NASA SP-174

CONFERENCE ON ELECTROMAGNETIC EXPLORATION OF THE MOON

Report of the Program Evaluation Committee

AMES RESEARCH CENTER

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The results of a conference held at the Ames Research Center at Moffett Field, California, on June 11 - 13, 1968

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CONTENTS

1. Introduction

Planning for the scientific activities in the later Apollo and post-Apollo period was accomplished by the 1967 Summer Study of Lunar Science and Exploration held at the University of California at Santa Cruz. The recommendations of eight working groups contributed to the final conference report and provide a detailed basis for the planning of future lunar experiments. The Geophysics Working Group, under Dr. Frank Press, offered a number of suggestions of suitable electromagnetic (EM) experiments but found that most of these suffered from a lack of definition. This lack arises for several reasons, among them the difficulty in even setting order of magnitude estimates on the electrical conductivity of the Moon, the lack of field experience with non-aqueous environments, and the truly nascent state of engineering and field development in certain areas, such as higher frequency geophysical and environmental radars.

In order to enhance the contributions that EM methods might make to lunar exploration and to provide NASA with a more practical and critical assessment of proposed experiments, the Conference on the Electromagnetic Exploration of the Moon was convened at NASA Ames Research Center on June 11-13, 1968, under the cosponsorship of the Space Science Laboratory of the University of California, Berkeley, and NASA Ames Research Center. Professor Stanley H. Ward of the University of California, Mr. Ed Davin of NASA Headquarters, and Dr. William I. Linlor of Ames Research Center acted as conference organizers. This report was prepared by a Program Evaluation Committee with Prof. Robert A. Phinney of Princeton University as Chairman, and Dr. Wilmot H. Hess of the Manned Spacecraft Center as Vice Chairman. The formal part of the conference consisted of a program of invitational papers and discussion periods. Speakers and other participants were apprised of the dual function of the meeting—to air and discuss the latest results in the field and to prepare recommendations for NASA. At the close, the draft recommendations of the Program Evaluation Committee (PEC) were presented to the conference for criticism and suggestions.

This document consists of the report and recommendations from the PEC. In sections 2 to 5, the setting is provided; we discuss the purpose and goals of electromagnetic lunar work, the criteria used to evaluate proposed experiments or methods, and the role of budgetary constraints in the recommendations. In section 6, we present recommendations regarding three types of experiments which appear to warrant inclusion in the program in the time period 1971-1975. In section 7 is a description of recommended experiments. In section 8, Supporting Research and Technology (SRT) which is germane to the recommended experiments is discussed, and recommendations are given concerning the types of SRT work of highest priority. Conference participants, the conference program, and the members of the PEC are listed in the appendixes. The technical proceedings will be published separately.

2. Purpose of Electromagnetic Experiments

The purpose of electromagnetic (EM) experiments on the Moon is to help answer important problems of geophysical and geological interest. The lunar exploration program must be as broadly based as possible, and we cannot see a rationale for experiments whose only justification is their intrinsic interest as EM studies. The general goals of lunar exploration are *to understand the present structure and constitution of the lunar interior, to understand the major geological processes responsible for the character of the lunar surface (including many aspects of the solar wind just above the lunar surface), and to understand the processes of internal evolution and their surface manifestations.* These are consonant with the prime NASA goals in the exploration of the Moon and planets: To discover the origin and evolution of the Earth, Sun, planets; the origin and evolution of life; and the dynamic processes that shape man's terrestrial environment. (See refs. 1 to 3.)

The work of this committee involves two provisions, both connected with limitations in the committee composition:

(1) Both active and passive methods have been considered in the frequency band from dc to about 10^{11} Hz only. This corresponds approximately to the frequency band in which coherent detection is possible, and, except for the upper two or three decades, the band where diffuse scattering is relatively unimportant as a mode of interaction with the Moon. We have specifically excluded imaging experiments from consideration.

(2) The committee does not adequately represent the community of scientists doing work on particles and fields in the lunar neighborhood. We regard questions of the magnetic field behavior near the Moon and the characteristics of the boundary sheath of interest only as they are boundary conditions that must, in various degrees, be known to properly design and interpret experiments aimed at the surface and interior. No priority judgments are made about particle and field experiments for their own sake; appropriate advice is available to NASA through other groups. Certain types of work in the lunar near-surface environment are important to the "solid body" studies, and they are endorsed on these grounds. The particles and fields recommendations from the 1967 Santa Cruz report are endorsed, and it is recommended that productive liaison be maintained with workers in this area.

3. Promise and Problems of Electromagnetic Exploration

For a geophysical method to provide information about the shallow or deep interior, the field must penetrate to appropriate depths. The three phenomena that obey a form of the wave equation, elastic waves, EM waves, and temperature perturbations, have the ability, in principle, to probe the interior of the Moon. Seismic methods are the standard for this problem and are principally sensitive to the elastic constants and density. An important question is whether the Moon is sufficiently seismic to make full use of the passive experiments. Surface heat flow represents an important boundary value and will constrain severely any models of the lunar temperature profile; it can be taken at only a few points, however.

