Site Selection strategy for a Lunar Outpost

A SITE SELECTION STRATEGY for a LUNAR OUTPOST

Science and Operational Parameters

Determining the Impact of Science and Operational Parameters for Six Sites on the Moon by Simulating the Selection Process

Conclusions of a workshop, 13 - 14 August, 1990

sponsored by the

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LUNAR AND MARS EXPLORATION PROGRAM OFFICE

A SITE SELECTION STRATEGY FOR A LUNAR OUTPOST

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FOREWORD

This report, **"Development of a Site Selection Strategy for a Lunar Outpost - Simulating the Selection Process,"** is the second of two reports sponsored by OSSA and OEAT that explore the problem of selecting a location on the Moon for a lunar outpost. The first report, subtitled **"Science Criteria for Site Selection,"** discusses multidisciplinary science criteria for site selection. The following report, subtitled "**Simulating the Selection Process,"** considers site selection more broadly. It represents an attempt to bring operational and science criteria together in a realistic way through considering the scientific and operational merits of six localities on the Moon that were specifically selected to be representative of a variety of potential sites. The characteristics of six sites were presented by advocates and the sites were then ranked as to their scientific and operational suitability. The results were instructive in revealing the complexities of site selection.

Copies of the workshop reports may be obtained from D.A. Morrison, SN14, Johnson Space Center, Houston, TX 77058.

EXECUTIVE SUMMARY

Introduction

Establishing an outpost on the Moon is a goal of the Space Exploration Initiative. The outpost will have a multitude of roles and its location on the Moon will be a subject of debate. A successful site selection strategy must incorporate the potentially competing interests of science, resource utilization, and operational constraints within the overall context provided by an overarching strategy for exploitation and exploration of the Moon.

A workshop was held at the Johnson Space Center in August of 1990 to continue development of a site selection strategy, building on an earlier workshop held in April of 1990 that developed multidisciplinary science criteria. The criteria for science resulted in limiting cases for outpost location (equatorial, near-limb sites would rank highest) but the criteria were developed in the absence of operational constraints and without considering whether or not the criteria could be implemented within an overall strategy. To explore the question further, the process of selection was simulated at the workshop. Six locations on the Moon, representing a range of choices in terms of latitude and longitude and in their responsiveness to science criteria and to possible operational requirements, were selected. The merits of the candidates' sites were discussed in terms of lunar geology, geophysics, space physics, astronomy and lunar resources and operational criteria. In addition, the impact of transportation system strategies (e.g., the use of lunar orbit rendezvous or direct descent , for example) was considered relative to the six locations on the Moon. The sites were ranked and the discussions resulting from the ranking plus guidelines from the Apollo Program experience form the basis for a series of recommendations concerning development of a site selection strategy.

The following paragraphs summarize the discussions that resulted from the simulation of the problem of choosing a site and the recognition of problems that currently exist or will exist in the process. Recommendations that would simplify the problem and provide an integrated approach are given following the summary.

Results of the Selection Simulation

The six candidate sites selected as examples for discussion were classified as equatorial (and limb or non-limb), mid-latitude and high latitude-polar. This geographic distinction reflects the consequences of transportation strategy. For the lunar orbit rendezvous mode, and with Space Station Freedom as a node, minimum mission duration is 13 days for equatorial sites, 35 days for mid-latitude sites and 27 days for high-latitude and polar sites.

Of the six sites considered (Mare Tranquillitatis, Mare Ingenii, Amundsen, Mare Smythii, Riccioli, and Aristarchus) the equatorial-near limb sites Smythii and Riccioli were most favored and the polar site Amundsen was least favored, however, the rankings of the six sites (excepting Amundsen) were approximately the same. No single site stood out as a clear winner. The following factors resulted in the lack of discrimination.

I. *The strategic vision for the outpost is not well defined.*

II. *Specific requirements for virtually every phase of operation or outpost use are non-existent.*

III. *Well-informed decisions will require global data from a Lunar Observer type of spacecraft.* Potentially attractive sites are not well enough documented to form reliable judgements about their suitability.

Although science criteria for a lunar outpost have been formulated, they are not mutually consistent, some criteria are competitive with others. Differences of opinion will exist even within the same discipline as to the relative merits of particular localities. Consequently, the following is appropriate:

I. *Weighting factors for science objectives should be developed.* (High rank should be given to a whole sky view - and this criterion may be a dominant factor in site selection).

II. *Agreement on an exploration strategy is required.* The discussions leading to formulating a strategy should consider the trade-off between the typical and atypical. Atypical localities may provide unique data but not form an adequate knowledge base for extension of exploration beyond the outpost location. A debate concerning a strategy for exploration should be encouraged.

The simulation of the selection process demonstrated the significance of the kinds of data necessary to determine whether or not objectives could be achieved at proposed outpost locations, apart from operational considerations. Only one of the sites considered (Tranquillitatis) has an adequate data base. It is evident that the site selection process is closely linked to the the availability of data vital for flight safety and for developing a science strategy.

I. *Safety considerations are paramount and will drive everything including operations scenarios.*

II. *The ranking of sites can be highly dependent on operations scenarios and assumptions* such as orbital transfer modes and surface transportation schemes employed that affect minimum mission time, minimum surface stay time and crew effectiveness.

III. *Operations scenarios may be (and possibly should be) driven by the steps in exploration that will follow lunar exploration or the establishment of an outpost.*

IV. *Surface certification requirements should be defined* (using the six sites selected, or others as examples).

V. *A detailed site survey plan that could be accomplished by a Lunar Observer type of vehicle should be developed.*

In general, the simulation process using site advocates was productive. It is not easy to distinguish sites at the current level of development. Operational strategies clearly can significantly broaden the range of viable sites in terms of location on the Moon.

Transportation:

Outpost locations, mission profiles and transportation system concepts (and strategies) are interrelated and should undergo frequent review as concepts mature. The transportation strategy employed should not constrain site selection (implying that it should allow global accessibility).

The lunar orbit rendezvous mode of operating at the Moon leads to an outpost location preference ranking based on operational simplicity as follows:

Most preferred	Equatorial sites
	Polar sites
	Mid-latitude - near side
Least preferred	Mid-latitude - far side

The use of Space Station Freedom as a low Earth orbit staging and recovery point imposes significant timing constraints. *The combination of a lunar polar orbit and SSF orientation results in trans-Earth injection opportunities separated by at least one month and, in some cases related to outpost location, up to two months.* If a lunar orbit rendezvous strategy is employed, then trans-lunar injection from SSF occurs on a 6 to 11 day cycle. Descent from lunar orbit to the outpost location is not necessarily immediate after lunar orbit insertion. *Depending on outpost location relative to the orbital plane, some delay, possibly measured in days, will occur as the outpost rotates with the Moon to a position coincident with the orbital plane of the spacecraft.* These timing problems are inherent in the lunar rendezvous mission mode and in the use of SSF. Their consequences must be thoroughly considered in developing a strategy.

Alternative transportation strategies relieve some of these constraints. There is a potential evolution in transportation - direct descent to libration point staging (both offering global accessibility) to lunar orbit rendezvous - that could be employed if the production of lunar oxygen at a lunar outpost becomes a reality.

Science and Mobility:

It is evident that lunar exploration and exploitation must involve global accessibility. *No single site satisfies all objectives. Transportation that is safe and allows traversing to locations in the vicinity of the outpost on a scale of tens to up to a hundred kms provides powerful leverage in site selection.* The traverse distances mentioned in most of the site descriptions are significant and would require long term operation (more than one work day) away from the outpost.

The tradeoff between long distance rovers, possibly pressurized, and their cost effectiveness versus the accessibility they provide - and alternate transportation modes such as "hoppers," is an essential study. The outcome will impact transportation strategy selected to establish and maintain a lunar outpost. The utility of telepresence and teleoperation will enhance exploration and exploitation abilities but cannot place humans at sites where their presence will be required, consequently, human mobility on the planet is an important issue that has significance for a site selection strategy.

Surface Operations:

Operations on the surface at a lunar outpost will be complex and it will be difficult to maintain appropriate standards of safety and efficiency. Certain fundamental data, regolith thicknesses, for example, are required to determine whether or not proposed operations at a site are indeed feasible and consistent with the resource materials present there. *The Apollo Program provides preliminary guidelines for site certification, but sustained operations call for a thorough knowledge of site properties and extension of the data base for hundreds of kms into the adjacent terrain.* A means of ranking sites could be based on the relative efficiency that a site may offer in terms of local operations. Topography, distances to targets, distances to resources, shielding factors (topographic shielding from cosmic rays) all have an effect on the efficiency of operations at a particular locality. The discussions illustrated that terrain types, on the scale of an outpost, are limited on the Moon. Development of an "envelope" of properties typical of major terrain types would provide fundamental data that would, in large part, satisfy "design to" criteria for design of machines to operate on the surface and of procedures for surface operations. Development of "design to" properties would be a useful service that would provide a means of ranking sites from the operational point of view.

Recommendations

A "Lunar Polar Orbiter" should be flown as soon as possible to provide the data base necessary to make sound scientific and operational judgements.

There should be further analysis of alternate orbital transfer modes to provide flexibility in operational scenarios and in the range of sites that would be accessible.

There should be further analysis of surface transportation modes that are decoupled from terrain considerations. The relative benefits of piloted and pressurized rovers versus vehicles capable of "hopping" or "flying" from one location on the surface to another should be assessed.

There is considerable multidisciplinary debate in the site selection process. A means of weighting criteria as a function of discipline would be useful. The capabilities that might be available for science at a site clearly have an impact on how science criteria would be weighted. Limited mobility, for example, would place greater weight on geological/ geophysical criteria to selectr a complex site that could be studied intensively and profitably with only local traversing than would be the case otherwise.

There should be study of means of creating mission assurance besides the "free return abort" mode. Free return is not possible with staging from Space Station Freedom.

A philosophy that supports developing a lunar infrastructure that may exist independently of future steps should be considered. This consideration should be a part of the overall development of the purpose and scope of a lunar outpost.

A SITE SELECTION STRATEGY FOR A LUNAR OUTPOST

Lessons from a Multidisciplinary Simulation of Selecting a Site for a Lunar Outpost

Conclusions of a Workshop, August 19-20, 1990
Johnson Space Center
Houston, TX

INTRODUCTION

The Space Exploration Initiative calls for establishing an outpost on the Moon early in the 21st century. A site selection strategy - a means for systematically reducing outpost location choices to the one site that represents the best possible choice - is an important element of outpost planning and is critical in determining the information that must be in hand to support the selection process. A site selection strategy includes four principal elements: science, operational considerations (both orbital and surface), resources and strategic purpose, as is illustrated in Fig. 1.

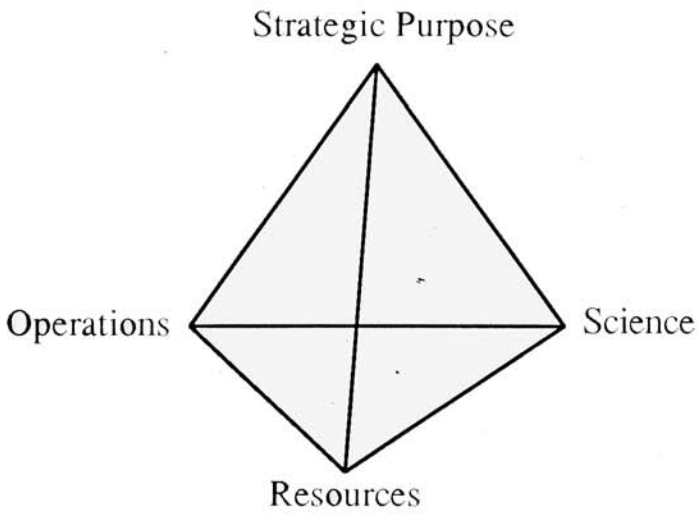


Figure 1: Essential elements of site selection. Criteria must be developed within the context of a strategic purpose or vision.

A workshop held at JSC in August, 1990, explored the relationship between science, operations and resources by conducting a simulation of the site selection process (participants are listed in Appendix I). Six potential outpost locations on the Moon were chosen to represent a range in latitude and longitude, terrain types and in scientific objectives. The locations selected represented east and west limb sites, an Apollo site, a high latitude and a polar site, and a location on the far side. The simulation exercise included the following steps

1. *Review of the Apollo Program.* As a framework for discussion of the merits of each locality, the criteria utilized by the Apollo Program were reviewed. A series of parameters based on the Apollo experience were developed to aid in ranking the sites relative to each other.

2. *Presentation of the sites.* The merits of the sites selected were presented based on their scientific potential, the operational implications arising from their location on the Moon, and their resource potential.

3. *Impact of transportation systems.* Operational constraints arising from fundamental decisions concerning strategy and the impact of flight systems and orbital mechanics on achieving goals at the sites selected were assessed and formed an important element in ranking the sites.

4. *Site assessment and ranking.* The six sites were ranked relative to each other utilizing a series of parameters based on the Apollo experience, and science criteria developed earlier. The rationale for the rankings were discussed and from these discussions a set of recommendations and conclusions were formulated as guidelines to the selection of a site for a Lunar Outpost. These recommendations complement those formulated based on science and resources criterion at an earlier workshop.

Science and lunar resource criteria for site selection were proposed at a multi-disciplinary workshop held in April at JSC (Science Criteria for Site Selection). These criteria formed the basis for site rankings based on scientific objectives. The criteria may be summarized as follows:

1. For purposes of astronomy, the lunar outpost should be located within 10 degrees of the equator and near the lunar limb. (Two locations selected for discussion satisfied this criterion).

2. For geological exploration, the outpost should be located near a mare/highland contact. (Four locations satisfied this criterion in the broad sense.)

3. For resource extraction, mature mare regolith offers the greatest flexibility, given present technology.

4. Large "flat" areas offer benefits for construction of large arrays and observatories.

5. Some experiments may be sensitive to the indigenous radiogenic background (i.e., K, Ur and Th rich regolith).

These criteria are not necessarily mutually consistent. One of the purposes of the simulation was to bring out competing interests, and the sites were deliberately chosen to present competing interests. High latitude or polar sites, for example, do not represent the first choice for purposes of astronomy. However, these criteria formed the basis for science ranking of the potential outpost sites considered in the simulation.

In addition, site selection must consider risk assessment - which includes operational capabilities, flight mechanics, and objectives - as well as the strategic purpose that the outpost represents.

The Apollo Program dealt with similar problems - the physics of the Earth-Moon system and the concern for human safety and mission success remain the same and the Apollo Program experience provides a basis for considering a site selection strategy for the Space Exploration Initiative. Parameters developed during the Apollo Program for assessing the suitability of sites from an operational perspective were adapted for use in discussions (Appendix II).

THE APOLLO PROGRAM EXPERIENCE

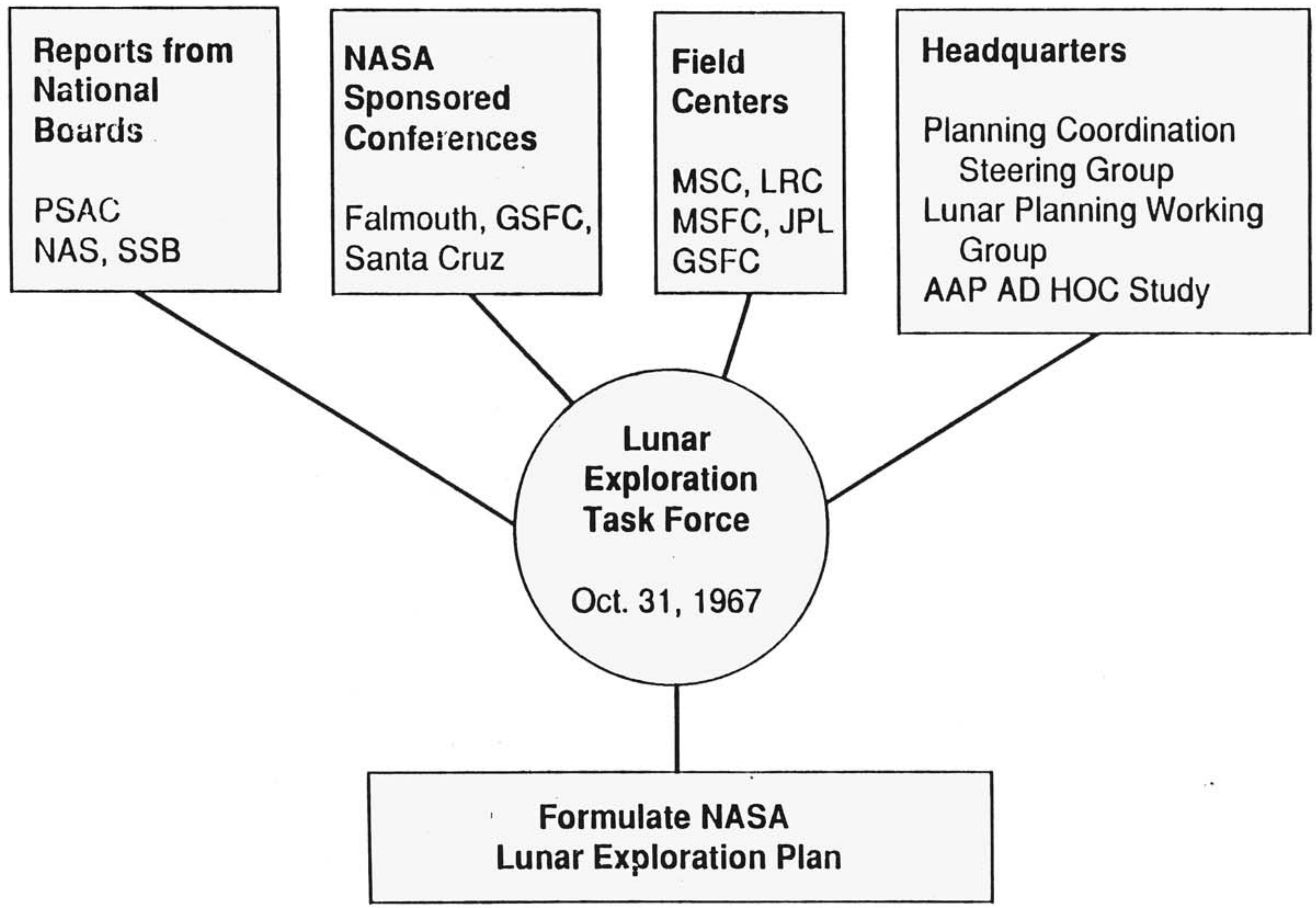
Site selection during the course of the Apollo Program was based on 1) safety, 2) science objectives established through a lengthy consultative process, and 3) evolving capabilities that developed as the program matured and experience operating at and on the Moon was gained. Lunar exploration plans were formed by the Lunar Exploration Task Force based on a series of studies that developed fundamental scientific priorities (Fig.1). Missions were classed as "H" and "J". H-missions were the first flown and were succeeded by "J" missions which had increased capability in mass deliverable to the Moon. Site selection was limited by abort requirements, sun angle requirements, and, most importantly, by the limited ability of the Lunar Excursion Vehicle to carry out extensive plane change maneuvers in order to rendezvous with the Command Module. This limited time on the surface to approximately three days.

A summary of the chronology of the Apollo Program is tabulated in Appendix III.

Figure 2 illustrates limitations based on abort and sun angle considerations. Potential sites were constrained to be within ± 5 degrees of the lunar equator for H-missions so as to provide for a free return abort capability. In the event of a failure to achieve insertion into lunar orbit, the spacecraft would be on a trajectory to return to Earth without requiring an engine firing. This criterion was modified subsequently for the J-missions to allow the possibility of a hybrid abort that would employ the Lunar Module engine for trans Earth injection in the event of a failure to achieve lunar orbit. This relaxation allowed access to higher latitudes. The sun angle at landing was required to be equal to or less than 20 degrees in order to have maximum terrain definition (details emphasized by shadows) for the piloted landings. This criterion limited sites to 45 degrees east or west longitude.

