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XXV. Future Projects Office

ADVANCED STUDIES

A. Lunar Mission Planning, *R. G. Brereton*

The intent of lunar mission planning is to define an optimum plan for lunar studies. Generally, the rationale for such planning proceeds from a set of scientific goals or objectives that define the "what" and "why" of the plan through a set of scientific experiments, utilization techniques, and time-phased spacecraft missions that define the "how," "where," and "when" of the plan. Considered in this way, lunar mission planning should be a relatively straightforward logic process.

Table 1 discusses the "what" and "why" for lunar exploration in terms of major features or processes that have been studied in the earth—our terrestrial analog. The first column describes the particular feature or process for the earth, the second column describes it for the Moon in terms of total knowledge to date and our terrestrial analog, and the third column presents some information to relate Table 1 to the actual mission planning given in Table 2.

Table 2 is an extension of Table 1, and it may be thought of as presenting the "how" for lunar mission planning and, insofar as is possible at this stage in the planning process, some information about the "where" and "when." A particular scientific objective (1 through 12) for lunar missions is defined in terms of the features or processes defined in Table 1. The first column gives the types of missions that may be useful (i.e., fixed stations, rovers, orbiters, manned, lunar base), the second column gives the principal scientific experiments for the task, the third column gives those experiments or missions that relate to the one under consideration and can be expected to provide correlative information, and the fourth column gives the "where" and "when" of the mission.

Tables 1 and 2 are vertically sequenced in terms of increasing mission complexity, thus investigations of the nature and dimensions of the lunar core are much simpler than the manned missions to study and define lunar structural geology or stratigraphy.

The two tables clearly indicate what types of missions and experiments are necessary to provide meaningful data towards the solution of specific scientific problems; and further, these are related to a real model for which we have much knowledge—the earth. From the tables, it seems that a few specific experiments can be expected to provide much new data on lunar body properties and solve major problems on the internal structure of the moon. These experiments are required to operate over a time span of months, if not years, so they are best automated.

The real significance of the man in the lunar program is in surface exploration, where his knowledge, training, and versatility make him a better data collector than even complex machines.

Table 1. "What" and "why" of lunar mission planning

Earth	Moon	Remarks
1. Core		
The diameter of the core is approximately 6946 km. The seismic velocity discontinuity, marking the mantle–core interface, is at a depth of 2898 km. The core appears to have negligible rigidity in that it will not transmit the shear energy of transverse "S" waves, and it is therefore probably fluid. Seismic data indicate there may be a solid inner core within the outer liquid core. Suggested composition is iron with some nickel, but phase change of mantle material to a more dense form may be the cause of the observed phenomenon.	The mass diameter of the moon does not seem to allow enough density for anything but a very small earth-type core, and most probably there is none. There is certainly no data at the present time that are conclusive either one way or the other as to a core in the moon. Temperature curves for the lunar interior suggest that melting could occur at relatively shallow depth, say 300 km, to produce a large liquid core.	Seismic techniques offer the most direct attack on this problem. A gravimeter at the center of the lunar disk or on the limb, which reads variation in the tidal forces between perigee and apogee, would be useful. Magnetic data as to the existence of a secular lunar magnetic field would be most interesting. The minimum flight program must allow the emplacement of geophysical stations at several geographic positions. Simultaneous operation of stations is required. Seismic source may be required.
2. Mantle		
The mantle of the earth extends downward from the Mohorovicic discontinuity to the core. It appears to be relatively homogeneous; however, it does contain two second-order discontinuities, at depths of 413 km (the so-called 20-deg discontinuity) and 984 km, as evidenced by inflections in the velocity–depth curve. The best guess for the material of the mantle appears to be a magnesium–iron silicate comprising the rock types of peridotite or dunite, and with eclogite present in the upper mantle. Except for local pockets of magma, the mantle appears to be solid.	The best guess appears to be that the whole moon, except for the churned-up surface, is mantle-like in structure. But at the present time, there is not enough data to construct a model of the lunar mantle, its composition, radial structure, state, or dimensions. Both melting and differentiation seem to have occurred, but whether or not this was universal enough to have separated the whole moon, as with the earth, into core, mantle, and crust is not known.	Seismic techniques offer the most direct attack on this problem, with both gravity and heat flow observations providing useful information. Chemical information suggesting the degree of differentiation would be informative. The minimum flight program to study the lunar mantle would be very similar to one designed to study the core—fixed geophysical stations located at several lunar geographic positions and capable of simultaneous operation. A rover may be required to provide gravity and chemical data.
3. Crust		
The terrestrial crust is made up of two major units: (1) a basal unit extending upward from the Mohorovicic discontinuity that is approximately 5 km thick, bowed down under continents and up under oceans, and is basaltic in composition; and (2) the continental blocks. The continental blocks are approximately 28 km thick with local thickening to perhaps 40 km in mountain areas. The continental blocks are generally in isostatic adjustment with the mantle. Approximately 95% of the surface areas of the earth are covered by a few kilometers of sediment.	The lunar terra and maria seem to differ in composition and appearance, thus indicating some differentiation may have occurred on the moon to generate a lunar crust; however, the thickness, horizontal extent, and composition of this crust, if it does indeed exist as a discreet lunar body structure, cannot be predicted from present scientific data.	Seismic techniques to observe the dispersion, or variation of phase and group velocity of surface waves as a function of period, can provide important information here. Perhaps gravity surveys to determine a depth-of-compensation, as well as heat flow and active seismic studies, could be necessary. The minimum flight program requires several fixed geophysical stations. Active seismic and gravity studies can be accomplished best with a rover.