Electromagnetic waves propagate in geologic materials in two possible ways, depending on whether conduction currents or displacement currents predominate. In either case, the depth of penetration is limited by losses, a situation that limits the applicability of EM methods compared with seismic methods that are formally similar. These considerations are summarized in figure 1, which shows the attenuation distance in certain model materials as a function of frequency. The dashed curve is one estimate of the depth of penetration in the Moon, with uncertainties that depend on the uncertainty in conductivity at low frequency and in loss tangent at high frequency.

Some of the characteristics that make EM methods look promising may be listed as follows:

(1) Ability to do electrical conductivity profiling and sounding at frequencies less than approximately 10^7 Hz.

(2) Ability to do dielectric constant profiling and sounding at frequencies greater than approximately 10^3 Hz.

(3) Availability of a wide range of natural and artificial signals.

(4) Well-established technology for detection of signals.

(5) Ability to work from orbit, with extensive coverage.

(6) The useful connection between conductivity and temperature under lunar interior conditions, and between conductivity, dielectric constant, and water content under near-surface conditions.

Some of the problems that arise in trying to program these methods for lunar exploration are as follows:

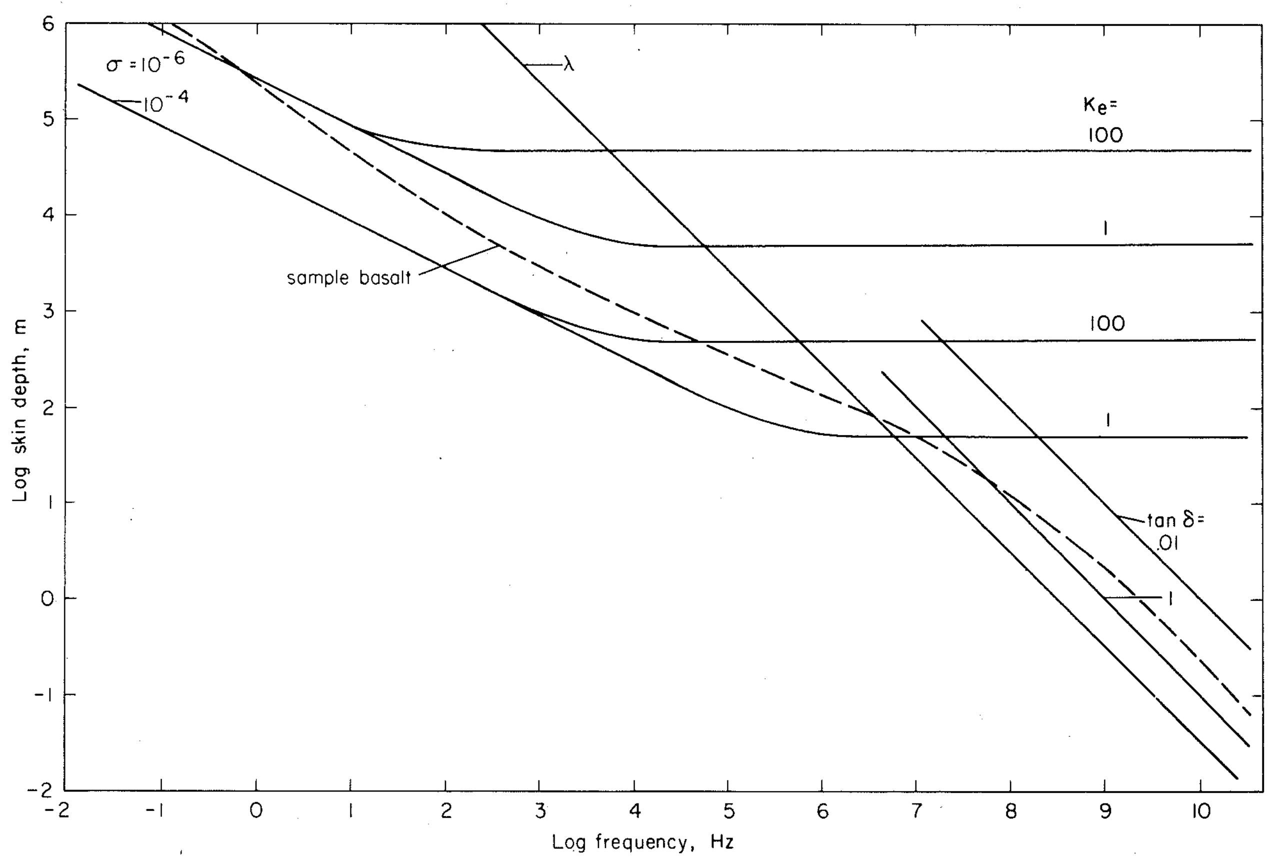

FIGURE 1.–Electromagnetic skin depth for various idealized media, with conductivity σ and dielectric constant K_e. Curves in the microwave region are given which assume constant loss tangent (tan δ). Dashed curve is estimated behavior of a real geological material (basalt).

