DEVELOPING A SITE SELECTION STRATEGY

for a

LUNAR OUTPOST

SCIENCE CRITERIA FOR SITE SELECTION

CONCLUSIONS OF A WORKSHOP

2-3 APRIL, 1990

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LUNAR AND MARS EXPLORATION PROGRAM OFFICE

Foreword

The following report "**Development of a Site Selection Strategy for a Lunar Outpost - Science Criteria**" is one of two reports that explore the problem of site selection on the Moon from both science and operational perspectives for the Lunar and Mars Exploration Office. The results reported here represent a cooperative effort between the Lunar and Mars Exploration Office and the Office of Space Science and Applications. The science criteria discussed in the report are a distillation of the opinions and perspectives of a part of the scientific community, and the general view of the discipline codes of the Office of Space Science and Applications. Clearly, perspectives and priorities may change with time, and this report is the beginning of a continuing dialogue that will take place as the Space Exploration Initiative Program moves towards establishing an outpost on the Moon.

Michael B. Duke, Lunar and Mars Exploration Program Office

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INTRODUCTION

In 1990, the Lunar and Mars Exploration Office of the Office of Exploration began a series of steps to develop a strategy for selecting a site on the Moon for a lunar outpost. Although the establishment of a outpost is not imminent, the problem is complex because of the impact that the site that is selected will have on systems engineering, process planning, preparation of materials, simulator construction, and training etc. The range of choices should be narrowed significantly before missions to the Moon are flown to provide the global data base that will be essential in site selection. Narrowing requires discussion and debate, consequently, it is not too early to begin to consider what will be important in site selection for the Moon, including consideration of the data that will be necessary to make sound judgements. Selection of a location for a Lunar Outpost should be an orderly process of elimination of choices based on selection criteria that represent science, engineering, resources and mission safety, all developed within the context of the strategic purpose of the outpost. The first step is to consider science criteria.

A successful site selection strategy for the Moon based on science criteria has four attributes. It should be flexible (a flexible strategy requires an extensive data base) and multi-disciplinary, it should be consistent with crew safety and utilization, and it should allow the fullest possible use of human capabilities in lunar exploration.

In cooperation with the discipline divisions of the Office of Space Science and Applications, a workshop to develop multi-disciplinary science criteria was held in Houston at the Johnson Space Center on April 2 and 3, 1990. The workshop was divided into discipline groups and each group formulated criteria particular to their discipline requirements. The discipline groups, group leaders and discipline Code representatives were as follows:

ASTRONOMY	Group leader: F. Vilas, JSC Code SZ representatives: P. Swanson, B. Hines

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SPACE PHYSICS	Group leaders: A. Potter, T. Wilson, JSC Code SS representative: K. Lang
LUNAR GEOLOGY	Group leader: M. Cintala, JSC Code SL representative: T. Morgan
LUNAR GEOPHYSICS	Group leader: R. Phillips, SMU, LEXSWG Chairman
LUNAR RESOURCES	Group leader: D. McKay, JSC

Participants are listed in the appendix.

SUMMARY OF SCIENCE CRITERIA

Site selection criteria were formulated based on the assumption that there would be one outpost on the Moon *on the near-side*, although there is no implication that the conduct of science would be limited to the outpost location. Latitude and longitude requirements (for observatories) and terrain criteria for lunar geosciences and resources are primary drivers. In addition, the physical characteristics of potential outpost locations, topography, for example, were considered and have some importance in site selection. The selection criteria developed for a single outpost location are the following:

1. Locate astronomical instruments within 10 degrees of the lunar equator to maximize access to the celestial sphere and ensure an adequate view of the Magellanic Clouds, and from 5 to 10 degrees of the mean lunar limb to maintain Earth always in the field of view, but low on the horizon. Space physics observations of the Sun require the outpost to be located within 2 degrees of the lunar equator.

2. The outpost should be located at a *carefully chosen* mare-highland contact and on a mare surface for purposes of geological/geophysical exploration. Access to adjacent highlands and to outcrop are requirements.

3. A mature regolith is required for solar wind implanted resources (hydrogen and helium, for example). Oxygen may be extracted from any material, but mare material may offer the most flexibility in resource design because undesirable components may be extracted from a component-rich mare soil whereas desirable components cannot be added to a

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component-poor highland regolith. The question (and criterion) however, remains open until an oxygen extraction process is selected.

4. Some potential space physics experiments require a region low in KREEP to minimize the radiogenic component of the lunar regolith and the indigenous radiation.

5. The outpost site should have a "flat" area for emplacement of instruments, e.g. observatories. A suitably located hill or large crater would offer substantial design advantages for interferometers. In addition, the location selected should allow placement of some instruments at a distance of several kms or more from the outpost so as to minimize interferences in instrument operation.

6. Some instruments (those that observe certain characteristics of the Earth) require being at the subearth point. The requirements for these instruments are not compatible with those requireing, or preferring, limb sites. Instruments that require a far-side equatorial or antipodal subearth point were considered; however, their location is independent of a near-side outpost.

FUNDAMENTAL CRITERIA BY DISCIPLINE

ASTRONOMY:

Criteria were based on the requirements for the following instruments:

- Lunar transit telescope
- Optical interferometer
- 4 meter telescope
- Submillimeter interferometer
- Very low frequency interferometer

The site selection criteria were based on field of view requirements (for the near and far side), topographic requirements for instrument placement, and communications and shielding considerations. For observatories located on the near side, there are two fundamental location criteria:

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1. Observatories should be located within 5 to 10 degrees of the mean lunar limb and within 10 degrees of the equator.

2. Observatories must be located so that observation of the Magellanic Clouds at an elevation of 15 degrees or more above the horizon is possible for a significant fraction of viewing time.

A near limb - equatorial location has the following advantages:

- Earth is always low on the horizon, minimizing light contamination effects (81.4 degrees E and W are longitude limits at which the Earth is always in view)
- Line of sight to Earth maintained for communications
- VLF observation of Earth's auroral radiation is possible
- Solar eclipse observation is possible

In addition, there are site selection criteria for astronomy based on simplifying design through judicious use of topography:

1. Select a flat plain or shallow bowl-shaped crater, thereby allowing maintenance of line-of-sight between array elements, maximizing the fields of view, and utilize a hill or a large crater for placement of beam combiners for interferometers to simplify design.
2. Locate instruments far enough from the outpost to minimize interferences and contamination from the outpost, consequently requiring a larger area than would otherwise be the case.

SPACE PHYSICS:

Criteria for space physics were based on requirements for the following instruments:

- Sun Imager
- Earth Imager
- Earth Sounder
- Solar Constant
- Solar Magnetic Field

Criteria primarily based on field of view requirements are:

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1. Equatorial latitudes, or nearly so, are required for Sun observing instruments - the Solar Constant Observatory, the Sun Imager and the Solar Magnetic Field Observatory. The Sun Imager should be located within ± 2 degrees of the equator.

2. The Earth Imager requires a location at the near side, close to the equator for observations of the Earth.

3. An anti-subearth point (180 longitude, 0 latitude) location is preferred for observation of the magnetotail and magnetopause by the Earth Sounder, but a near side location would be acceptable.

Topographic and regolith chemistry criteria are:

1. Select a flat plain with space to set up the 1.5 km focal length Sun Imager.

2. Place experiments which measure radiation in a region of low background radiation, a region low in KREEP (K, Rare Earth Elements, Phosphorus, U, Th).

LUNAR GEOLOGY:

Criteria for geologic exploration of the Moon are functions of lunar exploration objectives and are not sensitive to longitude and latitude requirements. Because it is unlikely that a single site will satisfy all exploration objectives, exploration of areas distant from the outpost will be required and such regions must be accessible, i.e., that the outpost cannot be isolated by virtue of topography. The fundamental criteria are based on an assessment of lunar exploration objectives and the impetus to maximize the number of objectives attainable at a single site:

1. Locate the outpost at a *carefully chosen* mare/highland contact.

2. The mare-highland contact area selected must have an avenue for access to highlands from maria or vice versa.

This criterion implies that topographic-cartographic data must be available to determine accessibility. Mare is defined as a flooded basin and highland is defined as an extensive region of lunar crust. In addition, the mare area should provide access to:

- Sequences of flows
- Outcrops

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The highlands should allow reasonable access to the following features:

- Plutonic rocks
- Structural features
- Light plains units
- Fractured floor craters

GEOPHYSICS:

Criteria were considered for lunar seismology, paleomagnetism and heat flow:

1. Locate the site near or within a multi-ring basin for subsurface structural studies (possibly also near shallow moonquake centers) or locate the site in a homogeneous crustal region for seismic array studies of crust/mantle structure, or allow access to such a region. The outpost location must allow regional geophysical studies of these two fundamental lunar features - mare and highlands, by humans. The outpost location should not exclude access to one or the other. Similarly, the outpost must allow access to geologically diverse regions, including a multi-ring basin near shallow moonquake epicenters.
2. Locate the outpost near strong magnetic anomalies and/or intact mare basalt flows of diverse ages for paleomagnetic studies. Oriented samples of in-place rocks that cooled as liquids through the Curie point will provide critical data in paleomagnetic studies.

3. Geophysical stations for heat flow should be emplaced away from mare/highland contacts for improved heat flow data.

Geophysical exploration of the deep interior of the Moon requires the emplacement of global geophysical stations. These stations have location criteria that are independent of the outpost location. For example, to look for seismic arrivals relevant to the existence of a central core, a global seismic array should be located to cover the antipodal region of known major deep moonquake epicenters. (The epicenters are 16.6S, 39.8W and 4.6N, 116.5E).

LUNAR RESOURCES:

Criteria were based on the potential for utilizing lunar: 1) oxygen; 2) hydrogen, 3) helium 3 and other volatiles or light elements; 4) building materials requiring little processing (shielding material, bricks, ceramics, glasses) and 5) materials requiring extensive processing of lunar feedstock to produce (metals, solar cells, cement, concrete).

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1. Oxygen

Criteria for oxygen are dependent on the process that will ultimately be selected for oxygen extraction. Given present data, criteria may be developed to select the type of site that appears to offer the best possibility of satisfying all feedstock compositional and physical properties requirements:

- Mare sites offer more chemical and mineralogical diversity.
- High Ti mare sites will make feasible a broader range of processing options.