Table 1 (contd)

Earth	Moon	Remarks
4. Gravity field		
The gravitational field of the earth is a function of its size, shape, and mass distribution. In general, it varies from about 982.3 gals at the poles to 978 gals at the equator due to the oblate spheroid shape of the earth and centrifugal acceleration. Large young structural features on the earth, such as mountains and island arcs and trenches, may have Bouguer anomalies of several hundred milligals. Usually, the isostatic anomalies associated with these features are quite small, thus indicating some type of compensating mechanism. Isostatic anomalies to perhaps 50 mg are known, however.	The gravity field of the moon is about 157 gal. The centrifugal effect is very small, but frozen tidal effects may have affected the gross field. A 1-km bulge would represent 190 mg. The tidal effect for an unyielding moon as it goes from perigee to apogee is about 1 mg, but for a yielding fluid moon tides to 16 m could produce gravity variations of about 4 mg. The one-sixth gravity of the moon as compared to the earth may allow for larger masses of material to be piled on the lunar crust, thus producing large Bouguer anomalies. This effect will be a measure of lunar isostasy.	An absolute gravity instrument located at the center of the lunar disk or at the limb through at least one lunar period would provide data on the yielding of the moon to tidal forces. Mobile gravity surveys are necessary to define the anomalous components of the lunar gravity field.
5. Magnetic field		
Both axial rotation and a liquid core seem to be required for the generation of a planetary magnetic field. The geomagnetic field is made up of three parts: (1) a large secular part approximating a dipole situated in the core but missing the center of the earth by 1200 km (the magnitude of this field over the surface of the earth varies from about 60,000 to 70,000 gammas near the poles to 30,000 gammas at the magnetic equator); (2) an external field resulting from interactions of solar particles and field with the geomagnetic field; and (3) an anomalous part produced in crustal rocks by virtue of their magnetic properties.	It is unlikely that the secular component of the lunar magnetic field is greater than 100 gammas; however, large magnetic anomalies resulting from susceptibility contrasts and polarization by flowage, relic fields, or solar fields are possible, as are anomalies resulting from concentrations of ferromagnetic material such as in nickel–iron meteorites.	It is desirable to measure any effects of external fields from both the earth and the sun on the moon. It is desirable to measure the magnetic properties of oriented lunar rock samples. Seismic, gravity, and temperature-gradient data and chemical studies will all provide useful information. Collection of these data will require a roving vehicle.
6. Density		
The density of the crust is 2.8 g/cm^3, but the mean density of the whole terrestrial sphere is 5.5 g/cm^3, suggesting that denser material must be concentrated towards the center. Further, the moment of inertia of the earth is 0.334, as determined from the precession of the equinoxes, but for a uniform sphere of the same dimensions it should be 0.4, which again suggests that denser material must be concentrated towards the center. Numbers depicting the density distribution within the earth are bounded by the total mass of the earth, its moment of inertia and seismic data. Calculations of this type suggest a density of 3.3 g/cm^3 at Mohorovicic, and this increases more or less uniformly to a value of 5.7 g/cm^3 at the base of the mantle. At the top of the core, the value jumps to 9.5 g/cm^3, and this increases to a value of about 17 at the center of the earth.	The average density of the moon as determined from its mass and radius is 3.34 g/cm^3. The pressure at the center of the moon is only 46,500 bars, or as occurs at a depth of 150 km in the earth, and this doesn't seem to be sufficient to have generated the same type of internal structure as the earth. Chemical discontinuities, where the density increases substantially with depth, seem to be limited by the low average density and moment of inertia for the moon. There seems to be evidence for density concentrations in the lunar crust (mascons); also, the moment-of-inertia data suggests a density inversion may occur ($C/MR^2 = 0.60$, i.e., hollow moon). Melting in the moon could have separated the body into a core mantle and crust without violating the mean density.	Seismic techniques to determine the "P" wave velocity–depth function are required. Information on melting in the moon, as may be determined from "S" wave studies and heat flow studies may be required. The minimum flight program here calls for several fixed geophysical stations as required for core and mantle studies. Density contrasts in crustal material, i.e., mascons, can be studied in detail with a rover.

