on a scale that is no longer preserved on Earth.

Like impact, volcanism is a fundamental process that shapes the planets. It occurs or occurred on the Earth, Moon, Mars, Venus, some asteroids, and Io. Based on terrestrial studies, there is a theoretical framework in place to test ideas about the physics and chemistry of the process. However, volcanic processes vary with the abundances of volatiles, atmospheric density and composition, gravity, and crustal composition, density, and thickness. The Moon offers gravitational and atmospheric conditions and volatile driving forces far different from those on Earth. A study of lunar volcanism can attempt to determine effusion rates (mass per time), pyroclastic eruption mechanics, role of volatiles in eruptions, emplacement mechanisms of pyroclastics and lava flows, nature of the volcanic plumbing systems, relationships between lava flows and pyroclastic deposits when they are associated, and the nature and efficacy of processes inside flows and pyroclastic deposits. Studies of a wide range of volcanic processes can be based on detailed study of a single varied lunar volcanic province, including both pyroclastic deposits (compositions of glasses and volatiles, thicknesses, bedding, grain sizes) and lava flows (compositions, vesicle sizes and distributions, flow structures, differentiation, crustal and mantle inclusions, etc.).

### Summary

Table 2-1 summarizes these science themes, the 22 science objectives that can develop these themes into real exploration goals, and relates them to the mission elements described below.

## MISSION ELEMENTS

The science themes described above can be addressed by a combination of several types of missions. These are the following:

**Polar orbiting spacecraft:** Using orbiting spacecraft to perform global surveys is the only practical way to obtain some types of crucial data. The science objectives and measurement requirements for such missions are summarized in section 3 and are covered in detail in LExSWG (1992).

**Geoscience rovers using telepresence technology:** Roving vehicles equipped with high-quality stereo imaging can make field studies by using telepresence—the ability to project human powers of observation into a remote vehicle. Such rovers can also carry instruments for chemical, mineralogical, geophysical, evolved gas, and atmospheric analysis and for ground-penetrating radar. The use of rovers for field observations is discussed in detail in section 4.

**Geophysical networks:** Global networks are required to address many geophysical problems in lunar science. Regional networks are also useful in investigating local variations in crustal properties, in exploring the structure and composition of the mantle, and in searching for a lunar core. Geophysical networks are described in section 7.

**Sample return missions:** Many studies require that samples be returned to Earth for study in terrestrial laboratories because remote analysis would be too difficult or too costly. For example, determining the radiometric age of a sample requires complex and costly instrumentation that could not be miniaturized and sent to the Moon. Sample return missions are discussed in section 5.

**Geological field work by humans:** For the sake of completeness, and to contrast with unmanned missions, it is important to consider those studies that require field work by humans. Once people return to the Moon, they will make geological field studies, among their other duties. Some of this may be done using telepresence technologies, providing easier global access from a single lunar base. Because this report focuses on robotic missions human field work is not discussed. However, the goals of field work by humans are considered in Table 2-2 and the types of observations made are outlined in section 4, which describes telepresent rovers.

Table 2-1 shows how the key data requirements are satisfied by the five mission elements. Several assumptions go into this table. First, we assume the minimum capabilities for orbital measurements (see section 3). Second, we assume that atmospheric, seismic, and direct heat flow measurements are made only by a geophysical network and not carried by a rover. Clearly, if a rover carried instruments to measure atmospheric composition, it would contribute no more to solving these problems than would a geophysical network. Third, as described in section 5, we assume that sample return missions do not make use of a rover. Fourth, we rate the contribution of some investigations low in part because of the probability of finding certain results. For example, the chances of a simple sample-return mission of returning a piece of the mantle brought up by a volcanic eruption is very small. In contrast, the chances of finding one on a rover mission is higher because there is time to search specific areas (e.g., near volcanic vents) likely to contain crustal and mantle xenoliths.

Table 2-1. Relationship of between *science themes*, objectives, and mission elements*.

| *Themes*<br>(n) objectives | **Orbital** | **Rovers** | **Geophys. Networks** | **Sample Returns** | **Human Field Work** |
|---|---|---|---|---|---|
| *Formation of Earth-Moon System* | | | | | |
| (1) bulk composition of the Moon | 1 | 3 | 1 | 4 | 3 |
| (2) compositions of unfractionated basalts | 3 | 2 | 4 | 2 | 2 |
| (3) thickness and composition of crust | 2 | 4 | 1 | 4 | 4 |
| (4) thickness and composition of mantle | 4 | 4 | 1 | 4 | 4 |
| (5) presence of a core | 2 | 4 | 1 | 4 | 4 |
| ***Thermal and magmatic evolution of the Moon***<br>(3 and 4 above, plus:) | | | | | |
| (6) lateral and vertical variability of crust | 1 | 4 | 1 | 4 | 4 |
| (7) compositions and ages of oldest rocks | 4 | 4 | 4 | 1 | 1 |
| (8) range of highland and mare rock types | 3 | 2 | 4 | 2 | 2 |
| (9) ages of youngest igneous rocks | 4 | 4 | 4 | 1 | 3 |
| ***Bombardment history of Earth-Moon system*** | | | | | |
| (10) ages of impact melts | 4 | 4 | 4 | 1 | 3 |
| (11) compositions of impact melts | 2 | 2 | 4 | 1 | 1 |
| ***Regolith formation*** | | | | | |
| (12) regolith thickness variations | 3 | 1 | 2 | 4 | 4 |
| (13) regolith/rock compositions | 3 | 1 | 4 | 1 | 1 |

* 1 = essential 2 = very useful 3 = useful 4 = not useful for that specific problem

continued on next page

Table 2-1, continued. Relationship of between *science themes*, objectives, and mission elements*.

| *Themes*<br>(n) objectives | **Orbital** | **Rovers** | **Geophys. Networks** | **Sample Returns** | **Human Field Work** |
|---|---|---|---|---|---|
| ***Solar history*** | | | | | |
| (14) compositions of selected regolith layers | 4 | 1 | 4 | 4 | 1 |
| (15) analyses of dated regolith | 4 | 4 | 4 | 4 | 1 |
| ***The lunar atmosphere*** | | | | | |
| (16) bulk atmosphere composition | 1 | 4 | 1 | 4 | 4 |
| (17) composition, T, and P with height | 3 | 4 | 1 | 4 | 4 |
| (18) sources and sinks | 1 | 4 | 1 | 4 | 4 |
| (19) atmosphere/surface correlations | 1 | 3 | 3 | 4 | 4 |
| (20) extra-lunar sources and influences | 1 | 4 | 1 | 4 | 4 |
| ***Planetary processes*** | | | | | |
| (21) mechanisms of cratering | 1 | 1 | 1 | 2 | 1 |
| (22) mechanisms of volcanism | 3 | 1 | 4 | 4 | 1 |

* 1 = essential 2 = very useful 3 = useful 4 = not useful for that specific problem

# 3. LExSWG STRATEGY FOR ORBITAL MISSIONS

LExSWG published its strategy for orbital missions in LExSWG (1992), except for the detailed measurement requirements. We summarize that strategy here, along with the detailed requirements, and assess the extent to which the objectives will have been met by the Clementine mission and the planned Lunar Prospector mission.

## Science objectives: priority list

Considerations for over a decade by LExSWG and previous committees have led to a firm consensus on the key science objectives for orbital missions. These stem, of course, from the main science themes described in section 2.

1. Constrain models of lunar origin by estimating the refractory element (e.g., U, Th, Al, Ca) concentration and MgO/(MgO+FeO) ratio of the crust.

2. Estimate the composition and structure of the lunar crust to model its origin and evolution.

3. Determine the origin and nature of the lunar magnetic field and estimate the size of a lunar core.

4. Determine the nature of impact processes over geologic time and how they have modified the structure of the crust.

5. Determine the nature of the lunar atmosphere and the physical basis for its sources and sinks.

## Measurement priorities

These objectives lead naturally to a series of measurements that must be made. In priority order, these are the following:

1. Determine globally the elemental composition of the surface.

2. Determine globally the topography and gravitational field.

3. Determine globally the mineralogical composition of the surface.

4. Map globally the distribution of surface magnetic anomalies and measure the magnitude of the induced dipole moment.

5. Obtain a global digital image database with limited color information.

6. Measure the microwave brightness temperature as a function of wavelength.

7. Measure globally the composition, structure, and temporal variability of the lunar atmosphere.

## Measurement requirements

The measurement priorities lead to a series of measurement requirements. That is, a definition of the *minimum* levels of precision, spatial resolution, spectral resolution, etc. necessary to advance our understanding of lunar and planetary origin, evolution, and processes. These are summarized in Table 3-1. In establishing these priorities LExSWG focused on problems that were global in their nature, rather than local or regional problems. It also recognized the current state of instrument technology. Thus, the spatial resolution for measurements of elemental abundances is 100 km, approximately the resolution of a gamma-ray spectrometer. This is adequate for determining the total abundance of plagioclase in the highlands, for example, but not for determining the inventory of all anorthosite exposures (which may require resolution of < 10 km).

LExSWG has also assessed the extent to which the Clementine and Lunar Prospector missions have fulfilled the measurement objectives. We give this assessment in Table 3-2 for each mission and the combination of the two. The last two columns of Table 3-1 give the measurement capabilities of the two missions, which can be compared to the LExSWG requirements.

Table 3-2 also includes a measurement not listed in original LExSWG studies, namely, the detection of water in permanently-shadowed regions at the lunar poles. The presence of abundant water in these regions might significantly affect planning for future habitation of the Moon, so determining the amount of water ice at the lunar poles is very important. It is also an interesting scientific problem as well.

*Surface elemental composition:* Clementine has provided a nearly global data set that allows calculation of the elemental Fe and Ti abundances, using techniques developed by Paul G. Lucey (see Lucey et al., *Science* **268**, p.1150-53, 1995). Because Al is inversely correlated with Fe, determining Fe also allows estimation of the Al abundance. These chemical data will have spatial resolution of only 200-400 meters, far below the minimum requirements set forth by LExSWG. Lunar Prospector will be able to further test these measurements and, most important, add measurements of the Th abundances, a crucial trace element. Together, these two missions basically meet the LExSWG requirements for orbital elemental composition. The only improvement would be to directly determine the abundances of Mg, Ca, and Al directly, at high spatial resolution.

*Gravity field:* Clementine data improved our knowledge of the lunar gravity field and Prospector will probably improve it further. However, we still need to determine farside gravity. This can be accomplished by two spacecraft orbiting the Moon simultaneously.

*Topography:* Clementine provided a sound topographic map of the Moon. Although the spacing varies along the ground track, the data set is suitable for global topographic analysis and many regional studies, such as of impact basins. Thus, the LExSWG requirement for a topographic data base has been met substantially.

*Surface mineralogy:* The 11 bands on the Clementine mission were carefully chosen for lunar mineralogy. The data will allow a sound determination of the relative abundances of olivine, low-Ca pyroxene, and high-Ca pyroxene, but not of plagioclase. The errors on those estimates will be about ± 10-20%. The data will also allow researchers to identify lithologic units and to map them. While these accomplishments do not completely fulfill LExSWG requirements, they make substantial contributions. What is needed is a more direct determination of the abundance of plagioclase, which requires data in the thermal infrared. Our knowledge of the mineralogy of the lunar surface would also be improved by additional data in the visible-near IR obtained with many more channels than the 11 bands available on Clementine. However, these data need not be global, as the basic global characterization has been provided by Clementine; data need to be obtained only on key areas identified on maps derived from Clementine data.

*Magnetic field:* Lunar Prospector will meet the main objectives set forth by LExSWG. It does not make electromagnetic sounding measurements of the lunar interior, potentially useful for determining the nature of the interior and detecting an iron core. Such measurement require two spacecraft in high and low orbits simultaneously.

*Imaging:* Neither mission will have added significantly new imaging data that could be used for geological studies and geodesy. Both are essential to understand lunar geological evolution, basin formation, and volcanism.

*Surface thermal properties and heat flow:* Neither mission provides thermal data.

*Atmospheric measurements:* Prospector measurements the abundance of radon in the lunar atmosphere, but does not carry instruments for more complete atmospheric measurements. The are excellent possibilities for inexpensive missions to characterize the tenuous lunar atmosphere.

*Water trapped in polar regions:* The Clementine mission conducted a bistatic radar experiment to detect water ice at the lunar poles. The data suggest that ice is present in the south polar region. This important result will be tested by the Prospector mission using a completely independent technique. The combined result will allow a good first estimate of the quantity of water ice present.