(1) Our present state of information about the solar-wind - lunar-surface interaction and about the interior of the Moon does not permit experiment analysis and design that can be made realistic with the desired degree of assurance.

(2) Our present state of information about the electrical conductivity and dielectric constant of geological materials does not permit us to estimate with the required degree of assurance the three-dimensional distribution of the electrical properties, given even the present state of geological knowledge derived from Surveyor and Orbiter.

(3) The use of EM methods for remote sensing on the Earth has suffered from a lack of focus on acquisition of basic information as contrasted to methodology. In comparison with seismology, for example, the literature is appallingly sparse regarding the practical application of, say, radiofrequency and microwave devices for geophysical purposes.

(4) Of the wide range of boundary value and initial value problems of mathematical physics that have immediate application to the design and interpretation of experiments, only a few have been solved. Consequently, many ground-based methods that have been used for years in mining and water exploration still are interpreted through very simple models. The degree of uniqueness in interpretation has suffered in comparison with the standards of seismology.

(5) Many EM methods appear promising if either the forcing field or the structure being studied satisfies certain simplifying assumptions with regard to scale, isotropy, homogeneity, etc. This problem of *characterizing the data* is commonly overcome by trying various experiments and making allowance for a certain fraction of failures. Such an approach is unsuitable for lunar work.

4. Goals of Lunar Electromagnetic Exploration

It is appropriate to discuss the specific geological and geophysical parameters of the Moon that may be investigated by EM methods.

(1) Temperature and conductivity profiles of the deep interior, with resolution of approximately 100 km or more.

(2) Temperature and conductivity profiles of the outer 100 km or so, with resolution on an appropriately smaller scale.

(3) Detection of variations in dielectric constant K_e and conductivity σ, which vary with depth near the surface: geological layering, permafrost, etc.

(4) Detection of lateral inhomogeneities in K_e and σ on a large scale and on a local scale, e.g., voids, water, geological structures, etc.

The dependence of conductivity on temperature is central to the use of EM in deep sounding. This makes a low-frequency EM experiment the most likely method of getting a reasonably direct determination of the interior temperatures in the Moon. For lunar materials under pressures above 1 kb and temperatures above 300° K, a number of conductivity mechanisms can be postulated, but, in every case, one has the activation model of temperature dependence (exp (-F/kT)). Authoritative interpretation of a conductivity profile requries the estimation of a limited number of other parameters, the most important being those which characterize the iron content. The consensus of workers in the field seems to be that reasonable temperature estimates are not out of the question, especially if the seismic results constrain the composition of the Moon. Simultaneous knowledge of the gross temperature profile and the surface heat flow can be a strong constraint on theories of the thermal history of the Moon.

The third and fourth items listed above represent information on a geological scale. As such, they are envisioned ultimately as a way of carrying out geological mapping and structure determination far more economically (and extensively) than possible by an astronaut. In the immediate future, there will be only limited opportunity for intensive manned studies of important small areas; we see, therefore, an importance in general studies of lunar geology and emphasize the place that orbital experiments can have in this work.

5. Criteria for Consideration of Experiments

For each experiment proposed, the overriding consideration is this: *Can it be designed to return, in acceptably unambiguous form, information of central interest in lunar science, and is the design based firmly enough at this time to permit the development of acceptable flight hardware for later Apollo flights?* In effect, we looked for experiments whose uncertainties and problems, as outlined earlier, are least, as compared with the scientific payoff. We also required that the mix of recommended experiments offer a maximum return across the range of possibilities, without being unnecessarily redundant. Because of financial constraints on NASA, we assumed that lunar exploration activities during the period 1971-1975 would be carried out at a "balanced minimum" level and tried to envision a practical flight program that could be justified in terms of scientific knowledge in competition with a host of other scientific activities.

6. Recommendations for an Experimental Program

We recommend that mission planning, supporting research and technology effort, and flight hardware development be addressed to the support of three specific types of experiment:

(1) Passive, deep-conductivity sounding using a combination of three or four three-axis magnetometers (frequency range dc to 10 Hz). The most promising arrangement appears to be one in orbit and the others landed.

(2) An active, radiofrequency (RF) (10^4 to 10^8 Hz) sounding device, to obtain structural information on the upper 10 kilometers of the lunar subsurface.

(3) An active, pulsed (or equivalent) radar (10^8 to 10^{10} Hz), for the structural sounding of the upper 100 meters of the lunar subsurface.