8 x 10 Km landing ellipses were defined for each potential site. "Smooth" ellipses were required. Smoothness was defined by a probability statement that considered slope frequency, crater distributions and the frequency of rough terrain such as crater ejecta sheets. The "smoothness" of potential sites was determined using lunar orbiter imagery and extrapolations made possible by Surveyor and Ranger data plus study of terrestrial analogues. A ranking factor, the "N" factor, was devised that expressed the "smoothness" of a site and considered the precision landing capabilities in devising tests of success. Simulations were run that incorporated terrain characteristics, navigation and guidance and landing ellipse dimensions, and the number of successful landings per N number of attempts was calculated. The "N" factor served to rank site suitability in a semi-quantitative way while taking into account the abilities of the methods and equipment. Because the vehicles were piloted and the final touchdown point was a pilot decision, the criterion was the probability of being able to translate to a suitable spot within the decision time allowed by the fuel remaining at touchdown. It was not necessary to be able to demonstrate that the landing point was certain to be free of obstruction.

Site selection involved prime and backup sites for the first missions to the Moon (the H-missions). Because of launch window constraints (based on sun angle requirements and lunar rotation), the prime and backup sites had to be separated by 23-1/2 degrees along the


Reports from National Boards
PSAC
NAS, SSB
NASA Sponsored Conferences
Falmouth, GSFC, Santa Cruz
Field Centers
MSC, LRC
MSFC, JPL
GSFC
Headquarters
Planning Coordination Steering Group
Lunar Planning Working Group
AAP AD HOC Study
Lunar Exploration Task Force
Oct. 31, 1967
Formulate NASA Lunar Exploration Plan

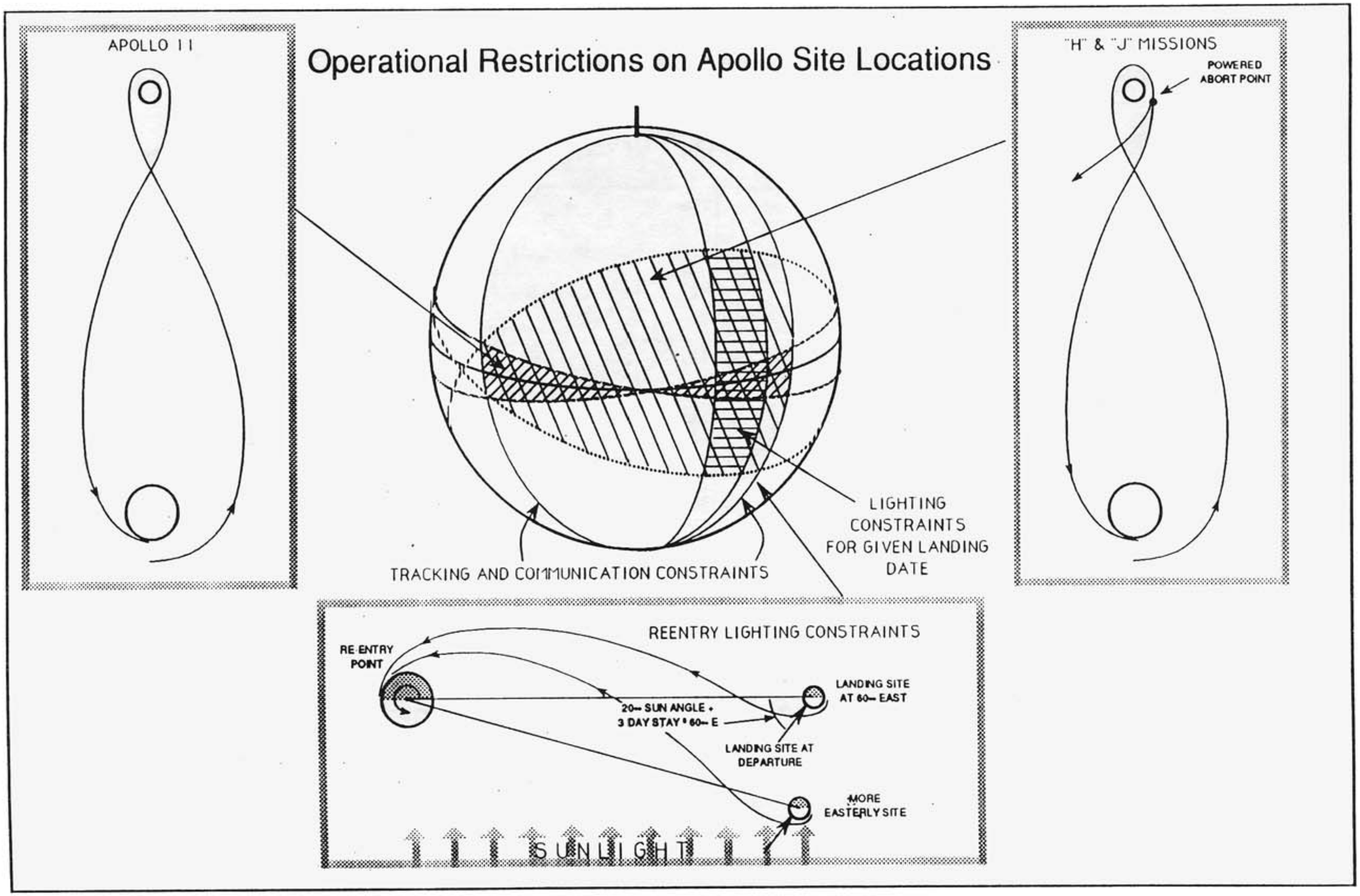


Figure 2: Operational constraints during the Apollo Program. Abort requirements, the capabilities of the Lunar Module and the requirement for 20 degrees or less sun angle on the lunar surface for illuminating sunlight limited the range for acceptable locations on the Moon to the area shown.

Significant Dates in the Site Selection Process

	1964				1965				1966				1967				1968				1969			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Ranger			VII		VIII IX																			
Surveyor										I				III	V	VI	VII							
Lunar Orbiter											I	II	III	IV	V									
S/OUC Meetings[1]							XX			X	XX	X	X	XX	X	XX								
ASSB Meetings[2]									X	X		X	X			X	X		X			X	X	
Apollo																						11		12

ASSB & S/OUC Formed in August 1965

[1] S/OUC - Surveyor/Orbiter Utilization Committee
[2] ASSB - Apollo Site-Selection Board

Some Characteristics of Lunar Orbiter Photographs

Mission	Typical spacecraft altitude, km	Photo characteristics (average values)					
		Medium-resolution frames			High-resolution frames		
		Photo scale (GRE scale)	Ground resolution, m	Framelet width,[a] km	Photo scale (GRE scale)	Ground resolution, m	Framelet width,[a] km
Photographs of near side							
Mission I:							
Exposures 5 to 27, 29, 31 to 34, 41, and 42	240	1:420 000	40	7.60	1:55 000	5 to 10	1.0
Other exposures	55	1:96 000	10	1.75	1:12 500	≈40	0.23
Mission II	50	1:87 000	10	1.60	1:11 400	1	0.21
Mission III	55	1:96 000	10	1.75	1:12 500	1	0.23
Mission IV:							
Perilune photos:							
Equatorial regions	2710	1:4 700 000	500	86	1:620 000	60	11
Temperate regions	2940	1:5 100 000	500	93	1:670 000	64	12
Polar regions	3520	1:6 100 000	600	111	1:800 000	76	15
Apolune photographs[b]	5650	1:9 800 000	1000	180	1:1 300 000	120	24
Mission V:							
Extreme value	97	1:169 000	20	3.1	1:22 000	2	0.4
Extreme value	243	1:423 000	40	7.60	1:55 000	5	1.0
Photographs of far side							
Mission I	1375	1:2 400 000	240	43	1:[illegible]10 000	[illegible]0	[illegible]
Mission II	1500	1:2 600 000	260	48	1:[illegible]40 000	[illegible]0	[illegible]
Mission III[c]	1463	1:2 500 000	260	46	1:[illegible]0 000	[illegible]0	[illegible]
Mission IV: Apolune photographs[b]	6150	1:10 700 000	100	195	Not applicable		
Mission V:							
Exposures 5 to 30							
Extreme value[d]	2548	1:4 400 000	450	81	1:580 000	[illegible]	[illegible]
Extreme value[d]	5758	1:10 000 000	1000	183	1:1 [illegible]00 000	[illegible]	[illegible]
Other exposures:							
Extreme value[e]	1181	1:2 000 000	200	37	1:[illegible]0 000	[illegible]	[illegible]
Extreme value[e]	1396	1:2 400 000	240	44	1:[illegible]0 000	[illegible]	[illegible]

± 5 degree equatorial band dictated by the free return abort requirement for the H-mission set. Later missions (the J-mission set) were not so limited.

Mission design for landing involved radar guided approaches to the target ellipses until an altitude was reached at which the pilot could assume manual control. Radar guidance required the development of terrain profiles accurate enough to allow precision landings. These terrain profiles were generated with stereo imagery obtained by the Lunar Orbiter missions. The existence of stereo imagery was an important criterion for J-mission site selection.

Precursor Information

Apollo 11 was preceded by the sequence of missions shown in the table "Significant Dates in the Site Selection Process" - Ranger, Surveyor and Lunar Orbiter. These missions characterized the lunar surface and the Moon in a complementary way.

Ranger data provided a series of images increasing in resolution at three localities. The images showed that the cratering phenomena was present at all levels of resolution, that the surfaces were relatively benign, and provided some confidence in extrapolation of properties from low resolution imagery. Physical properties such as bearing strength, however, remained a matter of speculation.

Surveyor missions provided basic soil mechanics data, showing that the lunar surface could sustain a vehicle and that the bearing strength of the surface material, and other properties, were within ordinary experience for a particulate. Imagery of the surfaces and basic chemical data for lunar material were provided for the first time. This kind of information from 5 different localities on the lunar surface provided a critical context for interpretation of Lunar Orbiter imagery.

The Lunar Orbiter missions, beginning in mid-1966, three years before Apollo 11, provided the primary site selection data. The table "Some Characteristics of Lunar Orbiter Photographs" shows the essential characteristics of each Orbiter mission in terms of the imagery returned. "Resolution" of the high resolution mapping phase of each varied from meters to hundreds of meters. Object recognition was several times less than the resolution shown. Lunar Orbiter imagery formed the basis for photogeologic studies of the Moon and for the production of maps photogrammetrically. These two products were fundamental in site selection for all missions, particularly the J-missions following Apollo 11. In addition, stereo coverage from which to produce topographic maps and terrains profiles for radar guidance requirements was extremely important. Stereo coverage was essential for a site to be considered. The data required consisted of surface roughness and slope distribution.

Surface roughness was defined as 1) discrete protuberances or objects (in 4-foot size range) on a relatively smooth surface, 2) a pattern of small scale (10-foot crest-to-crest) slopes or ridges, 3) cracks or depressions, and 4) a pattern of jagged protuberances.

Slope information needed was defined as 1) the percentage of a landing area exceeding a slope of 20°, 2) whether the pattern of slopes within a landing area were parallel or random-crested, and 3) for areas with parallel crests, a measurement of the median crest-to-crest distance.

Ranger, Surveyor and Lunar Orbiter supplied the necessary information in the opinion of the Apollo Program to make site selection decisions for the first several missions. Later missions provided vital data (the pan and metric camera photography) for selection of areas not well represented in Lunar Orbiter photography.

Because the Apollo missions were piloted, actual requirements for surface knowledge could be less than those that might be required for automated landings because of the ability of the pilot to re-designate the point of landing. But the estimates of surface properties of the Moon made from Ranger data served well enough to target the Surveyor spacecraft, none of which failed because of terrain problems.

The parameters used in the Apollo Program were adapted for use in the simulation of selecting a location for the Lunar Outpost. These parameters are described in Appendix II.

THE SITE SELECTION PROCESS

Introduction

One way to grasp the complexity of site selection is to simulate making choices. To this end, six locations on the Moon were selected as representing a reasonable range of outpost locations in terms of latitude and longitude, including near side versus farside, and in objectives. The six sites represent a diversity of terrain types and properties. The characteristics of the six sites were assessed in terms of science, resources and operations. Their properties and attributes were presented to workshop participants who then ranked them following the "site assessment" parameters represented in Appendix II.

The following ground rules were established to govern the decision-making process.

1. *The Lunar Outpost will be established at one location.* A single outpost site was considered to prevent diffusion of the issues and limit the range of possibilities. This proviso is consistent with the national strategies that have been discussed.

2. *Basic site certification data is provided by precursors.* This assumption eliminates site ranking on the basis of operational data, the requirements for which have not been established. This assumption did not include science objectives certification. Whether or not specific objectives can be met at a locality is a matter of debate. The data required for science objectives certification is not necessarily encompassed by site certification data because the area of operations can be much larger.

3. *First piloted landing is constrained by lighting, communications, and launch window requirements.* There are operational implications associated with locations on the Moon as a function of latitude and longitude and the node of the longitude of the spacecraft. Although an automated human landing could be achieved at a site previously visited by precursors, the possibility that humans will be required in an emergency dictates that the conditions at landing be compatible with human requirements such as lighting and Earth-to-spacecraft communications.

The six locations selected for consideration in the simulation are shown in Fig. 3. They are:

1. Mare Tranquillitatis (34.9N, 39.4E)

2. Mare Ingenii (35S, 165E, far side site).

3. Riccioli (3.5S, 74W, limb site)

4. Amundsen (88S, 60E, pole site)

5. Aristarchus (23N, 48W)

6. Mare Smythii (1.7N, 85.8E, limb site)

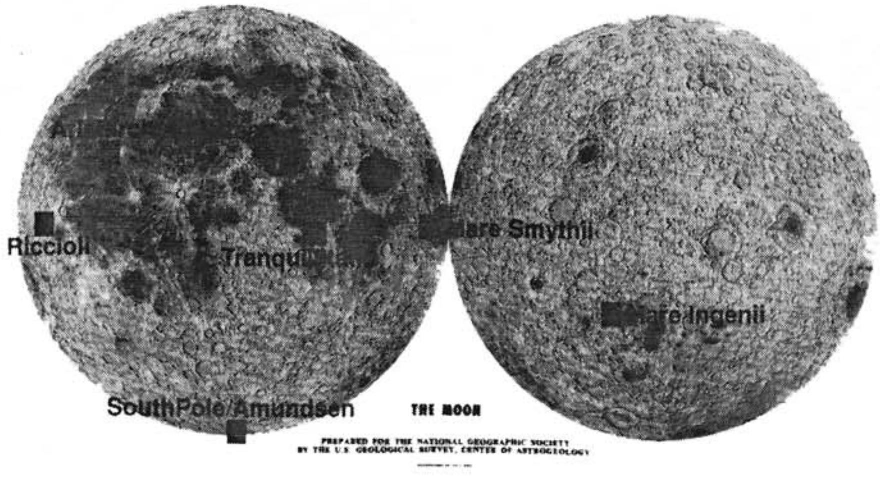


Figure 3. Index photo showing the six site locations selected.

These locations were selected to serve as examples only of potential outpost sites. They were selected to represent a range of responsiveness to criteria based largely on science requirements. They represent all of the major terrain types (mare, highlands etc.) on the Moon. Some data are available to rank them relative to major science objectives and requirements, particularly for lunar geosciences, and the data for some are much more complete than for others, a useful difference in considering the kinds of data that are necessary to have on hand in selecting a site. The number of sites considered in the simulation was limited to six for the sake of expediency but the six sites include the major classes of sites on the Moon.

Each site was evaluated by an independent site advocate (Appendix 1) according to a standard format as follows:

I. Principal Characteristics
II. Geoscience Goals
III. Geoscience Objectives (keyed to a map of the outpost)
IV. Astronomy and Space Physics (how well the site satisfies their location criteria)
V. Resources (based on oxygen production potential and construction materials)
VI. Operational Constraints (limitations imposed by flight mechanics)
VII. Summary

The merits of the candidate sites were presented to workshop participants who were divided into two groups - a "Review Board" that ranked the sites specifically and that included representatives from all of the interested communities (See the Review Board participants in Appendix 1), and a group that considered the questions of location versus objectives more generally.

The site rankings that resulted from discussions are reflected in the tables in the following section.

Candidate Site Descriptions

ARISTARCHUS

Aristarchus (Fig. A-1) is a high-latitude site of significant geologic interest. The following summary of its properties and its utility as a candidate site was prepared by B. Ray Hawke of the University of Hawaii.

Principal characteristics:

Coordinates: 23°N, 48°W
Near Side High Latitude Site
Earth View Constant
Mare/Highland Site
Volcanic Constructs

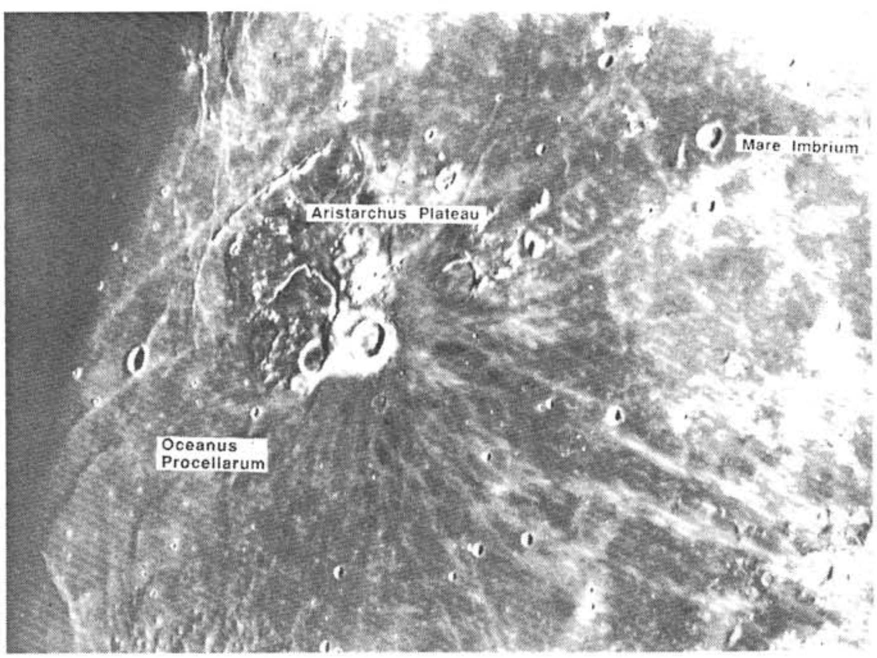


Figure A-1. Location of the Aristarchus Plateau in Northern Oceanus Procellarum. The geosciences goals are listed in table A-1 and specific objectives in table A-2.

Table A-1: Geosciences Goals at Aristarchus

- Determine the composition and stratigraphy of the lunar crust in the Aristarchus region.
- Investigate the composition and age of Imbrium basin deposits.
- Study impact cratering processes
  - Aristarchus crater
  - Smaller craters near outpost
- Determine the origin of sinuous rilles
- Study explosive volcanism
  - Classic dark mantle deposit
  - Source vents
- Determine the ages, compositions, and stratigraphy of mare basalt deposits
- Determine the origin of the thorium anomaly associated with Aristarchus
  - KREEP basalt
  - KREEP plutonics

Table A-2: Geoscience Objectives at Aristarchus

Number	Name	Dist.(km)	Objectives
1	Aristarchus crater	52	A Copernican-aged impact crater (dia = 40km) which should expose Imbrium ejecta as well as pre-Imbrian material.
2	Aristarchus plateau pyroclastic deposit	0	This dark mantling unit should be tens of meters thick in the vicinity of the outpost.
3	Cobra-head crater	28	The apparent source vent for the sinuous rille on the floor.
	of Vallis Schroteri	17	This is the largest and most conspicuous of all lunar sinuous rilles.
5	Aristarchus A crater	63	This young impact crater (dia = 10km) should expose highland debris from beneath the surface of the Aristarchus plateau.
6	Aristarchus secondary crater	10	Study of these typical secondaries will help provide answers to questions concerning secondary impact processes.
7	Herodotus crater	38	A flooded, Imbrian-aged impact structure (dia = 35km)
8	Eratosthenian mare unit	81	A low albedo, very blue basalt deposit southwest of the plateau.
9	Herodotus chi	99	An olivine-rich mountain which may expose pre-Imbrian material.