Table 3-1. Measurement objectives (in priority order) established by the Lunar Exploration Science Working Group (LExSWG).

| Measurement | Specific Requirements (all measurements to have global coverage) | Clementine (coverage is 90% of the lunar surface) | Lunar Prospector (coverage is 100% of surface) |
|---|---|---|---|
| 1. Surface elemental composition | Essential Elements: K, U, Th, Fe, Mg, Al, Ti<br>Spatial resolution: ≤ 100 km<br>Measurement accuracy: ≤ ± 20% | Fe, Ti<br>200-400 m<br>Fe: 1 wt%; Ti: 10% rel | Th, K, Fe, Ti<br>100 km<br>5-20% |
| 2a. Gravity field | Spatial resolution: ≤100 km<br>Measurement accuracy: < ± 1 mgal | Nearside only | Nearside only |
| 2b. Topography | Spatial resolution: ≤ 1 km<br>Measurement accuracy: ≤ ± 10 m vertical | 35 km<br>100 m | |
| 3. Surface mineralogy | Spatial resolution: ≤ 500 m<br>Measurement accuracy: ± 5% (mineral abundance) | 200-400 m<br>± 20% for mafic minerals produce rock unit maps | |
| 4. Magnetic field | Spatial resolution: ≤ 30 km<br>Measurement accuracy: ± 0.1 nT | | < 30 km<br>± 0.1 nT |
| 5. Imaging | Spatial resolution: 15 m/pixel<br>Positional accuracy: 100 - 300 m | 200-400 m/pixel | |
| 6. Surface thermal properties/heat flow | Spatial resolution: ≤ 100 km<br>Measurement accuracy: 0.5 K, ≤ ± 4mW/m$^2$ | | |
| 7. Atmosphere and ionosphere | Spatial resolution: 30 - 100 km<br>Sensitivity: $10^{7-8}$ cm$^{-2}$<br>Measurement accuracy: ± 10% | | |

Table 3-2. Assessment of the extent to which the Clementine and Prospector missions achieve the LExSWG measurement objectives for orbital missions. The numerical rating ranges from 5 (Excellent, meets all measurement requirements) to 1 (poor, very little progress). A "0" means that no new data were acquired at all.

| Measurement | Clementine | Lunar Prospector | Combination of Clementine and Prospector |
|---|---|---|---|
| 1. Surface elemental composition | 4 | 3 | 4 |
| 2a. Gravity field | 2 | 2 | 2 |
| 2b. Topography | 3 | 0 | 4 |
| 3. Surface mineralogy | 3 | 0 | 3 |
| 4. Magnetic field | 0 | 5 | 5 |
| 5. Imaging | 1 | 0 | 1 |
| 6. Surface thermal properties/heat flow | 0 | 0 | 0 |
| 7. Atmosphere and ionosphere | 0 | 0 | 0 |
| 8. Water in polar regions | 4 | 5 | 5 |

# 4. ROVERS AND FIELD SCIENCE

The idea of robotic vehicles exploring planetary surfaces has been a dream of scientists, roboticists, and science fiction writers. LExSWG has explored the potential of rovers for lunar science and strongly endorses the development of the capability of landing mobile vehicles on the Moon and other planets to examine geologic features at close quarters. In a way, rovers are orbital spacecraft with remarkable spatial resolution. Considered in another way, they are amazing tools for doing field geology without actually being in the field by using the special capabilities of telepresence—the ability to project a geologist's experience, intelligence, creativity, and judgment to a remote site through advanced teleoperation.

Vehicles, whether rocket-powered hoppers, walkers, or wheeled rovers, can be used for many purposes, ranging from installation of geophysical networks to intensive field investigations. LExSWG has considered only the use of rovers in field geological investigations. The installation of geophysical networks, considered in section 7, may use roving vehicles too, but the precise implementation mechanisms have not been evaluated. In the following discussion, we assume that the vehicle, which we call a "rover," is capable of moving the indicated distances and at the indicated speeds, but whether it has wheels (or how many wheels) or legs (or how many legs) is not considered. We develop the requirements for mobility, not how it is implemented.

## ROVERS AS FIELD GEOLOGISTS

Planetary rovers need to be designed to do field geological studies supported by analytical instruments for *in situ* analyses. Much of the science of geology is done in the field. The field work is supported by laboratory analysis of rock samples (in the case of planetary rovers, by the analytical instruments carried on board), experiments, mathematical analysis, and synthesis. Nevertheless, no matter how sophisticated our instruments, the data will not be understood without knowing the geologic context.

The goals of field geology are to (1) understand the geological evolution of a region by a detailed examination of key areas in it; (2) understand the processes that operated; (3) place all the geological materials into a three-dimensional framework. These goals are accomplished by making observations and measurements in the field, using those observations to reconstruct the geologic history while in the field, and then testing the working hypotheses. Field work also involves collecting samples for analysis, or in the case of planetary rovers, simply making the analyses *in situ*. Some examples may help clarify the nature of geological field work. Suppose a primary goal of a mission is to understand the nature of volcanism on the Moon. To understand the dynamics of fire-fountains, geologists would need to search for the presence of simple layers or cross beds, and the presence, abundance, and sizes of blocks of rocks in the loose deposits. As a second example, fire fountain or pyroclastic eruptions might alternate with effusive eruptions that produce lava flows. To determine if they do alternate and the thicknesses (hence information about the volumes) of the deposits, we would need to search for a vertical exposure (for example, in the wall of a rille) and assess whether both types of volcanic deposits are present their thicknesses. Or, to test whether flows were erupted as high effusion rate a‘a flows or as low effusion rate, internally-inflated pahoehoe flows, we would search for tumuli (10 to 100-m wide mounds) and study the abundance of vesicles as a function of depth inside individual flows. By observations such as these, geologists would build up a picture of how volcanism operated on the Moon, allowing comparison to similar observations on Earth and, eventually, Mars and Venus. Similar examples can be given of the emplacement of crater ejecta or melt sheets, and the nature of lunar intrusions (perhaps exposed in the central peaks and walls of large craters). Thus, field observations relate detailed, local observations to the much larger picture of how geological processes operate and how specific deposits are related temporally to each other.

The requirements to accomplish all this are good eyesight, human powers of observation and thought, geological experience, and a lot of time. A rover mission provides all of these, assuming it is teleoperated. If autonomous, rover missions to the Moon cannot possibly perform geological investigations. Robotic devices capable of discerning the subtle yet complex nature of rock formations are only dreamed of. No technology program is even close to providing such sophisticated capabilities in artificial intelligence. The fact is, people are needed to do field geology. And people are needed to be at the site—even if their presence is through remote operation via telepresence. The Apollo missions provided all but one of the requirements—***time***. A rover mission will not have this limitation: in even a single lunar day, there will be at least 280 hours of field time (12 Earth days available after landing and spacecraft check out), compared to 78 hours for all the Apollo missions combined.

One concern about field work on the Moon is the presence of a nearly ubiquitous blanket of rubble—the regolith. This material certainly obscures geological relationships in most places, but Apollo field experience and imaging shows that outcrops are clearly present in crater walls (including in small, traversable craters) and in rille walls. For example, on a so-called "dark mantle" deposit, thought to be deposited by volcanic fire fountains, fresh craters 20-100 meters across excavate materials from maximum depths of 2-10 meters and likely expose layers of pristine pyroclastic materials. These layers can be studied in detail to determine eruption styles, compositions, volatile element, and glass content. In addition, craters in all lunar terrains excavate large blocks that can be used effectively as outcrops. Even seemingly delicate materials such as pyroclastic deposits may survive ejection if they were welded sufficiently—the Apollo 15 green glass clod 15426 is an example of a welded deposit. Even though billions of years of impact has destroyed much geological information, numerous outcrops still exist where we can study the nature of impact deposits, pyroclastic deposits, lava flows, and highlands igneous complexes.

## ROVER CAPABILITIES

### The need for mobility

Use of a rover provides the necessary mobility to find appropriate outcrops. The ability to traverse large distances is important because geologists will be searching for contacts between mappable units, such as interlayed pyroclastic deposits and lava flows, mare basalts and underlying highlands materials, or impact melts and underlying breccias. If such contacts are not within a few hundred meters of a landing site (almost certainly the case) long traverses are obviously necessary. Even when outcrops are excellent, as along Hadley Rille at the Apollo 15 site, it is important to trace contacts for long distances because they frequently pinch out or change their nature. Traverse capability is also essential because safe landing sites may not be close to areas of geological interest; outcrop availability implies steep slopes, such as in rilles or crater walls, or numerous boulders, as on crater ejecta blankets.

The Apollo missions showed the usefulness of a roving capability. The final three missions (15-17), which had rovers, provided far more geologic insight and a more diverse sample collection than did the first three landings (11, 12, and 14), which did not have rovers. In short, rovers, whether walking on legs or driving on wheels, are essential for useful geological investigations of the lunar surface.

## Traverse range, rover speed, and lifetime

The Apollo missions that carried a rover, Apollo 15–17, provide some guidance when estimating the range an ambitious rover mission would need. The sites of the last three Apollo missions were selected for their variety of lithologic targets, so the rover had to be capable of reaching all of them. Total rover traverse distances were between 27 (Apollo 16) and 35 km (Apollo 17). The traverses were not the most efficient ones chosen, however, as the crew returned to the starting point (the Lunar Module) at the end of each EVA. The extremes of sampling stations along the Apollo traverses were typically 10 km apart. On the other hand, not all targets were reached (e.g., the North Complex at Apollo 15 and the Sculptured Hills at Apollo 17). Thus, a reasonable rover mission ought to be able to traverse a distance comparable to those of the Apollo missions, a few tens of km. Consideration of the sizes of potential regions for investigation and representative traverses throughout them leads to a recommended rover range of at least 100 km. For example, a mission to the Aristarchus Plateau to examine mare volcanic deposits, volcanic vents, and highlands materials ejected from Aristarchus Crater requires a traverse like the one shown in Figure 4-1. The landing site might be 30 km from Schroter's Valley, the large rille in this area. Geologists operating the rover would examine the pyroclastic deposit along the traverse, checking for lateral variations. Once at the rille, they would examine the walls and then traverse 20 km to the Cobra Head, a suspected volcanic vent. They would travel around this feature, roving for about 15 km, and then head for Aristarchus crater. It would require 40 km of traverse to reach the rim, and then another 20 to examine the ejecta thoroughly. The total traverse thus adds up to 125 km, and does not include many other possibilities, including descending into Schroter's Valley or Aristarchus Crater. Limiting the traverse to the volcanic features requires a traverse distance of 70 km. Thus, a sound lunar mission requires a rover capable of traveling no less than 20 km, and preferably more than 100 km.

This ambitious traverse implies that the system must be designed to survive many lunar nights. To be able to traverse such long distances and allow sufficient time for detailed field observations and other analyses, the rover must be able to move reasonably fast. While LExSWG has not made an exhaustive study of this issue, we estimate that the minimum speed for traversing relatively flat terrain is 100 to 200 m/hr. For comparison, the Apollo piloted rovers traveled 6–7 km/hr in most areas, but could reach 13 km/hr on smooth, level surfaces (*Lunar Sourcebook*, p. 524).

## Slope-climbing abilities

LExSWG has examined available topographic data for a number of interesting sites on the Moon to establish reasonable limits on how steep a slope a roving vehicle ought to be able to negotiate. Rovers must be able to move along the normal, hummocky lunar surface. The hummocky nature of the surface stems from the presence of numerous old, degraded craters. An old crater 100 m in diameter, a common feature on the Moon, has maximum slopes of 5-10$^{o}$. Somewhat fresher craters, such as Palmetto Crater (600 m in diameter) at the Apollo 16 site, have interior slopes of 15-20$^{o}$. Very fresh craters, such as South Ray Crater (500 m in diameter), also at Apollo 16, are steep, but not impassable. Getting to the rim of South Ray requires traveling on a slope of only 7$^{o}$. The steepest inside slopes are 35$^{o}$, but there are routes to the floor that are not as steep, 17-26$^{o}$. Fresh craters in the 10-100 meter size range also probably have outcrops of materials of interest in their walls and on their floors, and they probably have interior slopes similar to those in South Ray. At the other extreme, large craters tens of kilometers across have paths to their floors where the average slope is < 30$^{o}$. Thus, examining craters on the lunar surface appears to require the ability to climb and descend slopes of about 25$^{o}$.

Rilles provide excellent access to study lava flows and any associated pyroclastic deposits. Although locally there are very steep walls, some approaching vertical, there are many routes to the bottoms of rilles. The Apollo 15 crew reported that they could have reached the bottom of Hadley Rille if time had permitted. Topographic data for Rima Prinz and Rima Mozart show that there are numerous routes to the bottoms where the slopes are 15-25°, including routes where the slope does not exceed 15°. Thus, traverses into lunar sinuous rilles would require capabilities similar to those demanded by craters, the ability to climb and descend slopes of about 25°.