Table 1 (contd)

Earth	Moon	Remarks
7. Temperature		
The temperature gradient as measured within the crust averages about 30°C/km. This figure, along with measured thermal conductivity, gives an average mean heat flow of 1.2 × 1.0 cal/cm²—s for both continents and oceans. It seems certain that this temperature gradient does not continue to great depth, and in fact most estimates place the temperature at a depth of 200 km between 1400 and 1750°C, with the temperature depth curve becoming almost flat below a depth of about 400 km. Calculations of the temperature at the center of the earth range from a high of about 5000°C to 2000°C, depending on the thermal model assumed. Calculations seem to indicate that only about 20% of the present-observed heat flow comes from original heat, i.e., say a molten earth; the rest appears to be due to radioactivity of rocks.	The temperature gradient and thermal conductivity for the moon have not been measured. Temperature curves for the lunar interior, considering a range of compositions and ages for models, have been calculated. In general, the hottest models allow for large-scale melting at relatively shallow depth, say about 300 km, while the coldest models allow for interior temperatures of only about 1000°C and perhaps localized surface melting. It seems likely that the heating of the moon by radioactive elements is still continuing. The flux of radiogenic heat away from the moon is probably of the order of only a few ergs/cm²-s, and a measurement of this will be difficult.	*In situ* measurements in bore holes of the temperature gradient and thermal conductivity are required. Because of the length of time required to make measurements and the depth of measurement, fixed geophysical stations are required. These data from the fixed sites should be supplemented by heat flow data derived in roving vehicle traverses.
8. Radioactivity		
Radioactive elements within the earth possibly provide some of the fuel for endogenic processes, and they also provide the means for absolute age-dating of surface rock units. The distribution of the principal radioactive elements U^{235}, U^{238}, Th^{232}, and K^{40}, as well as some of the shorter life elements in the earth, cannot be directly measured; however, it is apparent that through the process of differentiation these elements have been concentrated in crustal rocks, especially the Sial rocks of the continents.	At the present time, there is no information about the amount or species of radioactive material in the mass of the moon. *Luna 10* did not indicate a gamma-ray count any higher than for normal basaltic rocks, so the lunar terra do not appear to be as radioactive as the earth's Sialic continents. A chondritic moon would have a radioactive content of 1.1×10^{-8} g/g uranium, 4.4×10^{-8} g/g thorium, and 8.0×10^{-4} g/g of potassium, and it should show far more endogenic activity than it does. If the moon is of chondritic composition, then heating has been gradual and is still continuing, and will reach its maximum some 2 or 3 billion yr in the future.	A gamma-ray experiment in an orbiter would provide some useful data on the concentration of radioactive elements in the surface of the moon. Geophysical studies at fixed sites to determine the heat flow and velocity-depth function of "P" waves and the transmissibility of "S" waves will provide interesting data. The degree of melting in the moon is of primary concern for understanding its past and present content and distribution of radioactive elements.