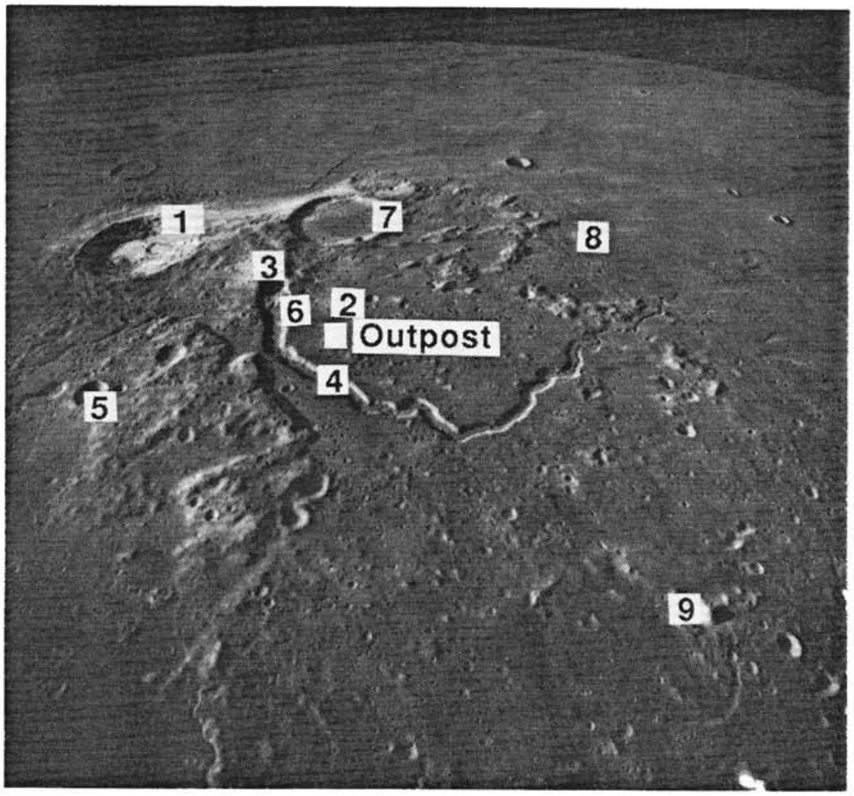


Figure A-2.

Table A-3: Astronomy and Space Physics at Aristarchus

- Astronomy

  Criteria for astronomy are not satisfied:

  - Site is not within 5° - 10° of mean lunar limb
  - Site is not within 10° of lunar equator
  - Still, many useful observations could be conducted from outpost on the Aristarchus plateau
  - Suitable topography for observatory construction
  - Nearside location would allow Earth observation

- Space Physics

  - Good location for most space physics observations
  - Terrain is suitable for the emplacement of large arrays and structures
  - Poor location for Earth Sounder
  - High concentration of radiogenic elements in Aristarchus region would complicate detection of non-lunar gamma rays

Table A-4: Resources at Aristarchus

- Oxygen
  - Site offers great flexibility
  - Located on a pyroclastic deposit composed of Fe-rich glass
  - Mare basalt present immediately north of outpost
  - Highlands material nearby
- Hydrogen, helium, and other solar wind gases
  - Large volumes of mature regolith are present
  - Moderate TiO_2 abundances
- Building materials
  - Mare composition of pyroclastic material (lower melting temperature than highlands material)
  - Highlands units nearby for other raw materials (e.g. anorthite)
  - Deep, loose pyroclastic debris would be ideal for quickly covering outpost modules with shielding material
- Other considerations
  - Lunar pyroclastics are enriched in certain surface-correlated volatile elements (Cu, Pb, AN, Cd, etc.)
  - Certain elements contained in KREEP would be useful
  - Pyroclastics excellent for mining operations
  - Extreme KREEP-rich or granitic ore bodies may be present in region

Table A-5: Operational Constraints at Aristarchus

- High Inclination Orbit
  - Limited Ascent/Descent Opportunities

Table A-6: Summary of Aristarchus as an Outpost Site

- The best site for geoscience investigations
- Major problems are addressable
  - Development and evolution of the crust and mantle
  - Impact History
  - Basin formation and chronology
  - Nature of impact processes
  - Eruption dynamics
  - Genesis of mare basalts
  - Origin of enigmatic features

• High resource potential of Aristarchus region

• Good location for most space physics observations

• Pyroclastic debris would be ideal for quickly covering outpost modules with shielding material

• Exciting location which would inspire public interest

MARE INGENII OUTPOST SITE

Mare Ingenii (Fig. I-1) is a high latitude site on the lunar far side. It was selected as representative of a far side site that combined advantages of shielding from the Earth with a location of significant geoscience interest. The following summary of its properties was prepared by Jeff Taylor, University of Hawaii.

Principal Characteristics:

Coordinates: 35°S, 165°E
Far Side High Latitude Site
Earth Shielded
Mare Site

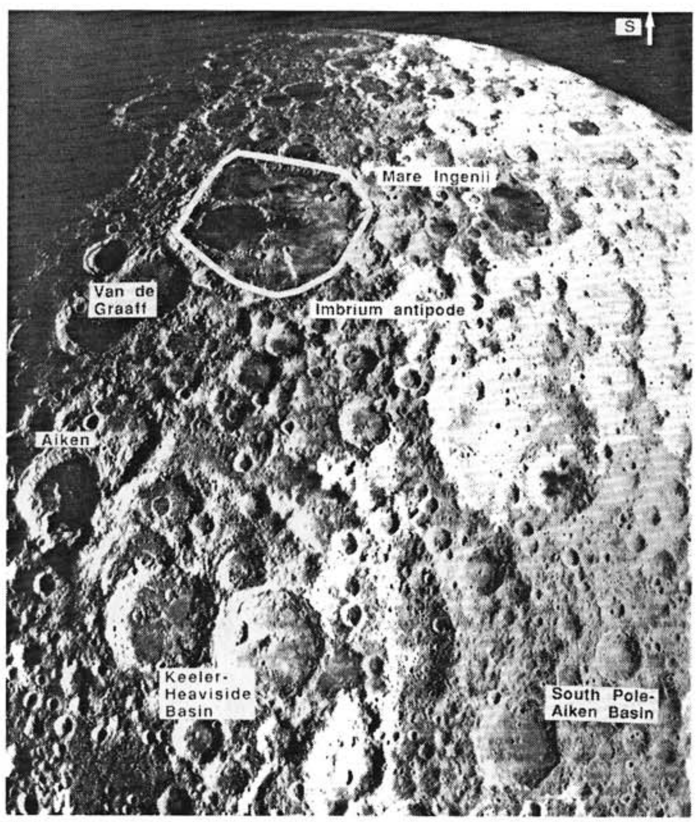


Figure I-1. Location.

Table I-1: Geosciences at Mare Ingenii

- Date South Pole - Aiken Basin
  - Sample impact melt from that basin
  - Date overlying basins and craters
- Determine origin of bright swirls
  - Obtain oriented basalt samples for paleomagnetic measurements
  - Sample regolith on bright and dark areas for solar wind measurements
  - Magnetometer traverse across swirls
  - Install solar-wind monitors across swirls
  - Best target is a traverse from outpost to number 2
- Determine origin of furrows on Ingenii rim
  - Field studies of structures
  - Sample debris in furrows (to search for Imbrium ejecta)
  - Best targets are numbers 2 and 6
- Determine age of Ingenii basin
  - Sample Ingenii impact melt
  - Best targets are numbers 8 and 11
- Determine Ingenii basin structure
  - Install local seismic network
  - Lay seismic lines across basin rim
  - Do geophysical traverse across basin rim
- Determine basalt compositions, ages, and stratigraphy
  - Collect surface samples
  - Stratigraphy from crater ejecta and possible rilles
  - Best targets are numbers 1, 2, 6, 7, 10 and the outpost site
- Study cratering mechanics
  - Field studies of craters
  - Collect samples of melt sheet, floor deposits, rim, ejecta blanket
  - Best targets are numbers 3, 5, 7, and 10

Table I-2: Geoscience Objectives at Mare Ingenii

Number	Name	Dist.(km)	Objectives
Outpost		<5	Swirls, mare basalts and vents (?) highland rocks
1	Swirls	25	Swirl boundary, mare basalts
2	Mare/Highland boundary	100	Mare/highland boundary, explore highlands, study furrows, geophysical traverse across basin ring
3	Fresh crater deposits	85	Crater deposits
4	Thompson crater rim	20	Highlands; large crater rim
5	O'Day impact melt	100	Ejecta (including melt) from O'Day Crater
6	Ingenii rim	70	Furrows and lithologies in highlands, mare stratigraphy in rilles (?)
7	Ingenii floor	35	Mare stratigraphy revealed by crater
8	S.E. Ingenii floor	80	Hummocky basin floor
9	Ingenii E. wall	100	Basin ring, highlands
10	Thompson floor	80	Mare basalt stratigraphy revealed by crater
11	NVV Ingenii floor	100	Basin floor to sample impact melt

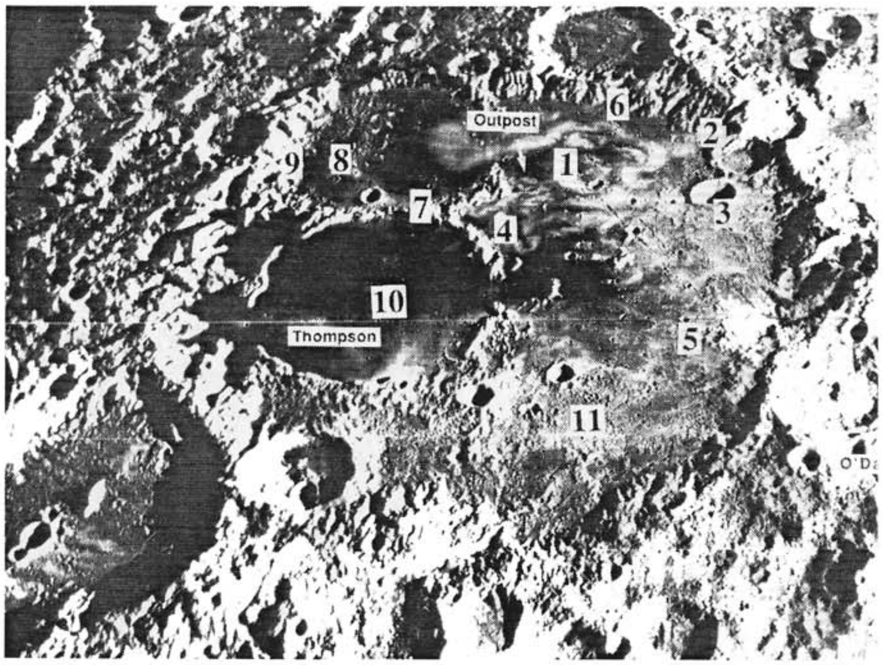


Figure I-2. Traverses.

Table I-3: Astronomy and Space Physics at Mare Ingenii

- Excellent site for very-low frequency array
  - Shielded from Earth at all times.
  - Thompson Crater (80km) provides large, flat area for ease of deployment; all of crater floor visible from rim.
- Very good site for optical-W-IR interferometric array.
  - Can be located on flat plains far from base and mining operations.
  - Farside location eliminates light contamination from Earth.
- Excellent site for radio astronomy in general
  - Shielded from Earth.
  - Many craters in which to construct Arecibo-type dishes.
- Generally good location for space physics observatories
  - Excellent location for Earth Sounder - On farside - Not far from anti-subearth point.
  - Reasonable location for the Sun Imager - Good topography for deployment.
  - Low gamma-ray background (in Ingenii, probably).

Table I-4: Resources at Mare Ingenii

• Oxygen

- Mare site, so offers flexibility
- Ti content unknown; might be moderate

• Hydrogen, helium, and other solar-wind gases

- Regolith mature (basalts are 3.5 Gy old)
- Moderate ilmenite content

• Building materials

- Mare site, so melting temperature lower than highlands
- Highland nearby for other raw materials (e.g., abundant anorthite)

Table I-5: Operational Constraints at Mare Ingenii

• High latitude site limited ascent/descent opportunities

• Communications relay required

Table I-6: Summary of Mare Ingenii As An Outpost Site

• Addresses fundamental questions in geoscience

- Basin chronology
- Basin formation
- Effects of basin-forming events
- Origin of magnetic anomalies
- Mare basalt genesis and lunar mantle evolution
- Cratering mechanics

• Excellent site for lunar observatories

- VLF array opens up new wavelength window
- Optical array deployment easy and shielded from site
- No earthshine

• Excellent site for sounding Earth's magnetosphere

• Complex operations help us get to Mars

- Need to communicate with farside
- Crew cannot see Earth (psychological adjustments)
- Overall more difficult than nearside (pushes technology)

MARE SMYTHII OUTPOST SITE

Mare Smythii is a site on the eastern limb of the Moon near the lunar equator and, as such, that satisfies the primary location criteria for astronomy. In addition, the outpost location is near the mare-highland contact, fulfilling the principal requirement for location of an outpost. The following description of the properties of the Mare Smythii site was prepared by Paul Spudis of the USGS.

Principal Characteristics:

Coordinates: 1.7°N, 85.8°E
Equatorial Limb Location - Earth View Intermittent
Mare-Highland Contact - Outpost on Mare

Table S-1: Geosciences Goals at Mare Smythii

- Highlands and crustal processes
  - Smythii basin: ejecta, impact melts, pristine highlands rocks from depth (> 50 km), basin rings
  - Highlands crust: thickness from seismometry, heat-flow measurements, traverse geophysics
  - Other basins: Smythii terra floor material-Crisium ejecta (?); date large craters for cataclysm
- Mare units and lunar volcanism
  - Mare Smythii basalts: young [~1 Ga (?)], very high-Ti, thin (~ 500 m) total fill (stratigraphy?)
  - Dark mantle: high-Ti (?) pyroclastics, vents and bedded deposits, xenoliths, eruption processes
  - Floor-fractured craters: mechanism of floor uplift, subsurface, volcanic fill and pyroclastics
- Cratering processes and history; regolith development
  - Regolith trench at Outpost: layers, soil-bedrock interface, solar history
  - Comprehensive sample of craters: flux changes through time, melt compositions, ejecta emplacement
  - Large crater processes: rays, ejecta stratigraphy, ejecta emplacement (Peek, Schubert C, Camoëns)

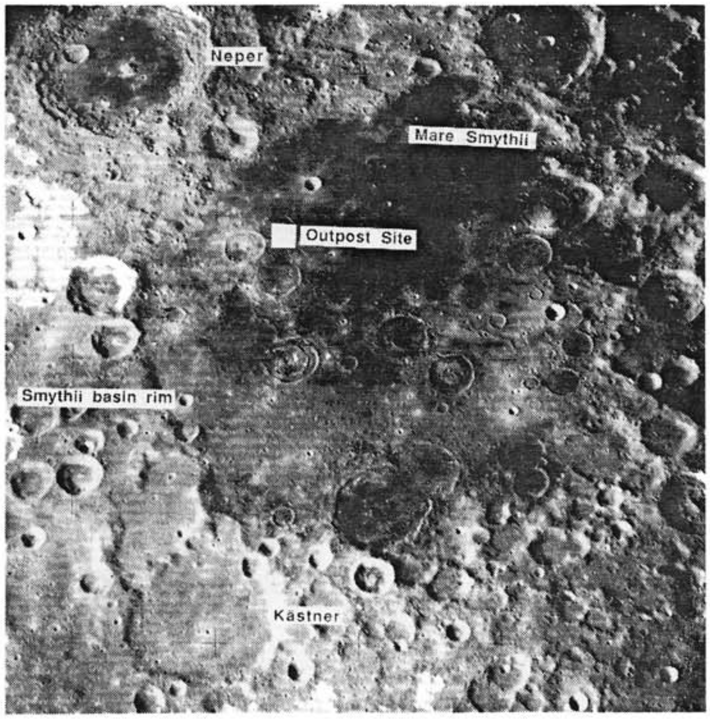


Figure S-1. Location.

Table S-2: Geoscience Objectives at Mare Smythii

Number	Name	Dist. (km)	Objectives
1	Ray crater	37	Fresh impact crater; age and composition
2	Massif	13	Basin massif (highlands) protrudes through mare
3	Peek	48	13 km crater through mare; age, compos., stratig.
4	Crater	75	4 km crater; age, compos., stratig.
5	Crater	60	3 km crater; age, compos., stratig.
6	Ray craters	13	< 1 km craters in highlands (basin floor)
7	Dark mantle	90	Thick, regional dark mantle; pyroclastics
8	Highlands	30	Basin floor and melt breccias; ejecta from Camoëns
9	Camoëns	42	Floor-fractured crater, pyroclastics, basalt fill
10	Vent	72	Pyroclastic vent and rille; bedded deposits
11	Vent	60	Pyroclastic vent; bedded deposits
12	Schubert C	35	Floor-fractured crater, basalt fill
13	Cracked-floor crater	70	Unusual floor material- basin secondary crater (?)
14	Basin rim	75	Highlands; basin melts, pristine rocks **(relay site)**
15	Wrinkle ridge	18	Fault scarps; field study of tectonics
16	Crater	10	< 1 km crater; age, compos., stratig.

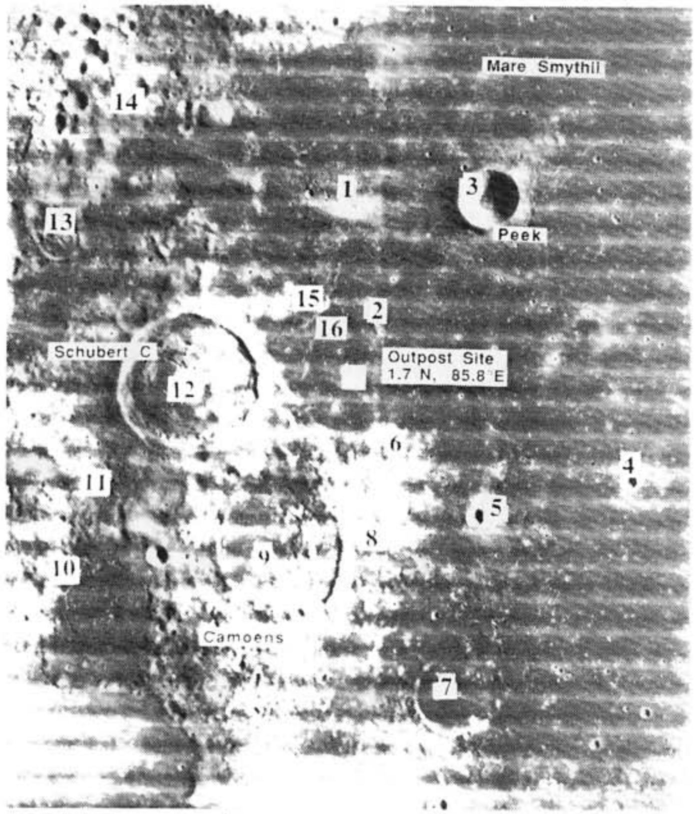


Figure S-2.