### Manipulators

A rover must have at least one manipulator arm. This device can be used to bring instruments into contact with or in proximity to surface materials for analysis. For example, a close-up imaging system may be mounted on a manipulator arm. An arm is also needed to deliver samples to some types of analytical instruments, such as gas analyzers or x-ray devices, and perhaps to work surfaces for specialized measurements, such as grain sizes. An essential task would be to dig small trenches in the regolith or in other loose surficial deposits such as pyroclastic materials. Such trenches are useful for observing layering, obtaining fresh materials, and for estimating some engineering properties. Trenches need to be up to 25 cm deep and 1 meter long. A manipulator arm can also be used with appropriate tools to chip and clean rock surfaces before chemical or mineralogical analysis and for viewing the rock textures.

## MEASUREMENT REQUIREMENTS

To significantly improve our understanding of lunar history and of planetary processes, we need to decide the most crucial measurements that will be made and to assess the quality needed (precision, spatial resolution). Our assessment is summarized in Table 4-1, which maps the quality of measurements needed to meet the six major exploration objectives (Table 2-1).

Space does not permit a thorough explanation of the reasoning that produced the list of measurements and their quality in Table 4-1, but some examples are instructive. Suppose, for example, that we wish to determine the relationship between pyroclastic deposits and lava flows in the Rima Prinz area. To accomplish this, we would need to examine the nature of the contacts between them, determine if they are interlayered, and measure the chemical composition of each. Or, if we wished to understand the eruption dynamics that produced pyroclastic deposits such as those near Rima Bode, we would need to check for the presence of simple layers or cross beds, and measure the abundance and sizes of blocks in pyroclastic deposits, and determine how these properties vary with distance from a suspected vent. To better understand the nature of the lunar highlands, we would study the rocks exposed in the central peak and walls of a highlands crater. This study would require identifying lithologic contacts between, for example, norite and troctolite, and identification of all the rock types present. Rock identification requires description of textures, measurement of grain sizes, mineralogy, and chemical composition.

### Imaging

Because we envision that the primary role of a planetary rover is to make field geological observations and measurements remotely, it must have a capable imaging system. Based on experiments conducted by several groups and the need for good imaging for navigation, LExSWG recommends the use of a stereo imaging system, at least for part of the imaging system. As noted in Table 4-1, required spatial resolution ranges from microscopic (0.05 mm) to fairly coarse (centimeter scale). There is obviously an interplay between resolution and distance to the outcrop of interest; it is unreasonable to expect to achieve a resolution of 0.05 mm from 100 meters away. The requirements in Table 4-1 represent the imaging resolution needed for the specific task, and do not specify the type of imaging system to be used.

A resolution of 0.05 mm easily allows grain size measurements in enough size bins to characterize regolith or pyroclastic deposits, or rock textures. For example, one can readily determine eight size bins in a regolith or pyroclastic deposit: > 1 cm; 4-10 mm; 2-4 mm; 1-2 mm; 0.5-1 mm; 0.25-0.5 mm; 0.125-0.25 mm; < .125 mm. While our one good sample of a pyroclastic deposit is so fine-grained that 80% of it is in the < 0.125 mm fraction, the measurement would at least characterize the upper part of the distribution for comparison. Furthermore, predictions indicate that deposits near a volcanic vent are probably coarser grained than those further away. Similarly, regolith grain sizes are very small, but immature regolith deposits are much coarser. So, although our suggested minimum spatial resolution may seem too high, it is important to bear in mind that useful data are still produced and that such resolution is readily achievable.

The imaging system would be even more useful if equipped with a set of filters ranging from about 0.4 to 1.1 microns for determination of rock mineralogy. The multispectral imaging would provide unit maps of key lithologies throughout a traverse area. Because these images can be obtained from a considerable distance, the use of multispectral imaging effectively enhances the range of the rover. LExSWG did not conduct a thorough study of the specific bands needed or how many bands would be required to be able to discern lithologic units, nor did the committee assess the value of using a full imaging spectrometer or a spot spectrometer. Such studies need to be conducted.

### Chemical analysis

Chemical analysis is essential to understanding lunar crustal genesis, volcanism, and regolith evolution. It is especially valuable when used in conjunction with good imaging systems, which enable remote geologists to choose appropriate samples for analysis. Use with mineralogical analyses also greatly enhances the value of chemical analysis.

Preliminary study suggests that chemical analyses must be at least as precise as listed in Table 4-1. The precision needed depends on the specific problem being addressed and varies considerably from element to element. The highest precision required, 5%, will allow investigators to distinguish between most types of highland rocks, to confidently identify new types of rocks, and to determine the extent to which mare basalts are chemically similar to associated pyroclastic deposits. This level of precision may be too high to do sophisticated regolith mixing studies to identify rock types present as components in the regolith. Nevertheless, useful inferences can be made from such studies. Although LExSWG has made a preliminary examination of the issue of precision of chemical analyses, there is a clear need for detailed studies to determine quantitatively the precision needed to accomplish the tasks listed in Tables 2-1 and 4-1. We draw attention in particular to the need to measure accurately the elements Fe and Mg, which have enormous petrologic significance. Instruments currently available do not measure Mg concentrations nearly as accurately as needed to make full use of chemical data to answer many questions about the evolution of the lunar crust.

It is also necessary to determine selected minor and trace elements, besides major elements. Which elements can be measured depends on the specific type of analytical device. However, in general it is necessary to measure at least one incompatible trace element, such as Th and Y, a minor or trace transition metal (Cr, Sc), and a monovalent large ion lithophile element such as K or Na.

### Mineralogical analyses

Mineralogical analyses provide information complementary to chemical analyses. Mineralogical analyses must be able to measure the abundances of key rock-forming minerals when they are present in amounts exceeding about 5%; these minerals are olivine, orthopyroxene, clinopyroxene, plagioclase, and ilmenite. In addition, for some studies, such as characterizing pyroclastic deposits and regolith, measurements of the amount of glass vs crystalline material are very important. Regolith studies are further aided by the ability to measure the amount of fine-grained metallic iron present, the chief parameter in determining the maturity level of a regolith sample. However, as for chemical analyses, a detailed study is needed to assess what we learn from different levels of uncertainty in mineral abundances.

### Gas and volatile contents

Gas analyses are needed for measuring the abundances and, where appropriate, isotopic composition of extra-lunar volatiles on the lunar surface. This is important for testing models of the sources and modes of implantation of these gases, searching for possible secular changes in their properties, and to characterize the history of individual regolith samples. Such analyses should focus not only on the composition of the volatile species but also on the distribution of those species within the regolith, e.g., their depth of implantation within individual mineral grains. Independent information on the age of such samples, whether regolith (including regolith breccias) or rock surfaces, would be of considerable value. Analyses of the gases released during heating also provide crucial data on volatiles associated with pyroclastic volcanism and about migration of those volatiles inside pyroclastic deposits. We estimate that precisions of ± 5% (relative) are needed for abundance measurements. Required precision for isotopic analysis varies with species, but is typically ± 0.5%.

## SURFACE OPERATIONS STRATEGY

The stereo imaging system can make scientific observations while traversing and at each worksite (areas chosen for detailed study because of their scientific interest). Worksites are nominally 50 m in radius. The distance between worksites is difficult to determine, as targets of opportunity would arise during a mission. Based on spacing of Apollo stations and examination of orbital images of prospective landing sites, a reasonable estimate is that worksites would be separated by about 2 km on average. At each worksite, images would be made to allow a team of investigators to make the measurements identified in Table 4-1: identify rock units, search for contacts between them, characterize the nature of layering or other features, describe the textures and structures in rocks and pyroclastic deposits, measure grain sizes, and detect color differences.

Stereoscopic imaging ought to be done approximately every 100 m of traverse, or more often if specific features of interest are recognized. These routine images should be archived and used for worksite selection by the science team involved in a given rover mission. At each worksite, a color stereo panorama should be taken (e.g., 72 images; 10-degree increments with two cameras). This image data base constitutes the first stage of field observations. High resolution black and white images could be taken of interesting targets within the worksite, perhaps averaging about 25-50 images per worksite; the use of black and white images reduces the demand on the communications system by decreasing the data rate. These will further characterize interesting targets and help decide which merit further investigation. Very high-resolution (microscopic) images will be needed of perhaps 10-20 samples at each worksite.

A one-year mission traversing 100 km probably requires a total of 50 worksites. At each site, chemical, mineralogical, and evolved gas analyses could be made. The total number of analyses depends on how long it takes to make each one and on the complexity of each site. We estimate that an average of approximately 5 chemical, mineralogic, and gas analyses would be needed at each site. Clearly, the entire analytical package needs to be explored thoroughly to know the power, data rates, masses, and volumes required by all potential instruments.

A viable mission is also possible within one lunar day and a total traverse distance of 5–10 km. The landing site would need to be chosen with the limited time in mind, so all objectives could be attained in 12 earth days (24 hours per day of operation). An area the size of the Apollo 15, 16, or 17 sites could be explored reasonably thoroughly in one lunar day. A short mission might cost less, because eliminating the thermal requirements for nightime survival would make rover design and construction simpler, and the costs of mission operations would be lower. On the other hand, unless the mass of the rover was substantially reduced so a smaller launch vehicle could be used, a one-lunar-day mission may not be as cost-effective as a long-duration mission.

## POTENTIAL LANDING SITES

Making full use of a rover for field geological investigations requires that it be sent to a geologically interesting place on the Moon. There are hundreds of suitable landing sites where diverse geological targets are available within tens of kilometers. An abbreviated list appears in a paper by G. Ryder, P. Spudis, and G. J. Taylor (*Eos* **70**, 1495-1509, 1989). The key characteristics are availability of a variety of materials of interest (including the likelihood of good outcrops). The Apollo 15, 16, and 17 sites are excellent examples of the type of sites where a rover mission would advance our understanding of lunar and planetary science.

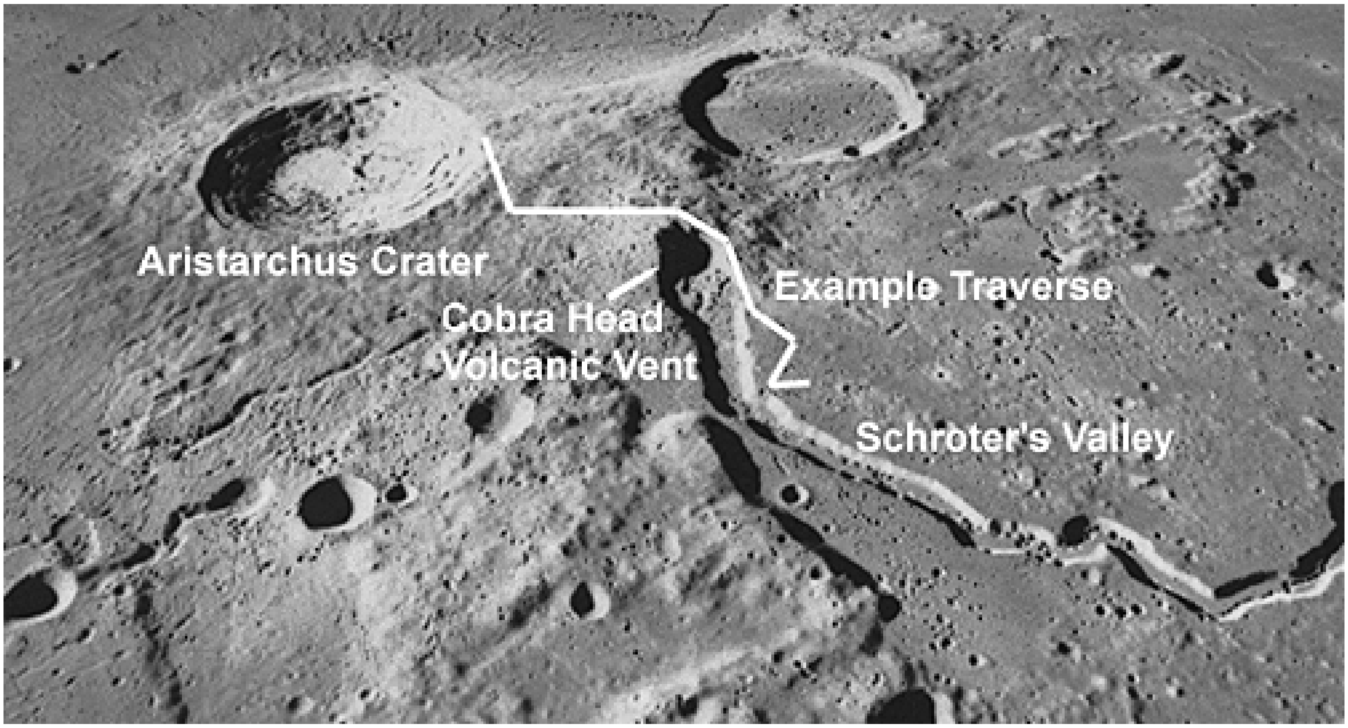

Figure 4-1. Example of a rover traverse on the Moon, in this case to examine volcanic features and a large impact crater. Total traverse distance is about 100 km.