Our analysis of these experiments constitutes the main body of this chapter. In these discussions, it is frequently convenient to assume implicitly or explicitly certain design or system characteristics. Suggestion of reasonable arrangements are to be taken only as such and not as strict criteria for evaluating proposals. It is expected that proposals will involve specific configurations not treated here. Evaluation should be based on the three principal recommendations and should follow the rationale of the discussions following. Analysis of the limitations, uncertainties, and advantages leads to the indication of relative importance given in the following table. As a guide, if a scale of one (lowest) to 10 (highest) is selected as a composite evaluation measure, the experiments are ranked as follows, with experiment (2) delineated into (2a) for the orbital and (2b) for the surface version:

Experiment		Evaluation
(1)	Magnetometer sounding experiment (MSE)	10
(2a)	RF electromagnetic lunar orbiter (EMLO)	10
(2b)	RF electromagnetic surface unit (EMSU)	5
(3)	Pulsed radar probe (PRP), surface	3

(1) A magnetometer sounding experiment (MSE) ranks first in terms of hardware development. As far as can be ascertained, the MSE may require modified versions of the ALSEP and IMP instruments. The MSE also ranks first

in scientific priority at this time, because of the great interest in knowing the central temperature of the Moon. These factors yield the composite evaluation number of 10 in the table. However, it is possible that the simultaneous operation of two early Apollo ALSEP magnetometers, together with information from Explorer XXXV magnetometers, may supply enough information that this more refined MSE configuration is less important. The ultimate priority of the MSE may thus be lower than we have given in the table.

(2a) An RF electromagnetic lunar orbiter (EMLO) bears a great resemblance to the Alouette ionosphere sounder and seems to present no special design problems. Of all the suggested, but undeveloped, experiments, this appears most likely to return worthwhile information; this is related in large part to the radar-based knowledge that reflection from the Moon in the megacycle region is overwhelmingly specular. Results from Explorer XXXV give strong encouragement that proper exploitation of frequencies in the range of 10^4 to 10^8 Hz may become a powerful exploration tool. These considerations of important scientific information, similarity to the Alouette satellite, and experience with radar probes yield the evaluation factor of 10 in the table.

(2b) The RF electromagnetic surface unit (EMSU), although nominally in the same frequency range as the EMLO and thus capable of equivalent depths of penetration, has a restricted mobility. Also, the state of hardware development and Earth-based experience are limited at present. These factors and the uncertainty of lunar missions yield the evaluation factor of 5 in the table.

(3) The pulsed radar surface probe (PRP) has been given a lower priority and a composite evaluation number of 3 in the table, because of the limited new scientific information that can be expected. A critical factor in the unresolved environmental characteristics is the effective loss tangent in the lunar surface debris over lengths of a few meters, and the question of whether scattering by rocks in the debris may completely dominate any reflected signals of interest. Such scattering would produce serious difficulties in an experiment from orbit; thus, only the surface location is recommended at present.

We recommend that full use be made of any opportunities to augment knowledge of the lunar electrical properties that may be discovered during lunar activities already programed. We feel, in particular, that the antenna and communications configuration on the first three Apollo missions offers such an outstanding opportunity. This committee could not study these questions definitively. The committee is impressed, however, with the potential of an experiment in which the steerable antenna on the lunar module is aimed at the nearby surface in a bistatic study of reflection from the debris layer. This would help immensely in the definition of the PRP experiment. It is quite important that experiments of this class be evaluated immediately to allow time to program the desired activities.

7. Description and Discussion of Recommended Experiments

The remainder of this chapter presents descriptions and evaluations of the three recommended experiments. Note that these are at best preliminary reports on experiment definition; for all three experiments it is clear that a great deal of refinement and close examination of assumptions will be required. The magnetometer is a case in point. The applications described here are extensions of "classical" geophysical methods used on Earth and have been high on all lists of candidate lunar experiments. A conventional justification for this inclusion is inadequate because it is not at all obvious that the solar wind-lunar interaction will somehow provide the kinds of magnetic fields that can be interpreted with three or four stations. It is estimated that some minority of the signals transmitted to the Moon by this interaction are appropriate to our needs, and we can guess which these might be (such as the sectorial field reversals in the steady solar wind stream). These issues require sorting out; in this example, we note that they are of immediate concern in the interpretation of the ALSEP magnetometer data as well.

Magnetometer Experiment

There is great interest in the deep electrical properties of the Moon because of the implications concerning the interior lunar temperature and composition. There is also an interest in the question of a lunar magnetic field, either remanent or electrodynamic. It seems that a magnetometer experiment has a good chance of giving us some insight on these problems. At the same time, of course, a magnetometer experiment will be of interest to plasma physicists studying lunar-plasma interactions.