These criteria reflect a strategy that seeks to maintain flexibility in resource utilization, for example, the location of the outpost should not be keyed to an oxygen extraction process. As noted, oxygen may be extracted from any lunar material. Mare regolith contains, on the average, a more complex mixture of mineral components than does a regolith derived from, say, an anorthositic substrate such as may exist at some places in the highlands. Consequently, mare material may be a more flexible feedstock. Undesirable components may be removed from a mare regolith whereas desired components may not be added to a regolith. In this sense, mare surfaces appear to offer more flexibility, and within the mare suite of materials, ilmenite or titanium-rich materials have the greatest potential for oxygen production. Regolith thickness is not a major consideration for oxygen production. Boulder-free terrain may make mining operations easier. Access to immature regolith is desirable for processes requiring mineral beneficiation.

2. Hydrogen

Hydrogen is a solar wind implanted component. All solar wind implanted resources increase in abundance with exposure to the solar wind. Solar wind exposure is directly proportional to regolith maturity as defined by a number of parameters including the effects of micrometeorite bombardment. Therefore, the criteria are:

- Regions with mature regolith preferred. Finer grain sizes have higher hydrogen concentrations.
- Hydrogen content is directly proportional to ilmenite content, ilmenite ($FeTiO_2$) rich, mature regolith is superior. For soils of similar maturity, mare soils contain more hydrogen.
- Regolith thickness is important for hydrogen recovery. Thicker regoliths tend to be finer grained and more mature. Consequently they are likely to have a greater concentration of hydrogen.

3. Helium 3

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- Same as hydrogen.

4. Building materials requiring little processing

- Mare materials superior (lower melting points).

5. Materials requiring significant processing

- All materials usable

SUMMARY OF SITE INFORMATION NEEDS

The working groups determined that the following kinds of information are required or highly desirable.

1. Meter class altimetry data for site selection for observatory instruments, particularly interferometers, would greatly facilitate instrument siting.

2. A thick regolith will be important for shielding, since a Coude' focus is possible if the regolith is thick enough. Regolith thickness can be estimated via crater morphology observations from high resolution imagery.

3. Some potential experiments are sensitive to the radiation background, particularly gamma rays, from the KREEP (K, REE, P and U, Th) component of the lunar regolith. Gamma ray data for the lunar regolith will be important in detector design.

4. Topographic data are essential for planning of geological and geophysical exploration. The accessibility of areas or features to be investigated from an outpost can be determined only through analysis of topographic data.

5. Chemical and mineralogical data and imagery provide a critical context for the planning of geological and geophysical exploration.

6. Resource potential evaluation is dependent on the measurement of regolith composition, maturity and thickness. All three parameters are determinable or can be estimated from lunar orbit with Lunar Observer instrumentation. Direct detection of solar wind hydrogen

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at 100 ppm levels is highly desirable. Regolith maturity mapping based on multispectral data would be of great benefit in estimating resource potential.

CONCLUDING STATEMENT

Definition of science criteria is one step on the road to developing a site selection strategy for a Lunar Outpost. The criteria so far defined are not mutually compatible in all instances and the resolution of conflict will be the subject of future programmatic and scientific debate to determine where compromise is required or is possible. Continuing dialogue is the key to developing a strategy that is satisfactory on a multidisciplinary scale. As is pointed out in the section on geological criteria, an increase in the knowledge base may have a profound impact on exploration strategy and result in a different weighting of the criteria. Judgements made from an adequate data base of global proportions are more likely to result in the achievement of objectives.

Science criteria are not the only parameters that will dictate outpost location. Operational considerations have an impact on how well science operations can proceed at a locality and may determine whether or not particular scientific objectives can be achieved at a given locality. Mobility strategies that may be employed are crucial as well. These considerations and the relationship between multidisciplinary science criteria were explored at a follow-on workshop held in August of 1990 at the Johnson space Center under the auspices of the Lunar and Mars Exploration Program Office. At that workshop, the process of selecting a site was simulated by considering the merits of six locations on the Moon that were selected to serve as examples of locations with a wide range of characteristics. Results are reported by the Lunar and Mars Exploration Office in A Site Selection Strategy for a Lunar Outpost.

Report

of the

Lunar Geology Working Group

Lunar Outpost Site Selection Strategy Workshop

2-3 April, 1990

Working Group Members

Mark Cintala

Paul Spudis

Graham Ryder

James J. Papike

Donald Bogard

B. Ray Hawke

Paul D. Lowman, Jr.

Jeffrey B. Plescia

Donald S. Burnett

LUNAR GEOLOGY AND A LUNAR OUTPOST

Introduction

The existence of a lunar outpost will revolutionize our knowledge about the Moon and, by extension, planets in general. Geological field work during Apollo was limited to relatively small areas around the landing sites, and each task to be accomplished by the EVA crew was part of a strict timeline imposed by engineering and life-support considerations. As a result, the geological traverses performed on each mission were planned in minute detail long before launch, and -- perhaps most importantly -- with little information available regarding the area to be explored. When plans were applied to reality, it was found to no one's surprise that flexibility was stifled by the constraints: unexpected discoveries or difficulties more often than not required deletion of planned objectives in order to accommodate the time demanded by the unforeseen circumstance. True geological field work, which is a highly iterative process that often takes years to complete, has been performed only on the Earth. This problem will be remedied -- at least conceptually -- upon beginning the first field trip mounted from the lunar outpost. That excursion will be to a location in the immediate vicinity of the outpost itself, and thus will be visited easily on any number of subsequent occasions, if deemed necessary. The extent to which the important problems in lunar geoscience can be attacked by these field activities will depend upon the *time*, *flexibility*, and, perhaps most importantly, *mobility* afforded by the lunar outpost.

> *Time* is required for the successful execution of field work because of the complexities of geologic processes themselves as well as the interactions between them. In addition to sampling activities, a geologist must study the physical properties and examine the overall context of a unit *in the field.* More often than not, this is a formidable undertaking on the Earth; on the Moon, where billions of years of impacts have done an admirably thorough job of randomizing the geological record, the task is even more daunting. The complexity of a problem, in general, determines the time required for its solution; on the Moon, few problems will be simple to solve.
>
> Taken as a whole, a planet possesses almost biological intricacy: the huge number of variables affecting geological processes and their interrelationships makes those mechanisms highly resistant to the "cookbook" application of physical or chemical equations. Because of these complexities, a geologist makes new discoveries of varying significance each time he or she ventures into the field; these discoveries combine with existing knowledge to determine the next step in the investigation. The result is a kind of "free-form" approach to problem solving -- one that requires a high degree of *flexibility* to implement. If one knew exactly what to expect at a given field site, there probably would be no scientific reason to go there, because the problem very likely would have been solved. Since the converse is much more often the case, the means must be made available to accommodate newly acquired information and to reformulate plans accordingly.
>
> Just as a physician cannot make a precise diagnosis on the basis of a single observation, neither can the geologist confidently extrapolate observations made at a single location to a process affecting thousands of cubic kilometers. A single process can assume many guises, and radically different mechanisms often possess

nearly indistinguishable manifestations. To compound the difficulties, the most important questions in lunar geoscience are, more often than not, planetary in scale. These realities necessitate significant *mobility* across the lunar surface. Mobility is, if such a prioritization could be made, perhaps the most important of the three requirements. The need for time in the geological exploration of the Moon should be met eventually as the lunar outpost consolidates and matures; once the time becomes available, it will be used to increase flexibility in the field. Neither, however, will be exploitable to its fullest extent without the ability of the explorers to go to the important localities.

This report of the Lunar Geology Subgroup's activities during the Site Selection Strategy Workshop assumes -- explicitly at some times, implicitly in others -- that time, flexibility, and significant mobility will be available to the people who will perform the field work. Should any of these three parameters be eliminated or eroded, the rationale, recommendations, and objectives presented in this report will require a fundamental reassessment.

Finally, it must be pointed out that the deliberations of the Subgroup were conducted with the prospect of *Lunar Observer* very much in the fore. If necessary, an outpost site could be selected for geoscientific purposes almost immediately. To do so in the face of such an exciting mission as *Lunar Observer*, however, would do a great disservice to lunar science in that the site would not be optimized on the basis of all data available before the construction of the outpost. Only a small fraction of the Moon's surface has been photographed at high resolution, and an even smaller fraction has been mapped geochemically. The explicit objective of *Lunar Observer* is to provide global coverage of the lunar surface with an array of instruments, among which are imaging systems and geochemical mappers. It should, therefore, be expected that once *Lunar Observer* data become available, new items will be added to the list of features to study and sites to be investigated .

Major Problems Addressable from a Lunar Outpost

In order to construct a framework within which the discussion would take place, the Subgroup decided to list the principal topics in lunar geoscience that could be addressed by a lunar outpost and its attendant capabilities. In doing so, we drew from a similar list constructed by the Lunar Exploration Working Group and modified it to fit within the Subgroup's purview. The list as used at the Workshop is presented below, with no prioritization either expressed or implied.

Development and Evolution of the Crust and Mantle

A "layer" of a planet's overall structure is effectively a key -- albeit often a complex one -- to deciphering the processes that occurred just above and beneath it. Thus, the structure of the lunar crust provides insight into the mantle below it. The upper mantle undoubtedly reflects aspects of the evolution of the deeper mantle and the lower crust, and so on. Taken as a whole, the lunar crust and mantle contain the history of the Moon within them. Any growth in knowledge of the Moon's formation and evolution will depend directly on our ability to interpret and document the history of its crust and mantle. This aspect of lunar science extends from the earliest time of lunar differentiation through the generation and eruption of mare basalts to the current state of impact-driven modification of the outer lithosphere. Identification and sampling of plutonic bodies, examining sequences of basaltic lavas, determining the existence and nature of highland volcanism,

establishing the spatial and temporal extent of partial melting at depth, and a myriad of other objectives all relate to the same overall goal of determining the processes and chronologies of crustal and mantle evolution.