Table 4-1. Minimum capabilities of instruments carried by rover for field geological investigations. Values for precision are _ the percentage of the amount present (for those quantities that exceed detection limits).

| **Measurement Objective** | **Specific Measurements (Representative List)** | **Imaging Resolution** | **Chemical Precision**[1] | **Mineral Precision**[2] | **Gas Precision**[3] |
|---|---|---|---|---|---|
| Lateral and vertical variations in crustal composition | chemical composition of regolith | - | 5% | - | - |
| | chemical composition of rocks exposed in crater walls and central peaks | - | 5% | - | - |
| Nature of oldest highland rocks and inventory of highland rock types | rock textures and grain sizes | 0.1 mm | - | - | - |
| | chemical compositions | - | 10% | - | - |
| | mineralogy | - | - | 5% | - |
| | nature of lithologic contacts | 1 mm | - | - | - |
| Regolith compositions compared with rocks beneath or nearby | chemical compositions of rock and regolith | - | 5% | - | - |
| Analysis of carefully selected regolith layers | Chemical composition | - | 5% | - | - |
| | mineralogy | - | - | 5% | - |
| | grain size | 0.05 mm | - | - | - |
| | maturity | - | - | 5% | - |
| | solar-wind gas contents | - | - | - | 5% |
| Composition and morphology of large crater and basin ejecta deposits | rock textures and grain sizes | 0.1 mm | - | - | - |
| | chemical compositions | - | 10% | - | - |
| | mineralogy | - | - | 5% | - |
| | nature of lithologic contacts | 1 mm | - | - | - |
| Detailed study of a lunar volcanic provence | grain sizes of basalts | .05 mm | - | - | - |
| | grain sizes of pyroclastic deposits | .05 mm | - | - | - |
| | phenocryst distribution | .1 mm | - | - | - |
| | vesicle distribution and sizes | .1 mm | - | - | - |
| | identify lava-flow type | 1 mm | - | - | - |
| | nature of pyroclastic bedding | .1 mm | - | - | - |
| | deposit thicknesses | 1 cm | - | - | - |
| | glass/crystal abundances | - | - | 5% | - |
| | mineralogy of lava flows | - | - | 5% | - |
| | chemical compositions | - | 10% | - | - |
| | volatile abundances | - | - | - | 5% |

1 These values apply to the major elements (those present in amounts greater than about 3 wt% of the oxide). Most important are $SiO_2$, $TiO_2$, $Al_2O_3$, FeO, MgO, and CaO. Analyses for minor elements would be very valuable, too (e.g., $Na_2O$, $Cr_2O_3$), as would measurement of at least one large-ion lithophile element such as a rare earth or thorium.

2. These apply to minerals present in amounts greater than 5% by volume. The most important minerals on the Moon are plagioclase feldspar, olivine, low-Ca pyroxene (orthopyroxene and pigeonite), high-Ca pyroxene (augite), and ilmenite. In addition, some problems (deposits of volcanic fire fountaining) require detection of glass, and regolith studies require determining the amount of submicroscopic metallic iron.

3. Solar wind gases include H, He, N, Ne, and Ar. Volatiles in pyroclastic deposits include CO, $CO_2$, $CH_4$, $SO_2$, and other sulfur species.

# 5. SAMPLE RETURN MISSIONS

## INTRODUCTION

The Apollo program conclusively demonstrated that study of samples acquired from another planetary body can lead to dramatic increases in knowledge about how planets form and evolve. The larger the mass returned, the greater the scientific yield, but acquisition and study of even small amounts of material can yield profound insights. For example, by studying a suite of small, light-colored rock chips extracted from the soil returned by the Apollo 11 mission, John A. Wood and J. V. Smith independently deduced how the bulk composition of the lunar highlands differed from that of the maria and formulated a hypothesis for the primordial differentiation of the Moon.

The optimum sample-return mission would combine rover and sample-return technologies, with a rover performing remote analyses along a traverse and simultaneously collecting the samples that would be returned and studied to provide ground truth. Although such a mission would have tremendous scientific yield and there are many questions that can be addressed only by this means (especially those requiring study of lunar volatiles and light elements), its complexity would make it very costly. Important scientific information can also be acquired by sample return conducted by a lander that has no mobility. This section primarily addresses a strategy that emphasizes maximum science return for minimum cost by assuming that the lander has no mobility, but we also include brief mention of the advantages of a combined rover and sample-return mission.

In planning sample-return missions, scientists and engineers must work together to answer several crucial questions: What type of sample will be collected? What mass of sample will be acquired? Where on the Moon will the sampling occur? How precisely should landing navigation be planned? How extensively will presampling field relations and sample orientations be documented? These issues are discussed below. They are, however, closely intertwined and hard to evaluate in isolation from one another. For example, choice of a landing site may dictate how precise navigation needs to be. Also, choices of the kind and mass of samples have direct bearing on the design and cost of the spacecraft and its sample acquisition equipment.

This report is based on a study made by the Curation and Analysis Planning Team for Extraterrestrial Materials. A more complete version of the report was published by P. H. Warren, B. G. Drake, G. E. Lofgren, and T. D. Swindle (1995, *EOS, Trans. Amer. Geophys. Union* **77**, 33).

## RATIONALE FOR RETURNING SAMPLES

### Critical types of data can only be obtained by study of returned samples

Although many important types of information can potentially be obtained remotely (such as the relative proportions of the major minerals in a rock and the rock's bulk content of selected elements), crucial types of measurement cannot be made with available remote technology or with technology that is likely to be developed in the foreseeable future. Examples are: petrography (which provides basic information on the homogeneity, origin, and history of a rock); chemical analysis of individual mineral grains; determination of the time of major events in a rock's history; and determination of the contents of many minor and trace elements and isotopes in bulk rocks. These techniques require special sample preparation and/or require analytical instruments that, with current technology, are very large and heavy. Construction of miniaturized, remotely controlled facilities for sample preparation and analysis by these techniques would be extremely difficult, perhaps impossible. Because the types of studies listed above are essential for understanding the origin and history of rocks and the planets from which they come, studies of returned samples are vital.

### Laboratory instruments have better resolution and precision than flight instruments

Analytical instruments, both terrestrial laboratory and flight instruments, are continuously being improved, but improvements in flight instruments generally lag far behind those in laboratory instruments. Because laboratory instruments do not have volume, mass, and power limitations, they can be improved far more easily. The difference is especially notable in instruments that perform complicated analyses such as isotopic and age determinations.

### Returned samples become resources to be reanalyzed as technology improves

Analytical instruments are continuously being improved, and, as new instruments are designed, new types of analyses become possible. A previously collected suite of samples can be subjected to analysis by the new or improved techniques, producing entirely new data sets. For example, the technology of mass spectrometry could not support Sm-Nd dating at the time of the Apollo missions, but several years after the missions the technique began to be used to provide crucial data on the ages of lunar rocks and on the time of primordial lunar differentiation. Similarly, latest generation ion microprobes allow for trace-element analyses of individual mineral and glass grains; such analyses were impossible when Apollo samples were first returned.

### Unforseen discoveries can lead to new experimental design

Flight instruments are chosen well before a mission begins, because flight qualifying instruments takes considerable time. While every effort can be made to maximize flexibility of the devices, the design is dependent on best guesses of what to expect. If the samples do not match our expectations, the instruments may not provide useful data. Such is not the case with returned samples. If one type of analysis proves unsuitable, other techniques can be used or new ones devised.

### The variety and complexity of laboratory instrumentation for sample studies are almost unlimited

Hundreds of different types of laboratory instruments have been used to analyze returned lunar samples. In contrast, missions for in situ analyses can carry only a few instruments. Even if the analyses generated were equal in quality to those obtained in terrestrial laboratories, the limit on number of flight instruments greatly constrains the number and type of analyses that can be done remotely.

## CONSTRAINTS ON SAMPLING STRATEGY FROM NATURE OF LUNAR SAMPLES

Lunar materials can be divided into two basic types: rocks and soils. The distinctive characteristics of these two types of materials greatly affect sampling strategy. In analysis of a lunar rock, it is important to study material that is representative of the bulk rock; thus, the requisite minimum size for analysis increases as size of the mineral grains increases (in relatively homogeneous rocks), or as the scale of heterogeneity increases (in relatively heterogeneous rocks). The results of many types of studies are difficult to interpret if rock samples are not at least several times bigger than the typical grain size or scale of heterogeneity. Fortunately for our understanding of the Moon, many of the lunar homogeneous rock types tend to be fine or medium grained (grains mostly <3 mm) and many of the lunar heterogenous rock types vary on scales not much greater than this. Accordingly, for many lunar rock types, samples in the 2-10 mm size range are adequate to ensure reasonably representative sampling.

Lunar soil, like soil on Earth, forms by disintegration of rocks that become exposed to a hostile environment (from a rock's viewpoint) close to the planet's surface. A crucial difference affecting sampling strategy is that the formation of terrestrial soil generally involves considerable chemical decomposition (e.g., hydration and oxidation of minerals, presence of organic materials), whereas on the extremely water-poor Moon, soil forms mainly by physical processes—comminution and melting by meteoritic impacts. Thus, small rock fragments in a lunar soil are much more representative of their parent rocks than similar sized fragments in a terrestrial soil.

Another significant Earth-Moon difference that affects sampling strategy is that, because of the pervasive nature of meteoritic bombardment, the material at the lunar surface is regolith, and outcrops of bedrock are rare. At most locations on the lunar surface, bedrock variations can only be sampled indirectly, by statistical assessment of prevailing types among rock fragments composing the regolith. This aspect of lunar geology is truly a mixed blessing. The major advantage is, because of the impact mixing, regolith at a given location contains a variety of lithologies derived from a large region and a small sample of bulk regolith samples a much larger region than an equivalent soil sample on Earth. The major disadvantage is, because bedrock is rarely exposed and the size of rock fragments in the regolith is generally small, the spatial relations between different rock types are generally indeterminate.

## TYPES OF SAMPLE TO COLLECT

### Bulk regolith

Bulk regolith would be the easiest and least costly type of sample to collect, requiring only a simple scooping device. The Apollo "contingency" samples and the Luna 16 and 20 samples were bulk regolith samples. Analysis of such a sample can constrain the bulk chemistry of the local crust and the maturity of the local regolith. The extremely fine particles (<0.1 mm, which constitute typically about half the total mass) and the surfaces of the coarser fragments provide extensive records of solar-wind, cosmic-ray, and micrometeorite interactions with the lunar surface. Studies of the larger rock fragments in a bulk regolith sample can also constrain the nature of the regional crust. Because bulk regolith provides a sampling of the finest material at the lunar surface and is easy to collect, we recommend that at least one sample of this material be collected by any sample-return mission.

The drawback to acquiring only bulk regolith is that an overwhelmingly large proportion of the sample would consist of very small fragments (>>90% less than 1 mm across); only about 2% of the mass would be in the form of fragments greater than 4 mm across. Although bulk regolith is the optimum sample to collect for studies that require fine lunar-surface material, the paucity of larger fragments greatly limits the studies that could be carried out with respect to several of our science themes.

### Sieved or raked regolith

On the last three Apollo missions, the astronauts used rakes to extract small rocks out of the regolith. These “rake sample” collections have proven to be very valuable scientifically. The samples are large enough (greater than 1 cm across) that a variety of analyses can be performed on each and they are numerous enough that the data base gives us a good idea of the range of rock types present in the regolith where they were collected.

An automated lander could be equipped with a simple sieving mechanism, to be used in conjunction with a scoop, or a scoop constructed to act as a rake. The extra effort of sieving or raking guarantees a much larger scientific return for a given total collected sample mass. Studied collectively, these numerous small rocks would provide important data relevant to several of the scientific themes we outline in Section 2.

The choice for the size of openings in the sieve or the spacing between tines of the rake determines the minimum size of fragment collected by this means. As discussed above, minimum sample sizes in the range 2-10 mm permit obtaining reasonably representative samples of many lunar rock types. The larger fragments in this range are preferred, however, because they have sufficient mass to be analyzed by a range of techniques; the maximum scientific return is obtained when several different types of analysis are performed on the same sample. Rock samples weighing 1-10 grams can be characterized quite well (if spherical geometry is assumed, the corresponding diameters for these weights are 9-19 mm). Rock samples weighing 0.1-1 grams (2-9 mm in diameter) can be characterized fairly well, although depending on rock type the full suite of techniques for age determination may not be feasible and sample heterogeneity may be a problem. For these reasons, a sieve/rake configuration that would concentrate fragments with minimum weights of about 0.5-1.6 g (diameters of 7-10 mm) seems optimal. (The gaps between tines on the Apollo rakes were about 10 mm.)