Table 1 (contd)

Earth	Moon	Remarks
9. Chemistry		
The average composition of the accessible portion of the earth's crust is approximately 50% oxygen, 26% silicon, 8% aluminum, 5% iron, 3% each for calcium, sodium, potassium, and magnesium, and 0.63% titanium. It should be observed that the atmosphere, the hydrosphere, the biosphere, and the crust contribute only about 1% of the total mass of the earth. Thus, the bulk composition of the earth is essentially that of the mantle and core. Meteorite data and certain geophysical observations suggest the earth has a periodtite mantle ana a nickel–iron core, with a bulk composition of approximately 28% oxygen, 13% silicon, 35% iron, 17% magnesium, 2.7% sulfur, and 2.7% nickel. Any phase-change hypothesis would of course alter these percentages closer to the composition of mantle material or even solar composition.	The composition of the material on the lunar surface, from *Surveyor* results, is basaltic, and, in general, it is similar to the average composition of the terrestrial surface. The average density of the moon suggests that it does not have the iron content of the earth, or the lunar mass must contain an anomalously high percentage of low-density materials that have not as yet been degassed. The possibility also exists that the apparent high density of the earth's core results from a phase change of magnesium–iron silicates and not a concentration of nickel–iron.	The average composition and mineralogy of the lunar surface must be determined. This will require sampling at a variety of lunar surface features and outcrops in the various geomorphic provinces of the moon. Obviously, this task will require a roving vehicle. These data in conjunction with fixed site geophysical data will permit calculations of the bulk composition of the moon.
10. Geomorphic processes		
Endogenetic processes, sometimes collectively referred to as diastrophism, operate within the earth to produce "constructional land forms," while exogenetic processes through weathering and erosion operate to sculpture and ultimately destroy the original constructional form. In the terrestrial environment of an atmosphere and abundant water, surface rocks are changed by chemical and mechanical processes called weathering. Weathered material may form a residual deposit, but usually agents of erosion—streams, glaciers, waves, wind, and gravity—accomplish loosening and transport of the accumulating material to an area of deposition. The erosional, residual, and depositional features produced on the surface of the earth by the forces of weathering and erosion are very diverse.	Endogenetic processes do not appear to have been as active on the moon as they have been on the earth. Very possibly the energy for the major constructional processes on the moon has come from large meteorite impact, and is therefore exogenetic in origin and in sharp contrast to the earth. Certainly there has been volcanism, and *Surveyor* results suggest considerable differentiation so endogenetic processes must have operated, but "constructional land forms" on the moon do not have a high correlation with terrestrial features. The key to exogenetic processes on the earth is the atmosphere and abundant water. These are absent on the moon, so the processes of weathering and agents of erosion there are not the same as for the earth. It would appear that the major processes operating to shape the surface of the moon are meteorite bombardment, solar radiation, gravity, seismic shock, and thermal shock. Considerable progress has been made in classifying lunar physiographic provinces.	The techniques of field geology offer the most practical approach for studying geomorphic processes. Field investigations will require an "on site" study of the various geomorphic provinces of the moon. The minimum flight program calls for both roving-vehicle and orbiter photographic data. Remote sensor data may be useful for mapping terrain units. Because of the number of sites that must be visited on the lunar surface, roving vehicles will play a very important part in the study of geomorphic processes.

Table 1 (contd)