Impact History

"Conventional wisdom" states that the Moon's impact history progressed from (1) extremely heavy bombardment during and soon after its formation through (2) a rapid decline in the impact rate to (3) an environment probably typified by its current state, in which large craters are formed only occasionally. Another school of thought -- formed just after the Apollo missions and largely disregarded until recently -- suggests that impact rates after the formation of the Moon were substantially lower than otherwise suggested by the "late heavy bombardment", and that a "cataclysm" occurred around 3.9 Ga. Unfortunately, our knowledge of the absolute lunar time-scale is insufficient to distinguish between the two with confidence; only detailed studies of samples from a variety of locations can provide the information necessary to evaluate these very different interpretations. The rate of collision with large meteoroids and asteroids early in lunar history is a critical parameter in understanding the early thermal state and differentiation of the Moon. Whether an early "magma ocean" existed has been the subject of a hotly contested debate whose resolution hinges on, among other things, the rate of infall of debris during the Moon's accretion. The remainder of the Moon's bombardment chronology has a direct bearing on the equivalent period of the Earth's history, which includes the beginnings of life and its early evolution. A better understanding of the impact history of the Moon -- indeed, a better understanding of *any* portion of lunar history -- will serve as a more complete basis for the interpretation of the histories of other planetary bodies.

Nature of Impact Processes

Impact cratering has been the most pervasive process affecting the lunar crust and perhaps even upper parts of the mantle. From the constant "sandblasting" by micrometeorites, to the drastic and global consequences of multi-ring basin formation, impact events have played a pivotal role in influencing lunar history. Much is known about the process, particularly at laboratory scales, but the very high impact velocities and extreme range of scales that occur in nature have proven to be difficult to simulate and model. Large impact craters exist on the Earth, but interpretation of their structures and effects is a singularly difficult proposition due both to the planet's efficient erosional environment and to plate-tectonic processes that bury, distort, and ultimately remove such features. Because of the stability of its lithosphere and the extreme age of its surface, the Moon is an ideal "museum" for the study of impact structures of all sizes and degrees of degradation. Only so much can be done with orbital and Earth-based data; "ground truth" in the form of well-chosen samples and field measurements is a necessity in the effort to understand this process, its effects, and the structures that it creates.

Regolith Formation and Evolution/History of the Sun

The lunar regolith is the most pervasive, physically distinct unit on the Moon and is that part of the planet observed directly by virtually all remote-sensing techniques. Except for deep drill-strings and fragments taken directly from outcrops, all samples collected on the lunar surface will, strictly speaking, have been part of the regolith. This unit is a complex construct comprising material from rock units both immediately below the debris layer and elsewhere in the region; not only is rock pulverized essentially in place, but fragments are transported from other locations at

random by impact events. Knowledge of the provenance of many collected materials will require an understanding of regolith development on the Moon, which itself is related to the relative efficiencies of vertical and horizontal migration of material. Interpretation of remotely acquired compositional information also hinges directly on its context in terms of regolith evolution.

The regolith constitutes the important interface between the Moon and the space environment around it and, as such, is a collector of solar-wind particles, cosmic rays, and the products created by the interaction of cosmic rays with regolith constituents. This can be utilized to advantage by sampling both regolith at various depths and "paleoregoliths" that are sandwiched between layers of mare basalts or impact melt rock units. By dating such units and studying solar and cosmically generated particles and their effects, unique windows into the history of the sun and galaxy will be opened.

Eruptive Dynamics

A variety of volcanic units exists on the Moon, ranging from vast mare plains to small, distinctive, pyroclastic deposits. Each represents a very different process, style, scale, and often composition of volcanic eruption. Remote-sensing data indicate that the Apollo missions sampled only a small subset of each; a much greater variety of volcanic features were never even visited. The mechanics of eruption and chemistries of the participating materials could hold valuable information about the thermodynamic state of the lunar interior through time, the types and sources of volatile elements and compounds, and the dimensions and characteristics of lunar magma chambers. On a more practical level, volcanic deposits may be the principal sources of raw materials for resource extraction; understanding their origins, modes of emplacement, and chemical characteristics will enhance the efficiency of their exploitation.

Enigmatic Features

A variety of morphological, spectral, and geochemical features have been identified on the Moon for which explanations are sparse, tentative, controversial, nonexistent, or any combination thereof. Examples of such entities include mare domes, spectral "red spots", U-Th anomalies, Reiner gamma and similar swirl fields, Ina (the "D caldera"), and Silver Spur at Apollo 15. Since little is known about these features other than their sometimes extreme peculiarity, their roles -- and their importance -- in lunar history can only be guessed. Because of our poor state of knowledge about these objects, a strict justification for their study in the overall context of lunar geoscience would be difficult to formulate: field investigations of these features would fall within the category of pure scientific exploration.

Origin of the Moon

The origin of the Moon is such a broad, all-encompassing topic that individual geoscience experiments dedicated specifically to that subject might not be possible to construct. Instead, the topic will be better served through the understanding that *everything* learned about the Moon would eventually be used toward deciphering the origin of the planet.

Additional Features of Particular Interest

The subgroup also identified a number of other specific and generic features as "desirable targets for study." The proximity of such features to a potential outpost site would be highly advantageous. They are presented in tabular form.

Targets	Specifics
Interiors of large craters*	Deep material in central peaks, impact-melt sheets for isotopic dating, cratering mechanics, stratigraphy
Pyroclastic deposits	Composition of pyroclastics and volatiles, volume of deposits, ages, eruption sequences
Structural features (graben, mare ridges, fissures)	Stratigraphic relationships, geometrics, ages
Volcanic vents and landforms	Ages, mechanics of origin, geometrics, stratigraphic relationships
Old (>3.8 Ga) mare basalts (probably excavated by dark-haloed impact craters)	Unsampled basalts, evolution of the mantle, history of melting at depth, stratigraphic marker horizon
Young (<3 Ga) mare basalts	Unsampled basalts, evolution of the mantle, history of melting at depth
Swirl fields (e.g. Reiner ©)	Unknown origin, magnetic anomalies, composition, ages
Any outcrop	Sample rocks in place, paleomagnetics
Crater walls	Known locations of outcrop in maria, structure, stratigraphy, cratering mechanics
Basalt sequences	Evolution of the crust and mantle, paleoregoliths
Basin and crater melt sheets and continuous deposits§	Melt sheets: ages, old clasts, homogenized local crust, cratering mechanics, impact-melt generation, paleomagnetics Continuous deposits: ejecta from various depths, radial variations, dynamics of emplacement, local mixing, cratering mechanics
Ray deposits from large craters*	Local mixing, dynamics of ejecta emplacements, cratering mechanics
Geochemical and spectral anomalies (e.g. spectral "red spots", possible KREEP concentrations, etc.	Origins, compositions, ages
Light-plains units	Possible highland volcanism, basin ejecta, local mixing
Small-crater melt deposits	Ages of smaller craters for periodicity analyses, cratering mechanics, impact-melt generation
Fractured-floor craters	Possible sites of intrusive rocks, ages, structure

* Diameters of ~50 to several hundreds of kilometers

§ Diameters of ~3 to 50 kilometers

Solving the Problems: The Geological Approach

In order to understand lunar geologic processes and history as completely as possible, it is necessary to study the Moon's rocks in their natural environment and in laboratories -- both on the Moon and on Earth. Investigation of lunar rocks in their natural environment requires geological exploration, whose techniques have been proven by over 200 years of experience on the Earth; these methods can be adapted to the Moon with relative ease. Because of the very restricted set of samples available, laboratory work on lunar samples has continued to evolve to impressive levels of precision and efficiency.

The objective of geological field work is to develop an understanding of the regional and local context of a given rock unit, its detailed setting and structure, its composition from a chemical and mineralogical standpoint, its stratigraphic position relative to other units, and its absolute age. A basic protocol is typically followed in the conduct of such field activities. *Regional reconnaissance* is performed first to catalog the number and variety of rock units in a given area, to assess their relative ages, and to determine their gross compositions. On the Moon, this will be accomplished both from orbit (by remote sensing and photogeologic mapping) and on the ground (by simple, probably automated, return missions that will collect bulk regolith and rock samples). Reconnaissance is generally done on a regional basis, but complex areas may need geological reconnaissance of very small (kilometer-scale) areas.

Once this overview is completed, *detailed field studies* can begin. The goal of field study is to investigate and comprehend geologic processes and history at all levels of detail. Field work is a complicated, ongoing process that involves observation, sampling, revision of working hypotheses, revisits, and resamplings. A detailed field study can take many years and does not end after an area is visited and sampled, because it necessitates the option of revisiting the locality and spending as much time as is necessary to understand the process or rock unit under consideration.

The final step in this process involves *laboratory study*, which will always be necessary irrespective of the degree of sophistication and complexity of field equipment: a given measurement *not required to be done in the field* will always be performed with more accuracy and precision in the laboratory. Laboratory work involves detailed and sensitive measurements of sample mineralogy, physical properties (such as paleomagnetism), chemistry, and isotopic composition. (The latter is particularly important in determining the absolute ages of rocks, which is always a very important piece of information.) The results of laboratory investigations provide feedback to the field studies. For example, a sample might be "identified" in the field, only to be recognized as something quite different after an analysis in the laboratory. This is a frequent occurrence in terrestrial field work and one that could substantially alter the geologist's interpretation of the field site; such a situation would call for a revisit to, and resampling at, the field site for the collection of data in light of the lab results.

Site Selection Guidelines and Recommendations

It is evident from the preceding few sections that the successful conduct of geoscience activities on the Moon will require access to a variety of different terrains and units, not all of which will occur in the same small area. Clearly, each of the two fundamental terrain types -- mare and highland -- poses its own particular set of problems and holds its own promise. The maria, for instance, are constructed of basalt sequences that were generated by partial melting at depth; coordinated sampling of those sequences will be important in learning about the evolution of the mantle during that period. Ejecta deposits from basins, on the other hand, can be visited only in highland terrain; attempts to sample different crustal layers as they existed at the time of basin formation will almost certainly be done by traverses radial to multi-ring basins. These are only single examples of a large number of different approaches to the two terrains; others certainly exist. It is fundamental and important that the maria and highlands were formed not only by very different processes, but also that they represent two complementary periods of the Moon's history. To learn about one, however, is to obtain less than half of the total picture. Processing of highland material did not stop as soon as the first basaltic lava was extruded; conversely, pieces of mare basalt have been dated as being older than the more recent lunar multi-ring basins.