### Individually selected rocks and regolith samples

The capability to return individually selected samples of rocks and soils would enhance the value of any sample return mission. Examples of types of samples that could be collected are: rocks that appear to be the dominant lithology at a given collecting site (for ground truth); rocks of unusual or especially interesting lithology (such as potential relics of the Moon’s primordial crust or fragments of its mantle); rocks with pristine, unexposed surface; and ancient soils. The ability to return specially selected samples would be essential for a combined rover-sample return mission. The ability to collect such samples would be desirable on a mission with a non-mobile lander but, because the number of special samples within reach of such a lander would be small, not as important as on a mission with a rover.

### Cores

All of the Apollo missions returned drill cores and/or drive tubes, the deepest going to almost 3 m. Luna 24 also returned a shallow drill core. These cores have been very useful, particularly for investigating the record of bombardment of the Moon by solar and galactic cosmic rays. There are a few problems for which coring might be the optimal sampling technique. For example, if remote sensing determines that there is appreciable water ice in lunar polar regions, a drill core (coupled with a cryogenic return capsule) would be useful for a first-order investigation. For most investigations requiring regolith material, however, a bulk regolith sample would be nearly as useful as a core sample of equivalent mass. Given the probable complexity and cost of a coring device, we surmise that for most sites coring would not be worthwhile.

### Engineering questions

Several engineering problems relating to sample acquisition require study. How expensive are various sampling devices likely to be? In particular, can a sieve/rake system be placed on a lunar sampler without greatly increasing complexity and expense? What would be the optimal low-cost method to acquire and return a shallow (e.g., 1 m deep) core, and how risky and expensive would this method be? How much more difficult would it be to acquire a deeper, say 5 m, drill core?

## SAMPLING DOCUMENTATION

The importance of documentation on a future mission will depend on the type of sample collected. Little documentation is necessary for a core, sieve/rake, or bulk regolith sample, but it would be desirable to know the local geography, especially the locations and sizes of craters likely to have contributed ejecta to the sample. For a sieve/rake sample, a photograph of the surface before collection might make it possible to identify any large individual rocks that had been at the surface.

The requirements for sample documentation are considerably greater on a combined rover-sample return mission or on any mission in which selected samples are being collected. It would be impossible to select an individual rock, or chip a rock from an outcrop, without an imaging system movable in both altitude and azimuth and capable of high resolution and both high and low magnification. Furthermore, if rocks are to be selected, some capability for petrologic characterization prior to collection would be highly desirable (for example, determination of mineralogy by visible, UV and/or IR spectroscopy). The value of sample selection would be negated, however, if the selected samples could not be identified when they were returned to Earth. The Apollo missions demonstrated that distinguishing individually collected samples would have been extremely difficult without careful photodocumentation prior to and during collection and separate storage of samples, and determining the lunar surface orientation of samples from lunar surface photographs was far more difficult than expected. Thus, careful photodocumentation would be necessary before and during collection of specific samples and it would be necessary to be able to store the individually selected rocks separately during transit to Earth.

There are several engineering questions relating to sample documentation. How complex and costly would it be to construct the sophisticated imaging system required for collection of individual samples? How difficult would it be to devise a spacecraft sample container in which samples can be segregated from one another?

## MASS OF SAMPLE TO BE RETURNED

The six Apollo missions returned a total of 382 kg of samples. The three Luna sampling missions returned a total of only 0.3 kg, but studies of this material demonstrated that even a very small amount of sample, if derived from a location remote from other samples, can be extremely valuable.

Due to the chaotic impact-gardened nature of the lunar regolith, a great diversity of rock types will be found at almost any site. We would probably only need to study 10-20 rocks from a given site to confidently identify the most common rock types. To characterize diversity within the dominant rock type, however, we estimate that more than 50 rocks would have to be studied. Any search for relatively rare rock types clearly requires examination of a large number of fragments. For example, if only 1% of the rocks at a site are of a given rare rock type, then we would have to study at least 100 fragments to identify the presence of this rock at the site; a total of roughly 500-1000 fragments would have to be studied in order to characterize diversity within this rock type. In terms of total mass of sample returned, 500-1000 fragments would weigh roughly 0.7-1.3 kg, assuming that the sample is a >6 mm sieve or rake fraction of typical lunar regolith with no one fragment much coarser than 3 cm. Without sieving, obtaining the same number of >6 mm rocks would require a vastly higher total mass of sample, by a factor of roughly 90 (63-117 kg).

Critical engineering questions are as follows: How does varying the mass of the acquired sample over the range of 0.1-100 kg affect the cost of a mission? (The minimum weight given — 0.1 kg — is that returned by the Luna landers; the maximum weight given — about 100 kg — is that required to characterize diversity in rare rock types if only bulk regolith is returned, as discussed above.) Are there thresholds where returning a slightly larger mass is far more costly? If such thresholds are sensitive to the basic design of the sample-return vehicle, then the vehicle should be designed with these thresholds in mind. In particular, the cost of a hundred-fold increase in total sample mass should be compared with the cost of incorporating a simple device for sieving or raking the regolith.

## LANDING SITE SELECTION

The type of landing site selected for a sampling mission depends critically on whether the mission will be a non-mobile lander or a combined rover-sample return mission. If the lander cannot move, then the goal of the mission should be to collect a single rock type and the landing site should consist of an area that is geologically simple, so that there can be no ambiguity as to what geological unit was sampled. If the mission is a combined sample return-rover mission, then the site selected should be geologically complex so that sampling over a traverse of reasonable length can yield samples from diverse geologic units.

Apollo results have shown that the Moon is geologically complex and there are significant lateral variations in the compositions of the rocks that make up its crust. For safety and other reasons all six Apollo landing sites were confined to the Moon’s central nearside; the three Luna samplers also all visited a small region of the east-central nearside. A polygon formed by connecting all nine sites covers merely 4.4% of the Moon’s surface, so that we have not actually sampled very much of the Moon’s surface. One of the most exciting aspects of a new lunar sample-return mission (or missions) is the prospect of sampling the many interesting sites that were inaccessible to the Apollo and Luna missions.

There are many sites on the Moon where a simple sample-return mission would yield valuable data. We have not constructed an exhaustive list of such sites and will list only a few obvious examples. For example, sampling of different flows of basalts having a wide range of crater densities and remotely sensed compositions would yield much information on lunar thermal history, on the variation of lunar volcanic processes with time, on lateral and vertical heterogeneity of the mantle (from which basalts are derived), and on the flux of impacting bodies in the vicinity of the Earth-Moon system. As another example, sampling of impact melt rocks inside and surrounding craters would permit determination of compositions of impacting bodies, ages of impacts, compositions of the average preimpact crust at the impact sites, and the nature of the rock types at the sites before the impacts. As yet another example, sampling of rocks exposed in the central peaks and walls of large craters will yield information on the variation of rock type with depth in the crust. Specific sites at which sampling would address these and other questions are listed by Ryder et al. (*Eos* **70**, 1495-1509, 1989).

Numerous engineering questions relating to landing site selection require study. Are there latitudes and/or longitudes that are precluded by certain mission profiles? For example, would sampling at near-polar latitudes require a two-spacecraft mission with rendezvous in lunar orbit? Could a modern, inexpensive spacecraft be capable of sampling the farside autonomously or would farside sampling require a communications relay satellite? What would be the extra expense of a communications relay satellite? In general, what is the anticipated trade-off between landing-position flexibility and mission cost?

## LANDING PRECISION

Many of the targets for simple sample-return missions would be regional targets, for example, the surface of a given basalt flow or a given melt sheet surrounding a complex crater or basin. Targeting accuracy of about 10 km would be sufficient for such missions. Other types of targets would require a landing ellipse radius of <1 km, for example: the floor of a small polar crater where the surface is permanently shadowed, in an attempt to sample a high concentration of lunar volatiles; or the central peak of a crater such as Copernicus or Tycho, to sample materials from deep in the crust or even from the mantle.

Engineering questions relevant to landing precision that should be investigated are as follows: What sort of landing ellipse can be expected with available technology? How does the cost (either in terms of complexity or dollars) vary with the landing ellipse? A related question is, how smooth must an area be for an unpiloted spacecraft to land successfully? The combination of a rugged spacecraft and a small landing ellipse makes scientifically fascinating missions possible (for example, in and around craters), but at what cost?

## CONCLUSIONS

A simple, relatively inexpensive sample-return mission, or a series of such missions, can add greatly to our knowledge of the Moon's nature and history. Simple missions, if sent to strategically selected locations, can effectively address a variety of specific problems of great planetological importance. Any payload of lunar sample collected at any of the many geologically interesting sites remote from all previous sampling sites would be enormously valuable scientifically. Our recommendations concerning goals of simple sample-return missions are summarized below. Other important problems can be addressed only by more complex and costly missions: combined rover-sample return missions or sample return missions that have the capability to select specific samples.

### RECOMMENDATIONS: SIMPLE SAMPLE-RETURN MISSIONS

- A sample of bulk regolith weighing at least 100 g should be collected on every sample return mission.

- The primary goal of most missions should be to collect at least 50-100, and preferably 500-1000, rocks having minimum weights of 0.5-1.6 g (about 7-10 mm in diameter).

- Sieved or raked regolith is probably the optimal type of sample. If the set of 50-1000 rock samples that we recommend is collected by sieving or raking typical regolith, the mass that must be returned to

Earth is nearly two orders of magnitude smaller than if the sample is bulk regolith and the rock samples are extracted after return to Earth.

- Detailed sample photodocumentation is not necessary for a bulk or sieved/raked regolith sample, but a capability to photograph the immediate landing area would be desirable.

- The scientific potential of a simple sample-return mission depends critically on the range of accessible sites. An ability to sample polar regions and the farside is highly desirable. A targeting accuracy of about 10 kilometers would be sufficient for many scientifically important tasks, but an accuracy of 1 km or better would make an entire new class of sites accessible.

# 6. GEOPHYSICAL NETWORKS

Geophysical measurements are the best or in some cases the only way to obtain information about the composition and thicknesses of the lunar crust, mantle, and core, and to determine the properties of the atmosphere (Table 2-1). The Apollo program deployed geophysical instruments at each landing site, and the network provided very valuable information. However, the Apollo network was not distributed sufficiently to address many important questions. This section discusses the distribution of geophysical stations; seismic, heat flow, and atmospheric measurements; and methods of deploying such a network. It is adapted from chapter IV of *Geoscience and a Lunar Base* (NASA Conference Publication 3070, G. Jeffrey Taylor and Paul D. Spudis, eds., 1990).

## Distribution and length of operation of stations

The single most important deficiency of the Apollo geophysical network was the small number and poor areal distribution of stations. Future seismic, heat flow, and electromagnetic sounding measurements obtained over a sufficiently long time (decades) at widely separated stations around the Moon will result in much better constraints on the density variation, bulk composition, and thermal structure of the interior. Atmospheric monitors with a similar wide distribution will determine atmospheric dynamics and composition, provided that the measurements are obtained prior to strong contamination of the lunar environment by human activities. External plasma monitors will help determine those properties of the surface and regolith that are dependent on the solar wind ion bombardment.

In principle, detection of a metallic core can be achieved with as few as four seismic stations, two located on opposite sides of the Moon and the others located at intermediate angular distances. Occurrence of a number of large meteoroid impacts or shallow moonquakes near the two antipodal stations would provide the needed seismic energy sources. However, a network of eight stations would improve the quality of the data substantially. Consistent detection of substantial P-wave arrival delays at the opposite station as checked by arrivals at the intermediate stations would prove the existence of a low-velocity core (expected for a core with a dominantly iron composition). Japanese scientists are currently planning such a core detection experiment using seismometers to be deployed by penetrators in the late 1990's.

In order to establish with greater precision the seismic velocity structure of the crust and mantle, as needed to constrain the bulk composition, the depth of initial melting, and crustal composition and thickness, a series of regional passive seismic networks are needed. Detailed near-surface crustal structure could be investigated using Apollo-type active seismic sources near single stations. A series of regional networks ultimately would establish the seismic velocity structure of the mantle. These networks would simultaneously establish the nature of lateral variations in crustal thickness and upper mantle velocity structure, as well as provide an alternate determination of the existence, size, and probable mass of the core.

The requirements of wide distribution and long operating periods for seismometers are shared by other geophysical instruments including heat flow probes, magnetometers, atmospheric and plasma monitors. Co-location of these instruments in geophysical stations analogous to the Apollo lunar surface experiments package (ALSEP) therefore is preferred. Specific recommendations for individual instruments are given below.