In order to probe the deep lunar interior electromagnetically, it appears that one must depend on studies of the Moon's response to the natural variations of the external EM fields. (This includes also the Moon's response to a steady field blown past the Moon by the solar wind.) Because of anticipated difficulties with electric fields in the lunar surface, which are not associated with this EM response, it is felt that at this stage one must consider the magnetic measurements as the only workable technique. This technique, in theory, involves a knowledge of the magnetic field variations over an area whose dimensions are a good deal larger than the depth of investigation. Thus, for deep lunar studies one should know the field variations over the entire lunar surface. It is felt, however, that useful results can be obtained from a very modest number of stations by working with special signals whose basic geometric properties are well understood. This may well involve some bootstrapping because the Moon's effect on the fields will of course alter the fields seen at the surface. This is especially true in the solar wind environment. Some serious planning must be done about the design criteria for experiments beyond ALSEP, both concerning the geometric setup and the frequency range and sensitivities required. The relatively slow velocities of the source fields and the possibly rather modest conductivities of the Moon lead the difficulties in the use of the method that are quite different from those experienced in Earth studies. That is, the skin depth in the Moon may be equal to or greater than the wavelength of the incident signal. Under these circumstances conventional conductivity profiling might be difficult, although some limits could still be placed on the average conductivity. From present estimates of lunar conductivities and EM perturbation velocities, it seems that the frequency range of dc to 10 Hz is the most likely range for deep lunar studies.

The dc capability is required for the magnetometers because very sensitive evaluations of a permanent lunar magnetic field can be made by comparing time-averaged magnetic field values at different points with time-averaged orbital measurements. The response of the Moon to the steady component of the solar wind will also produce some dc magnetic field, which can be studied by such time-averaged measurements.

On a very preliminary basis, it is felt that a minimum magnetometer experiment (beyond ALSEP) should consist of two landed three-component magnetometers placed some 90° apart supplemented by magnetic measurements made from an orbital vehicle. The magnetometers should have the highest possible sensitivities in the dc to 10 Hz frequency range while maintaining a good absolute accuracy.

It is also recommended that a regional magnetometer expe.iment be done using a moving vehicle working in conjunction with a fixed station. The experiment should also provide data that will be an important check on the assumptions made in the interpolation of the data between the fixed stations that is necessary in any interpretation scheme. Lateral conductivity variation anomalies result from currents flowing parallel to the strike of the variations, and thus to improve the possibility of crossing such anomalies, one should direct the vehicle in a direction parallel to the general fluctuating magnetic field direction. In the case that the fixed stations have detected a remanent magnetic field, the moving vehicle could study the geometric scale of such fields.

In summary, the recommendations for a magnetic experiment are as follows:

(1) A magnetometer network to measure the lunar response to varying natural EM fields using a minimum of three detectors, two on the Moon at well-separated stations and one in orbit about the Moon. The detectors must be three-component magnetometers whose orientation is known and which have a frequency range from dc to 10 Hz.

(2) A regional magnetic variation study using one of the fixed stations and a moving vehicle equipped with a three-component magnetic field detector having a dc to 10-Hz frequency range.

The Radiofrequency Probe

The class of experiment considered here has the following characteristics:

Active, monostatic or bistatic.
Frequencies between 10^4 and 3×10^8 Hz.
Penetration depths up to about 20 km.
Reflection very nearly specular.
Two modes, orbital and traverse.
Possible use of Earth-based facilities in bistatic operation.

On the next higher scale of resolution from the MSE, one concentrates on a geophysical description of the lunar crust at a scale that provides an extension of photographic-geologic information into the third dimension. Selection of a frequency band is based on several considerations:

The dominant role of solar-wind plasma conductivity below 10^4 Hz.
Problems of antenna size below 10^4 Hz.
Limited depth penetration above 10^8 Hz and scattering problems due to surface roughness above 10^9 Hz.
The existence of an analogous Earth-oriented technology, in ionospheric sounding (the Alouette satellite), and EM prospecting methods.

On the basis of current knowledge, two classes of radiofrequency systems are warranted: orbital reflection experiments (EMLO) and surface (not necessarily manned) mutual impedance measurements (EMSU).

The objectives of the orbital EMLO include the following:

(1) Three-dimensional geophysical mapping from near surface to depths of the order of 10 km.

(2) Detection and mapping of solid or liquid water.

(3) Detection and mapping of unusually strong heat flow anomalies by virtue of the association between temperature and conductivity. The conspicuous lack of such features is a conceivable and useful outcome of this kind of analysis.

(4) A search for pronounced layering or pronounced large-scale angular variation of the electrical parameters, to depths of the order of 10 km.

(5) Global mapping of the variation in the depth of the debris layer, using the higher frequencies (e.g., the 136 MHz bistatic radar study of Explorer XXXV reflections).