This temporal and physical overlap must be accommodated in any geological program that has a hope of unraveling lunar history. Such a program must address the basic questions and problems inherent to the maria and highlands -- both individually and collectively -- and, in doing so, make a concerted effort to learn about the history of the lunar interior: an attempt to choose which is more important would be meaningless. It is abundantly obvious that a single outpost site will not provide the answers to all or even perhaps a majority of the important problems without the mobility to support the necessary field work. It is equally apparent, however, that a variety of localities exist which are so complex and hold the prospect of sufficient return on the investment that it would be advantageous to have a permanent "field station" in the form of the outpost near one of them. This field station would also serve as the "base camp" for geoscience operations, from which forays of increasing length, complexity, and duration will be conducted as capabilities grow.

The Subgroup recommends that the lunar outpost be located at or near a carefully chosen mare/highland contact , and that the development of extended mobility and duration in the field -- both human and robotic -- be given high priority.

One Possible Approach to Geoscience from a Lunar Outpost: The Transect Method

The Subgroup found it very helpful to have a candidate plan of attack in considering the approach to performing science from the lunar outpost. The one chosen in constructing the recommendation above was the *transect method*, which is a technique that has been and continues to be used to advantage in terrestrial field studies. It is a systematic approach that involves a variety of geoscience disciplines, relying on interaction between those disciplines to unravel what are often highly complex problems. This is a "whole is greater than the sum of its parts"

synergism, in that geology, geophysics, and other related fields combine to extend the reach of each discipline.

We defined a lunar transect to be a segment of lunar terrain (roughly 50 by 500 km, for example) that traverses geologic units, contacts, and structures, which would be chosen on the basis of their scientific merit. With the outpost located on a mare/highland contact, the transect would extend in both directions, covering the two terrains. (A *mare/highland contact* in the context used here is defined as a site that will permit visits to *bona fide, in situ* mare and highland material during the Emplacement Phase of lunar outpost operations.) Thus, the section extending into the mare would include a variety of basalt units, and would provide access to basalt sequences in the form of either outcrop or a good site for deep-drilling operations. The mare units should also include volcanic pyroclastic deposits or "dark mantle". The highland segment of the transect should include one or more of a variety of features, including but not limited to impact-melt sheets, exposures of plutonic rocks, light-plains units, structural features (graben, ridges, etc.), and fractured-floor craters. (See the section on **ADDITIONAL TOPICS AND FEATURES OF PARTICULAR INTEREST**.)

The transect, it should be emphasized, is not a "straight-line" construct. It is instead a region within which boundaries are crossed, structures are included, and individual units are available for study within a larger context. By extending across a mare/highland contact, it would provide a large diversity of geological terrains, units, and features for study as parts of a unified framework. If necessary or advantageous, its boundaries can be adjusted and new "subtransects" could be added. It is easily envisioned that the transect would become rather amorphous with time, gradually extending in *all* directions from the lunar outpost.

Summary

The problems of lunar geoscience vary in scale, complexity, and location. The outpost should be located at a complex site of geological significance whose understanding will require an extended effort of surface and subsurface investigation. This site will be the pivot point for a major transect extending in two or more directions (and very probably in *all* directions as time passes and capabilities increase), which will permit the incorporation of a wide variety of terrains, features, and units into a regional context. ***This type of strategy will require extended periods of time in the field, flexibility to cope with new discoveries and unanticipated difficulties, and the mobility to permit human activities hundreds of kilometers from the outpost. The Lunar Geology Subgroup recommends that the lunar outpost be located at or near a carefully chosen mare/highland contact, and that the development of extended mobility and duration in the field -- both human and robotic -- be given high priority.***

Report

of the

Lunar Geophysics Working Group

Lunar Outpost Site Selection Strategy Workshop

2-3 April, 1990

Working Group Members

Roger Phillips

Lon Hood

Yosio Nakamura

GEOPHYSICS AND THE LUNAR OUTPOST

Objectives

The geophysical objectives in lunar exploration are concerned with gaining an improved understanding of the internal structure and physical state of the Moon. These objectives can be further specified to answer certain important questions left unanswered after the successful Apollo project. Such questions include the size and thermal state of the core, the structure of the mantle (including presence of major discontinuities and lateral heterogeneity), the regional and global variation in crustal thickness, major basin structure, the mechanism of apparently tectonically shallow moonquakes, global heat flow, the origin of lunar paleomagnetism, and the structure and composition of the atmosphere.

These objectives can be separated into two broad categories: (1) global and (2) regional geophysics. Each of these has a distinctly different impact on outpost site selection.

Global Geophysics

Global geophysics objectives are associated with the deployment of a *global geophysical network*, each station containing a three-axis broad-band seismometer, a three-axis magnetometer, a heat flow experiment, and mass spectrometers to measure lunar atmospheric composition. The first three instruments will improve our knowledge of the structure and thermal state of the Moon and are designed to answer such questions as the existence and state of a core, the structure of the mantle, the gross structure of the crust, the mean lunar heat flow, and present temperature profile of the Moon. In turn, this information is directly linked to questions regarding the origin of the Moon, the thermal state of the Moon just following accretion, and the composition of the Moon. Lunar atmosphere experiments will help map out the physics of the lunar atmosphere (including the effects of human-induced contamination), and the composition, including an under-standing of major sources and sinks. The global network, through detection of meteoroids impacting the lunar surface, also significantly expands our knowledge of the directions of approach, thus orbits in the solar system, of clusters of meteoroids crossing the orbit of the Earth-Moon system.

Regional and Traverse Geophysics

Regional geophysics addresses major questions about lunar crustal structure and possibly the mechanism of shallow moonquakes, and includes investigations into highland-maria boundaries and the nature of multi-ring basins. These latter types of studies are fundamental to the improvement of our understanding of the effects of large impacts on planetary interiors. The objectives of *traverse geophysics* are:

(1) To understand subsurface structure in support of geological investigations, such as studies of basin structure and stratigraphy.
(2) To carry out subsurface surveys for outpost-related and geological applications. Examples: (i) location of subsurface lava tubes for possible habitats, and (ii) location of favorable sites for drilling to paleoregolith.

(3) To carry out resource prospecting.
(4) To detect regions of interior outgassing.
(5) To understand the origins of lunar paleomagnetism.

Criteria for Site Selection

Global Geophysics

(1) Seismology:

The criteria for selecting the outpost site for global seismology are only indirect in that the outpost must be located in such a location that it is convenient to serve the global network. Thus, the location is only mildly constrained by the criteria for selecting the sites of the global network stations, which are more specific. For example, one of the more important questions the global seismic network should address relates to the existence of the lunar core. This question is probably best answered by having an array of stations at the antipode of the most active of the deep moonquake hypocenters, namely: the A1 moonquakes at about 16.6^{o}S, 39.8^{o}W. An alternative site will be the antipode of the major farside moonquake hypocenter, A33, at 4.6^{o}N, 116.5^{o}E. The global network to address the questions of mantle seismic velocity profiles, including lateral variation, and global and regional variations in crustal thickness, faces less restrictions in its location.

(2) Heat Flow:

Previous lunar heat flow measurements, at the Apollo 15 and 17 sites, were obtained near the edges of maria where the heat flow may be anomalously high compared to the global average. Future measurements should be obtained at a number of highland and central mare sites to more accurately determine the global average heat flow. Location of the lunar outpost near such areas would be helpful in assuring that the needed measurements will be obtained.

(3) Magnetometry:

A global magnetometry array for electromagnetic sounding of the Moon has no special requirement imposed on outpost site selection.

(4) Atmospheric Measurements:

Prior to outpost emplacement, measurements of lunar atmospheric species abundances could be made. The network monitoring will allow coarse determination of the location of sources and sinks of atmospheric constituents. With the emplacement of the outpost, the Moon could well become a laboratory for studying the physics of those planetary bodies with boundary layer exospheres (e.g., Io, Mercury). Release of known quantities of trace gases at specific times will allow the network measurements to assess the fate of atomic, ionic, and molecular species (regolith trapping, exospheric escape, etc.). These experiments place no particular constraint on outpost location.

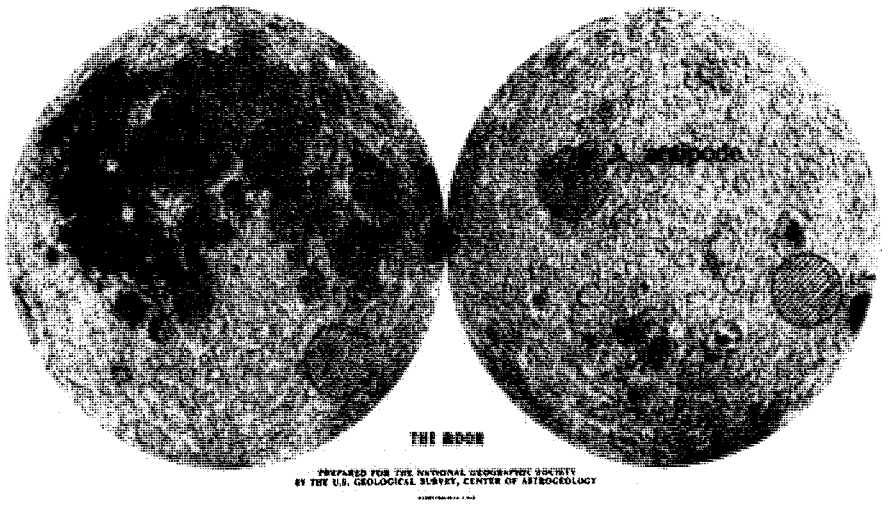

Figure 1a: Location of the A_1 antipode of major lunar seismic events. Circular areas represent locations for deployment of complementary geophysical arrays to provide global coverage and sensitivity to core definition.

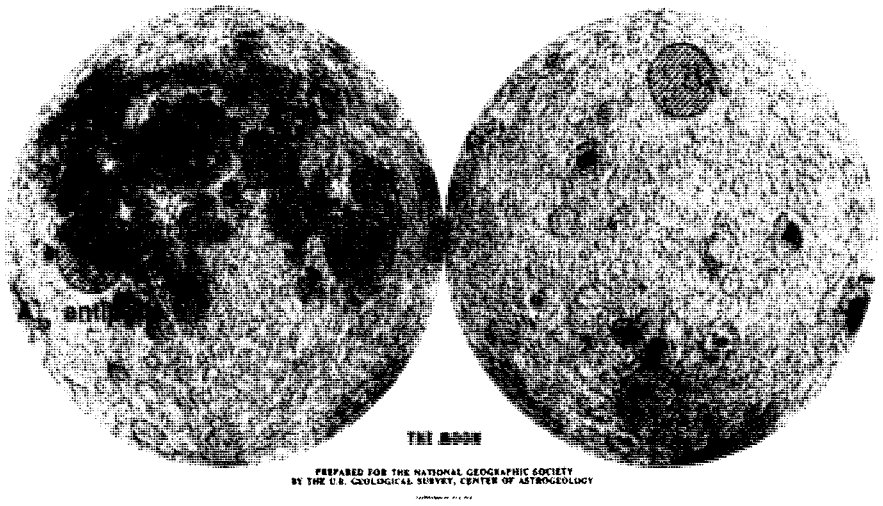

Figure 1b: Location of the A_{33} antipode of major seismic events. Circular areas have the same meaning as in 1a.