Table S-3: Astronomy and Space Physics at Mare Smythii

- Mare Smythii as an astronomical observatory

    - Approximately on equator (1.7°N), so entire sky visible
    - On limb (85.8° E), so Earth constantly on or near horizon
    - Far side is close to Outpost: max. libration longitude (98°E) is 360 km away
    - Good site for very low-frequency radio interferometer
    - Smooth, flat mare site for optical and radio arrays available
    - Bowl-shaped craters (e.g., Peek, 13 km dia.) available for radio-telescopes

- Mare Smythii as a space physics laboratory

    - Site is near equator, so sun imager requirement is satisfied
    - Global Earth imager feasible, but near-horizon location of Earth makes observations difficult
    - Magnetospheric imager cannot see full magnetosphere at this location
    - Low-KREEP content of this site results in low indigenous radiation environment

Table S-4: Resources at Mare Smythii

- Very high-Ti mare basalts and regolith
  - Orbital data suggest Apollo 17-type mare basalts (up to 8 wt. % Ti)
  - Basalts young, so regolith relatively thin (< 1 to 4 m thick; median ~2 m)
  - Ilmenite disaggregated by regolith development and separable for ilm. reduction
  - Regolith generally less mature than Apollo ll-type; solar wind gas concentration unknown
- Highlands materials
  - Orbital data suggest high-Al soils make up Smythii basin rim (up to 12 wt.% Al)
  - Highlands regolith is extremely thick (> 30 m) and mature; mostly agglutinates
  - Highlands material present in minor quantities at Outpost in mare soils
- Other resources
  - Very high-Ti (?) pyroclastic glasses abundant; "pure" deposits within 60 km of Outpost
  - KREEP materials very rare here; nearest deposits at Balmer (600 km away; low-grade deposits)

Table S-5: Operational Constraints of Mare Smythii

- Outpost at 1.7° N, 85.8° E; not in constant view of Earth (need radio relay at ~ 83° E)
- Near-equator; easily accessible in LOR transportation mode
- In "excluded" zone for direct-descent transportation mode; need trans-lunar coast maneuver
- Pre-landing trajectory (if descending from retrograde orbit) or postliftoff trajectory (if heading to posigrade orbit) will be obscured from Earth tracking.
- Outpost site flat and smooth; young mare, so many angular blocks and thin (< 2 m) regolith
- Total relief in region small; rover traverses should be easy to plan and execute

Table S-6: Summary of Mare Smythii As An Outpost Site

- Mare Smythii site offers excellent science opportunities and resource possibilities
  - Geosciences: highlands composition and crustal magmatism, basin and cratering processes, mare volcanism, thermal and tectonic history, regolith growth in early stages of formation
  - Astronomy and Space Physics: equatorial, limb site, whole sky visible, flat terrain for interferometers, low indigenous radiation (poor in KREEP)
  - Resources: ilmenite abundant in very high-Ti mare basalt regolith (ilm. reduction for O_2; solar wind gases (H_2) on ilm. grains), high Al highlands regolith, volatiles on pyroclastic glasses

- Mare Smythii site poses some minor operational difficulties
  - Young basalt flows means thin regolith, many angular blocks; difficult Outpost emplacement?
  - Need maneuver during trans-lunar coast to reach Smythii in direct descent mode
  - Outpost location beyond 82° E longitude means Outpost will observe Earth radio silence; need repeater
- Virtues of Mare Smythii site greatly outweigh difficulties; site offers excellent opportunities to every potential user of a Lunar Outpost

RICCIOLI OUTPOST SITE

Riccioli is located on the west limb of the Moon near the lunar equator and represents an alternative to Smythii in terms of suitability for astronomy siting. In addition the site is of geoscience interest. The following summary of its properties as a candidate for a location of a lunar outpost was prepared by Paul Lowman of the GSFC.

Principal Characteristics:

Coordinates: 2.5° S, 83° W
Near Side Limb Site
Earth View Constant
140 KM Diameter Crater with Mare Fill

Table R-1: Geosciences at Riccioli

- Age, structure, origin of Orientale Basin (youngest large multi-ring basin); nature of impacting projectile; cratering mechanics
  - Radial and concentric transects of Hevelius Formation, with sampling, traverse geochemistry, reflectance spectroscopy, gravity, magnetic surveys, reflection seismology.
- Age, composition, structure, origin of pre-Nectarian highland crust; age and nature of first differentiation of Moon
  - Mapping and petrographic study of non-melted fragments ("pristine") in Hevelius Formation and exposed in Riccioli rim and central peaks.
- Age, composition, eruptive history of Riccioli mare fill; history of lunar magnetism
  - Mapping of mare basalts in Riccioli, sampling, reflection profiling, core drilling for study of paleomagnetism.
- Nature, extent, and age of post-mare volcanism; composition and structure of lunar mantle, lower crust.
  - Mapping and sampling of rilles and chain craters in Riccioli, esp. deep crust and mantle fragment.

- Nature and origin of light plains material: impact, volcanic, both?
  - Mapping and sampling of Hevelius Formation and intergrading light plains material NE and SE of Riccioli rim.
- Age and structure of mascon basins
  - Sampling, mapping, geophysical profiling of NW rim of mare-filled crater Grimaldi (mascon) Traverse across Grimaldi with geophysical surveys when possible (over 100 km from Riccioli Outpost)
- Structure and age of graben systems, i.e., fractured floor craters
  - Mapping and geophysical surveys of grabens in floor and rim of Riccioli

Table R-2: Geoscience Objectives At Riccioli

Number	Name	Dist.(km)	Objectives
Traverse I			
1	Central Peak of Riccioli	At site	Uplifted deep crustal material, probably with thin cover of Orientale ejecta.
2	Mare fill, floor of Riccioli	2 - 40	Mare basalt; regolith few meters deep overlying one or more basalt flows. Occasional impact craters.
3	Transverse facies of Hevelius Formation	60	Probably deceleration dunes of Orientale ejecta. Ridges consisting of thoroughly mixed fluidized ejecta consisting of fragmental impact debris from pre-Orientale highland crust (pre-Nectarian).
4	Light plains material on NE outer rim of Riccioli	90	Low relief, heavily-cratered, intermediate albedo material, thick regolith. Probably analogous to Cayley. Formation. Either fluidized ejecta or volcanics; nature unknown.
Traverse II			
5	Rilles and chain craters, with dark halo, cutting Hevelius Formation inside rim of Riccioli	35	Probably volcanic features, specifically diatremes. Fragmental one volcanic material, possibly with hydrous minerals (e.g., serpentine?). Deep mantle material in ejecta. Possible gas accumulations in NW subsurface. Area cut by NW-trending grabens, mantled by Hevelius Formation.
Traverse III			
6	SE rim of Riccioli	90	Light plains material outside rim, partly covered by younger lobate flow of similar material. Low relief, heavily-cratered, intermediate albedo, thick regolith. Younger lobate flow probably fluidized Orientale ejecta (see above); older material ejecta or volcanics; nature unknown.
7	SE rim of Riccioli;	80	Pre-Nectarian material. High relief, thick regolith. Probably crest of rim. lifted pre-Riccioli highland crust; nature unknown.
8	Volcanic vents or rilles in SE floor of Riccioli	50	Probably diatremes with associated flows and fragmental ejecta. See 5 above.

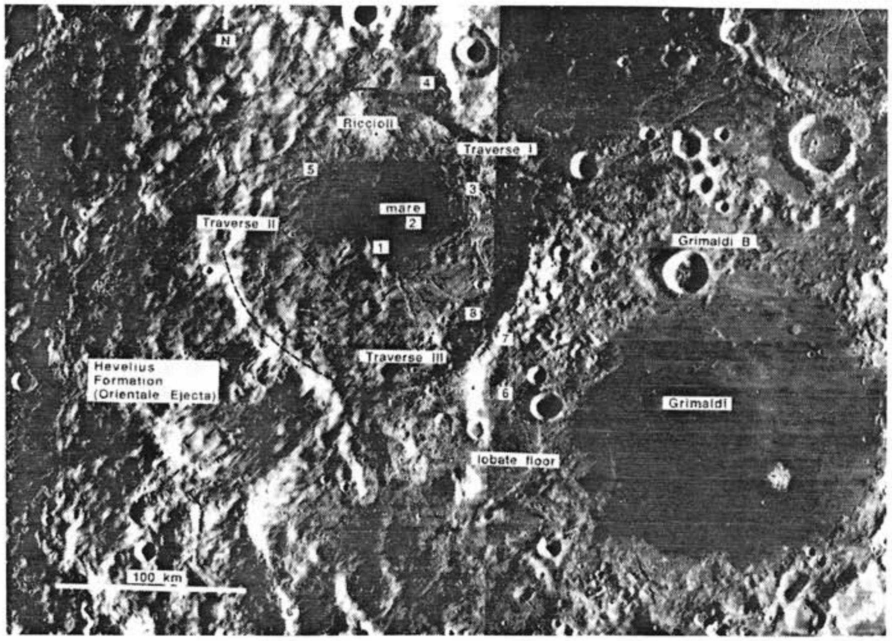


Figure. R-1.

Table R-3: Astronomy and Space Physics at Riccioli

- Characteristics of Riccioli as an Observatory Site
  - Assumption: Main outpost and observatory facility is on top of central peak of Riccioli, as shown on photos: some instruments on surrounding mare if desirable.
- Advantages
  - Longitude of 83 deg. W and site location on central peak insures continuous line of sight to Earth at all librations.
  - Latitude of 2.5 deg. S provides visibility of almost entire celestial sphere over one month. Sun Imager could be located on mare at 2 deg. S, just north of central peak.
  - Topography favorable to siting of any astronomical instrument: central peak surrounded by mare. Mare excellent location for Optical Interferometer; other instruments on central peak.
  - Regolith on central peak probably thick (tens of meters), permitting burial of radiation - or temperature-sensitive instruments.
  - Region is low in KREEP, minimizing regolith radiation that could affect instruments, esp. gamma ray detectors.
- Disadvantages
  - Like any earthside location, Riccioli is subject to VLF interference from auroral kilometric radiation (but AKR of interest itself), and SETI subject to terrestrial and outpost-generated RFI.
  - Central peak location for main outpost + observatory is also important geologic site; geologists may spend some years ravaging terrain.

Table R-4: Resources at Riccioli

- Hydrogen, Helium-3, other volatiles Fe, Mg, Ti

  - Mare basalts covering crater floor; Ti content not known
  - Possibly in ejecta from diatremes, dark-halo craters, chain craters
  - Possibly in subsurface gas reservoirs, structural traps associated with (2) or with grabens

- Oxygen

  - Mare basalt and associated regolith, esp. Ti-rich areas
  - Any other area, e.g., Hevelius Formation

- Aluminum

  - Feldspathic highland rocks, esp. Hevelius Formation

- Construction materials: shielding, bricks, tiles, etc.

  - Areas of thick regolith, specifically Hevelius Formation, central peaks, Riccioli rims, walls, light plains material - Mare basalts; good for Fe-rich material, lower melting point; for cast basalt pipe, etc.

General Prognosis: Riccioli Crater contains deposits considered useful for all types of material resource extraction, including volcanic areas (mare and non-mare), within ca. 50 km of outpost site. More information of Ti distribution needed.

Table R-5: Operational Constraints of Riccioli

- Wide variety of structures, rock types, landforms. Good access on surface from Riccioli Outpost. Wide variety of apparently volcanic features (beside mare basalt material).

- Area always visible from Earth; ground-based pre-mission telescopic study, radar study possible.

- Extremely complex local history; several major impact basins superimposed (Riccioli, Grimaldi, Orientale). Hevelius Formation covers much of area.

Table R-6: Summary of Riccioli As An Outpost Site

- Combines high geoscience interest with near-perfect astronomical characteristics, high resource potential, trafficable and workable terrain, and high dynamic accessibility from or to lunar orbit.

- Area is of great geologic interest: flank of youngest large multi-ring basin (Orientale); adjacent to mascon mare basin (Grimaldi); central peak, mare fill, volcanic features, fractured floor crater exposures of western limb highland crust; access to Oceanus Procellarum when long-range traverses possible (Reiner Gamma, Marius Hills, Aristarchus).

- Mare floor of Riccioli provides good landing field, base for interferometer arrays, resources. Central peak probably climbable by wheeled vehicles; north ridge slope not over 30 deg. Thick regolith on central peak, adjacent Hevelius Formation.

• Area close enough to far side for surface access when long range surface traverses possible. Adjacent highlands analogous to Fra Mauro Formation, probably easily traversed.

• Public relations value: location permits flashing strobe light at outpost to be telescopically visible from Earth at convenient time, i.e., first quarter to gibbous. Mare fill makes Riccioli easily identified with binoculars at full Moon.

SOUTH POLE/AMUNDSEN OUTPOST SITE

Amundsen is a large crater near the lunar south pole. Selection of this site for consideration explored the advantages and disadvantages of a polar site. Jeff Plescia of JPL prepared the following description of the characteristics of the Amundsen site.

Principal Characteristics:

Coordinates: 88°S, 60°E
Near Side, Polar Location
Near Limb - Earth View Constant
Highlands Site

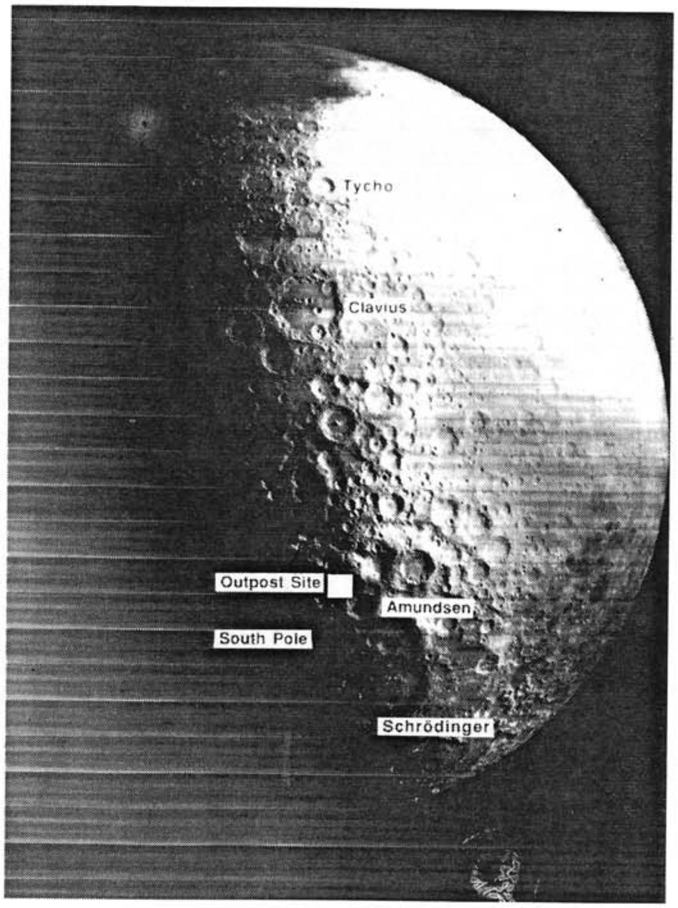


Figure AM-1.

Table AM-1: Geosciences Goals at Amundsen

- Highlands and crustal processes
  - Crustal composition: all sites, lateral variations on 100 km scale, from depths up to 15 km (central peak)
  - Highlands crust: thickness from seismometry, heat-flow measurements, traverse geophysics
  - Deep crust: Schrodinger basin ejecta, South Pole-Aitken basin ejecta
- Cratering processes and history; regolith development
  - Regolith trench at Outpost: layers, solar history, volatiles in permanently shadowed areas (?)
  - Comprehensive sample of craters: flux changes through time, melt compositions, ejecta emplacement
  - Large crater processes: ejecta stratigraphy and emplacement, central peaks and melt sheet studies (Amundsen)
  - Basin processes: isolated massifs (basin under Schrodinger), South Pole-Aitken basin massifs and crater retention age of the highlands

Table AM-2: Geoscience Objectives at Amundsen

Number	Name	Dist.(km)	Objectives
1	Amundsen A flank	80	Highlands crust; breccias, pristine rocks
2	Amundsen A rim	30	15 km crater into rim of Amundsen A; ejecta
3	Amundsen A floor	35	Ejecta from Amundsen; pre-existing floor units
4	Amundsen flank	90	Ejecta from Amundsen (100 km dia.)
5	Amundsen central peak	85	Peak from 12-15 km depth; crust, pristine rocks
6	Schrodinger ejecta	85	Distal margins of 300 km dia. basin ejecta
7	Amundsen L	100	25 km dia. crater; crust from 3-4 km depth
8	Massif	70	Rim massif of extremely old, 300 km dia. basin
9	Pole	75	20 km dia. crater; permanently shadowed floor (?)
10	S.Pole-Aitken basin massif	83	Largest basin on Moon; melt breccias, highland crust
- POWER -			
A	Rim of polar crater	65	Continuous sunlight (?)
B	Peak	70	Continuous sunlight (?)

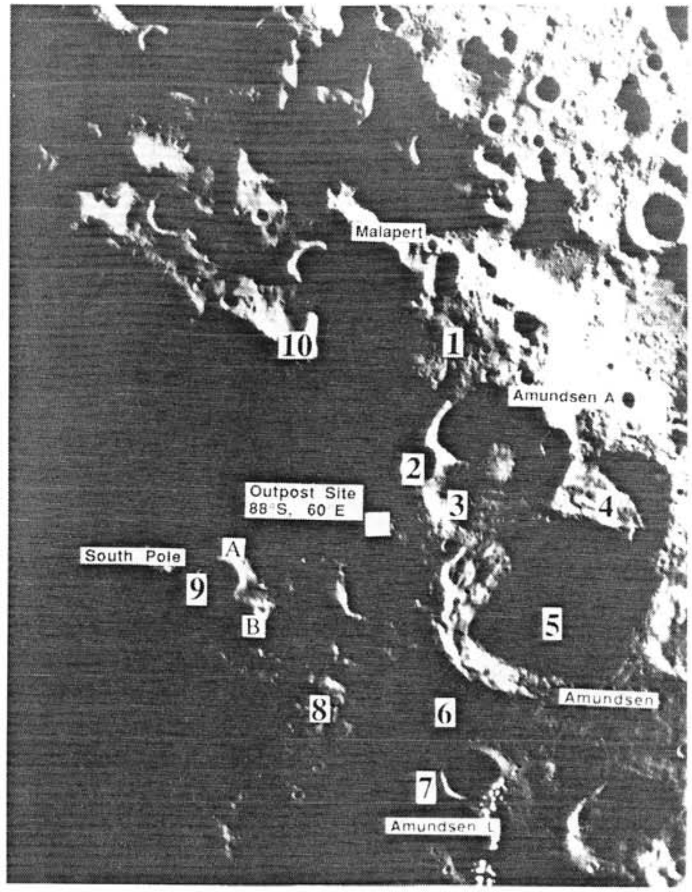


Figure AM-2.

Table AM-3: Astronomy and Space Physics at Amundsen

- South Pole/Amundsen as an astronomical observatory
    - Polar site, so only one-half of sky (southern hemisphere) is visible
    - On limb (88°S, 60°E), so Earth constantly on or near horizon
    - Far side is close (within 100 km) to Outpost; possible site for VLF interferometer
    - Flat areas rare to non-existent; may be difficult to erect arrays
    - Bowl-shaped craters available for radio-telescopes
- South Pole/Amundsen as a space physics laboratory
    - Sun is always near horizon (< 5°) so sun imager may have difficulties
    - Earth is always near horizon, so Earth imager may have difficulties
    - Magnetospheric imager cannot see full magnetosphere at this location
    - KREEP content unknown, but possibly moderately high-indigenous radiation (?)