Any one or all of the above objectives are extremely important in studies of the origin, history, composition, thermal state, and dynamic behavior of the Moon. These objectives can be met by a system that permits measurement of the complex reflection coefficient as a function of frequency. This can be interpreted, with varying degrees of uniqueness, to give the electrical parameters (conductivity and dielectric constant) as a function of depth at the reflection points. This experiment was recommended previously at both the Falmouth (ref. 2) and Santa Cruz (ref. 3) meetings.

Several types of orbital EMLO may be suggested. For operation in the lower frequencies, an electric dipole about 500 m long may be deployed from a vehicle in polar or near-polar orbit and used in a monostatic mode. At higher frequencies, above the ionospheric cutoff, an Earth-based station may be operated bistatically in combination with the orbiter, or the orbiter may be operated monostatically with appropriate antennas. The exact experiment will depend on a complete system analysis, which will depend strongly on the mix of frequencies studied. It is important that enough effective bandwith be provided, either through sweep-frequency, pulsed, or multiple discrete frequency operation to provide a suffficiently unique geophysical result. Data for a single frequency cannot be used alone to construct a useful model of the lunar crust.

The surface-based mutual impedance probe has the same general objectives as given above for the orbital experiment. An important difference lies in the scale and scope of the experiment and the significantly higher resolution possible. Its strength is as a direct geophysical support to detailed surface investigations being made in the neighborhood of a landing site or on an extended traverse. A fixed station would be inappropriate, although the experiment is not dependent on the activities of an astronaut. Some form of the impedance probe is clearly the best way to study near-surface structures such as voids, "drainage" craters and crater chains, wrinkle ridges, etc.

Several forms of EMSU are possible; the hardware would be quite different from the EMLO. For work in a limited area, one would deploy a horizontal loop of large moment, to serve as a transmitter, with one or more induction coil sensors carried about on a roving vehicle. Such a system is capable of a 10-km separation between transmitter and receiver. On extended unmanned traverse, at least two fixed coils must be carried on the vehicle. Because the coil placement is an integral part of the experiment design, possible conflict with vehicle design should be considered at an early stage.

In summary, the recommendations for the radiofrequency experiment include

(1) An orbital reflection experiment for global geophysical mapping.

(2) A landed, movable, mutual impedance device for local subsurface studies, in support of other scientific activities of the Apollo landings and of long unmanned traverses.

The Pulsed Radar Probe

Great interest attaches to the detailed characteristics of the surface debris layer on the Moon. A great deal of photographic evidence, coupled with the Surveyor soil-sampler experiment, is beginning to provide answers to the first-order questions about the processes governing the evolution of the lunar surface. The focus of interest is now shifting to the characteristics of this debris layer in the third dimension. Some pertinent questions are as follows:

What is the distribution of large fragments in the debris?

What kind of transition exists between the debris and the underlying rock? Is it sharp or gradual? Is the underlying rock compact by virtue of physical compaction only, or does it contain principally coarse-sized clasts? Is this bottom interface the same under maria and highlands?

How does the thickness of the debris vary from place to place?

Do any of the electrical parameters vary from place to place in a way that can be diagnostic in the understanding of the geology?

At this scale of investigation, frequencies from about 10^8 to 3×10^{10} Hz give the appropriate resolution. In its simplest form, one pictures a radar that transmits narrow beam pulses downward into the surface layer and receives and processes the signals reflected from below the surface. An analogous acoustic experiment, the acoustic reflection profiler, is productively used to map the variations in sediment thickness on the ocean floor. Under an optimistic prognostication, one can postulate such a radar reflection experiment on either a roving vehicle or in orbit that returns "echograms" of the structure of the upper 100 meters.

We have listed above the properties of the debris that are of interest and may be answered by a PRP. The success of the experiment for sounding the bottom of the debris depends on the following:

Existence of an impedance contrast from top to bottom of the debris, to produce a reflection.

Sufficiently small value of loss tangent for lunar surface materials.

Sufficiently little scattering by large fragments in or on the debris. Scattering both attenuates the main signal and contributes clutter to the return. Surveyor pictures give reason to worry about this problem.

If the bottom sounding does not work out, then the only remaining objectives are the study of the large debris fragments and the study of the surface dielectric constant.

A great many unresolved questions regarding the definition of this experiment still remain, principally because of a lack of ground truth information on the effective electrical parameters of the debris. *The sense of* *this recommendation, therefore, is that the potentially great usefulness of probing at microwave frequencies justifies development and definition support to a radar probe.* The kinds of work required before flight hardware can be programed include

Use of opportunities on the first three Apollo flights to test the response of the debris layer to microwaves from a near-surface antenna.

Theoretical investigation of a realistic reflection experiment, in which a model of the debris layer is based on a synthesis of Surveyor, Earth-based, and laboratory results. This includes proper consideration of antenna design with the surface in the near field of the antenna.