Regional Geophysics

Seismology: The regional seismic array located near or around the outpost will serve several purposes. First, it can be used to determine the regional crustal structure, if appropriate artificial sources (such as impacting of spent spacecraft and possible explosive charges used in mining operations) are found. For this purpose, the criteria for the site selection will be dictated by geologic interest of the site, i.e., there must be a need to determine the detailed crustal structure of the region. Second, the regional array can be used to locate meteoroid impacts within and near the array. Impact sites thus located will be extremely attractive sites for a study of freshly excavated craters, and also serve to calibrate various crater scaling laws to estimate current and past impact flux. Third, the regional array, if located not too far from a potential epicenter of a shallow moonquake (but not at the epicenter because of possible hazard), may enable us to deploy a local array of portable seismic stations in the epicentral region of a shallow moonquake to detect possible aftershocks, thus allowing us to determine the mechanism of these tectonic quakes, which hold a key to understanding the present thermal state of the lunar interior. There is a distinct possibility that atmospheric disturbance associated with degassing may also be observed. If that is the case, a visit to the site will become very rewarding scientific exercise for the outpost occupant. The selection criteria for such a location are dictated by a proximity to known shallow moonquake epicenters of potential sites, which include edges of major basins.

Traverse Geophysics

The criteria for site selection (in order of decreasing priority) are listed below:

(1) Site should be in a geologically diverse region where major geological problems can be addressed. It is highly desirable for the site to be within or near a multi-ring basin where traverse geophysics would be best applied to determine subsurface structure.

(2) From the standpoint of paleomagnetic studies, location of an outpost near intact mare basalt flows would allow oriented samples to be returned. This would provide an important constraint on the origin of lunar paleomagnetism, specifically the former existence of an intrinsic lunar magnetic field. It would also be desirable to locate the site within traverse distance of strong magnetic anomalies such as those associated with the Reiner Gamma swirls.

Mobility

Global Network

By definition, global access is required. Global access by humans is possible but may not occur until many years after an outpost is established. Nevertheless, human deployment of sensitive geophysical instruments is the best single approach. Softlanders represent a less expensive option that would result in acceptable deployment of geophysical instruments. Modified surface penetrators (decelerated by retro-thrusters in the airless lunar environment) represent the least expensive option. However, it is unclear whether acceptable deployment of sensitive geophysical instruments, with long energy supply lifetimes, is possible via this technique.

Regional Network

Mobility over a range of at least several hundred kilometers from a manned outpost is required to deploy geophysical stations in a regional network. Human deployment via surface rovers would result in the most reliable emplacement of the instruments. Alternatively, separate deployment via softlanders or surface penetrators may be more practical, especially if a global network will also be deployed in this manner anyway.

Report

of the

Lunar Astronomy Working Group

Lunar Site Selection Strategy Workshop

2-3 April, 1990

Working Group Members

Faith Vilas

Harlan Smith

Mark Sykes

Christine O'Neill

David Talent

Paul Swanson

Brian Heard

ASTRONOMY AND THE LUNAR OUTPOST

Introduction

The goal of NASA's astrophysics program is to understand the origin and evolution of the universe and the laws of physics that govern it. Emplacement of selected instruments on the surface of the Moon that utilize the Moon's unique characteristics promotes progress towards achieving that goal. Instruments selected for consideration as lunar-based observatories have high scientific merit, complement existing and/or planned programs and are instruments for which the Moon represents an ideal platform. Five instruments were selected for consideration. These are:

1. Lunar Tansit Telescope
2. Optical Interferometer
3. 4-Meter Telescope
4. Submillimeter Interferometer
5. VLF Interferometer

Instrument Descriptions and Objectives

Lunar Transit Telescope:

The Lunar Transit Telescope will be a 1 to 2-meter fixed telescope that utilizes the motion of the Moon to scan the sky. The instrument will observe in the ultraviolet/visible/near infrared (0.1 to 2 μm) with a spatial resolution of 0.1 arc sec. The objective of the instrument is to conduct a deep sky survey down to objects of 28th visual magnitude. CCD detectors will be passively cooled on the lunar surface to 100° K.

Optical Interferometer:

The optical interferometer is an extremely high angular resolution instrument operating from 0.1 to 10 μm. The interferometer will be a modular instrument, assembled incrementally and employing elements of the 16-meter filled aperture telescope. It will begin during the inital phase of development of the Lunar Outpost with the signal combiner and four mirror elements. Until the interferometer is complete, the initial four meter element of the 16-meter filled aperture telescope will serve as the fifth element of the interferometer. The sixth and final element of the interferometer will be deployed when outpost development has been completed.

The individual collectors will have apertures of about 1.5 meters and, when complete, the total collecting area will be about 21 square meters. The baseline will be from 1 to 10 km. Stability of the surface is a key factor in creating an accurate baseline for the interferometer.

Submillimeter Interferometer:

The submillimeter interferometer will consist of segmented apertures of 4 to 5 meters diameter. Two elements will be set up as the outpost is developed, and three when the outpost is mature for a total collecting area of at least 60 square meters. The instrument will observe from 30 to 300 μm with a spectral resolution of 10^6 and an angular resolution of 1 to 10 milliarc seconds. The final baseline will be approximately 10 kms.

Low nighttime temperatures will provide a stable operating environment for the reflectors and the detectors will be cryogenically cooled.

Very Low Frequency Interferometer:

The low frequency interferometer will consist of a large number of simple meter-long dipole antennas and receivers arranged in a y-shaped array, and observing in the 10 to 300 meters wavelength range. The dimensions of the array should be as large as possible, hundreds of kms for example. The interferometer will have an angular resolution of 6 arc seconds to 3 arc minutes at a frequency of 1 MHz.

Terrestrial radio wave interference is of concern and an interferometer located on the back side of the Moon will be shielded from such interference. Interim data will be collected with deployment of a VLF array on the near side in the vicinity of the Lunar Outpost. The VLF interferometer will observe Earth's kilometric auroral radiation.

Filled Aperture Segmented Telescope:

The filled aperture telescope is a passively cooled diffraction-limited telescope with a diameter of 16 meters and a field of view of 1 arc minute. The complete telescope is massive, necessitating modular construction beginning with a 4-meter central module (see optical interferometer section) and deployment of the remaining modules as capacity becomes available. The Lunar Outpost provides a stable platform for high precision pointing and control.

Fundamental Site Selection Criteria for Near Side Observatories

Criteria for the location of observatories are based on field of view requirements for observing celestial objects, observing the Solar System, site topography, and communications requirements.

For near side observatories, the working group derived the following location criteria:

1. **Observatories should be located within 5 to 10 degrees of the mean lunar limb.** At these longitudes (81.5E and 81.5W are the limits at which the Earth is always in view), the Earth is visible but low on the horizon at all times. Line-of-sight with the Earth is maintained for communications but the Earth is near the lunar horizon, minimizing requirements for shielding from Earth light. In addition, one of the test objectives of the Very Low Frequency Array is observation of the Earth's decametric auroral radiation (although the VLF test array suffers one dimensional foreshortening when observing the Earth).

Solar eclipse observation is also feasible from near the lunar limbs but all interferometers suffer from poor UV coverage of eclipse events.

If observatories were to be moved closer to the center of the near side, more shielding would be required to shield instruments from Earth light and proportionately larger segments of the sky would often be unavailable for observation.

2. **Observatories should be located within 10 degrees of the lunar equator.** The location should be such that observation of the Magellanic Clouds at an elevation of 15 degrees or more above the horizon is possible for a substantial fraction of viewing time. At equatorial latitudes, most of the sky is available for 50% of the possible viewing time. Figure 1 illustrates the percent of the sky that is excluded from observation at various lunar latitudes and with two different degrees of obscuration by topography.

Temperature extremes are a concern at equatorial latitudes, and effective shielding of telescopes and detectors will be required. Although polar sites may offer more stable (and lower) temperature regimes, and allow 100% observing time, one half of the celestial sphere is lost at a polar site. Full sky coverage would require a site at each pole.

The working group formulated recommendations for instrument placement at an outpost. These recommendations impact the scale of the area to be considered for an outpost and, therefore, are selection criteria. The physiographic and/or topographic considerations and criteria are the following:

1. **Instruments should all be situated at the same general location to facilitate maintenance and communications and power linkages to the outpost.** The Lunar Transit Telescope, 4-meter telescope, and the VLF submillimeter interferometer should all be located approximately 1 km from outpost. This minimizes the time required to get to and from the observatories for equipment transport and safety.

2. **The Optical Interferometer should be located a few km (~10 km) from the outpost.** This distance would minimize vibrations from outpost activity. The actual distance required to satisfactorily damp microseismicity awaits more detailed study of micro-seismic effects expected from outpost activity. Siting an observatory at a distance of ~10 kms from the outpost enlarges the scale of the outpost domain significantly.

3. **Flat plains with a conveniently located hill or a bowl-shaped crater would simplify interferometer design.** Flat areas avoid topographic blocking of the field of view and permit line-of-sight between array elements. A conveniently located hill or crater would allow the beam combiner station of the interferometer array to be in line-of-sight of all array elements. The Moon is a relatively small planet and the surface curves rapidly on the scale of a lunar outpost. Figure 2 illustrates the curvature of the surface by showing the distance from the surface to a plane tangent to the surface and originating from the observer's location. Curvature is approximately 2.9 meters per km. Design would be simplified, and precision not jeopardized by intermediate relays, by siting the beam combiner on a feature visible to all elements.