### *Seismometry*

We recommend that three-component seismometers with a better sensitivity than that of the Apollo seismometers be deployed in a series of regional networks. Specifically, ground motion sensitivity should be less than 0.3nm (preferably, 0.03nm) and the frequency bandwidth should extend at least between 30 Hz and 0.03 Hz. In order to minimize thermal effects, it is desirable that the instruments be emplaced at least 1 meter beneath the surface. Emplacement in deeper bore holes could also reduce the near-surface scattering of seismic waves that was an impediment to the interpretation of Apollo seismograms. The capability to measure long-period free oscillations of the Moon is a desirable attribute of future lunar seismic instruments. The functioning operating period of a global seismic network should be at least ten years.

Each regional seismic array must consist of at least four seismometers in order to determine the four unknown variables of a typical event, i.e., epicenter and focus locations, intensity, and time. Because deep moonquakes originate at depths as large as 1000 km, the surface separation of stations in the regional array should be comparable in length. For example, three stations could be located at the corners of an equilateral triangle with 1000km sides and the fourth could be located at the center of the triangle. Of course, the addition of stations to the array would provide redundancy in case of hardware failures and would increase the accuracy of inversions. To obtain an adequate global data set, a minimum of four regional arrays whose centers are located equidistant from one another is suggested. Such a configuration would allow S-waves from any one deep moonquake source to be detected by at least two arrays. A lesser number of arrays would result in S-waves being absorbed by the zone of low seismic Q-values (high attenuation) deep in lunar interior before reaching all but one of the regional arrays.

In addition to regional arrays, local arrays with smaller separation distances should be established to study shallower structure including variations in crustal thickness and the subsurface structure of basins. Active seismic sources (such as impacts of expended rocket boosters and explosive charges used during the Apollo missions) may provide the most efficient means of determining near-surface crustal structure near single stations.

### *Heat flow*

Heat flow measurement at the Apollo 15 and 17 mare sites may not be representative of the Moon as a whole. Consequently, future measurements must be obtained from sites with a greater variety of geologic settings. In particular, measurements at highland sites on both the near and far sides and at sites near the centers of circular maria would be most useful in establishing the true global average heat flow. To obtain an accuracy comparable to Apollo measurements, detailed analysis over a period of years of subsurface temperature measurements at each heat flow measurement site is required. Ground truth heat flow values at the selected sites would complement orbital measurements of lateral heat flow variations by microwave radiometry that might be acquired by an orbiting instrument.

From Apollo experience, it is known that a successful lunar heat flow probe must measure the ambient regolith temperature at depths between approximately 0.5 and 1.5m to an accuracy of about 0.05ßK in a temperature range between 200ß and 270ß K. The thermal diffusivity of the regolith can be determined from long-term measurements of the daily and yearly variations in temperature at these depths. This quantity together with the measured overall gradient (and the specific heat of the soil already derived from Apollo laboratory measurements) determines the heat flow. Orbital measurements of microwave radiance may provide a means of determining lateral variations in heat flow as a function of position on the Moon. It is possible that such measurements at a few carefully chosen surface sites could result in a very precise estimate of the global heat flow.

### *Magnetometry*

For accurate magnetic measurements at the surface, an oriented three-axis magnetometer with power supply and communication capability must be deployed. We recommend that magnetometers be emplaced at a minimum of 4 sites at a range of latitudes in conjunction with the deployment of other geological instruments. For the purpose of investigating crustal magnetization, some of these sites should be chosen to coincide with surface locations of large magnetic anomalies seen from orbit. To apply the surface measurements to deep magnetic sounding, an additional magnetometer in lunar orbit is required. The orbital instrument would measure the incident solar wind magnetic field.

For deep sounding studies (e.g., core detection), a major problem encountered by the Apollo magnetometers was gain degradation and calibration differences between magnetometers. For these studies, therefore, calibration and accuracy requirements are greater than for the Apollo instruments. Periodic calibration checks during the operation of these instruments will also be required.

For the purpose of investigating regional electrical conductivity anomalies, analogous to those found at the Apollo 15 and Lunakhod 2 sites, portable magnetometers carried from site to site on piloted or automated rovers may be employed. However, the use of surface magnetometers to detect regional conductivity anomalies should be studied further using low-altitude orbital data prior to undertaking large-scale surface effort. As always, magnetic measurements must be obtained at some distance from metallic vehicles or equipment that generate significant magnetic fields. Such measurements are planned by the Lunar Prospector mission.

### *Atmospheric Monitoring*

To understand the dynamics of the lunar atmosphere and to determine its composition unambiguously, an array of sensors must be placed at different latitudes. At a minimum, three stations could be deployed, one at the equator, one at a mid-latitude, and one at a pole. Installation of two additional stations toward the other pole would test for symmetry of global atmospheric patterns. Each station should have instruments similar to LACE and SIDE (Apollo instruments), and one station, perhaps located at the lunar base, should have a full complement of atmospheric and plasma instruments comparable to or better than the Apollo instruments.

The minimum experiment package for a singe station would include a neutral mass spectrometer and an ion mass spectrometer. Detection capabilities should be similar to or better than those of Apollo instruments, and they should be able to operate during daytime on the Moon. In addition to global-scale studies, specific investigations of probable sources of outgassing are of special interest. For this reason, some sites should be chosen near shallow moonquake epicenters and near surface features where transient phenomena have been reported (e.g., Aristarchus).

Finally, it should be emphasized that the mass of the natural atmosphere of the Moon is only a few tons. An Apollo-type piloted landing adds a comparable mass of exhaust products to the atmosphere that takes several months to dissipate. Hence, the natural lunar atmosphere must be studied prior to the time when piloted landings take place regularly.

*External Plasma Monitoring*

Solar wind spectrometers should be deployed at a range of latitudes in order to study the overall interaction of the Moon with the solar wind. In addition, it is desirable to locate some of these spectrometers at sites of strong local magnetic fields in order to evaluate the ability of strong anomalies to deflect the ion bombardment. Such an evaluation is needed to establish the surface and regolith properties that are dependent on solar wind ion implantation.

## Deployment Options

Engineering, efficiency, and cost considerations are of primary importance in selecting the appropriate means for deployment of geophysical instruments on the lunar surface. This deployment can be accomplished in principle via (I) surface penetrators; (ii) soft landers; (iii) automated rovers released on the surface from a lunar base or landing vehicle; and/or (iv) direct human emplacement (Table 6-1).

For several reasons, it is questionable whether penetrators provide an adequate deployment option. A simple penetrator with no attitude control or thrusting capability would impact the surface at near-orbital velocity (about 1.7 km/s). It is uncertain whether sensitive geophysical instruments can be designed to withstand such an impact. In addition, a simple penetrator may not be able to carry a long-term power source such as an RTG or solar cells; if not, then the lifetime of the station would probably be limited by the battery supply to a period of the order of weeks, drastically less than the needed period of years. Although penetrators would automatically deploy seismometers and heat flow probes at the depth of burial, other instruments such as atmospheric monitors and magnetometers, as well as communications devices, must be deployed at the surface, probably on a penetrator afterbody that separates on impact. It is uncertain whether surface deployment of sensitive instruments by penetrator is feasible.

Soft landers represent a more realistic (but more expensive) option. In addition to attitude control, communication, and thrusting capability, these landers would need to be able to effectively deploy the instrument and power supply. In many cases, accurate orientation and balancing of instruments such as magnetometers and three-axis seismometers is necessary. In order to deploy seismometers and heat flow probes beneath the surface, a drilling capability is also required. In the case of the Apollo seismometers, a significant source of noise was vibration caused by thermal expansion and escape of fluids from nearby landing vehicles and equipment. Consequently, it is desirable for the landing vehicle to leave the area after deployment; this implies either lateral mobility or an ability to thrust away from the immediate vicinity. If the lander returns to orbit, then it could be refitted with new instruments and reused. Otherwise, the lander could be designed to impact not far from the deployed station thereby providing a useful seismic data point (one whose event time, energy, and location are known). These various requirements mean that the soft lander would be a fairly sophisticated spacecraft, implying a higher cost than for a simple penetrator. Thus a considerable development and testing effort may be needed. However, the quality and time span of the resulting geophysical measurements is likely to be much greater than would be acquired by penetrator-deployed instruments.

If the deployment of sensitive geophysical instruments via soft landers does not occur prior to resumption of piloted landings, then the network may be established by automated rover or piloted expeditions from established bases or outposts. Because automated rover expeditions and piloted sorties will probably be required for other purposes such as geological exploration, these same expeditions could be designed to deploy geophysical instruments. In the case of deployment by astronauts, the method of emplacement could be similar to that for the Apollo instruments.

Because initial activities presumably will be confined to the near vicinity of a base, the first network to be established will probably be regional, covering a surface area of hundreds of kilometers around the base. However, as exploration continues, short-hop piloted landings at other sites around the moon will occur, providing the opportunity for deployment of an increasing number of high-quality geophysical instruments.

We recommend that all four major deployment options (penetrators, soft landers, automated rovers, and by humans) be studied further to determine the most effective role(s) of each in allowing improved global-scale and regional geophysical measurements. Each method of deployment has its own set of problems to be resolved.

Table 6-1. Methods for deploying geophysical instruments.

| **Deployment Method** | **Advantages** | **Disadvantages** |
|---|---|---|
| Penetrators | Inexpensive<br>Global access<br>Good coupling of seismometer to surface | Lifetime short?<br>Survivability<br>Instrument alignment difficult |
| Soft Landers | Surface emplacement feasible<br>Long-lived power sources | Several costly spacecraft needed<br>Coring required<br>Alignment possible? |
| Rovers | Surface emplacement feasible<br>Moderate expense<br>Long-lived power sources | Long-traverse range needed<br>Coring required<br>Global access |
| Humans | Ease of emplacement<br>Ease of alignment<br>Possible repair of instruments<br>Long-lived power sources | Expensive<br>Life-support needed<br>Protection from radiation<br>Global access? |

# 7. *IN SITU* RESOURCE UTILIZATION

Ambitious, piloted space exploration will require use of materials obtained on other planetary surfaces. The Moon is not only a destination of future exploration. It is also the natural focus for development of industry and commerce that may return new economic benefits to the people of Earth. It is a readily accessible testbed for resource extraction experiments. This section summarizes the motivation, technology needs, experiments needed, and benefits to the nation's technological and educational base of missions to the Moon for the purpose of extracting and using lunar resources. There are overlapping goals of resource missions and science missions using telepresence rovers. The emphasis in this section is on applied science, technology, and engineering, although the relationship between basic and applied science is also addressed.

## RATIONALE

The motivation for developing the technology needed to use materials on other planets comes from several directions. These include technological development, potential economic and environmental benefits, fundamental scientific research, educational inspiration, the potential for international cooperation, and as a precursor to human expansion beyond low Earth orbit.

### Technology

Use of the Moon's resources will allow development of important mining, extraction, and analytical technologies for use at future lunar colonies, in developing space industries, and on missions to other planets. The Moon can serve as a long-term operational testbed, with progressively more complicated and technologically advanced missions adding equipment and capabilities. Many of these technologies will be useful in other applications on Earth. Examples include automation and robotics, environmental monitoring, pollution control, recycling, chemical processing, dust management, remote power generation and solar cell development, and key elements of the information highway.

### Potential future economic and environmental benefits

The technologies developed for extraction of lunar and other space resources will provide economic benefits to the nations that develop them. Some technologies have clear dual uses, as outlined above. Based on previous experience, other technologies will provide direct economic benefits that cannot be predicted in advance. Furthermore, the Moon may be an essential future source of non-fossil energy, such as solar power or $^3$He for use in nuclear fusion reactors. Finally, pursuing an active program in lunar resource utilization will benefit our space infrastructure in general. It will lead to improvements in communications and reductions in transportation costs by providing an extraterrestrial source of hydrogen and oxygen for fuel. Looking further into the future, aggressive use of the Moon will lead to creation of a space tourism industry and unique forms of entertainment and education, such as trips to the Moon through virtual reality or telepresence.

### Scientific research

In spite of 25 years of work on lunar samples, not all is known about the Moon. Part of the problem lies in our limited sampling (only six Apollo sites and three Russian Luna sites). A significant part of the problem stems from the fact that some measurements can be made only *in situ*. For example, experiments on returned Apollo samples showed that volatile elements can be lost by handling the lunar regolith; thus, all samples have been compromised by their acquisition, flight to Earth, and laboratory processing. Furthermore, the unique lunar environment allows for innovative scientific experiments, such as high-vacuum and low gravity materials science.

### Educational benefits

Development of lunar resources requires research and design in geology, chemistry, physics, mathematics, materials science, and mechanical, chemical, civil, electrical, and aerospace engineering. There is, therefore, a natural, powerful, and motivational link to education at all levels. Any resource utilization mission can engage the minds and imaginations of students at all levels, from simple experiments in lower elementary school to complex design projects in graduate school. Future ready access to information will allow observation of experiments and monitoring of results by anyone or any class interested in the subject. Frequent flights could provide opportunities for student experiments.

