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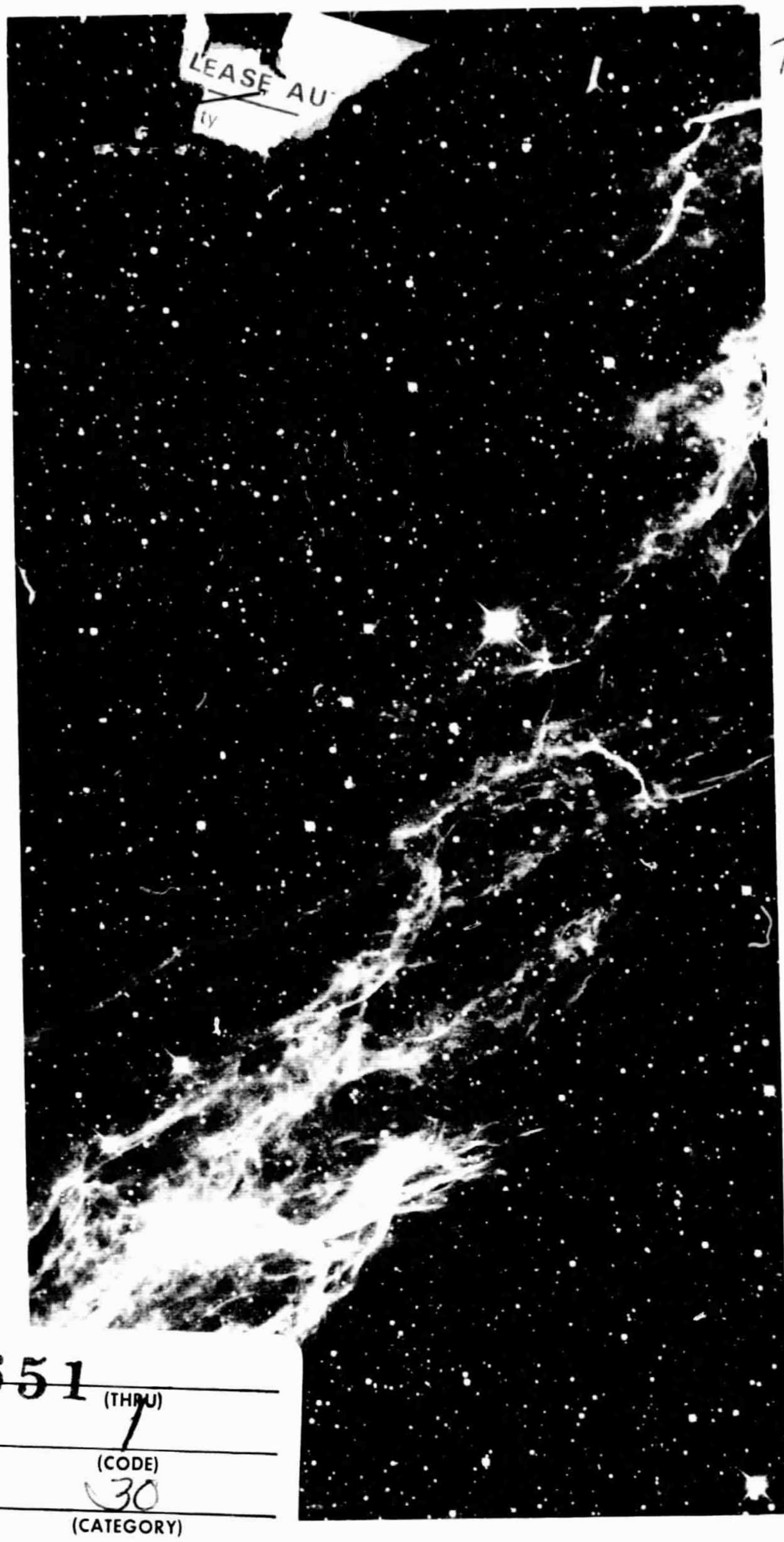

Report No. P-33

THE ROLE OF SUBSATELLITES IN THE EXPLORATION OF THE MOON

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THE ROLE OF SUBSATELLITES IN THE EXPLORATION OF THE MOON

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SUMMARY

The purpose of this study is to consider the need for Apollo CSM subsatellite orbiters as a subset of a broader class of lunar orbiters. The basis of the evaluation is the orbital science measurements which should be performed in the exploration of the Moon. Consideration is given to all modes of investigation except photography. A subsatellite is defined, for the purpose of this study, as a spacecraft which initially is incorporated in the Service Module, which is released in or into lunar orbit, and which can function completely independent of the Service Module. Its complexity may range, conceptually, from a simple beacon to a large automated spacecraft and the relevance of subsatellites over this whole range is considered.

The scientific objectives which indicate the need for orbital measurements are specifically:

1. What is the spatial distribution of the density and composition of the transitory lunar atmosphere?

2. What is the nature of the solar wind-lunar surface interaction and what sort of bright side "boundary layer" (if any) exists?

3. What are the details of the solar wind flow around the body, particularly at the limbs?

4. What is the precise cause of the field pattern and particle distribution in the wake?

5. What are the physical processes at the wind-wake interface?

6. What is the exact magnitude and configuration of a possible intrinsic lunar magnetic field?

7. What is the surface temperature distribution and how does it relate to observable features?

8. Are there areas on and beneath the lunar surface containing moisture?

9. What is the nature of the lunar interior? Does a distinct core exist?

10. What are the important selenodetic properties, such as the precise value of mass, principal axis, moments and products of inertia?