Far side sites were not generally considered, however, the utility of far side sites for measurements that can be made only in an environment free of terrestrial radio wave interference is well understood. The VLF far side array and the SETI instrument, for example, require minimal radio interference. Consequently, the lunar far side should be designated as a radio silent zone.

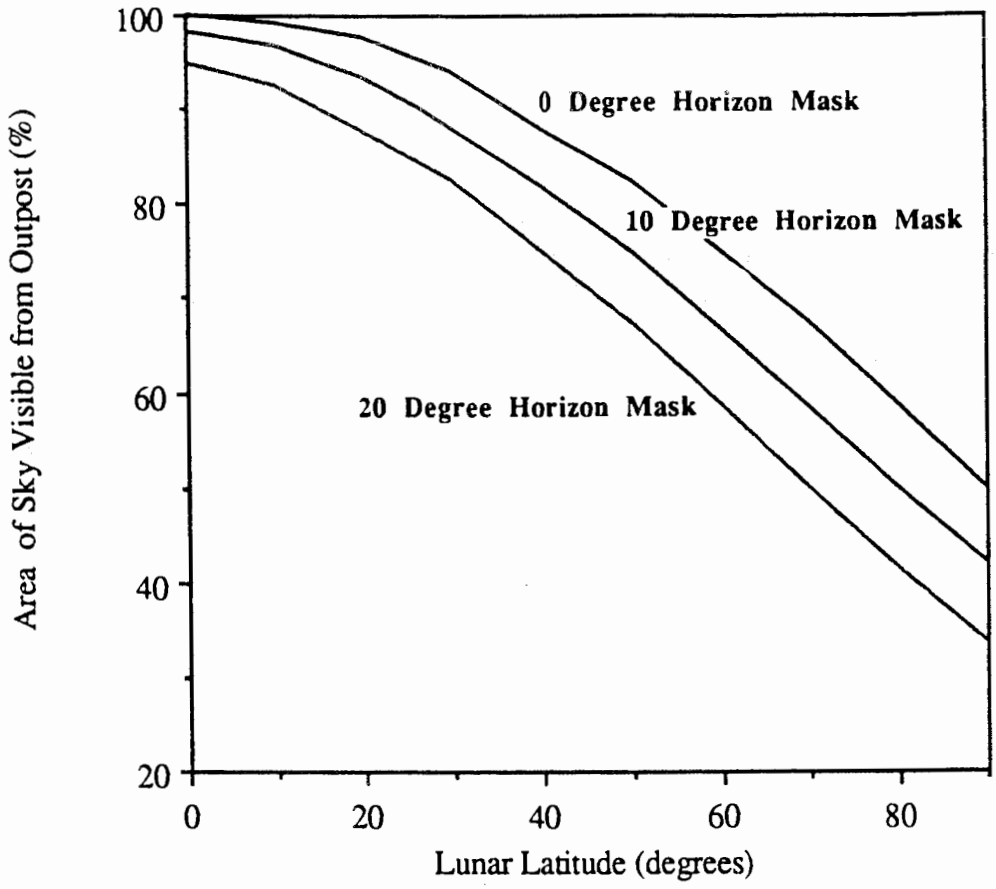

Figure 1: Percentage of sky visible versus latitude with 0, 10 and 20 degree masks

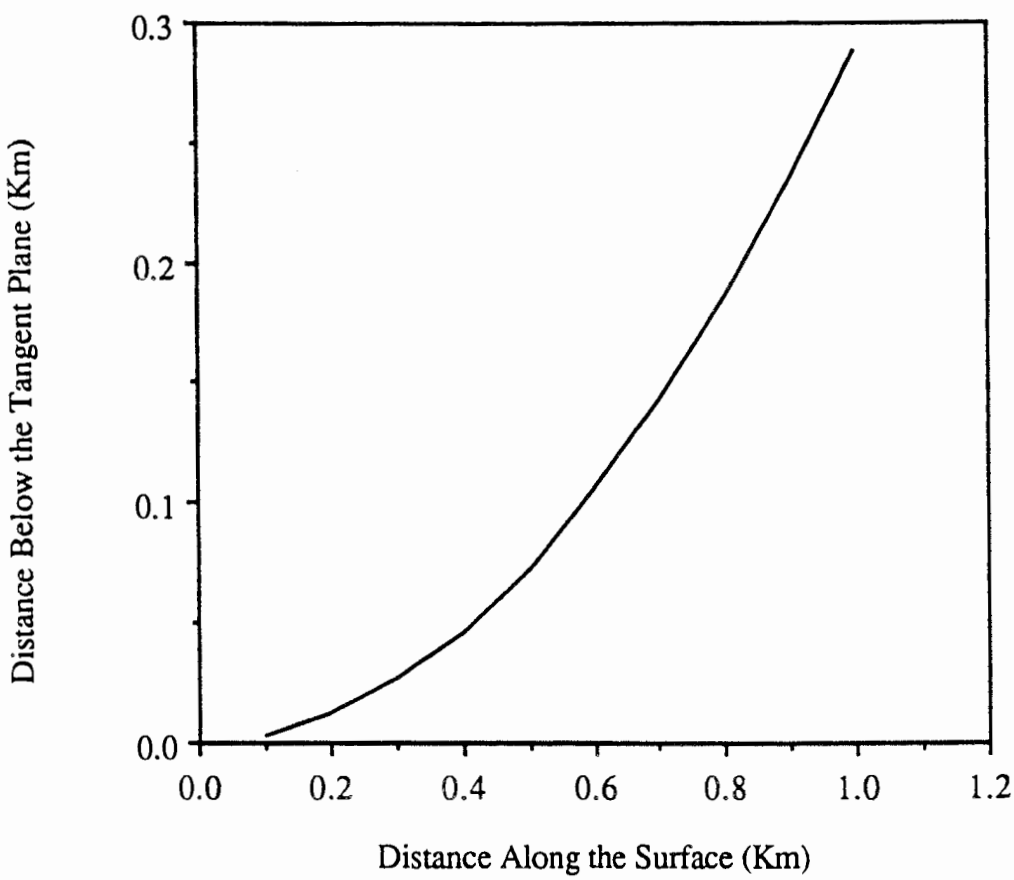

Figure 2: Curvature of the lunar surface measured normal to the surface to a tangent from the observer's location.

Site Information Requirements

The selection of a location within the domain of a Lunar Outpost site for the emplacement of arrays, particularly large arrays like the optical interferometer, would be greatly facilitated by high quality cartographic-geodetic data. *Meter class altimetric data* like that potentially available from Lunar Observer would be very useful for astronomical site selection, particularly for interferometers. Rough terrain prevents line-of-sight for interferometers, potentially obstructs the view for observing some astronomical objects and could hamper maintenance. Topographic maps with meter-scale contouring would allow an assessment of topographic effects. Regolith thicknesses at potential sites is a measurement of interest because it may be advisable to utilize a Coude' focus to detectors located below the surface to minimize the effects of cosmic rays.

Observatory Operational Considerations

The working group considered potential operational problems that could arise in the emplacement and operation of observatories.

- Microseismic activity due to habitat construction/expansion and operations.

  Vibrations form the Lunar Outpost could reduce the quality of observations made using the 4-m telescope and astrometric accuracy from the optical interferometer. Potential magnitude of vibrational disturbances must be quantified.

- Dust contamination from nearby vehicular and EVA activities, launches and landings.

  The observing environment should be as dust-free as possible. Contamination from launches and landings and from local dust generated by motion should be minimized. An approach is to establish an "Astronomy Preserve" dedicated solely to astronomy.

- Degradation of mechanisms and optics.

- Gas contamination from the habitat or other outgassing, and from launches and landings.

  Outgassing from the lunar base is expected to be of low density. Particles will follow a ballistic trajectory. Outgassing is not expected to be a serious threat.

- Thermal cycling over a lunar day.

- Diurnal electrostatic charging of the lunar surface.

These potential operational problems could be assessed by initial emplacement of several meter-class telescopes to evaluate operations under site-specific environmental conditions, test solutions to problems, and provide immediate scientific return.

The Lunar transit telescope and Planetary telescopes, for example, could provide continuous monitoring of planets, including the Earth, for atmospheric/climatological studies. These first instruments would be located at various distances from the lunar habitat (a local source of microseismic activity, and dust and gas contamination) and the launch/landing site (a potential source of high-velocity particulate and gas contaminants).

The selection of an equatorial site will necessitate a high level of shielding from solar and ground thermal cycles over the month-long lunar day. Monitoring the effects of this cycling on these testbed telescopes is critical to the evaluation of observatory performance at the lunar equator. Instrumentation should also be provided to determine the effect of diurnal electrostatic charging of the lunar surface arising from photoionization. This effect is thought to be latitude dependent.

Together, small precursor telescopes have a multi-functional role. Their instrumentation should span a broad spectral range, enabling the effects of site-associated environmental conditions to be evaluated for detector systems and optics which can be translated to future large and expansive facilities prior to their construction. On the Earth, this situation would be analogous to the small telescope used for site testing prior to the construction of a large observatory, with the exception that these meter-class precursors would also be significant research tools in their own right.

Report

of the

Space Physics Working Group

Lunar Outpost Site Selection Strategy Workshop

2-3 April, 1990

Working Group Members

Andrew Potter

Tom Wilson

Kenneth Lang

James Keith

John Freeman

SPACE PHYSICS FROM THE MOON

Introduction

The development of a Lunar Outpost will allow the investigations of fundamental problems in physics and space physics. Goals of space physics from the Moon fall into three primary categories: 1) phenomena affecting the Earth and humanity, 2) traditional space physics research including solar physics, solar-terrestrial interactions and particles and field investigations, and 3) fundamental physics in space that are made possible or greatly improved through observation and experimentation from the Moon, such as surface and condensed matter physics, cosmology, and basic particle investigations.

The Moon offers some unique advantages in the case of space physics as in the case of astronomy. The Moon is a stable platform with a continuous view of the Earth and its environment - the aurorae, the atmosphere, ionosphere and magnetosphere. The Moon allows high resolution observation of the Sun for as long as 14 days. The Moon's negligible atmosphere and magnetic field allow sampling of energetic particles from space at the Moon's surface without the scattering, absorption and production of secondaries, as is the case on the Earth. Low levels of light pollution and the absence of radio noise on the far side permit unique observations of the Sun and other celestial bodies.