### Precursor missions to aid in human expansion beyond low Earth orbit

Long-term habitation of other planets by earthlings will require the ability to use extraterrestrial resources—to live off the land. Because the technology to do this does not exist at present, it must be developed before humans begin to colonize other worlds. A program of robotic missions would demonstrate the feasibility of resource utilization and lead to practical, reliable techniques and equipment to do it.

### Potential for international cooperation

There appears to be widespread interest in the use of extraterrestrial resources by most space-faring nations. One way to mitigate the sometimes intense international economic and political competition would be to explore other planets together. A series of robotic missions to the Moon to conduct experiments in resource mining and extraction presents a long-term, exciting way to cooperate in space both publicly and commercially.

## GOALS OF LUNAR MISSIONS FOR RESOURCE UTILIZATION

The goals of missions designed to extract resources from the lunar surface fall into three main categories: to do measurements that contribute to our understanding of fundamental lunar science, to make a thorough exploration of specific potential lunar resources, and to conduct engineering and technology tests.

### Fundamental lunar science

Many fundamental problems in lunar science have direct bearing on the abundances of potential resources and on the techniques devised to extract them. Solar-wind derived volatiles, such as hydrogen and helium, will be important extraterrestrial resources. Many uncertainties remain about them. One is the effect of mechanical manipulation on gas retention. How much hydrogen, for example, comes off by handling the lunar regolith? Does it escape in the form of elemental hydrogen, or as a hydrogen compound such as $H_2S$? Similarly, at what temperatures do volatile gases escape when pristine lunar regolith is heated? Are our observations on returned Apollo samples valid? For example, do solar wind gas contents increase with soil maturity, as measured by the amount of submicroscopic iron metal present in the regolith? How do volatile contents vary with depth in the regolith? Is there a horizon where volatiles concentrate because they are driven down by high surface temperatures during the lunar day? What happens to lunar regolith from depth when it is exposed to the ambient temperature at the surface? Could substantial amounts of gas be extracted by mechanical manipulation or exposure to the surface temperatures, obviating the need for additional heating? All these questions can be addressed by controlled experiments with pristine lunar surface materials, with analysis by appropriate analytical devices (see below).

Fundamental science problems other than those directly related to resource extraction can also be attacked during a resource-driven mission. Obtaining ground truth on the chemical and mineralogical compostion of new areas on the Moon is valuable, and helps in the interpretation of remotely sensed data. Furthermore, visual observations of rocks and their constituents provides information about a variety of lunar processes and lunar evolution. Even if a mission returned to an Apollo site, new and important observations can be made. For example, not all planned sites were visited during the Apollo missions, such as the “north complex” at the Apollo 15 site or the Sculptured Hills at the Apollo 17 site.

Other types of scientific research could also make use of the lunar environment, especially engineering science. For example, merely by operating a device that produces and handles gases will provide new insight into fluid dynamic processes because of the lower gravity on the Moon than on Earth. The extremely dry nature of the Moon may also allow production of completely anhydrous materials, which may have useful properties such as high strength.

### Site-specific lunar science: pyroclastic deposits

There are many interesting sites where resource extraction experiments could be done. This section describes one of the most intriguing places, a large deposit of explosively erupted volcanic material called a pyroclastic deposit (literally, “pieces of fire”). We know from remote sensing of the Moon that vast regions are covered by pyroclastic deposits, and we sampled one at the Apollo 17 landing site. Other samples were collected on other missions, too, but none is large or in place. Thus, a landing on a pyroclastic deposit would contribute mightily to our knowledge of how lunar volcanism operates.

The resource potential of pyroclastic deposits is considerable. They are enriched in endogenous volatile elements such as zinc, chlorine, and flourine. The high-titanium varieties may be enriched in solar wind gases, too, but we have no direct data on this issue. Some of the measurements needed are the following:

**Depth and thickness:** Photogeologic observations give a good idea about the depth of pyroclastic deposits, but do not provide details about how depth varies spatially. This information can be obtained by sounding the subsurface, either by electromagnetic sounding or active seismic experiments. Such measurements also provide important information about the layering in the deposit and the structure of the subsurface beneath it.

**Mechanical and geotechnical properties:** Apollo results provide sound information about the geotechnical properties of the lunar regolith, but we have no information about the properties of pyroclastic deposits. Such tests require digging and penetrating the surface, and driving a rover over it.

**Physical properties:** To assess resources and the dynamic evolution of a pyroclastic deposit, we must obtain data on the grain size and soil maturity (solar gas contents, amount of submicroscopic iron). In addition, information is needed about the thermal and optical properties to relate to remote sensing measurements and to help design engineering equipment.

**Variations in the concentration of volcanic volatiles with depth, or laterally:** It is possible that in hot pyroclastic deposits, the volatiles move from hotter to cooler regions, thus concentrating. This needs to be measured by coring or trenching the deposit, and by measuring concentrations during traverses by roving vehicles.

**Volcanic vents:** We have little knowledge about the nature of the areas from which pyroclastic deposits erupted. If accessible, these could be studied for comparison to those on Earth, and to determine if there are exceptional concentrations of volatile elements.

**Volcanic history of the deposit:** The overall history of the deposit can be deduced from all of the above information, coupled with regional data obtained by orbital and Earth-based remote sensing.

### Engineering and technology tests

The essence of a resource-development mission is testing hardware and approaches to resources utilization. Such missions will be designed around such tests. Examples of the types of tests are the following:

**Validation of lunar simulant and lunar sample results:** Resource extraction techniques have been developed first using simulated lunar materials and then tested on small amounts of lunar samples. It is essential to validate those results by using pristine lunar rocks and regolith under lunar conditions of high vacuum and no surface modification by reactions in the terrestrial environment. Even small amounts of reaction products, such as oxidized iron, might alter results. Once verified, scientists and engineers will know what types of terrestrial experiments provide the most useful data.

**Validate technology in realistic setting:** No matter how carefully we control an experiment in a laboratory, it is impossible to simulate everything. Thus, after extensive tests on Earth, extraction processes must be tested on the Moon, using unmodified lunar materials. Key features of the lunar environment are its high vacuum, large temperature variations, high flux of many types of radiation, and lower gravity compared to Earth.

**Study usefulness of lunar material and environment:** Besides using the lunar regolith as feedstock for extraction experiments, tests could be made on its utility as a thermal blanket (the regolith is an excellent insulator) or even a catalyst. Experiments could also be conducted on power production on the Moon, possibly using solar cells derived from the regolith, making use of the intense sunlight during the lunar day.

**Test techniques for beneficiation in realistic setting:** Industrial processes can be made more efficient if feedstocks are optimized by removing unwanted or harmful materials. Some techniques for separating phases in the lunar regolith have been devised and some have been tested in the lab, but how efficient they are will not be known until they are tested on the Moon. All processes may be affected by the high vacuum, electrostatic properties of the regolith, and modest gravity.

**Demonstrate ability to automate processes in remote, hostile environments:** The lunar surface and its unusual materials provide a rigorous test of remotely-controlled processing equipment. Such apparatus must be robust and autonomous. The value of a lunar test is that the equipment can be monitored in nearly real time (the round trip light travel time is 2.6 seconds), so faults in an autonomous system can be detected and damage averted. In addition, it is important to show that environmental, feedstock, and product monitoring devices operate autonomously and reliably in the remote lunar environment.

**Test materials processing:** Besides beneficiation, all materials handling techniques need to be tested in a realistic lunar environment. Use of a conveyor belt or drag line has never been demonstrated on the Moon. The same applies to chemical processing, from simple heating and gas extraction to reaction in vessels at high temperatures.

## TECHNOLOGY REQUIRED

There are magnificent opportunities for technological development associated with an ISRU mission to the Moon. The needed technologies fall into two main categories: measuring instruments and systems, engineering technologies (including resource experiments).

### Scientific and monitoring instruments

Several scientific instruments are needed to make *in situ* measurements of the lunar surface. These include the following, which would also be carried on a rover mission that focused entirely on scientific objectives (see section on telepresence rovers).

**Gas analyzer:** This is needed to measure the amounts of solar-wind implanted gases in the lunar regolith.

**Chemical analyzer:** Several types of analyses are needed to characterized the nature of the lunar surface. The abundances of major and minor elements need to be measured at roughly 5-10% relative accuracy. An example of an appropriate technique is x-ray fluorescence.

**Mineralogical analyzer:** The most important mineralogical characteristic to determine for resource utilization is the abundance of submicroscopic metallic iron, a measure of how long a regolith sample has been exposed at the very top of the lunar surface. It is also useful to determine the abundances of major minerals, such as pyroxene, olivine, and ilmenite. A suitable technique for such measurements is Mossbauer spectroscopy.

**Subsurface sounder:** The nature of the subsurface must be known to plan mining or drilling operations, and to understand the fundamentals of regolith formation. This requires either electromagnetic sounding (ground penetrating radar) or active seismic exploration with geophone lines.

**Imaging system:** It is essential to be able to view the lunar surface being tested and the equipment in operation during a resource mission. Thus, a high-quality stereo imaging system is needed. This allows an assessment of boulder abundance, lithologies present, and the condition of the spent feedstock. Imaging systems are most useful when equipped with filters to allow multispectral imaging.

### Engineering technology

**Development of materials that are durable and long-lasting in the lunar environment:** It is essential to validate that materials developed for spacecraft and other hardware last a long time. Key components include coatings, computer chips, solar cells, optical surfaces, and batteries.

**Resource extraction experiments:** Testing extraction and storage techniques is clearly a prime goal of any resource-driven mission. High priorities are an oxygen/water extractor and a volatile gas extractor. Both require considerable engineering and development of efficient, long-lasting furnaces.

**Use of Apollo and Surveyor spacecrafts as long-duration exposure facilities:** Landing a resource package at one of the old Apollo or Surveyor sites would allow for examination of the effects that decades of exposure have had on spacecraft materials. Measurements would be largely done with the imaging system.

## BENEFITS FROM RESOURCE MISSIONS: DUAL USE TECHNOLOGIES

One of the most useful aspects of space exploration is that it pushes technological developments to the limits of our abilities. This frequently leads to development of new techniques and materials for use on Earth. Some examples of possible advances in some key areas are sumarized here.

### Robotics, automation, and communications

The Moon is a remote and hostile environment, so remote operation of equipment there will help develop more robust remotely-operated gear for use on Earth. This includes ways to mix autonomy with teleoperation, efficient data distribution, and distributed control using systems such as internet.

### Environmental monitoring

Many industrial areas need to monitored continuously to detect leakage of hazardous substances into the environment. Similar devices need to be used to monitor lunar resource utilization experiments. These must be state-of-the-art, autonomous, rugged, and light-weight. They would be used on the Moon for gas analysis, solids analysis, and spectral analysis. Once devloped, the market on Earth could be very large: underwater studies, work in hazardous environments such as nuclear and chemical waste sites, biomedical monitors (disease, nerve gas detection), superfund site monitoring, and terrorist weapon detection (at airports, for example).

### Pollution control and recycling

There will be special needs to minimize emissions on the Moon because all volatile substances are rare, hence precious. This will be accomplished by new designs and materials for seals, recycling systems, and internal traps for volatiles. Once new techniques are developed, they could be used on Earth to meet new environmental regulations, develop better monitoring and feedback control systems, advanced scrubber systems in stacks, and trapping of fugative emissions from refilling operations, locks, material transport systems, and gasoline fueling of cars.

### Chemical processing

Extraction of lunar resources will drive the development of innovative techniques for chemical processing. Examples include better vapor phases processing; development of long-lasting high-temperature materials; new methods to process chlorine and other highly reactive substances; significant advances in fluidized bed technology; pneumatic transport of solids at low pressures; new ways to heat gases (e.g., honeycomb ceramics); and heat treatments for thermal cycling, known as pinch technology.

### Dust management

The lunar surface contains a high abundance of dust. Twenty percent of the typical regolith consists of particles smaller than 20 micrometers across. Thus, control of this dust will be a high priority. The techniques and technologies developed for the Moon will be helpful in controling particulates in dusty environments on Earth, too, such as in coal mines, electronic chip factories, management of tailings from uranium and other mines, asbestos removal, virtually all superfund sites, nonmetallic mines such as gravel and perlite, and in agriculture. Solving the dust problems will require advances in seals, anti-dust coatings, development of electrostatic controls, use of fluid based systems with filters, and positive-pressure air bearings.

### Mineral exploration and mining

Assessing lunar resource potential will require remote sensing techniques that may lead to improvements in remote *in situ* analysis, multispectral mineral mapping, gas sniffers, environmental monitoring, and the use of lasers for remote chemical analysis. The mining industry will benefit from dust control (as mentioned above), automation, the use of radar to assess the characteristics of deposits before mining.