Use of opportunities to try out the experiment concept on the Earth, using special areas where surface water is not a limiting parameter.

Construction of promising designs for Earth-resources applications.

It is fairly clear that the lead time for the experiment, which includes time to carry out this definition work, puts it closer to 1975 than to 1971. By flying an exploratory experiment in 1971, the information obtained could be fed into the design of the full exploration system. *Consideration should be given, therefore, to making use of communication links on Apollo missions to carry out appropriate testing on or near the lunar surface.* The real question is this: Can any useful subsurface information be obtained at these frequencies? Testing with available equipment may be the only way to establish the real value of the PRP type of experiment.

Other Methods

This committee has considered a variety of specific experiments and classes of experiments that have been proposed for lunar explorations. Many of these were discussed in the conference, and will be described in the full conference proceedings. The committee's recommendations deal with those experiments that cover the range of penetration depths appropriate to the Moon in as economical a way as possible. Several other methods not discussed here are considered to be insufficiently definable at this time because of an almost total lack of knowledge of many relevant parameters. Because of the similarities between many methods, it is felt that the supporting research and technology (SRT) activity recommended will provide suitable long range cognizance of potentially promising experiments.

Experiments in the audiofrequency range were not given priority because of the high effective conductivity of the solar wind plasma. None of the conventional approaches look feasible. Certain possibilities do appear to this committee to be worth looking into, in view of the unique range of penetration depths (10 to 1000 km) available at audiofrequencies. These possibilities involve taking advantage of special frequencies where the plasma is either totally opaque or fully transparent. Pending further investigation, the audiofrequencies represent terra incognita with respect to lunar investigations.

8. Supporting Research and Technology

All electromagnetic (EM) methods are faced with a number of unanswered questions that require supporting work. The three types of experiments recommended by this committee are felt to be those which pose the fewest unanswered questions and show the most promise. These questions are, however, central to the final design of experiments and the interpretation of the data. *We therefore recommend that SRT activities in support of the recommended three types of experiments be considered an integral part of the experimental program.* The following activities are involved:

(1) Modeling of experimental geometries, theoretical and laboratory.

(2) Laboratory measurements of the EM properties of appropriate materials.

(3) Earth analog studies, the testing of experimental ideas on Earth.

Theoretical and Laboratory Modeling

Interpretation of EM experimental data requires an understanding of the interaction of various types of signals with different geometric shapes. Except for problems like the plane-parallel-layer problem or the dielectric-sphere problem, most of these are unsolvable in the usual sense of there being a numerically usable closed-form solution. Many of these cases can be solved in a practical sense by skillful use of approximate methods or by direct numerical integration of the relevant difference equations. In many cases, analog modeling of the geometry is convenient. The need for continued work in this area is due to the following needs, which are fully discussed under the specific experiments in "Recommendations for an Experimental Program."

To understand better the EM fields produced in the vicinity of the Moon by the solar plasma.

To simulate numerically the response of various Moon models to these incident fields.

To simulate numerically the response of various Moon models to artificially produced RF and radar-frequency signals.

To produce initial experiment definitions and designs that take proper account of all constraints; geophysical, engineering, cost, etc.

Laboratory Measurements

Measurement in the laboratory of several physical properties of well-characterized geologic materials are needed for the design of lunar EM experiments and for the interpretation of the data to be returned to Earth. Values of electrical conductivity, dielectric constant, magnetic permeability, and loss tangent should be measured as a function of pressure, temperature, composition, and frequency. Effects on physical properties of saturation, pore fluid pressures, and pore fluid composition should be examined. These studies should be carried out on suitably chosen Earth materials and artificial solids, as well as on the early returned lunar samples. It is noted that recent work and work in progress have become increasingly pertinent to the special problems of lunar exploration, and certainly a reasonable understanding of many of these properties is not far off.

Earth Analog Studies

Demonstration of several experimental concepts on Earth analogs of the lunar surface is encouraged, utilizing highly resistive environments as available. Overflight of parts of the Antarctic with airplanes carrying prototype lunar-exploration devices would contribute materially to qualifying these devices for lunar work. Only in the polar regions of the Earth are the surface temperatures sufficiently near the temperatures likely to persist in the Moon at depths of a few meters.