The Space Physics Working Group considered the following instruments for purposes of discussion in formulating site selection criteria:

1. Earth Imager
2. Earth Sounder
3. Radiation Warning
4. Solar Constant
5. Radio Sun
6. Sun Imager
7. Radiation Monitor
8. Solar Wind Composition
9. Cosmic Ray Telescope
10. Large-Area Cosmic Ray Telescope
11. Gamma-Ray Telescope
12. Neutrino Telescope
13. Gravitational Radiation Laser Interferometer
14. Surface and Condensed Matter Physics Laboratory
15. Fundamental Physics Laboratory

Instrument Description and Objectives

Brief descriptions of the discussed instruments are given in Table 1. Of the instruments considered, only the Sun Imager, Earth Imager, Earth Sounder, Solar Constant and Solar Magnetic Field Instrument have requirements that pertain to the location of the Outpost.

Fundamental Site Selection Criteria

Criteria for location are based on view angle requirements, topographic considerations that simplify design, as is the case for astronomical observatories, and potential interferences from the Lunar Outpost. Criteria are:

1. The lunar outpost should be located near the equator for utilization of Sun observing observatories - The Solar Constant Observatory, The Sun Imager and The Solar Magnetic Field Observatory.

   The outpost should be located within ≠ two degrees of the equator for emplacement of the Sun Imager.

2. The Earth Imager requires a near side equatorial location for observations of the Earth and its aurorae, atmosphere, ionosphere, and magnetosphere in the UV/IR/V and radio spectrum and for observation of energetic neutral particles. Consequently, if the Earth Imager is emplaced at the Lunar Outpost, the outpost should be located at or near the equator.

3. The preferred location for the Earth Sounder is the far side anti-subearth point for observation of the Earth's magnetotail and magnetopause. However, if the Earth Sounder were to be emplaced at a near side outpost, the criterion for location would be the nearside subearth point for the Sounder.

The Space Physics Working Group also considered site criteria from the point of view of interferences with detection and experimentation. The detection of non-lunar gamma rays is sensitive to the gamma ray flux on the Moon arising from in-situ decay. It would be useful to select a site with low concentrations of radiogenic elements or map the abundances present at the selected site with sufficient precision and in time to allow effective experiment design. Therefore, the criterion for location of the outpost is:

1. Locate the outpost in an area that minimizes the indigenous radiation so as to reduce signal to noise in radiation detection, particularly gamma rays. Chemical mapping of the lunar surface is an important aspect of site selection.

2. The outpost should be located in a terrain that is suitable for the emplacement of large arrays and/or structures.

The Sun Imager is a solar observatory that uses the Moon as a stable platform for observing the Sun in the UV/IR/OP at a focal length of 1.5 km. Topography suitable for siting an instrument with such a focal length constitutes a criterion for site selection.

Some instruments considered (Table 1) must be located in the vicinity of the Lunar Outpost, the Lunar Environmental Stations, for example, but otherwise have no characteristics that are sensitive to location.

TABLE 1

SPACE PHYSICS FROM THE MOON

INSTRUMENT DESCRIPTIONS

SOLAR CONSTANT – Monitor long-term variations in the total solar output (the solar constant).

RADIO SUN – Early warning monitor of energetic solar flare events and tracking of these energetic particles in transit to the Moon or Mars.

SUN IMAGER – A lunar solar observatory that uses the Moon's stable platform for long-focal-length solar imaging in the UV-OP-IR range. Focal length 1.5 km. Resolve magnetic structures on very small scales to study coronal heating, magnetic reconnection, and flare energy release.

RADIATION MONITOR – A solar flare energetic particle detector that monitors the dose rate of solar cosmic rays, and measures the flux and mass composition.

SOLAR WIND COMPOSITION – In-situ measurement of the flux and mass composition of the solar wind (e.g. electrons and ions) and detector should have a wide field of view.

SOLAR WIND MAGNETIC FIELD – In-situ measurement of the magnetic field of the solar wind and the Earth's magnetotail.

SMALL-AREA COSMIC RAY TELESCOPE – Detect low-energy cosmic rays that cannot be observed from the Earth's surface because of absorption in the Earth's atmosphere. Long observing times possible.

LUNAR ENVIRONMENTAL STATIONS – Establish baseline data, monitor the effects of manned exploration activities on the lunar environment and search for natural transient or episodic events. A suite of instruments (a lunar environment station) will be deployed at several sites. These instruments will include: Dust Detector; Neutral gas Mass Spectrometer; Ion Mass Spectrometer; electron energy Spectrometer; Magnetometer; and Electric-field detector.

LARGE-AREA COSMIC RAY TELESCOPE – Conduct cosmic ray astronomy and investigate high-energy cosmic rays. Study secondaries from the interaction of cosmic rays with the lunar surface. Detect or provide stringent limits to anti-proton flux.

COSMIC ABUNDANCE OBSERVATORY – Measure abundances of cosmic ray nuclei at both low (<50 MeV/nucleon) and high (> 50 MeV/nucleon) energies.

LARGE-ARRAY X-RAY TELESCOPE – High-resolution, wide-field-of-view, long exposure, all-sky mapping without atmospheric background. Monitor X-ray bursts and supernovae, resolve structure of galactic center.

GAMMA-RAY TELESCOPE – Investigate the cosmic gamma-ray background at Gev energies. Search for gamma-rays from the annihilation of dark-matter particles.

NEUTRINO TELESCOPE – Search for diffuse galactic background neutrinos as well as supernovae neutrinos. Search for anti-neutrino spectra of reflect supernova. Perform neutrinos oscillation studies (Earth-to-Moon).

EARTH IMAGER – Image the Earth's atmosphere, aurora, ionosphere and magnetosphere from the Moon using visible, infrared, ultraviolet, radio, X-rays and energetic neutral particles.

EARTH SOUNDER – Lunar-based magnetopause and magnetotail sounder. Image the Earth's magnetic environment by exciting it with pulsed radio emission and detecting the reflected signal.

RADIATION WARNING – Early monitoring of current solar activity and flare prediction. Build up a capability with space stereoscopic views and space observations of the entire Sun at all times. Visual, X-rays and radio.

MICROMETEORITE DETECTOR – Detect the combined flux of micrometeorites and lunar secondary ejecta particles. Use velocity and directional detection to discriminate the two populations. Must be located at some distance from outpost to avoid particles generated by local activity.

Addendum to table 1

In August 1990, the Space Physics Division, Code SS, drafted a preliminary list of lunar base experiments, as follows:

- 0 Lunar Calorimeter
- 0 Lunar Neutrino Telescope
- 0 ENA/EUV Imager
- 0 Lunar Solar Observatory
- 0 Lunar Pinhole Occulter Facility
- 0 Sounder
- 0 LSSHAP

Lunar Calorimeter - Measure the spectrum and elemental composition of protons through iron up past the "knee" in the cosmic ray spectrum, including cosmic rays with energies from 10^{14} to 10^{17} eV. Use lunar regolith for bulk of calorimeter material to construct a large calorimeter (> 100 tons) on lunar surface.

Lunar Neutrino Telescope - Search for a diffuse flux of possible heavy neutrinos and for a directional flux of weakly interacting massive particle (WIMP) annihilation products from the Earth or Sun. Neutrino telescope to be constructed some 10 meters below the lunar surface, perhaps in the side of a crater or rille.

ENA/EUV Imager - Global/macroscale observations of magnetosphere, magnetotail, plasmasphere, and plasmasheet through Ultra Violet/Extreme Ultra Violet and Energetic Neutral Atom imaging. Lunar based observatory with neutral atom and scanning imaging instruments.

Lunar Solar Observatory - High resolution observations of the solar atmosphere across all wavelengths from gamma rays to radio. Develop lunar observatory over a two decade period, beginning with an optical telescope, then gradually adding instruments to expand wavelength coverage.

Lunar Pinhole Occulter Facility - Hard X-ray and gamma ray imaging of the Sun with very high spatial and spectral resolution. Use lunar surface to base a larger, higher resolution instrument than those currently proposed for Station or Shuttle.

Sounder - Conduct active sounding of the Magnetopause boundary to investigate its structure and dynamics. Use radio transmitter in 2-100 kHz range and phased array receiver on lunar surface to sound the Earth's magnetosphere.

LSSHAP - Solar Hazard Assessment and Prediction (SHAP), monitoring solar activity for SEI mission safety as well as scientific observations, from the Lunar Surface (LS).

Report

of the

Lunar Resources Working Group

Lunar Outpost Site Selection Strategy Workshop

2-3 April, 1990

Working Group Members

David McKay

Tom Sullivan

David Vaniman

Larry Taylor

LUNAR RESOURCES

Introduction

It has long been recognized that the Moon is a potential source of resources that may be employed at a Lunar Outpost to further development of the outpost, and as materials that may be exported from the Moon to Earth or to other planets or to space for use in spacecraft. The Resource Working Group considered lunar outpost site selection criteria from the point of view of the objectives of resource utilization. The objectives of resource utilization on the Moon at the Lunar Outpost are to:

1. Use local resources in support of Lunar Outpost
2. Learn how to "live off the land", self-sufficiently
3. Prepare for Martian resource utilization
4. Reduce long term lunar base operation and support costs
5. Increase outpost capabilities more quickly
6. Provide materials for use in space or on the Earth

The principal resources and materials that have been proposed as offering potential dividends either on the Moon, in space, or on the Earth are:

1. Oxygen
2. Hydrogen
3. Helium 3, and other volatiles (N_2, CO, CO_2, etc.)
4. Low tech building materials (shielding, bricks, ceramics, glasses)
5. High-tech products for construction, rocket fuel (metals, solar cells cement, concrete)

Use of local materials for radiation shielding will likely be the first application. Production of oxygen for propellant will likely occur early and will have significant cost-saving impact. As the lunar outpost evolves, greater self-sufficiency can be developed by using some of the co-products of oxygen production to provide metals, structural ceramics, and volatile compounds. This will generate the material necessary to expand the outpost with less support from Earth than would otherwise be the case. Helium 3 is a potential source of fusion energy that is available in large quantities only from the Moon.