### Power production and transmission

Any lunar mining operation will need durable and efficient power sources, which will have value on Earth for power generation in remote areas, such as using solar thermal generators, and for long-distance transmission. Lunar mining and exploration activities will likely lead to development of improved solar cells with long lifetimes, and durability against dust and thermal cycling. In the long run, it may be possible that considerable amounts of power will be produced on the Moon and transmitted back to Earth by microwaves or lasers, or that 3He will be brought to Earth for use in nuclear fusion power plants.

## MISSION SCENARIOS

We present here an outline for an inexpensive robotic mission to test technologies developed to extract resources from the Moon. Such missions are necessary precursors to more ambitious missions that extract industrial levels of resources for use of people on the Moon and to export elsewhere in the Solar System. The mission probably can be done within the guidelines for the Discovery Program, but we have not made a thorough analysis to demostrate this.

Payload for minimum mission.

| **Payload item** | **Comments** | **Mass(kg)** |
|---|---|---|
| Imaging system | Stereo, full band width for real-time viewing | 5 |
| Instrument for *in situ* chemical analysis | Mossbauer/x-ray fluorescence combination | 5 |
| Instrument for *in situ* gas analysis | Could use laser heating | 5 |
| Sampling device | Mechanical scoop capable of transferring to integrated package, possible via a mechanical manipulator arm to test for gas evolution during handling | 10 |
| Integrated resource utilization package | Combines furnace, evolved gas analyzer, and hydrogen reduction water factory | 15 |
| Total mass | | 45 |

Enhancements to minimum mission.

| **Payload item** | **Comments** | **Mass (kg)** |
|---|---|---|
| Rover | To deploy geophysical equipment, make geological studies | 50 |
| Water electrolysis and oxygen capture | To further test aspects of oxygen production from lunar materials | 10 |
| Hydrogen recycling system | Test ability to recycle reduction gases and monitor gas loss | 5 |
| Subsurface sounding experiment | Explore nature of upper layers of the Moon | 10 |
| Solar thermal test system | Test power output and longevity of system | 20 |

# 8. THE MOON AS A TESTBED FOR TECHNOLOGY DEVELOPMENT

## INTRODUCTION

There is an acute need for a strong technology development program leading to less expensive yet better spacecraft and instruments. Suggestions during the past three years for a technology development program have gone by several names, such as Tech-Sats, Asteroid-Comet-Moon Explorer (ACME), Tech-Scouts, and New Milenium Spacecraft. For convenience, we will call experimental spacecraft “Tech-Sats.” A program like this could have commercial spin-offs and would enable new science throughout the Solar System by development of smaller, more capable instruments and spacecraft components. Furthermore, rapid mission development and frequent launches make it possible for graduate students and entry-level professionals to design, build, and fly hardware with far greater frequency than possible at present. In the past, there has been a problem with efficiently and rapidly integrating new technologies into planetary spacecraft. Technology developers bring new technology up to a certain level, but not one sufficient to confidently use it when planning missions. The desire to reduce risk of science-driven missions makes mission planners reluctant to use unproven technologies. At the same time, constrained funding on missions prevents testing and space qualification of new technologies. The way out of this dilemma is to fly experimental missions to test new technologies.

LExSWG has championed the idea of using the Moon as the testbed for such technology-driven missions. We have concluded that a Tech-Sat program, even though driven by technology development, would provide excellent opportunities for sound lunar science. The Clementine mission is a good example of how science benefits from a mission designed to test spacecraft hardware and sensors.

Clementine has contributed to several of the LExSWG goals for orbital missions (see section 3) at low to moderate levels, at times providing valuable cross linking data (e.g. altimetry; multispectral data base) that improve the science return from future missions. The Clementine mission, of course, was not designed nor claimed to be a comprehensive study of the Moon. It does not address priorities 1, 4, 6, and 7 (section 3) at all. Nevertheless, it did contribute in other areas and coupled with available Apollo data (from both rocks and remote sensing) and Earth-based remote sensing, its vast data set will produce valuable insights into the nature and evolution of the Moon. It was especially strong in determining global mineralogy (objective 3), though because it has only 12 wavelength bands it may not make as quantitative an assessment of mineral abundances as would a full-fledged mapping spectrometer. However, an extremely useful global data set in which regional and local lithologic differences can be seen is now available to the scientific community, and we now have the first global image data set. The mission also produced a good global topographic data set. Finally, Clementine improved gravity data for the nearside and produced some valuable imaging at high spatial resolution. The mission has made a solid contribution to our understanding of the distribution of rock types across the lunar surface and (by examining ejecta from basins and large craters) at depth in the crust.

These accomplishments are all bonuses from a mission designed to test new space technologies. Besides exciting lunar science as a by-product, there are several reasons why the Moon makes an excellent testbed for both orbital and landed missions, and these are discussed in this section. In contrast to the rest of this report, emphasis is given to orbital missions rather than landers. However, virturally all the arguments apply to landed packages, as well as orbital spacecraft. The emphasis on orbital science stems from the fact that our knowledge of other planets and satellites is so primitive that orbital missions are still clearly worthwhile.

## A LUNAR TECH-SAT PROGRAM

### The Moon is close to the Earth

The Moon is located close to Earth, so cruise time is insignificant, hence mission operations are minimized. On the other hand, flight times can also be longer if desired. It is easy to track spacecraft in lunar orbit, and data can be transmitted back with a relatively small antenna compared to other planetary missions. Finally, there are frequently launch windows, hence many mission opportunities.

### The Moon is an exceptional calibrated standard

Although there is no global coverage for any type of data except those obtained by Clementine, the Moon is nevertheless well calibrated (Table 8-1). The Apollo missions and subsequent data analysis provided detailed chemical and mineralogical analyses of samples from several locations, as well as detailed measurements of surface properties. There is a good data base of Earth-based observations of the nearside, including images, spot spectra, multispectral images, and radar data. Apollo orbital measurements provide chemical data, magnetrometry, and high resolution photography (though not digital). The Lunar Orbiter missions provided almost global coverage of the Moon, though not all at suitable sun angles or spatial resolution, and none is digital. The Clementine mission provided a global multispectral data base at better than 500 meter spatial resolution.

### Advances in lunar science

Significant lunar science can be done, in spite of Tech-Sat missions being driven by technology development, as Clementine proved. Each mission would provide data for areas not presently covered, while at the same time using the present coverage as calibrations. Even where measurements are repeated, there would likely be improvements in spatial resolution, analytical detection limits, and precision.

### New instrument technologies

Advances in instrumentation can provide better performance, lower power requirements, lower mass and volume requirements. *It is absolutely essential that new technological initiatives emphasize instrument development, not only spacecraft development.* Otherwise, sophisticated, advanced spacecraft will have no scientifically useful instruments to carry, so will do no new planetary exploration. Spacecraft without instruments should not be flown by NASA. Some generic instrument characteristics include low-mass optics, high-temperature detectors, high-denisty packaging, fiber optic technology, large-format IR detectors, x-ray generators, and neutron detectors.

The list of specific potential instruments is too long to list here, but a couple of examples will give the reader a feeling for the possibilities. Both examples are of instruments that make orbital chemical measurements. One is an x-ray imager, which uses solar x-rays to fluoresce elements on a planet's surface. Such an instrument could provide elemental abundances at improved spatial resolution than do present x-ray devices, and might be capable of making useful measurements on a fly-by of Mercury or a near-Earth asteroid. The other example is a secondary ion mass spectrometer, which uses solar wind protons as a sputtering source. The major challenge is the quantitative use of such an instrument to derive chemical compositions (sputtering efficiencies are not fully understood as yet) from known locations on the Moon (the ions are detected from orbit, so their starting points need to be calculated).

### Relationship of new instruments to missions throughout the Solar System

The technologies developed would be ready to use on other planetary missions. Some examples of the types of measurements made by new instruments that could be tested at the lunar testbed and where they could be used are given in Table 8-2.

### New spacecraft technologies

The list of new spacecraft technologies is also nearly endless; a summary is given in Table 8-3. There could be experimental components in all major spacecraft subsystems: Components in the command and data system, such as new high-capacity solid state memory, micropackaging techniques, and ASIC (Application-Specific Integrated Circuits) electronics, and innovative data compression techniques. Devices in the attitude control system, such as ultra-miniaturized gyros and star trackers with highly capable image processing. Energy production and storage devices in the power system, such as advanced types of batteries or solar cells; demands on the power system is also affected by use of low power electronics in the rest of the spacecraft. The propulsion is aided by the presence of miniaturized high performance subsystems and development of reliable autonomous control of the spacecraft. Most important, to rapidly bring new technologies to planetary missions, many new systems need to be tested simultaneously. Thus, the integrated spacecraft with its innovative architecture is itself a new technology that can only be tested properly by flight operation.

### Examples of technology-development missions

LExSWG has discussed several ideas for missions. Two examples give the flavor of the enterprise. In one, a new, small spacecraft containing many new components carries a UV spectrometer. The spacecraft could fly by the Moon and provide enough data to substantially characterize the lunar atmosphere and search for water at the poles. In this case the technology tests would concentrate on the spacecraft. In the other example, a Tech-Sat carries a prototype camera system, which may involve an integrated imager and mapping spectrometer, using common optics. The camera makes measurements during a two-month mission in lunar orbit, allowing a rigorous test of the system and possibly providing improved spectral coverage of the Moon. In this case, the technology tests involve both the spacecraft and the instrument.

### Beyond orbiters: Landed Tech-Sats

Landers (rovers and network stations) are the next level of mission element beyond orbiter missions for the Moon. It is clear from the LExSWG landed science strategy reported here that future landed science on the Moon and elsewhere would benefit greatly from a technology development program. There is a need to develop inexpensive ways of landing packages on the Moon, and to develop rovers and the analytical instruments they must carry. In the case of landers there are opportunities for collaborations with other agencies of the federal government, such as the Air Force. There are also synergism with other programs such as Mars Pathfinder. Furthermore, an aggressive program to develop robotic rovers could lead to rapid transfer of technology to the private sector, as outlined in section 4.

Table 8-1 Available data about the Moon.

| Measurement | Present Data | Clementine |
|---|---|---|
| **Surface elemental composition** | | |
| Geographic coverage | 22% | |
| Ground resolution | 100 km | |
| Measurement accuracy | ± 20% | |
| Elements | Fe, Ti, Mg, Al, Si, K, U, Th | |
| **Topography** | | |
| Geographic coverage | 10% | ≈ 60% |
| Ground resolution | ≥ 1 km | 100 m (2 km spacing) |
| Measurement accuracy | ≥ 100 m | ≤ 50 m |
| **Gravity field** | | |
| Geographic coverage | 45% | |
| Ground resolution | ≥ 100 km (80% >200 km) | |
| Measurement accuracy | ± 2 mgal | |
| **Surface mineralogy** | | |
| Geographic coverage | Selected spots (several 100) | 100% |
| Ground resolution | 5-10 Km | 125-500 m |
| Spectral coverage | 0.7-2.5 _m | 0.3-5µm (11 bands) |
| Spectral accuracy | ± 0.5% | 5% |
| **Surface Imaging** | No digital data | |
| Geographic coverage | Apollo: 8%<br>Lunar Orbiter (LO): 99%<br>Telescopic: 55% | Global digital data |
| Ground resolution | Apollo 2-10 m<br>LO: 100-300 m<br>Telescopic: 0.5-3 km | 400 m |
| **Magnetic field** | | |
| Geographic coverage | < 20% | |
| Ground resolution | 100 km | |
| Measurement accuracy | ± 0.1 nT | |
| **Atmosphere/Ionosphere** | | |
| Geographic coverage | < 20% | |
| Sensitivity | $10^{11}$ particles/cm$^2$ | |
| **Thermal properties/heat flow** | | |
| Geographic coverage | two landing sites | |
| Measurement accuracy | ± 20% (~ 0.5 µW cm$^2$) | |

Table 8-2 Relationship of instrument development to missions to other bodies

| | |
|---|---|
| **Surface chemical composition** | Asteroids, Mars, Mercury, comets, outer planet satellites |
| **Imaging** | All bodies |
| **Remote mineralogical mappers** | Virtually everywhere |
| **Magnetometry** | All bodies |
| **Atmospheric composition** | Mercury, asteroids, comets, triton, Pluton-Charon |

Table 8-3 Examples of new spacecraft technologies.

| Spacecraft System | New Technology |
|---|---|
| Command and Data System | High-capacity solid state memory<br>Micropackaging techniques<br>ASIC electronics<br>Innovative data compression |
| Attitude Control System | Ultra-miniaturized gyros<br>Star trackers with very capable image processing |
| Power system | Advanced batteries or solar cells |
| Propulsion | Reliable autonomous control<br>Miniaturization in rest of s/c |
| Integrated Spacecraft | New architecture |