References

1. Space Research: Directions for the Future—Vol. I: Planetary and Lunar Exploration. Report of a Study by the Space Science Board (Woods Hole, Mass.), 1965
2. NASA 1965 Summer Conference on Lunar Exploration and Science (Falmouth, Mass.), NASA SP-88, 1965
3. 1967 Summer Study of Lunar Science and Exploration (Santa Cruz, Calif.), NASA SP-157, 1967

Appendix A:
Titles of Papers Presented at Conference

Syvertson, C. A.	Welcome
Phinney, R. A.	Purpose of meeting
	Geophysical recommendations, Falmouth and Santa Cruz
	Guidelines for meeting
Williams, D. J.	Fields and particles recommendations, Falmouth and Santa Cruz
Allenby, R. J.	Lunar exploration plan
Ward, S. H.	Geological and electrical models of the Moon
	Outline of possible experiments, orbit and surface
	A possible lunar exploration sequence
Sonett, C. P.	Results to date for lunar environment, including magnetic fields, electric fields, and solar wind
	Future surface and orbital magnetometer experiments for lunar exploration
Simmons, Gene	Electrical parameters of the lunar interior
Strangway, D. W.	Possible electrical and magnetic properties of near-surface lunar materials
Campbell, Malcolm	Electrical parameters of lunar surface rocks
Hapke, Bruce	A survey of optical, IR, UV, microwave properties of lunar surface; possible experiments
Anderson, H. R.	Sources and methods of electric fields at and near lunar surface
Runcorn, S. K.	Magnetic variation deep sounding at lunar surface

Tyler, G. L.	Past results and future experiments in radar scattering
Love, Alan	High frequency radar reflectivity at lunar surface
Cohn, Marvin	Some factors affecting electromagnetic detection of lunar subsurface features
Linlor, W. I.	Low frequency radar reflectivity in lunar orbit
Hohmann, G. W.	Inductive electromagnetic methods at lunar surface
Hoffman, A. A. J.	Magnetoselenics
Cook, J. C.	Capacitive coupling method for lunar subsurface exploration
Salisbury, W. W.	Refractive effects of Moon for subsurface exploration

Appendix B:
Attendance and Committee Lists

I. Meeting Cochairmen

W.N. Hess
NASA Manned Spacecraft Center

R.A. Phinney
Princeton University

II. Meeting Organizers

E.M. Davin
NASA Headquarters

W.I. Linlor
NASA Ames Research Center

S.H. Ward
University of California, Berkeley

III. Program Evaluators

R.A. Phinney (Chairman)
Princeton University

W.N. Hess (Vice Chairman)
NASA Manned Spacecraft Center

R.J. Allenby, Jr.
NASA Headquarters

E.M. Davin
NASA Headquarters

Gene Simmons
Massachusetts Institute of Technology

H.W. Smith
Electrical Engineering Research Laboratory

C.P. Sonett
NASA Ames Research Center

S.H. Ward
University of California, Berkeley

IV. Attendees

R.J. Allenby, Jr.
NASA Headquarters

Hugh R. Anderson
Rice University

Orson Anderson
Lamont Geological Observatory

Jerry Arnett
General Dynamics Corp.

William D. Becher
University of Michigan

Glen Brown
American Nucleonics

Walter E. Brown, Jr.
Jet Propulsion Laboratory

Malcolm Campell
Cornell University

George Chang
Bellcomm, Inc.

Marvin Cohn
Beckman Instruments

J.C. Cook
Geotech

E.M. Davin
NASA Headquarters

Richard R. Doell
U.S. Geological Survey

John Freeman
Rice University

Brent D. Fuller
University of California, Berkeley

Robert Gaal
TRW Systems

Jack C. Graves
Boeing Company

Bruce Hapke
University of Pittsburgh

Otto Heinz
U.S. Naval Postgraduate School

John Hermance
Massachusetts Institute of Technology

W.N. Hess
NASA Manned Spacecraft Center

A.A.J. Hoffman
Texas Christian University

G.W. Hohmann
University of California, Berkeley

Geoffrey Holstrom
Jet Propulsion Laboratory

George V. Keller
Colorado School of Mines

W.I. Linlor
NASA Ames Research Center

Alan Love
Autonetics

T.R. Madden
Massachusetts Institute of Technology

R.K. Moore
The University of Kansas

Thomas Parr
Massachusetts Institute of Technology

Arnold Pearce
Bellcomm, Inc.

R.J. Phillips
University of California, Berkeley

R.A. Phinney
Princeton University

William L. Piortrowski
Bellcomm, Inc.

W.R. Ramsay
Lockheed Corp.

P.W. Rodgers
University of California, Berkeley

S.K. Runcorn
The University
Newcastle upon Tyne

W.W. Salisbury
Smithsonian Institution

Gerald Schubert
University of California, Los Angeles

Ken Schwartz
American Nucleonics

Charles B. Sharpe
University of Michigan

Samuel Silver
University of California, Berkeley

Gene Simmons
Massachusetts Institute of Technology

H.W. Smith
University of Texas

C.P. Sonett
NASA Ames Research Center

David W. Strangway
Massachusetts Institute of Technology

G.L. Tyler
Stanford University

S.H. Ward
University of California, Berkeley

Ken Watson
U.S. Geological Survey

NASA-Langley, 1969 —— 30

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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