The strategy of resources assessment and the development of Lunar Outpost site selection criteria as a function of resource availability is a complex problem because the criteria are fundamentally dependent on the process or processes that are selected for the extraction and the utilization of a particular resource. This is particularly true in the case of oxygen. The Moon is

rich in oxygen, nearly 50% by weight and over 90% by volume, and oxygen can be extracted in large quantities from any lunar material. The issue is cost-effectiveness which involves not only cost but safety, reliability, and long term maintainability. Cost-effectiveness criteria are dependent on process selection, a selection that will not be made for some time.

Site selection can be assessed in general, however, by considering the potential of various kinds of known lunar material relative to possible processes for using these resources.

Fundamental Site Selection Criteria

The resource potential of the Moon is a function of the chemical composition, mineralogy and petrology, and the maturity (length of time exposed to space) of the local materials. The resource potential for some products depends critically on the resource properties. For other products, the resource potential is relatively insensitive to the specific properties of the local lunar materials. In general, the products can be ranked by their sensitivity to the properties of the local materials:

MOST SENSITIVE

↑

- Hydrogen, helium-3, other volatiles

  The abundance of solar wind-implanted volatiles such as hydrogen and helium is closely related to the maturity and composition of the regolith. Abundance increases with exposure to the solar wind, and ilmenite tends to retain more of these elements than other minerals.

- Oxygen (process dependent ranking)

  Ilmenite is a potential feedstock for a number of different oxygen extraction processes. In addition, iron-rich compositions are important for other potential oxygen production processes.

- High-tech building materials (metals, etc.)
  Building and construction materials are not particularly sensitive to regolith properties.

- Low-tech building materials (shielding, bricks, etc.)
  Specific metal production (Ti, Fe) may only be practical at mare sites.

↓

LEAST SENSITIVE

Fundamental Criteria for Oxygen:

The Moon is oxygen-rich and all potential Outpost sites have abundant oxygen, but cost effective extraction of oxygen is a requirement and the technology for extraction may require feedstock compositions within a certain range. Consequently, there are two strategies that may be employed:

Strategy 1:	Site criteria based on feedstock flexibility Choose oxygen extraction processes that are site independent, *e.g.*, magma electrolysis or the fluoride process.
Strategy 2:	Site criteria based on a specific process and feedstock (*e.g.* ilmenite reduction or pyroclastic glass processing).

Selection of a strategy will be dependent upon the following factors and the weight given to each:

- power requirements
- plant mass
- mining volumes
- by-product types and potential value (volatiles, metals)
- beneficiation requirements
- complexity
- maintenance
- operational demands
- consumables required (electrodes, reagents, etc.)
- feedstock physical properties (soil vs. rock)
- development risks
- safety

Although a process may be developed that is so efficient that it would dictate a feedstock, it appears that the most reasonable course to follow is to maintain flexibility and adapt the oxygen extraction process to the site. If such is the case, the following site selection criteria result:

1. Mare sites preserve most resource options.

   - Plagioclase is a major mineral in mare material and can be concentrated if necessary.
   - Ilmenite is a major mineral in some mare basalt terrains, but is a minor or trace mineral in highland terrains.
   - Some mare terrains contain 3 to 4 times as much iron and more than 10 times as much titanium as typical highland terrains.

2. High ilmenite mare sites would be preferred.

   - Ilmenite can be removed from soil-rock feedstock if an ilmenite-free material is required, but ilmenite cannot be concentrated from an ilmenite-free (highland) feedstock.

- Iron-titanium rich materials have the lowest melting temperatures for molten magma processes.

Fundamental Criteria for Hydrogen (and Water):

Several sources of hydrogen are possible, namely:

1. As water at the poles in permanently shadowed areas.
2. In cometary materials emplaced by impact.
3. Magmatic water is possible but is extremely unlikely.
4. As solar wind implanted hydrogen in regolith materials exposed to the solar wind.

The most certain of these sources of hydrogen is solar wind implanted hydrogen in the lunar regolith. Hydrogen concentrations in the regolith have the following properties:

- Hydrogen abundance increases with exposure and, therefore, maturity of the regolith.
- Hydrogen is retained in ilmenite to a greater degree than in other lunar minerals, therefore, ilemnite-rich (titanium-rich) materials are superior sources.
- Finer grain sizes retain more hydrogen per gram than coarser grained materials. More mature soils are finer grained.

Consequently, the criteria for site selection that applies to hydrogen is to select an ilmenite-rich mare site with mature regolith. Pyroclastic (dark mantle) areas may offer an ideal combination of high maturity, high ilmenite content, fine grain size, and thick regolith. Areas to avoid for hydrogen:

1. Fresh large craters; immature regolith has had little time to collect solar wind
2. Steep slopes; difficult to negotiate with large mobile miner
3. Blocky areas; difficult to negotiate with large mobile miner
4. Thin regoliths; volumes of material inadequate for production

There exists a small chance that abundant water may be found in small local concentrations at the poles but that does not mean that it would be easy to extract. Ice at the poles would require machinery capable of operating at temperatures as low as 40° K. It is not at all clear that this would be a preferred option.

Finally, anomalously high concentrations of solar wind hydrogen may exist and should be sought with Lunar Observer. For example, the large magnetic anomalies such as Reiner gamma, may concentrate and focus the solar wind into local regolith areas, creating anomalously high concentrations of hydrogen and other solar wind species.

Fundamental Criteria for Helium 3 and Other Light Gases:

Helium 3 is implanted in the regolith by the solar wind, consequently, the criteria for selection of areas that may be helium-rich, relatively speaking, are the same as those for hydrogen. Helium 3, however, is in much lower abundance and much larger mining operations, processing significantly larger volumes of material, would be required.

Fundamental Criteria for Simple Building Materials:

Simple (low-technology) building materials include shielding material, sintered regolith or cast basalt bricks, ceramics and glasses produced from the lunar regolith. Mare areas have lower sintering and melting temperatures by about 200° C and consequently have lower power requirements than other materials. The plagioclase-rich materials typical of the lunar highlands produce a higher strength and more transparent glass (however, anorthite can be beneficiated from any soil for specific processes). Because most of these technologies involve heating the regolith to or near its melting point, the lower the melting point the lower the power consumption.

Some processing technologies (i.e., microwave), may require ilmenite-bearing feedstock for electromagnetic coupling.

The shielding properties of mare soil (ilmenite-rich) are superior for radiation protection. The higher density of the high titanium mare regolith promises to provide better protection from radiation.

The fundamental criterion for site selection based upon simple materials: A mare site is superior, but highland materials will work.

Fundamental Criteria based on Complex Materials:

More complex materials (or high technology materials) include metals for various construction and manufacture applications, solar cells, cement and concrete. Solar cells, as presently produced, use silicon, and silicon may be more easily extracted from highland materials, although plagioclase concentrated from mare material may be equally good feedstock. CaO-based cement may be more easily made from CaO-rich highland materials. But these materials are available at any site and their use, if any, will not develop until the Lunar Outpost is well established. Consequently, there are no fundamental site selection criteria that arise from the potential usage of lunar resources in producing complex materials.

Lunar Resource Criteria and Information Needs

The selection of sites based on considerations of resource potential would be significantly enhanced if the following data were available.

- Titanium abundance mapping

  at ~100 M spatial resolution (selected site areas for accurate volume/tonnage estimates.

- Iron abundance mapping

  at ~100 M spatial resolution (selected site areas for accurate volume/tonnage estimates.

- Maturity index (+/- 5%) mapping at 100 M resolution for selected sites, for reasons as above.

- Direct hydrogen detection and mapping

- Direct water/ice detection and mapping

It is, of course, possible that new observations and data would result in the unexpected, such as:

- Ice at poles
- Detection of Comet water in the regolith (bound or trapped)
- Ilmenite ore bodies
- Other oxide ore bodies
- Halogen ore bodies (utilize as flux for electrolysis processes)
- Extreme KREEP-rich ore bodies
- Extreme differentiated granitic ore bodies
- Other unexpected results with resource implications

New observations such as those that could be provided by Lunar Observer can provide a wealth of new data which will help us to more carefully choose sites with the highest resource potential. An exciting aspect of Lunar Observer is that it may reveal some totally unexpected surprises which could fundamentally change our approach to extracting oxygen, hydrogen, water, and other potentially very valuable products from native lunar materials.

TABLE 2

Ranking of Site Preference for Products

	USEFUL PRODUCTS (priority order)	LOW Ti MARE	HIGH Ti MARE (with pyroclastics)	HIGHLANDS
1	Oxygen*	2	1	3
2	Hydrogen	2	1	3
3	Helium-3, other light volatiles	2	1	3
4	Low-tech building materials (shielding, bricks, ceramics, glasses)	2	1	3
5	High-tech materials (metals, cement, concrete, glasses)	2	2	1

*ranking depends on oxygen extraction process selected.

Given the rankings shown in the table, we conclude that from the point of view of resource utilization, a viable strategy would be to select a high titanium mare site, perhaps on or near a pyroclastic area, and near a highland area so that calcium-rich feedstock would also be available.

LUNAR OUTPOST SITE SELECTION WORKSHOP

APRIL 2-3, 1990

WORKSHOP PARTICIPANTS

ASTRONOMY/ASTROPHYSICS

Faith Vilas	Team Leader, JSC
Harlan Smith	University of Texas
Mark Sykes	University of Arizona
Brad Hines	Jet Propulsion Laboratory
Paul Swanson	Jet Propulston Laboratory
David Talent	LESC
Christine O'Neill	JSC

SPACE PHYSICS

Andrew Potter	Team Leader, JSC
Tom Wilson	Co-Team Leader, JSC
John Freeman	Rice University
Kenneth Lang	Tufts University
James Keith	JSC

LUNAR GEOLOGY

Mark Cintala	Team Leader, JSC
Paul Spudis	USGS, Flagstaff
Don Burnett	CalTech
James Papike	South Dakota School of Mines
B. Ray Hawke	University of Hawaii
Paul Lowman	Goddard Space Flight Center
Tom Morgan	Code SL, NASA Headquarters
Graham Ryder	Lunar and Planetary Institute
Jeff Plescia	Jet Propulsion Laboratory

LUNAR GEOPHYSICS

Roger Phillips	Team Leader, Southern Methodist University
Lon Hood	University of Arizona
Yosio Nakamura	University of Texas, Austin

LUNAR RESOURCES

David McKay	Team Leader, JSC
Lawrence Taylor	University of Tennessee
David Vaniman	Los Alamos National Laboratory
Tom Sullivan	JSC