Earth	Moon	Remarks
11. Structures		
Diastrophism has compressed and folded great wedges of sedimentary rock, formed linear igneous mountain belts, uplifted and lowered great tracts of the crust thousands of feet, and has apparently moved continental blocks thousands of miles. The processes of ocean-basin spreading and continental migration are being seriously studied. The crust of the earth has apparently been very mobile throughout geological time, and it is now broken into structural units that portray its origin and evolution. The study of terrestrial structural units and features has always represented the best effort from earth scientists in the sense that several different geological disciplines may be used to understand a particular problem; also, the field observations can only be made by a highly trained and experienced specialist.	The linear and arcuate structures that characterize the earth are generally replaced on the moon by circular structures. No chains of folded or batholithic mountains are evidenced, nor is there evidence of large horizontal and vertical faulting. Linear scars that radiate from some of the circular basins have been mapped, also rift zones marked by volcanism, such as the area from the Marius Hills on the south to Rumker on the north, which appears as an incipient "Mid-Atlantic Ridge." Although diastrophism has not been as dynamic on the moon as it has been on the earth, the lunar "crust" is very complex and formed of discrete structural units, and the study of the origin and evolution of these may prove important towards understanding geological processes on the earth.	The major structural units, faults, contacts, and lineaments on the moon will have to be mapped and studied by field geology techniques. Orbiters, rovers, and a variety of manned missions will be required. The investigation of lunar structures will involve a rather thorough program of surface exploration with roving vehicles.
12. Stratigraphy		
The sedimentary layers of the crust of the earth were deposited by the geological agents of running water, wind, glaciers, marine action, and gravity. Stratification of this material has usually resulted from changes in the rate, type or nature of the depositing agent, changes in source material, or changes at the site of accumulation. Consolidation of deposited material is accompanied by cementation, metasomatism, and other forms of diagenesis and metamorphism. The law of "faunal succession" based on biological change is used for determining the chronology of the earth's sedimentary record, and this has been selectively related to absolute age dating by radiological methods.	The time and rock stratigraphic units presently defined for the lunar surface were derived from telescopic observations of surface morphology and albedo. At the present time, the major stratigraphic units are, from oldest to youngest, the Imbrian System, which has now been broadened to include the Procellarum Group, the Eratosthenian System, and the Copernican System. Several rock stratigraphic units have been defined within this broad time stratigraphic framework. Stratification is not as pronounced as on the earth, and no color-banded formations and obvious albedo differences signifying layering are observed in vertical exposures. Witness the thousands of feet of vertical exposure in the rim of the crater Copernicus and other craters.	Field mapping will have to include vertical sampling by drilling as required. The investigation of lunar stratigraphy will interrelate and be carried on contemporaneously with studies of lunar structures, geomorphic processes, rocks, minerals, etc. The flight program will need to include orbiters, rovers, and a variety of manned missions. Certainly surface exploration with roving vehicles is required.

Table 2. "How," "where," and "when" of lunar mission planning

Mission type	Principal scientific experiments	Secondary scientific experiments	Remarks
1. Nature and dimensions of lunar core			
Fixed geophysical stations.	Three-axis seismometer. Tidal gravimeter (absolute).	Heat flow studies at fixed geophysical stations.	A minimum of four seismometers on the front face of the moon should be adequate. One of these should be on terra in the southern region, one on the western limb in Oceanus Procellarum, one in Mare Serenitatis, and one in Sinus Medii. These locations are adequate for the gravity experiment. If the moon is aseismic, an artificial source in the northern hemisphere will be required. Simultaneous operation is required.
2. Nature and dimensions of lunar mantle			
Same as above.	Same as above.	Same as above.	Same as above.
3. Nature and dimensions of lunar crust			
Same as above.	Same as above.	Same as above. A rover carrying several seismic sources to work out from fixed geophysical station. Rover gravity studies.	Same as above with emphasis on the observation of surface seismic waves.
4. Shape and magnitude of lunar gravity field (shape of the moon)			
Rover.	Gravimeter. Ranging.	These data will be useful for defining the lunar ephemeris and motions, and may be related to objectives 1, 2, and 3.	Will investigate gravity anomalies in the crust and provide data for isostatic computations and locating frozen tides.
Orbiter.	Radar altimeter. Ranging and orbit parameters.		Will define the shape of the moon and locate large gravity anomalies
Fixed geophysical stations.	Tidal gravimeter (absolute).		Will provide a base for absolute gravity and its variation.
5. Shape and magnitude of lunar magnetic field			
Rover.	Magnetometer (vector).	Observation of electric fields.	Will define anomalies in the lunar magnetic field and locate their source.
Fixed geophysical stations.	Magnetometer. Various fields and particles detectors.		Will define the magnitude and fluctuation of any lunar field.
6. Vertical and horizontal density distribution			
Fixed geophysical stations.	Same as for objectives 1, 2, and 3.	Relates to objective 4.	Same as for objectives 1, 2, and 3.
Rover.	Gravimeter.		Will locate horizontal density contrasts.
7. Vertical and horizontal temperature distribution			
Fixed geophysical stations.	Drill. Thermal probe.	An orbiter infrared radiometer experiment may provide interesting data. A thermal probe on a rover may be useful.	The drill hole should be at least 3 m deep. A greater depth, say 10 m, is desirable. Observations should continue through at least a lunation. The previously-mentioned seismic sites would be suitable for this measurement.