Table AM-4: Resources at Amundsen

- Highlands materials
  - Cratered terrain suggests thick (~30 m), mature highlands regolith
  - Al content unknown, but probably moderately high (at least 10 wt.% Al)
  - Trace element concentrations (e.g., KREEP) unknown, possibly present in moderate quantities based on analysis of KREEP distribution within opposite margin of South Pole-Aitken basin
- Volatile elements
  - Polar crater (20 km diameter) may have permanently shadowed floor; other permanent shadows may exist close to pole
  - Presence or absence of cold-trapped volatiles awaits testing by polar-orbiting spacecraft
  - No pyroclastics identified in area
- Solar power
  - Two potential locations identified for continuous illumination; awaits testing by polar orbiting lunar spacecraft

Table AM-5: Operational Constraints of Amundsen

- Outpost close to pole (88°S, 60°E); direct descent or LOR transportation modes easily supported
- Pre-landing trajectory (if descending from retrograde orbit) or post-liftoff trajectory (if heading to posigrade orbit) may be obscured from Earth tracking
- Outpost within constant Earth view throughout libration cycle; ease of communications
- Far side within 100 km of Outpost; set up VLF radio astronomy array
- Terrain is rugged cratered highlands; flat areas rare to non-existent (difficult to set up surface arrays); may make rover traverses difficult to plan and execute
- Sun always < 5° from horizon; surface operations may be difficult
- If continuous sunlight available, solar energy may ease Outpost power requirements
- If polar volatiles available, could greatly facilitate propellant/consumables production

Table AM-6: Summary of Amundsen As An Outpost Site

- South Pole/Amundsen site offers some science opportunities and potentially great resource possibilities

  - Geosciences: highlands composition and crustal magmatism, basin and cratering processes, regolith processes and growth, possibly volatile history on lunar surface; *no volcanism, or tectonism*

  - Astronomy and Space Physics: only southern hemisphere of sky visible, rough cratered terrain (flat areas rare), poor observation site for Earth and Sun (both always on horizon)

  - Resources: *Potential:* large quantities of volatiles in permanently shadowed regions, continuous sunlight for solar power (2 possible sites identified), possible high KREEP areas. *Known:* mature, high Al highlands regolith, *no mare basalt resources (including ilmenite)*

- South Pole/Amundsen site offers both operational advantages and disadvantages

  - Polar site results in easy, continuous access in direct descent or LOR modes

  - Outpost in constant radio view of Earth, but far side is close (100 km)

  - Terrain is rough and hilly; surface traverses may be difficult to plan and execute

  - Lighting is always from very low sun angles (<5 degrees), so surface operations may be difficult.

- Potential resource virtues of South Pole/Amundsen site are great, but must be tested by polar orbiting spacecraft to determine feasibility of this site.
  Science opportunities are present, but limited; operational aspects are similarly mixed.

TRANQUILLITATIS OUTPOST SITE

The Tranquillity site revisits an Apollo location. Data available are adequate (for landing safety and materials properties at the site) and includes ground truth, particularly useful for assessing resources potential. Selection of this site explores the questions inherent in revisiting an Apollo site. The following description was prepared by Dave Vaniman of the LANL.

Principal Characteristics:

Coordinates: 3.87°N, 38.39°E
Near-Side Equatorial Location
Earth View Constant
Mare Site

Figure T-1.

Table T-1: Geosciences Goals At Tranquillitatis

- Access to several major mare-basalt types
    - Probable wide age range
    - Above the "continental shelf" of a major basin
- Access to variety of mare volcanic features
    - Crater-chain and probable shield vents, vents with rille associations
    - Enigmatic Eratosthenian mare units
    - Old lavas at highland contacts
- Wide variety of accessible "islands" and "promontories" of pre-Imbrian to Imbrian highlands
- Possible basalt outcrops
    - Paleomagnetic and fossil regolith studies
    - Domes, chain craters, and linear rilles

• Shallow lava fill (~250 m, + 250 m)

  - Intersecting basin rims suitable for geophysical exploration

• Heat-flow studies facilitated

  - Site is 100 km from major highland contacts
  - Low-KREEP regolith

Table T-2: Geoscience Objectives at Tranquillitatis

Number	Name	Dist. (km)	Objectives
1	Old volcanism	80	Early-Imbrian lavas, >3.8 Gy (highland composition?)
2	Young volcanism	65	Eratosthenian deposits <3.2 to ? Gy (pyroclastic?)
3	Shield volcanoes	95	Central Tranquillitatis
4	Chain craters and isolated volcanic craters	35 - 100	Linear rille with chain craters, Near Secchi B
5	>7 Copernican impacts	100	"Extinction impact" calibration (esp. Taruntius F)
6	>7 Eratosthenian impact structures	100	Taruntius E, at 70 km
7	>25 highland islands or promontories of Imbrian and pre-Imbrian age	15-100	Pre-Imbrian hills to SE at 85km
8	Basin-ring intersections	15-100	Tranquillitatis, Nectaris, Fecunditatis, Crisium Serenitatis

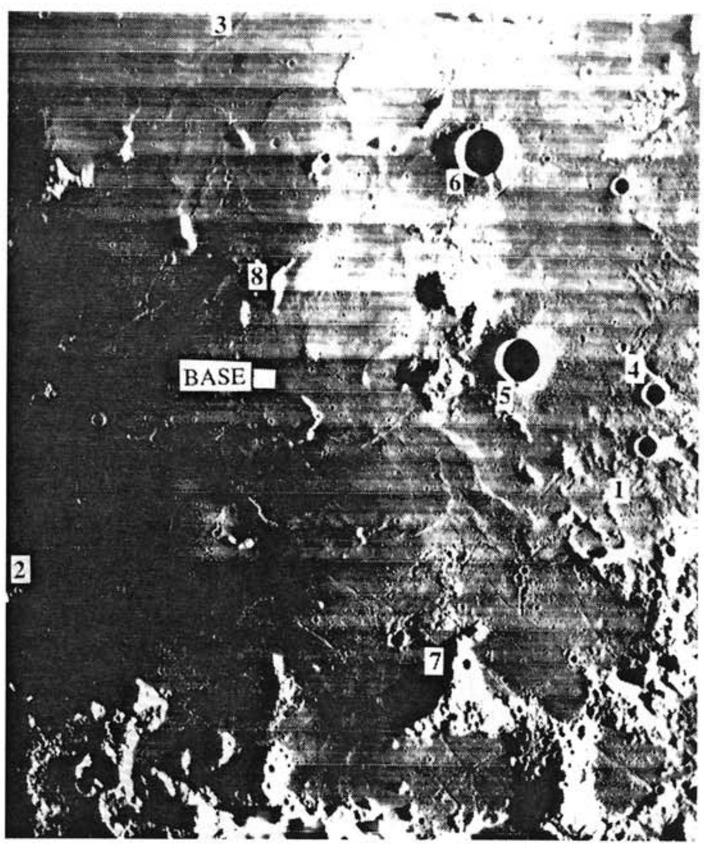


Figure T-2.

Table T-3: Astronomy and Space Physics

- Observatories
  - Location within 4° of the equator allows observation of both northern and southern skies
  - 6.7° inclination of Moon's rotational axis to its orbital plane will allow at least part-time access to all of the southern realm
  - Location at 52° from the limb will limit those observations affected by earthshine, unless adequate shielding can be provided.
  - Location at 52° from the limb will allow effective Earth observations (aurora, solar eclipses) and telemetry
  - Sun Imager at 2° north of equator would be 55 km from base (possible location also for optical interferometer, closer to equator and far from base vibrations)

Table T-4: Resources at Tranquillitatis

- Spectrally "blue" mare basalts
  - Site located on (high-Ti) mare basalts (ilmenite for O_2)
- Wide range of basalt types and ages
  - With probable wide maturity range
  - Provide latitude to search for mature ilmenite-rich regolith of high solar-wind content (H_2, He, N, C)
- Wide variety of highland areas
  - Probably include anorthosite from depth
  - Subsites could process anorthite (O_2, Si, Al)
- Data from polar-orbiting satellite needed to confirm resource types and distributions (VIMS~ x-ray, gamma-ray data)

Table T-5: Operational Constraints of Tranquillitatis

- Near-equatorial location allows access by a variety of transportation scenarios.
- Location at ~52° from the east limb allows for communication time with Earth, prior to landing, for missions in retrograde orbits.

Table T-6: Summary of Tranquillitatis As An Outpost

- The major advantages of a base in SE Mare Tranquillitatis are:

  - Favorable transportation logistics, both from orbit and on the surface (terrain "problems" comparable to Kansas)

  - Access to a wide variety in ages, thicknesses, and types of mare units, with variable regolith thicknesses (i.e., crater densities), providing multiple resource and exploration targets (spectral mapping and imaging by LO are needed)

  - Location over a relatively shallow mare "continental shelf" (mare deposits of ~0-500 m, compared to ~500-1000 m in western Tranquillitatis), where ring structures from many basins intersect, leaving islands of highland crust and structure for geophysical exploration (gravity data from LO are needed)

  - Space observations are possible of northern and southern skies with a ~360° flat horizon (topographic control from LO is needed)

- The major disadvantage is

  - Location far from the limb may limit astronomical observations because of earthshine interference

IMPACT OF TRANSPORTATION STRATEGIES ON SITE SELECTION

Introduction

Transportation consists of the means and the strategies that are involved in transporting people and material from the Earth to a planet surface (the Moon's in this case) and back again. For purposes of the simulation of the site selection process, some assumptions were made concerning the ground rules for transportation system utilization. These assumptions were as follows:

1. Spacecraft depart from and return to Space Station Freedom in low Earth orbit.
2. The transportation system utilizes the lunar orbit rendezvous mode (Fig. 4).
3. Earth-based tracking, navigation and communications will be required during the landing phase and for surface operations.
4. Long duration (several months) outpost support missions will be the normal mode, but minimum possible missions, in terms of time, and whether or not there is an opportunity for an abort-to-Earth, could be important considerations.
5. Landing site topography will be well characterized by robotic precursors.
6. Landing navigation aids will be available as soon as possible.

The use of Space Station Freedom in LEO implies **no free return abort**. Consequently, there are no landing site latitude limitations as would result from a free return abort requirement. Similarly, longitude restrictions because of Earth re-entry lighting requirements are removed and there is no requirement for a retrograde orbit.

Lighting requirements for descent to the lunar surface as restrictive as for Apollo (a sun angle greater than 6 and less than 20 degrees) probably cannot be met. These lighting restrictions, combined with the constraints associated with staging from Freedom, would result in infrequent launch windows and long stays in orbit.

Far side, and possibly limb sites, will require communications and telemetry relay (Fig. 5). Limb site descent and ascent trajectories may be occluded (depending on lunar orbit orientation).

Classes of Outpost Locations and Orbital Inclinations

The location of the lunar outpost on the Moon has a direct impact on the strategy selected for transportation of people and material to and from the outpost. Potential outpost locations and the resulting orbit possibilities for the transportation system spacecraft can be grouped into three classes: 1) equatorial, 2) mid-latitude, and 3) high latitude and polar

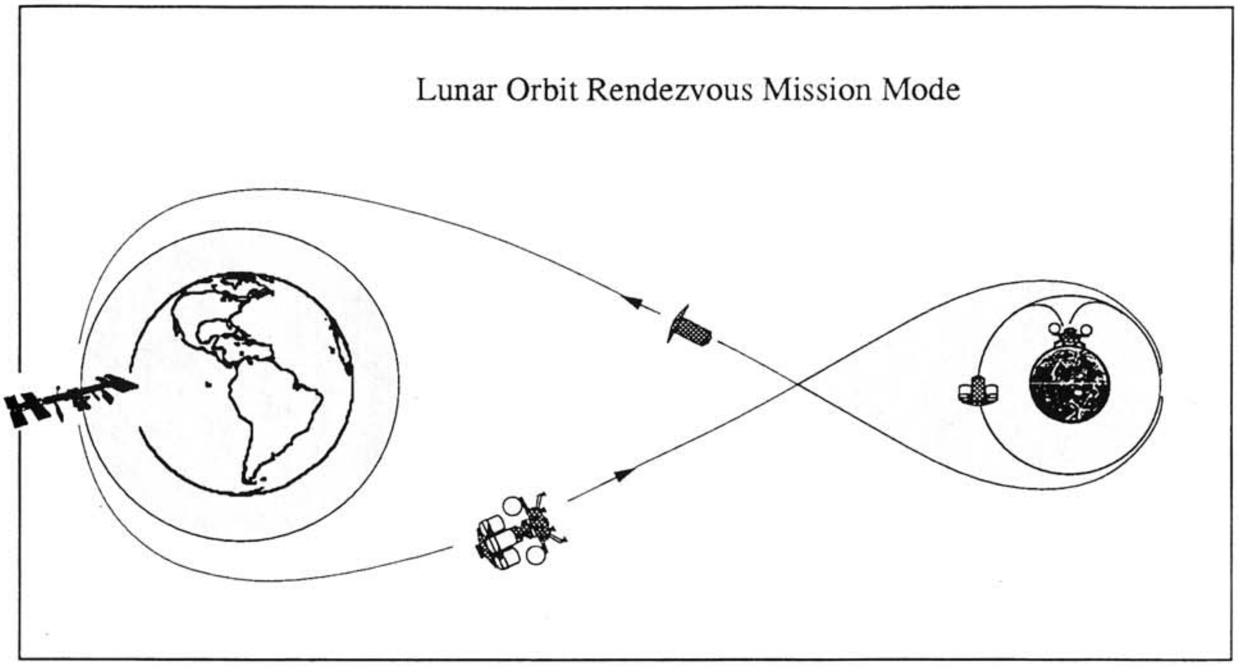


Figure 4: The lunar orbit rendezvous method of staging missions to the Moon and back. Trans-lunar injection is made from low Earth orbit from the Space Station Freedom orbital plane. Other mission modes are shown in figure 11.

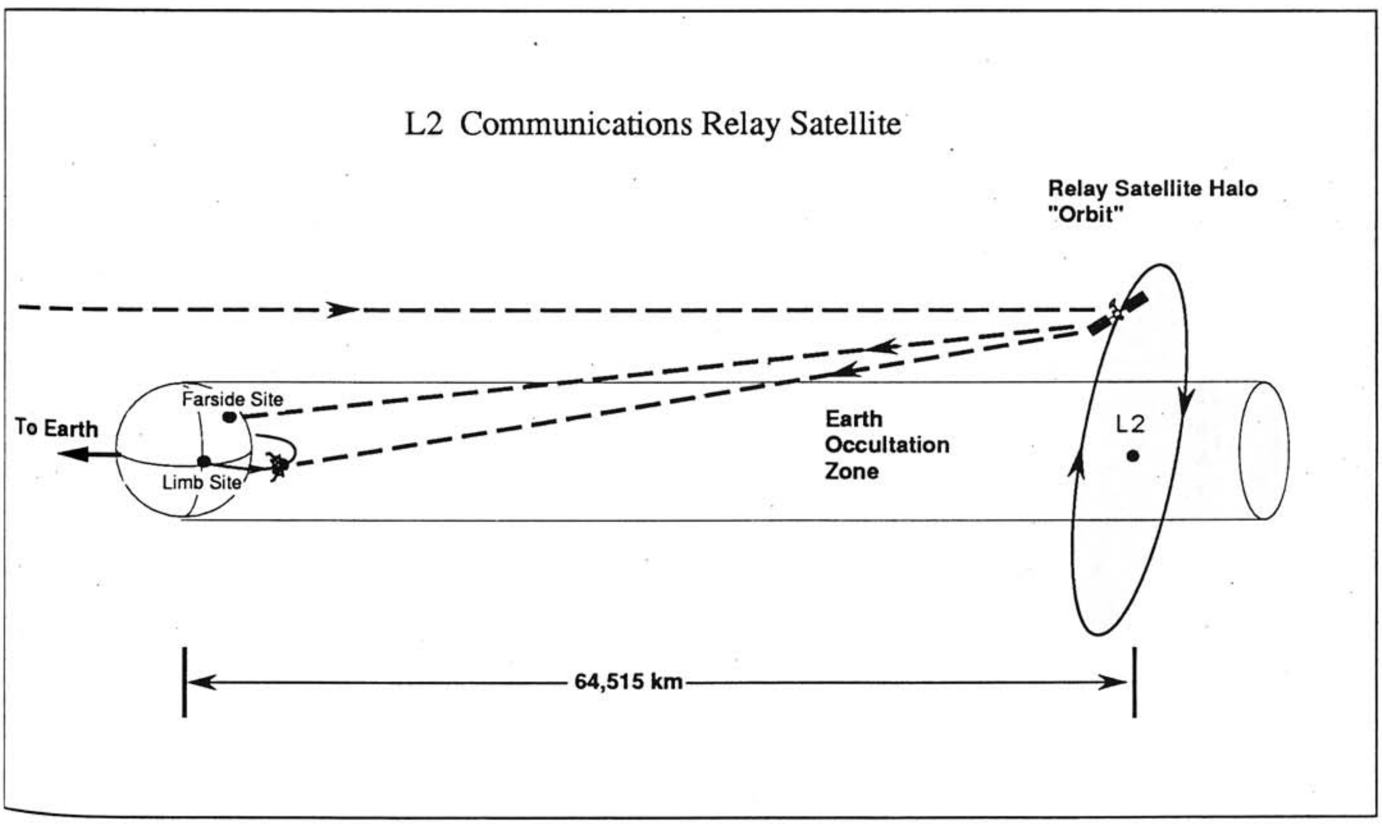
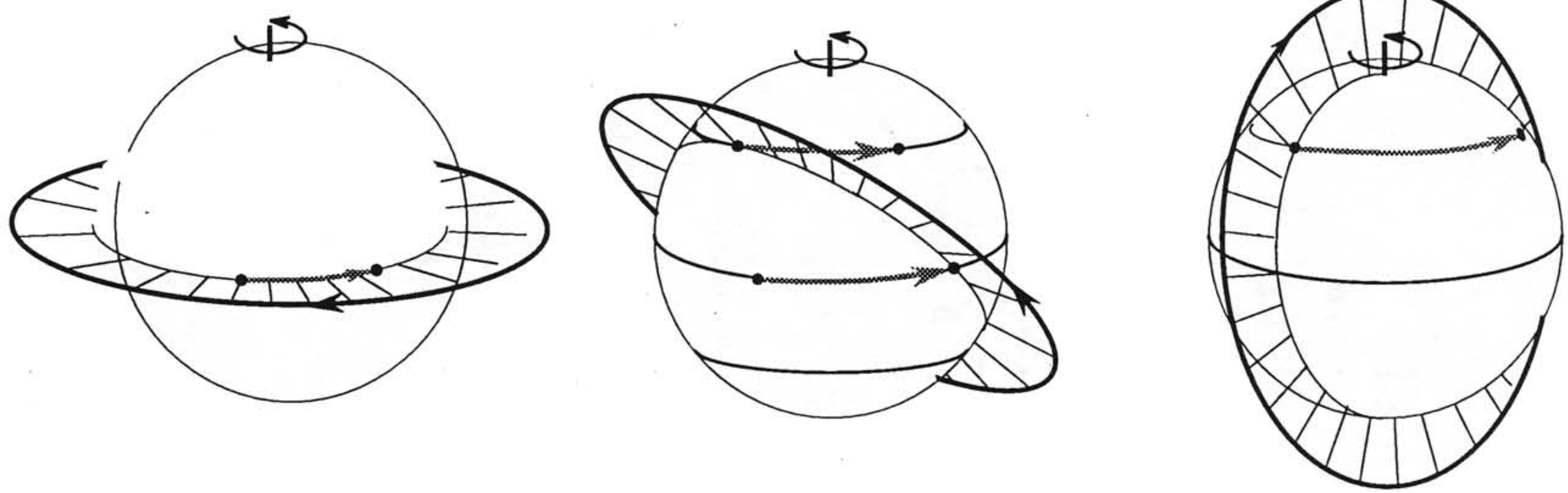


Figure 5: A relay communications satellite scheme necessary to provide communications to far side sites and to some sites on the limbs.

Classes of Outpost locations and Orbital Inclinations



Equatorial Class:

Equatorial location (+/- 5 degrees). Equatorial lunar orbit provides continuous access to equatorial sites. For 100-300 km. orbits, expect uncorrected altitude variations of up to 80 km.

Mid-latitude Class

Locations between 5 and 45 degrees. Inclined lunar orbit provides access to sites whose latitude is less than the orbital inclination. The moon's rotation dictates descent/ascent windows every 14-27 days, or requires orbit plane change maneuvers (generally quite expensive). Large altitude variations (140 km) can be expected.

High latitude and Polar Class:

Locations between 45 and 90 degrees latitude. Polar orbit provides global access. Descent/ascent windows exist every 14 days to any site, but continuous access is available to the polar regions. Small (<20 km) altitude variations are experienced at this inclination.

Figure 6: Classes of outpost locations on the Moon based on latitude and the implications of the locations arising from orbital mechanics. Lunar orbit rendezvous and staging from Space Station Freedom is assumed.

(Fig. 6) as a result of the ground rules, and the selection of the lunar orbital rendezvous mode for transportation. These three classes have the following characteristics:

1. Equatorial Class (± 5 degrees of the lunar equator)

   Equatorial outpost locations permit orbits (± 5 degrees) that allow nearly continuous access (descent and ascent) from equatorial locations (Fig. 3). Descent opportunities occur every 2 hours. Ascent opportunities are continuous as phasing can be done in orbit (Fig.6). For eastern sites, a posigrade orbit provides the best tracking, whereas a retrograde orbit is best for western sites. Lunar mass concentrations (gravity anomalies) cause significant drift in altitude for spacecraft in long term equatorial orbits.

2. Mid-latitude Class (from 5 to 45 degrees lunar latitude)

   For mid-latitude sites, (Fig. 6) there are two options. The first option is to establish a near-polar orbit to provide ascent and descent opportunities every 14 days. This option restricts the orbit orientation at insertion and at trans-earth injection, implying longer on-orbit wait times and infrequent Earth return opportunities. The second option is to establish an orbit whose inclination is equal to the outpost latitude. This option provides more flexibility in orbit orientation and longer trans-Earth injection windows. However, descent/ascent opportunities are restricted to once every 27 days. Furthermore, large altitude drifts occur for objects in long term mid-latitude orbits at 100 km or lower altitudes. These factors and the more frequent access to and from lunar orbit and greater orbit stability suggest using polar orbits for mid-latitude sites.

3. High latitude and Polar sites Class (45 to 90 degrees lunar latitude)

   For high latitude sites, polar orbits provide the best access (Fig. 6). Descent/ascent windows occur every 14 days. But there is continuous access for latitudes greater than 85 degrees. For latitudes less than 85 degrees but greater than 15, high latitude sites are similar to mid-latitude sites - return to Space Station Freedom opportunities occur every 27 days, and the minimum mission duration is 35 days. Small altitude (20 km) drifts occur for objects in long term polar orbit.

Mission Profile - Lunar Orbit Rendezvous Mode

A typical mission profile is shown in Fig.7. The following points are illustrated in the figure.

1. Trans-lunar injection (TLI) must be made nearly tangential to the orbit of Space Station Freedom. Out-of-plane thrusting imposes severe performance penalties.

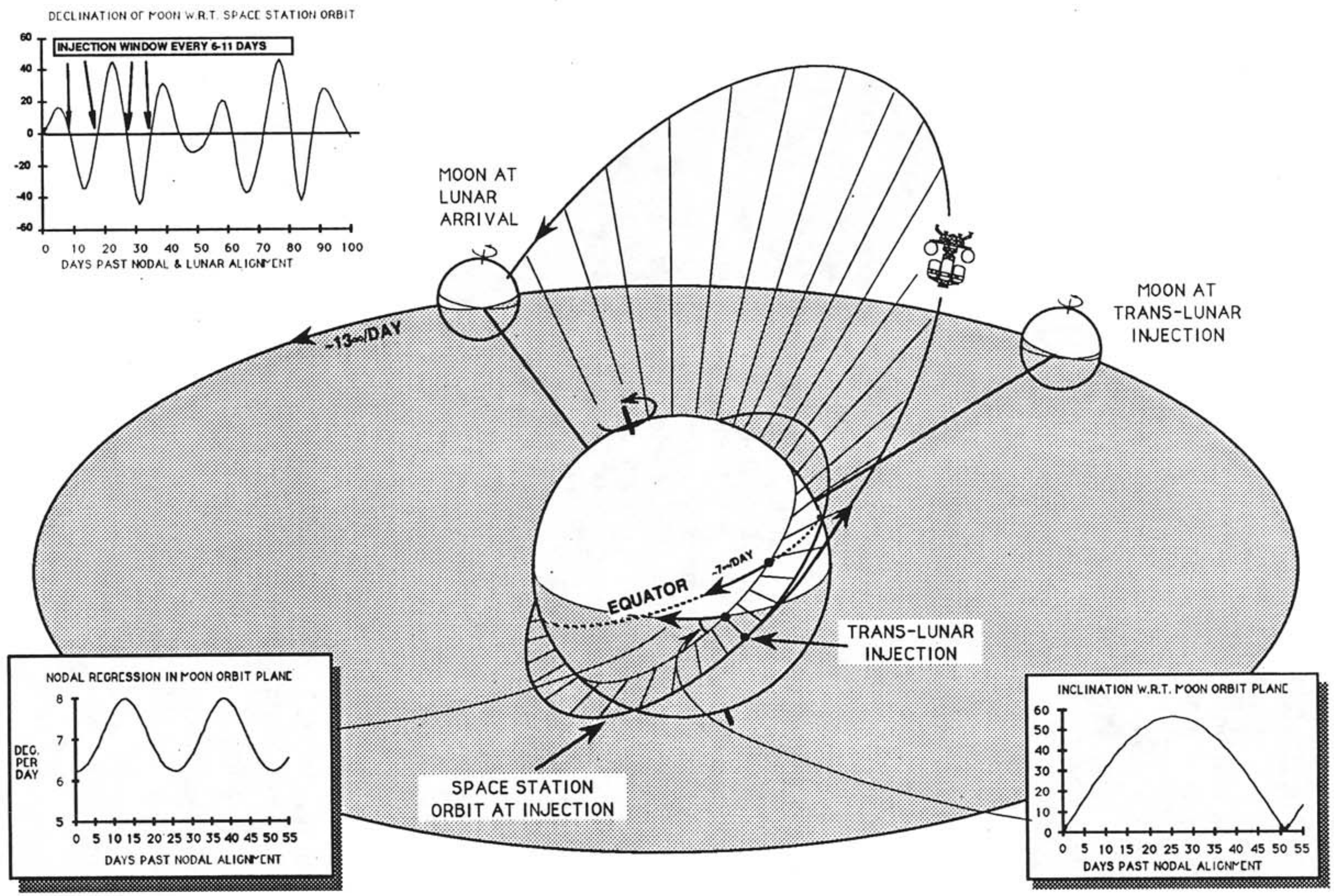


Figure 7: Trans-lunar trajectory from the Space Station Freedom orbit plane. Declination of the Moon with respect to (W.R.T. in the insets) nodal regression and inclination with respect to the Moon's orbital plane are shown in the insets. After Joosten, 1990.

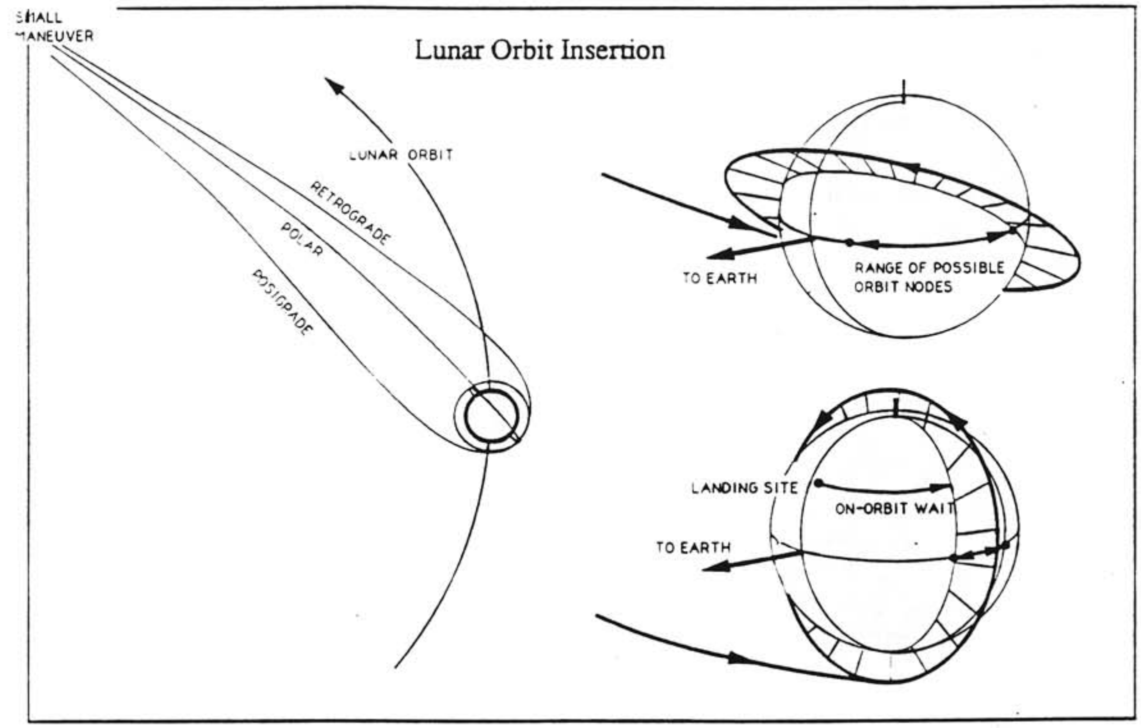


Figure 8: Lunar Orbit Insertion (LOI). Only small maneuvers are necessary to select various orbits. There is no performance penalty for selection of an equatorial orbit versus a polar orbit for example. Note the on-orbit wait as the landing sites rotate with the Moon to a position beneath the orbital plane of the spacecraft.

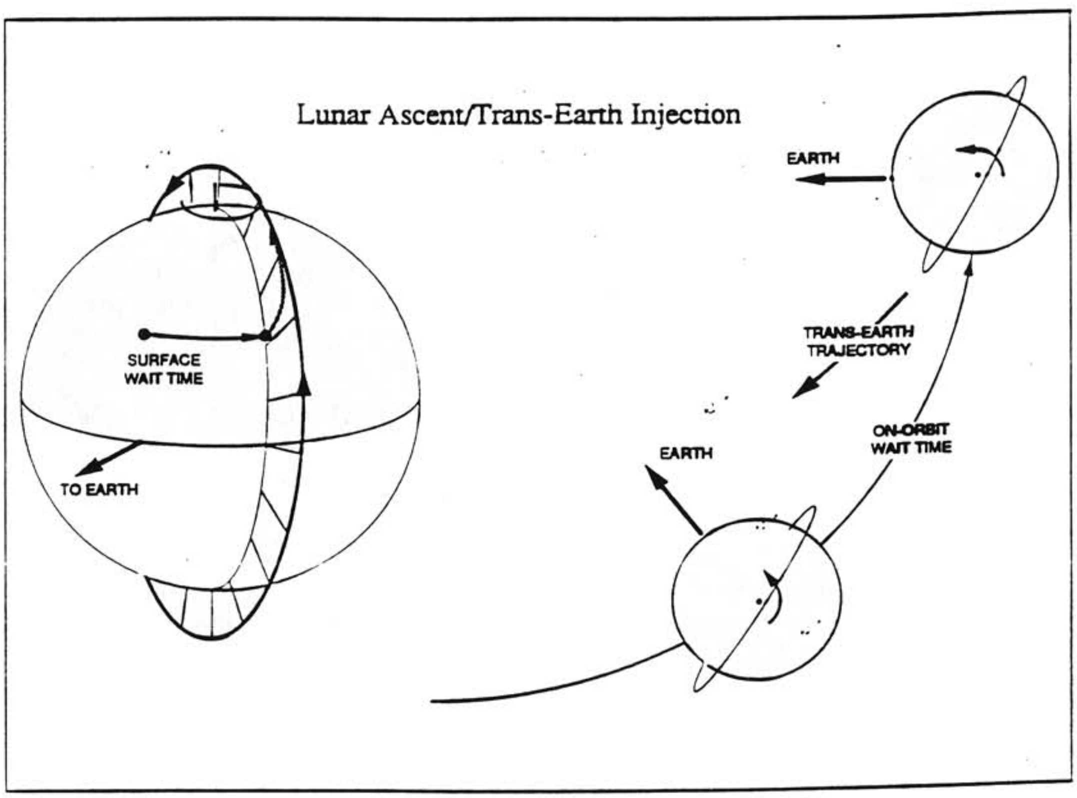


Figure 9: Ascent from the surface of the Moon and trans-Earth injection to SSF's orbit.

2. A combination of the Moon's rotation (13 degrees per day) and Freedom's orbital regression (7 degrees per day) results in injection opportunities varying from 6 to 11 days and averaging every 9 days.

3. Launch windows typically are less than one day.

4. Trans-lunar coast is 3 to 5 days.

5. Trans-lunar injection is independent of landing site or outpost location.

After a 3 to 5 day trip to the Moon, the spacecraft enters lunar orbit (achieves lunar orbit insertion - LOI, Fig. 8). The inclination of the orbital plane of the spacecraft relative to the Moon must be greater than or equal to the latitude of the outpost or landing site. For economical ascent or descent, the spacecraft lunar orbit must be established so that the outpost site is, or will be, under the spacecraft orbital plane. The spacecraft orbit plane remains fixed in inertial space while the Moon rotates 13 degrees per day, bringing locations under the orbital plane of the spacecraft (Fig. 8). There is essentially no performance penalty associated with orbit inclination, even a polar orbit. Only small mid-course corrections are required during trans-lunar coast to achieve high inclination orbits.

Although an orbit of any inclination may be established, the orientation of the orbit (i.e., the longitude of the node) becomes more restrictive with higher inclination (site latitude). On-orbit waits may occur prior to landing as a result of site longitude. This situation is shown in Figs. 6, 7, and 8.

Trans-Earth Injection:

Three conditions must be met to return to Space Station Freedom in low Earth orbit (Fig. 9).

1. Successful ascent from the lunar surface to lunar orbit rendezvous. This capability is continuous from equatorial sites and occurs every 14 days for mid-latitude and high latitude sites as previously discussed and shown in figs. 6, 7 and 8.

2. The correct lunar orbit orientation (of the spacecraft) with respect to the trans-Earth trajectory must exist. For orbits with inclinations of less than 15 degrees latitude there is a continuous capability. For polar orbits, there is a 3 day window every 14 days.

3. The trans-Earth trajectory must be nearly co-planar with the Space Station Freedom orbit at the time of Earth return. This constraint is independent of outpost latitude, and it has the same 6 to 11 day frequency as for the outbound (TLI) case (Fig. 10).

The combination of lunar polar orbit and Space Station Freedom orientation requirements results in TEI opportunities separated by at least one month and, in some cases, up to 2 months.

Trans-Earth Trajectory

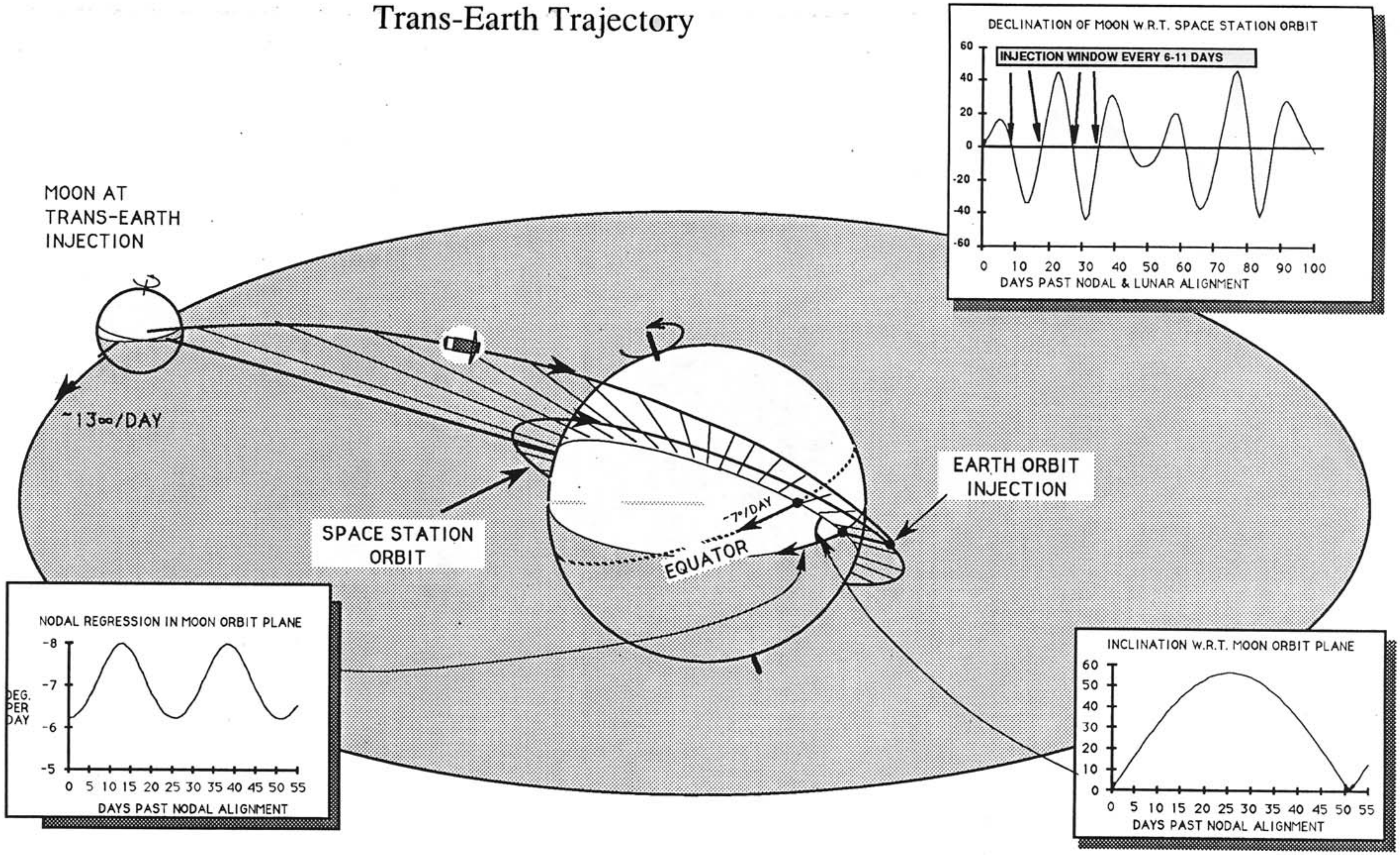


Figure 10: Trans-Earth trajectory to low Earth orbit (LEO) and rendezvous with the Space Station. The trajectory must be nearly co-planar with Freedom at Earth return. The combination of lunar polar orbit and Freedom orbit requirements results in trans-Earth opportunities separated by at least one month and in some cases by up to two months. (After Joosten, 1990).

Site Evaluations

The three site and orbit inclination classes (equatorial, mid-latitude, and high latitude) are represented among the six sites considered.

Equatorial class	Mid-latitude class	High latitude and Polar class
Tranquillitatis	Aristarchus	Amundsen
Smythii	Ingenii	
Riccioli		

Equatorial sites (Tranquillitatis, Smythii, Riccioli):

TLI and TEI constraints are the same for these three sites, namely, TLI from, or TEI to, Space Station Freedom every 6 to 11 days. There are continuous opportunities for descent to the lunar outpost and for ascent to lunar orbit rendezvous. The minimum mission duration for equatorial sites is 13 days.

For theTranquillity site, communications and navigation are adequate from either a posigrade or retrograde orbit. A posigrade orbit provides the best Earth-based communications for the Smythii site on the east limb (1.7N, 85.8 East). A communications relay may be required for terminal descent and ascent depending on the local topography and libration effects.

For Riccioli on the west limb, a retrograde orbit provides the best Earth-based communications during descent. A communications relay may be required for ascent (Fig. 1).

Mid-latitude sites (Aristarchus, 23N, 48W; Ingenii, 35S, 165E):

The constraints are similar for these two sites, differing only in that Ingenii is on the far side, necessitating a communications relay for all operations. Otherwise the following result from the mid-latitiude location of Aristarchus:

1. TLI every 6 to 11 days

2. A polar orbit offers descent/ascent opportunities every 14 days.

3. A polar orbit and the 48 W longitude of Aristarchus result in no on-orbit wait prior to landing but a 4 day on-orbit wait, approximately, prior to TEI.

The polar orbit orientation requirement for TEI and the Space Station Freedom orientation requirement for rendezvous implies return opportunities once a month at best and every 2 months (76 days) at worst, and the minimum mission duration for an Aristarchus outpost is from 35 to 76 days.