Table 2 (contd)

Mission type	Principal scientific experiments	Secondary scientific experiments	Remarks
8. Distribution of radioactive elements and age dating of lunar rocks			
Sample return. Orbiter. Rover. Manned.	Sample acquisition and storage. Gamma-ray spectrometer. Gamma-ray spectrometer. Drill or surface samples. Age dating and stratigraphy by field geology techniques. Manned rover.	The techniques of lunar field geology will be important to this objective since they will define the stratigraphic relationship of layered rocks. A rover may be used to acquire samples for sample return mission.	This probably implies manned mission since the sample needs to be rationally selected. This will give the distribution of radioactive material over the lunar surface to a depth of perhaps a few centimeters. To investigate the radioactivity of specific sites. The sample will probably have to be returned to earth for analysis. Sample selection and ascertaining its stratigraphic relationship requires a trained geologist.
9. Composition and distribution of lunar material			
Sample return. Rover. Manned.	Sample acquisition and storage. Drill and sample preparation. X-ray spectrometer. X-ray diffractometer. Sample acquisition. Field geology. Manned rover.	The techniques of lunar field geology will define the interrelationship of rock units. The composition of the interior of the moon will have to be extrapolated from geophysical data and surface chemistry. A rover may be used to acquire samples for sample return mission.	This probably implies manned mission since the sample needs to be rationally selected. Provides the capability to sample large areas of the moon. Acquired samples can be delivered to a pick-up point for earth return. Provides the capability for detailed sampling of limited areas of the moon.
10. Endogenetic and exogenetic processes and features of the moon			
Orbiter. Manned. Rover. Fixed geophysical station.	High-resolution stereo and color photography. Field geology. Manned rover. High-resolution camera. Camera. Micrometeoroid detector. Fields and particles detectors.	The techniques of lunar field geology are important to this objective. This objective is tied in with objectives 9, 11, and 12. A lunar base from which detailed studies could be carried out will eventually be required.	It is desirable to cover as much area as possible at 1-m resolution. Manned exploration of the various physiographic provinces is required. Supplement manned observation in rough or difficult-to-reach areas. Observe those phenomena on the lunar surface that operate slowly and so may not be apparent to short stay-time missions.
11. Structural units of the lunar crust			
Orbiter. Manned. Rover. Rover (geophysics). Lunar base.	High-resolution stereo and color photography. Field geology. Manned rover. High-resolution camera. Drill and sample preparation. X-ray spectrometer. X-ray diffractometer. Petrographic microscope. High-resolution camera. Magnetometer. Gravimeter. Active seismometer. Field geology. Manned rover. Deep drill.	The techniques of field geology are paramount for this objective. This objective is a rather fundamental one to earth sciences and so it is related to many of the other objectives.	It is desirable to cover as much area as possible at 1-m resolution. Manned investigation of the various structural units and field mapping. Supplement manned observations in rough or difficult-to-reach areas. Provide profile data over extended areas or geophysical data in conjunction with manned missions. The very detailed study of an interesting lunar site. Considerable maturity in lunar geology is required for site selection.

Table 2 (contd)

Mission type	Principal scientific experiments	Secondary scientific experiments	Remarks
12. Stratigraphic sequence for lunar rocks			
Orbiter.	High-resolution stereo and color photography. High-resolution oblique photography.	The techniques of field geology are paramount for this objective. This objective relates strongly to objective 8.	It is desirable to cover as much area as possible at 1-m resolution.
Manned.	Field geology. Manned rover.		Investigation and mapping of lunar outcrops.
Rover.	Same as above		Supplement manned observations in rough or difficult-to-reach areas. Provide geophysical support.
Lunar base.	Field geology. Manned rover. Deep drill.		The very detailed study of a significant lunar site.