The situation is similar for the Ingenii site except that its longitude (165E) plus a polar orbit implies an 8 day on-orbit wait prior to landing and a six day on-orbit wait, approximately, prior to trans-Earth injection. For Aristarchus and the mid-latitude class of sites, the minimum mission duration is 35 days at best and 76 days at worst. High latitude and Polar sites (Amundsen, 88S, 60E):

For the Amundsen south pole site (and all polar sites), there is no on-orbit wait for ascent and descent or TEI. The polar orbit requirement implies the same return opportunities as for other non-equatorial sites. For Amundsen, the minimum mission duration is 21 days at best and 62 days at worst.

A communications relay may be required for descent, ascent and for surface operations depending on local topography and on libration effects.

Alternate Mission Modes

Three alternatives (Fig. 11) to the lunar orbit rendezvous method of mission staging and the constraints that it imposes, were considered: 1) libration or Lagrangian point staging, 2) direct descent to the lunar surface and direct return to Earth, and 3) bypass of Space Station Freedom. The characteristics of these alternative methods are as follows:

1. Libration or Lagrangrian point staging:

    a. vehicle staging occurs at one of the colinear Earth-Moon libration points instead of low Earth orbit .
    b. the entire lunar surface is accessible; **performance is nearly independent of outpost location.**
    c. Earth, the libration point and the lunar surface maintain constant relative geometry so that the only constraints are those involving LEO Space Station Freedom injection (6 to 11 days) and surface lighting.
    d. the minimum mission duration is 21 days for all sites.
    e. free returns generally cannot be accomplished.

2. Direct to the surface-direct return:

    a. all systems needed for Earth return are brought to the lunar surface, and there is no lunar orbit rendezvous.
    b. the mission mode is characterized by low performance and large vehicles.
    c. with direct descent to the surface, lunar orbit can be bypassed entirely, however a small zone of exclusion occurs near the eastern limb in the equatorial zone. If necessary, the excluded zone can be reached by using a mid-course correction during trans lunar coast.
    d. lunar orbit can be entered temporarily, followed by descent to the surface. this provides improved performance and global access. **Performance is independent of outpost location.**
    e. Free returns generally are not possible.

3. Bypass of Space Station Freedom depart-return mode:

    a. The mission profiles become identical to Apollo

b. Free return abort is possible. If a free return abort capability becomes a requirement, then site latitude constraints will be a function of the auxiliary propulsion system(s) capability (e.g., of the descent/ascent stage). Polar sites will be inaccessible because they are incompatible with a free return abort mode requirement. East limb sites will require a communications relay. Descent/Ascent opportunities for non-equatorial sites will be every 27 days because polar orbit is not available.

c. Earth departure and return constraints are relieved by bypassing Space Station Freedom. Daily launch windows probably will exist. Minimum mission durations for non-equatorial sites will be 21 to 35 days utilizing a polar orbit (if free return is not required). Lighting constraints for Earth return will exist.

Conclusions

The three location-orbit inclination classes have characteristic impacts on mission planning in the lunar orbit rendezvous mission mode. These impacts are summarized in Fig.12. Although no site is inaccessible, and performance penalties are not great for non-equatorial locations, the use of high inclination orbits corresponding to mid and high latitude sites imposes stringent descent/ascent and trans Earth timing requirements and increases minimum mission duration as is illustrated in the figure. The outpost location will have an effect on the transportation strategy, and the reverse is also true.

The use of Space Station Freedom as a LEO staging point and recovery point imposes additional trans lunar and trans-Earth constraints.

Mission modes such as libration point staging greatly decouple landing site location from the mission planning process and shorten minimum mission duration.

Outpost location, mission profile, and transportation system concepts are interrelated and should undergo frequent review as concepts mature.

Transportation Operations Summary

The lunar orbit rendezvous mode leads to a site ranking based on accessibility and operational simplicity. The ranking is:

more preferred	equatorial, near side
	polar, near side
	mid-latitude, near side
less preferred	mid-latitude, far side

The direct descent/direct return or libration point staging modes relieve some constraints. There is a modest preference for near side sites using these modes based on line-of-sight communications.

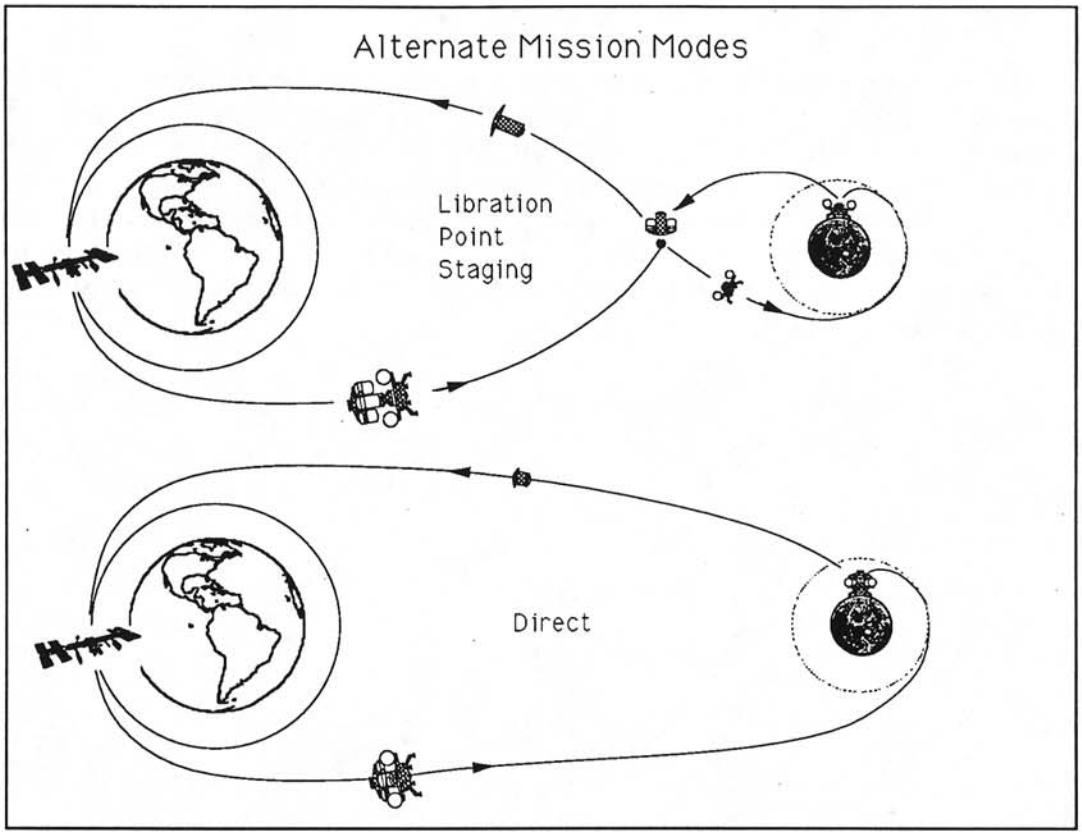


Figure 11: Alternate mission modes (as compared to lunar orbit rendezvous). A third alternative is direct return to Earth without use of Space Station Freedom.

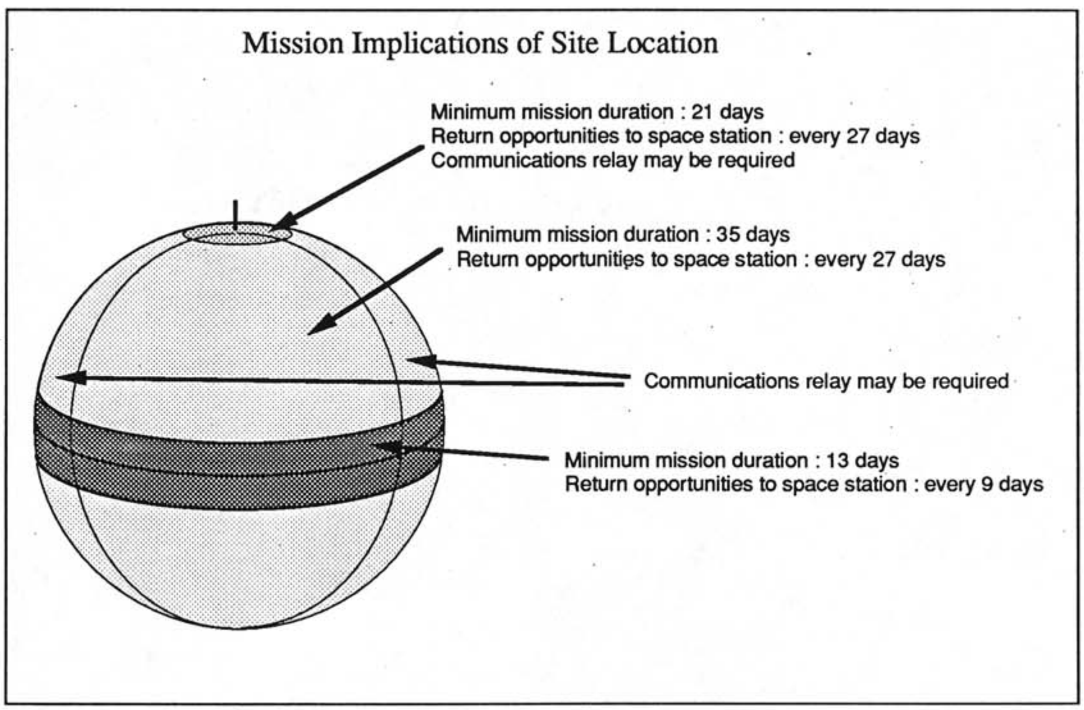


Figure 12: Summary of operational implications of locations on the Moon in terms of mission duration and communications requirements. (After Joosten, 1990).

The transportation architecture or mission mode should not constrain site selection. Maximum flexibility (in terms of global accessibility) and minimum operational restrictions are achieved with direct descent or libration point staging. If lunar oxygen production and use becomes an important component of operations in cis-lunar space, then the transportation architecture could evolve in different ways, from direct descent to libration point staging to the lunar orbit rendezvous mode assumed for the purposes of this discussion, for example. Studies of various evolutionary paths based on outpost strategy would be of benefit.

RESULTS OF THE SITE SELECTION SIMULATION

Introduction:

The six candidate sites were assessed by discipline groups. Each group utilized science criteria developed earlier (see Science Criteria for Site Selection) and incorporated constraints deriving from the consequences of employing a lunar orbit rendezvous mission mode with Space Station Freedom as a node. Assessments were reduced to a numerical evaluation of each site. Each discipline group then presented their evaluation to workshop participants and the results were discussed within the framework of the Space Exploration Initiative. Recommendations were formulated as a result of these discussions Following is a summary.

Lunar Geosciences-Geology

Results of the rankings for lunar geosciences are shown in the chart "Lunar Geoscience". Mare Smythii, the Aristarchus Plateau and Mare Ingenii were the preferred sites for geological exploration, although the sites were ranked relatively evenly. It was the consensus that atypical sites such as Aristarchus and Ingenii have great interest but, unless they allow fundamental questions to be answered, they are less attractive than more typical sites such as mare Smythii that provide access to a broader array of general problems. However, what is typical and what is atypical depends on the current data and major parts of the Moon are not adequately represented or studied. A lunar observer type of mission would be of great importance in determining whether or not current perspectives are biased by lack of information and would aid in placing the site ultimately chosen within a broad exploration context.

All of the sites were assessed based on their merits in the absence of an overall exploration strategy and this lack of a framework accounts for the relative lack of discrimination between the suitability of the sites considered. Clearly an enlarged data base would be important in developing an exploration strategy.

The discussions of the relative merits of the sites illustrated that the lunar outpost site will be extensively studied, and that few sites will lack potential for studies of major importance, but that some will rank more highly than others even if only marginally. Lunar geoscience strategy must ultimately depend on extension of human capabilities, either robotically or directly beyond the outpost, and the results of site-intensive study should provide a fundamental framework for extension beyond the site. This philosophy formed the basis for the science criteria developed for lunar outpost site selection by lunar geoscientists earlier (see Science Criteria for Site Selection) The question is one of efficiency, what type of site, geologically speaking, provides the most appropriate context within the overall constraints provided by science interests? This question should be debated in the larger planetary community. From such a debate, a means of weighting geological objectives can be derived. Development of such a weighting system, in effect an exploration plan, is recommended for all of the disciplines to be represented at a lunar outpost.

Lunar Geoscience

	M. Tranq. Apollo 11	M. Igenii far side	Riccioli limb	M. Smythii limb	Amundsen S. pole	Aristarch plateau
Development and evolution of the crust and mantle						
Chronology	2	2	1	2	0	2
Impact History						
Early bombardment	1	2	2	2	2	1
Cataclysms	1	2	2	2	2	0
Nature of impact process						
Multi-ring basin formation	1	1	2	1	1	1
Impact-melting	0	1	1	1	2	2
Vertical and horizontal struc.	2	2	2	2	1	2
Regolith formation-evolution/ history of the sun						
Paleoregolith	2	2	1	2	0	2
Eruptive dynamics						
Pyroclastics	0	0	0	2	0	2
Origin of the Moon						
Enigmatic features	0	2	0	0	1	1
	9	12	11	14	9	13

Lunar Geophysics

Site selection criteria for lunar geophysics are shown in the chart "Geophysics" along with the results of ranking for the six candidate sites. Lunar geophysics (seismology, heat flow, magnetism) consists of local, regional and global studies. Global geophysical exploration of the Moon calls for the emplacement of geophysical stations consisting of a variety of devices at four areas. These station arrays probably will be emplaced robotically primarily.

In addition, there will be intensive geophysical exploration at the local and regional level and the outpost will be the center of regional to local geophysics. These studies require access to highlands from the outpost site, access to mare terrain far from the outpost for emplacement of heat flow probes among other experiments, and access to layered units for paleomagnetic studies. Some geophysical exploration will require the presence of humans, for emplacement of heat flow probes, for example, or sampling for paleomagnetic studies of layered units. These requirements drive site selection from the geophysical standpoint and lead to a higher ranking for the mare sites Smythii, Ingenii, and Riccioli that provide access to mare units as well as to adjacent highland within a reasonable distance. In addition, the presence of a significant magnetic anomaly in Mare Ingenii led to a high ranking for it. Tranquillitatis was not as highly ranked for geophysics because of more limited access to highland terrain.

Astronomy

Science criteria for astronomy and the results of site ranking are shown in the chart "Astronomy". Site selection for astronomy is primarily a function of the celestial field of view afforded by a location on the Moon, and secondarily, by the desire to limit earthshine by being located near a lunar limb. Two sites considered meet these requirements (Smythii and Riccioli) and were ranked highly for astronomy, whereas a third (Tranquillitatis) ranked equally as well because of its near-equatorial location. In addition, Mare Ingenii on the far side ranked relatively high because of its unique property, among the six, of providing shielding from Earth and its radiation.

An additional criterion for astronomy is topography and the use of topographic features for observatory elements (see Science Criteria for Site Selection). The central peak of Riccioli, for example, appears to offer the potential for advantage in this respect.

Celestial field of view is an overriding criterion for astronomy and may be central to site selection. There was considerable discussion about the consequences of field of view restriction arising from the observation that the site rankings for astronomy were not very discriminatory. Weighting of sites based upon field of view penalty (or lack of it) was called for and there is a clear need to assess the field of view requirements for astronomy so as to more thoroughly understand the consequences of locating a lunar outpost in locations not optimum for astronomy. Field of view weightings could be folded into a more general weighting scheme for sites for science.

Geophysics

	Tranquillitas	Ingenii	Riccioli	Smythii	Amundsen	Aristarchus
1) Near or in a multi-ring basin (regional seismic studies)	0	2	2	2	0	0
2) Global seismic studies (antipodal to deep moonquake epicenter)	0	0	2	0	0	0
3) Geologically diverse	1	2	2	2	1	2
4) Good for heat flow (away from mare/highland contact)	2	2	1	2	2	2
5) Near strong magnetic anomalies	0	2	1	1	0	0
	3	8	8	7	3	4

Space Physics

The results of site evaluations for space physics are shown in the chart "Space Physics."

The essential elements for space physics in site selection are views of the Sun, the Earth, and the celestial sphere whereas topographic features are not of primary importance. Consequently, the Tranquillitatis site, the mare site most centrally located, is favored for purposes of space physics.

Because some instruments that would be extremely sensitive to gamma rays may be emplaced at a lunar outpost, there is a need to assess the indigenous radiation component of the regolith at a proposed site. Such an assessment could be made from orbit. The sensitivity and the level of precision required are to be established.

A space physics science strategy calls for certain experiments to be placed at the subearth point (or the antipodal subearth point). These experiments, like the geophysical arrays, may be emplaced robotically and are independent of outpost location. However, successful robotic deployment may call for a higher level of information of the selected localities than is currently available, particularly for locations on the far-side.

Resources

Results of sites evaluations from the perspective of lunar resources utilization are shown in the chart ""Resources."

If the strategy for the lunar outpost involves lunar materials utilization, then resources-based criteria become a major component of the site selection process. Criteria, as shown in the chart "Resources," are based on oxygen, volatiles, solid materials usage and the possible presence of extraordinary materials such as water.

Discrimination between sites is difficult in view of the lack of a strategy for resource utilization and the importance that resources will play (or not play) in the purpose and the functioning of the outpost. Clearly, if a particular resource is an absolute requirement, then the outpost location is highly constrained to that resource's properties and occurrences, ^{3}He is a case in point. In the absence of a strategy, some general discrimination between candidate sites is possible based on the guidelines developed earlier (Science Criteria for Site Selection/LMEPO). In general, if oxygen is to be produced, mare material may be processed by either of the two processes currently most favored (ilmenite reduction, and magma electrolysis). True discrimination between sites would require selecting a process, if the process were the primary driver, and correlating the process with material and tonnage available at sites considered in the selection process. Alternatively, tonnage available may be more important and the process adapted to the site selected.

Solar wind species are not as abundant in highland solids per unit volume as in mare soils. If these resources are important , then mare sites are preferred.

Space Sciences – Astronomy

	Site 1 Tranq.	Site 2 Ingen.	Site 3 Riccio.	Site 4 Smyth.	Site 5 Amund.	Site 6 Arist.
Coordinates	3.87°N 38.39°E	35°S 165°E	2.5°S 83°W	67°N 85.8°E	88°S 60°E	23°~ 48°W
View						
– Celestial	8	7	9	9	7	5
– Earth	4	10	9	9	9	5
Topography						
– Area	8	8	8	8	5	8
– Features	7	9	9	9	6	8
Data Availability – See List						
Regolith	7	6	7	7	6	4
Other						

Space Sciences – Space Physics

		Site 1 Tranq.	Site 2 Ingen.	Site 3 Riccio.	Site 4 Smyth.	Site 5 Amund.	Site 6 Arist.
Coordinates		3.9N, 39.4E	35S, 165E	3.5S, 75W	1.7N, 85.8E	88S, 60E	23N, 48W
View – Sun		10	5	10	10	5	7
– Celestial		10	5	10	10	3	7
– Earth (Magnetosphere)			3	7	5	10	10
Topography – Area	Not overriding						
– Features	Not overriding						
Data Availability	Not overriding						
Regolith γ - Radiation		6	10	4	8	?	5
Overall Rating		9.0 Good	5.8 Fair	7.8 Good	8.3 Good	6.0 Fair	7.3 Fair

These considerations, among others, led to ranking the Tranquillitatis highest among the six sites because of its mature mare regolith that is known to be relatively rich in ilmenite. A different strategy and a more extensive data base may well lead to a different choice.

Summary

The results of the site ranking discussions are illustrated in the Summary of Numerical Rankings of Sites following. Of the six sites considered, Mare Smythii was most favorably viewed whereas the polar site (Amundsen) was least favored. The numerical differences between the sites are small however, and there is a lack of clear discrimination between them. The most favored sites, Smythii and Riccioli, were relatively highly ranked for astronomy, as was the far side site, Ingenii. This fact prompted some discussion of the role that field of view criterion should play in site selection, and whether or not it would be possible to more quantitatively categorize locations on the basis of the field of view of the celestial sphere. The penalty paid for field of view limitations should be more thoroughly defined.

Geological and geophysical exploration of the Moon will require global access ultimately. No single site will be sufficient, although some will be better than others, as is indicated by the numerical rankings shown. Diversity and access to fundamental lunar units (i.e., mare and highlands) are key properties. The development of means to travel on a scale of one hundred kms or so to exploration targets in the vicinity of the outpost is an important component in site selection. The mobility available will have an impact on how sites are ranked. Because lunar exploration must be global to be complete, the site selected should fit effectively within a strategy of global human and robotic lunar exploration. The relative fitness of potential sites could be weighed and prioritized relative to the strategy. Development of a exploration framework, therefore, is a requirement for judging the suitability of sites from a geological and geophysical point of view. Development of an exploration framework is dependent on a global data base. The existing data are not adequate for determining whether or not specific objectives could be accomplished at potential sites. Well informed decisions require a global data base of the type that could be produced by a Lunar Observer (1990 type) of spacecraft (or a series of smaller spacecraft).

The general concept of utilizing lunar resources implies that feedstock will be an important criterion. How important depends on the product to be produced and the process selected to produce it. In general, the site rankings for resources show the importance of thick regolith. Whatever the component to be extracted, regolith will be the medium from which a resource is extracted and thick regolith, therefore, offers a premium. Ranking sites for resources beyond a general classification based on regolith thickness is premature and should be deferred until products and processes are more clearly defined.

Operational considerations of safety and cost-effective operations are of great importance. Equatorial sites are operationally simplest, offer the greatest flexibility in terms of mission duration and satisfy field of view criteria. Non-equatorial (except polar) sites involve delays in site accessibility from orbit and in trans-Earth injection opportunities. These operational considerations will play an important but as yet undefined role in site rankings. Program policy will ultimately dictate the operational rules that will influence selection.

Resources

	1. Tranquility	2. Ingenii	3. Riccioli	4. Smythii	5. So. Pole	6. Aristarches
Oxygen						
Mare Materials (Ti)	10	?6	8	10	1	6
Volume	10	10	10	6-8	–	10
Highlands Materials	5	5-7	5	5	10	5
Volume	2	2	2	2	5	2
Hydrogen, ^3He						
Mare Materials (Ti)	10	?5	8	10	1	6
Vol.-Maturity	10	10	10	6-8	–	10
Highlands Materials	5	5	5	5	10	5
Building Materials						
Low Tech	10	10	10	10	8	10
High Tech	8	10	10	9	6	8
Special Materials					(Water) 10 (Solar Power)	5 (Pyroclastics)
TOTALS/10	7.0	6.5	6.8	41-51 4.6	41-51 4.6	62-67 6.4

Summary of Numerical Rankings of Sites

	Tran.	Ingenii	Riccioli	Smythii	Amundsen	Aristarchus
Lunar geology	9	12	11	14	9	13
Lunar geophysics	3	8	8	7	3	4
Astronomy	6.8	8	8.4	8.4	6.6	6
Space Physics	9	5.8	7.8	8.3	6.0	7.3
Resources	7	6.5	6.8	4.6	4.6	6.4
Average	7	8.1	8.4	8.5	5.8	7.3

APPENDIX I

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APPENDIX II

SITE ASSESSMENT PARAMETERS

In the Apollo Program, a large number of sites were proposed as candidates for an Apollo mission landing. To screen the candidate sites, a series of parameters was developed to determine whether or not proposed sites were suitable and to develop a priority ranking for candidate sites. Operational safety was paramount (although its definition changed during the course of the program) and science objectives were given a high priority within the framework of operational safety. Appendix III describes the evolution of the selection process during the program.

The operational parameters considered for Apollo have essentially the same impact for the SEI Program because the problems are similar, namely: crew safety and human capabilities and the nature of the lunar surface. The Space Exploration Initiative, however, involves long term use of a lunar outpost and considerations of operational efficiency on the lunar surface and utilization of lunar materials have a greater importance. In addition, the complexity of the operations that will occur is much greater, placing a premium on locations that serve multidisciplinary purposes.

A series of site assessment parameters modified from those employed by the Apollo Program, were devised to rank proposed lunar outpost sites. The parameters consist of the following:

Launch/Orbital Operations

Lunar Orbit Rendezvous Mode
Direct Descent Mode

Approach and Landing

Surface Operations

Operational Parameters

Launch/Orbital Operations:

Orbital operations parameters are divided into two types according to mission class - Lunar Orbit Rendezvous (Table OP1) and Direct Descent (Table DD).

For the *Lunar Orbit Rendezvous* mission class, the essential operational parameters for site evaluation purposes are (Table OP1):

Table DD

Operational Parameters

Direct Descent Mission Class

Launch/Orbital Operations

	Site 1 Tranq.	Site 2 Ingen.	Site 3 Riccio.	Site 4 Smyth.	Site 5 Amund.	Site 6 Arist.
Trans-Lunar Traj. Class Single Maneuver Multiple Maneuver	single	single	single	multiple	single	single
Possible Abort Class Free (No Hybrid Class) Other	Free	None	Free	Free	None	Free
Windows * * Not a discriminant for direct descent						
Lighting * (Descent)	full range possible				low-sun	full range
Site Class (Comm. & descent/ascent tracking) Limb Non-limb Far-side	non-limb	far-side	west limb	east limb	nearside limb	nearside

** Sun Angle Requirements impose launch*

Table OP1

Operational Parameters

Lunar Orbit Rendezvous Mission Class

Launch/Orbital Operations

	Site 1 Tranq.	Site 2 Ingen.	Site 3 Riccio.	Site 4 Smyth.	Site 5 Amund.	Site 6 Arist.
Orbit Inclination Class Equatorial (±5° of equator) Mid-Latitude (>5° <45°) High-Lat/Polar (45°-90°)	Equat.	Mid	Equat.	Equat.	Polar	Mid
Possible Abort Class* Free Hybrid Other(Non-traj. approach)	Free	Hybrid	Free	Free	Other system redundancy	Hybrid
Windows Surface to L.O.** Polar-continuous Mid -14 - 28 days Equatorial-continuous T.E.I.	equat. cont.	mid 14-28	equat. cont.	low cont.	polar cont.	mid 14-28
Lighting *** (Descent)	full range possible				low-sun	full range
Site Class (Comm. & descent/ascent tracking) Limb Non-limb Far-side	non-limb	far-side	west limb	east limb	nearside limb	nearside

Assumes no use of space station* * Minimum Stay-time on surface*
**** Sun Angle Requirements impose launch window constraints*

Orbit Inclination Class (equatorial, mid-latitude and high latitude-polar) reflects minimum surface stay time and launch windows. These classifications are discussed more fully in the section on transportation.

Possible Abort Class assumes no use of Space Station Freedom. Free return aborts are not possible with Freedom as a staging point.

Windows refers to lunar surface to lunar orbit opportunities and is reflected in minimum stay-time on the surface. Windows are dictated by outpost location and are keyed to the orbital inclination classes of equatorial, mid and high latitudes as shown in the table.

Lighting and/or sun angle requirements impose launch window constraints for Earth to Moon transit if a descent to the surface is made within a specified time frame, or effects lunar orbit stay-time because sun angle (angle of incidence of sunlight on the lunar surface) varies with lunar longitude, latitude and time

Site longitude - limb, non-limb, and far side locations have different communications and descent/ascent tracking requirements, consequently, an important operational parameter consists of the communications requirements that an outpost location might impose.

The ***direct descent class*** of missions includes a parameter - Trans-lunar trajectory - that reflects whether or not a correction burn is required to land in an "excluded" zone (table DD) and launch windows are not a site discriminant when the direct descent mode is employed. In other repects the parameters are the same. Characteristics of the 6 sites for the direct descent mode are shown in Table DD.

Approach and Landing:

Approach conditions affect safety and are dictated largely by topography for any given site. The quality and completeness of data, including gravity, are critical considerations. The important parameters are shown in Table AL as they apply to the six sites studied. These parameters are the following

Imagery is essential for approach and landing, ***for the first landing***. In the Apollo Program, as discussed previously, terrain models were developed for each landing site using imagery and geodetic data (elevations). These terrain models enabled, or could enable, automated descent of manned or unmanned vehicles. Their fidelity is a function of the quality of the imagery available. Terrain model construction requires stereo imagery.

Approach topography - the terrain profile on approach to a site - affects risk assessment, also for a first landing. Topography that requires steep descent to a location poses a hazard.

Landing ellipse properties (roughness, i.e. boulders, microtopography, craters and associated terrain features and slopes) are critical factors in ranking sites.

Table AL

Operational Parameters

Approach and Landing*

	Site 1 Tranq.	Site 2 Ingen.	Site 3 Riccio.	Site 4 Smyth.	Site 5 Amund.	Site 6 Arist.
Coordinates	3.9 N, 39.4 E	35 S, 165 E	3.5 S, 75 W	1.7 N, 85.8 E	88 S, 60 E	23 N, 48 W
Imagery scale/source	mod-high L. Orb.	low-mod L. Orb.	mod-high L. Orb.	mod-high L. Orb.	low-mod L. Orb.	mod-high L. Orb.
Stereo for Radar Approach	yes	no	yes	yes	no	yes
Approach Topography	smooth	rough	rough	smooth	rough	smooth
Ellipse Roughness (rocks?) Craters Slopes	TBD					
% Acceptance						
"Risk" Factor						

* "ELLIPSE" within 10 x 10 km site

L. Orb. = Lunar Orbiter

Risk factors (a measure of the properties of the landing ellipse plus the approach path and data quality that pertain to risk assessment) are dependent on data quality and completeness. The degree of risk that is acceptable, and the degree to which data can be extrapolated from a giving resolving power or resolution to make inferences held to be true at higher resolution are important factors in determining requirements for approach and landing parameters.

Surface operations:

Operations on the surface are based on a measure of efficiency in the construction of outpost components such as the habitat and launch/landing sites, for example. The relative distance between these components, measured as the number of acceptable 100 x 100 meter areas within a 10 by 10 km region, impacts the operational efficiency of the operations at the outpost. Slopes and surface roughness also affect operations. An important parameter is the ease of access to distant terrains. Some site locations require traversing highland terrains with relatively steep slopes in order to travel to science objectives. Other things being equal, a site with ease of access would be preferred. Surface Operations parameters are shown in Table SO relative to the sites considered. Lack of data precluded a rigorous application of these criteria, primarily the following:

The percent of acceptable 100x100 meters areas per region based on lunar geothechnical (soil mechanics) properties,slopes, subsurface characteristics, surface features utility is a useful measure of the relative acceptability of a site.

Operations efficiency is reflected in mobility efficiency, between points within an outpost area and to other locations, possibly remote. Potential experiment areas and /or exploration targets must be accessible with a specified efficiency.

Communications (Earth direct or indirect i.e., limb vs non-limb or far side site) and element to element communications within outpost region is a critical parameter.

Resources (type/availability) for a variety of purposes ranging from the simple to the complex are a critical parameter. At a minimum, regolith properties at a proposed site should satisfy minimum construction requirements.

Minimum Mission Time (determined by latitude and the transportation strategy employed) is an important parameter from the point of view of risk management, and its criticality is a function of the outpost design.

Table SO

Operational Parameters

Surface Operations

(based on 10 x 10 km regions at each site)

	Tranq.	Ingenii	Riccioli	Smythii	Amund.	Aris.
Percent of possible 100m x 100m areas/region - Regolith - particle size distribution - slopes - subsurface - surface feature utility	known	TBD	TBD	TBD	TBD	TBD
Operations Efficiency - Mobility - Intra-site accessibility - Inter-site accessibility	high?	TBD	TBD	TBD	TBD	TBD
Communications (Limb, Non-limb, Far side) - Earth direct or indirect - element to element	direct	indirect	limb	limb	indirect	direct
Resources/Availability	high	TBD	TBD	TBD	TBD	TBD
Minimum Mission Time	13 days	35 days	13 days	13 days	21 days	35 days

APPENDIX III

Highlights of Apollo Site Selection

August 1965

NASA established Apollo Site Selection Board. 1st, 2nd or 3rd landing sites for operational considerations. Science priorities were low. ~36 potential sites selected from Earth-based photos, 21 to be covered by Orbiters I and II and subjected to more detailed analysis. Site requires: ± 5° lat., ± 45° long., 7 to 20° sun angles, fairly smooth, 1 m photo resolution, max. slope 12°, max. humps 2', no boulder fields, no concentrated craters.

March 1967

From Orbiters I, II, and III, 8 final sites chosen for detailed analysis for 1st landing. Maps and detailed operations analysis for each to be completed. All were Mare sites.

August 1967

Santa Cruz Summer Study considered science input for later landing sites. From over 80 potential sites the first cut narrowed to 21.

December 1967

ASSB narrowed list for 1st two landings to 6; 3 east, 2 west, 1 central.
GLEP recommended that the 1st 3 missions be to eastern mare, western mare, and "old" unit, preferably Fra Mauro. Also counting on 12 lunar landings, 9 other sites were recommended: Censorinus, Littrow, Abulfeda, Hyginus, Apennine-Hadley, Tycho, Copernicus, Schroeters Valley, Marius Hills.

March 1968

ASSB narrowed landing sites for first 2 missions to 5: 2 east, 2 west, 1 central. Began consideration of science sites from GLEP.

September 1968

ASSB retained same 5 sites for 1st landing. Second landing would be another of the 5. For 3rd landing 8 of the 21 sites from Santa Cruz were to be analyzed in detail: Apollo Zone — Censorinus, Fra Mauro, Mosting C, Hipparchus Non-Apollo — Hyginus, Tycho, Littrow, Gassendi should provide good walking missions.

June 1969

ASSB 1st mission to be in July-Aug.-Sept. Of 5 sites one in west dropped because not available till Dec. and one in east dropped for operational reasons. If 1st is in east 2nd is in west. Possibly 2nd landing at Survey I or III location. Operational analysis has 3rd site down to 4. Censorinus, Tycho, Fra Mauro, Littrow.

June 1969

GLEP added Descartes to the 9 Dec. 1967.

July 1969

ASSB selected the following after the GLEP recommendations. GLEP against Sur. site for Apollo 12. A-11 (G) Same 3 possibilities, A-12(H) Sur. III site or one of the 3 A-11 sites, A-13(H) Fra Mauro, A-14(H) Censorinus, A-15(H) Rima Bode 11, A-16(J) Tycho, A-17(J) Copernicus, A-18(J) Marius Hills, A-19(J) Descartes, A-20(J) Rima Prinz 1.

July 1969

A-11 successfully completed.

August 1969

GLEP made 2 changes. A-13 (H) Fra Mauro, A-14 (H) Censorinus, A-15 (H) Littrow, A-16 (J) Tycho, A-17 (J) Copernicus, A-18 (J) Marius Hills, A-19 (J) Descartes, A-20 (J) Hadley-Apennine.

October 1969

Large meeting on landing sites at JSC changes order. A-13 (H) Fra Mauro, A-14 (H) Littrow, A-15 (H) Censorinus, A-16 (J) Descartes (needs photos), A-17 (J) Marius Hills, A-18 (J) Copernicus, A-19 (J) Hadley, A-20 (J) Tycho.

October 1969

ASSB decision on A-12 and A-13.A-12 (H) Sur. III. A-13 (H) Fra Mauro (Mar. 1970), A-14 (H) Littrow (July 1970), A-15 (H) Censorinus (Oct. 1970), A-16 (J) Descartes (March 1971), A-17 (J) Marius Hill (July 1971), A-18 (J) Copernicus (Feb. 1972), A-19 (J) Hadley (July 1972), A-20 (J) Tycho (Feb. 1973).

November 1969

A-12(H) successfully completed. A-13 (H) Fra Mauro, A-14 (H) Littrow, A-15 (H) Censorinus, A-16 (J) Descartes, A-17 (J) Marius Hills, A-18 (J) Copernicus, A-19 (J) Hadley, A-20 (J) Tycho.

January 1970

A-13 (H) Fra Mauro, A-14 (H) Littrow, A-15 (H) Censorinus, A-16 (J) Descartes, A-17 (J) Marius Hills, A-18 (J) Copernicus, A-19 (J) Hadley, A-20 deleted from program.

February 1970

GLEP meeting suggested Tycho deletion because it will probably drop for operational reasons. Possibly replace Censorinus on A-15 with Davy Crater Chain if photos of Davy are obtained on A-13 Davy has multiple objectives of: upland fill highlands material deep-seated rocks?

A-13 (H) Fra Mauro, A-14 (H) Littrow, A-15 (H) Davy/Censorinus, A-16 (J) Descartes, A-17 (J) Marius Hills, A-19 (J) Copernicus, A-20 (J) Hadley.

April 1970

A-13 (H) failed. A-14 (H) Littrow, A-15 (H) Davy/Censorinus, A-16 (J) Descartes, A-17 (J) Marius Hills, A-18 (J) Copernicus, A-19 (J) Hadley.

April 1970

GLEP meeting — No photos for Davy unless from A-14. A-15 site may be wide open question. A-14 (H) Replace Littrow with Fra Mauro, A-15 (H)?, A-16 (J) Descartes, A-17 (J) Marius Hills, A-18 (J) Copernicus, A-19 (J) Hadley.

May 1970

ASSB No Davy photos on A-14, and 15 site must be selected before A-14 flies. Get Descartes photos on A-14. A-14 (H) Fra Mauro, A-15 (H)?, A-16 (J) Descartes, A-17 (J) Marius Hills, A-18 (J) Copernicus, A-19 (J) Hadley.

Summer 1970

Two more missions cancelled. Entire problem of sites is reopened. A-14 (H) Fra Mauro, A-15 (H) Mission cancelled, A-16 (J) Renumbered as A-15 (July 1971), A-17 (J) Renumbered as A-16 (Jan. 1972), A-18 (J) Renumbered as A-17 (June 1972), A-19(J) Mission cancelled.

September 1970

ASSB review of possible sites for A-15. Tycho out operationally. Davy no photos. Descartes no photos. Copernicus needs Rover. Littrow is another Mare. Marius OK, Hadley OK and has multiple objectives: Rille, Mare, Highlands. A-14 (H) Fra Mauro, A-15 Hadley, A-16 - Descartes if photos obtained, A-17 Marius, Copernicus, or a highland site from A-15 photos.

February 1971

Camera failure on A-14 did not allow hi-res photos of Descartes. Med-res. taken with hand-held camera. Question of A-16 site open again. A-15 Hadley, A-16 Marius, A-17 Copernicus, Dec. 1972 or a highland site from A-15 photos.

Spring 1971

Reschedule A-16 and 17. A-15 July 1971, A-16 Mar. 1972., A-17 Dec. 1972.

May 1971

Ad Hoc Comm. for Site Selection was clearly in favor of a Highland site for A-16. Thus Marius out. It was also out in new time frame. Copernicus out because of possible sampling on A-12 and in same quadrant of Imbrium as A-12, 14, 15. Alphonsus is a new candidate with multiple objectives: Highlands and dark volcanic? craters. Descartes possible if photos acceptable. Alphonsus preferred. A-15 Hadley, A-16 Alphonsus/Descartes A-17 ?

June 1971

ASSB. Draping of younger volcanics over old highland walls of Alphonsus, slightly better operational statistics and lack of data from highland materials of A-14 and 15 led to selection of Descartes for A-16. A-15 Hadley, A-16 Descartes, A-17 Alphonsus leading candidate but still consider-A-15 photos SW of Crisium Copernicus, and new one, Gassendi.

July 1971

A-15 successfully completed. A-16 Descartes, A-17 same as in June.

January 1972

Ad Hoc Comm. for Site Selection considered 5 sites. Copernicus out for previous reasons. Gassendi is reasonable. Alphonsus out for previous reason. SW of Crisium out because Russians got samples there. New Taurus-Littrow site has multiple objectives: Mare Highlands Dark, young volcanics? A-16 Descartes, A-17 Taurus-Littrow leading candidate.

February 1972

ASSB met for final time to select A-17 site. Gassendi ruled out for operational reasons. A-16 Descartes, A-17 Taurus-Littrow.

April 1972

A-16 sucessfully completed. A-17 Taurus Littrow.

December 1972

A-17 successfully completed.