11. What is the thermal history and age of the Moon? Has substantial melting ever occured?

The experimental techniques for providing solutions to the above questions are discussed, and detailed measurement specifications are provided for the following measurements and measurement groups:

Particles and Fields	Magnetometry Plasma Detection and Analysis Electric Field Detection
Mapping	IR radiometry μ-wave radiometry IR spectrometry
Atmosphere and Surface Environment	Mass spectrometry γ-ray detection x-ray detection Neutron detection α-particle detection UV spectrometry
Selenodetics	Gravity field determination

The measurement specifications identify those parameters such as lifetime, scientific cleanliness, orbit requirements, orientation etc. which preclude the measurement from Apollo CSM missions. A total of seven classes of subsatellite orbiters are identified on the basis of the range of measurements to be performed. They differ principally in their scientific experiments, in the attitude control requirements, and in the propulsion and guidance needed to change the spacecraft orbit. The seven classes of subsatellites are summarized briefly in Table S1.

TABLE S1 ROLE OF SUBSATELLITES

ORBIT	ATTITUDE	SEPARATION	CANDIDATE EXPERIMENTS
1.CSM	None	Lunar Orb.	Geodetics
2.CSM	Spin	Lunar Orb.	Particles and Fields? Mass Spectrometer?
3.CSM	3-Axis	Lunar Orb.	Particles and Fields? Environment? Mapping?
4.CSM $\epsilon > 0.3$	Spin	Lunar Orb.	Particles and Fields Environment?
5.Polar and Circular	3-Axis	Lunar Orb.	Environment Mapping
6.Polar and Circular	3-Axis	Cislunar	Environment Mapping
7.Polar any Orientation	3-Axis	Earth Orb.	Mapping

? = Limited value in performing experiments from given orbits

In summary, it is recommended that Classes 1, 4, and 7 are the only suitable subsatellite exploration modes. Class 1 is basically a beacon of the TETR type and is limited to just a selenodetic experiment via orbit tracking. Class 4 is basically an Explorer 35 with a very low periapsis and is adequate for particles and fields experiments. Class 7 is basically a Lunar Orbiter type spacecraft and may be used for mapping experiments.

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1. INTRODUCTION

The purpose of this study is to consider the need for Apollo Subsatellite orbiters as well as a somewhat broader class of lunar orbiters for scientific investigations and to outline the experiment classes for which they are required. This document briefly reviews the kinds of data pertaining to the Moon and its environment which have thus far been obtained and suggests the kinds of information orbiters should obtain in the near-term future time frame. Consideration is given to all modes of investigation except photography, since this latter can be performed satisfactorily from the Apollo CSM.

The set of experiments and investigations which are considered are based upon the concept of a relatively early mission or set of missions, before much more surface and atmospheric contamination occurs. The essential concern is with the interactions of the solar plasma and magnetic fields with the Moon, with the particles and fields environment of the lunar surface, with spectrally resolved examinations of surface and atmospheric properties, and with properties of the lunar interior. In this sense, interest centers on the Moon itself as well as on the phenomena for which the presence of the Moon is necessary. The specific requirements which follow take full recognition of the important data thus far obtained by the Explorer satellites; in some instances there is a need for extending these data, and in others, the areas in which new data are required have become established. The subsequent discussions use the Explorer data as well as recent theoretical work to establish the basis for current planning, provide a set of scientific objectives based on this work, and follow with specifications for required measurements.

2. BACKGROUND DISCUSSION

2.1 Solar Plasma Properties

The ion flux in the undisturbed solar wind is between 10^7 - 10^9 p/cm^2-sec. with energies between 200 ev and 10 kev. The velocity is between 300 and 900 km/sec, with an average value of approximately 385 km/sec. The temperature is about 1.7 x 10^5°K, and the density is between 1 and 35 p/cm^3. The average value of the interplanetary magnetic field is 5γ. The near-lunar field is nominally 5 to 8γ in the interplanetary medium, and 8 to 12γ in the geomagnetic tail. The Mach number in the case of the solar wind is measured by the ratio of the plasma bulk velocity (V_s) to the magnetohydrodynamic wave phase velocity (V_a). In the interplanetary medium the velocity V_a is approximately given by the Alfven velocity, so that the Mach number is usually between 4 and 20.

Explorer experiments have measured the proton and electron flux and counted and related them to the shadowing effect. It was found that the unshadowed proton intensity is isotropic and that distributions which are anisotropic at the onset of an event relax in about an hour. The electron flux is isotropic at all points observed except where there was lunar shadowing.

An additional important feature of the interplanetary medium, with respect to its interaction with planetary objects, is that it is a magnetized plasma and thus supports magnetohydrodynamic wave propagation.

2.2 Lunar Magnetic Field and Properties of the Lunar Interior

The existence of a lunar magnetic field is important in the development of adequate theories to explain planetary magnetism and the origin of the solar system. The physical characteristics of the lunar surface depend strongly on whether there is shielding by a lunar field or a shock wave.

Most theoretical treatments of the Moon and its environment include:

a) infinitely conducting fluid in interplanetary medium

b) magnetic field aligned with the streamlines

c) non-conducting or infinitely conducting body

d) mean free paths in the solar wind much smaller than other characteristic lengths.

Few of these conditions are genuinely satisfied in the real case of the Moon-solar wind interaction.

If the Moon were a perfect conductor, no interplanetary field could penetrate, so on the sunward side the field would build up. The other extreme is a perfect insulator, where the field lines penetrate easily, and the plasma flow impinges directly on the surface. Data indicate that the latter is more nearly the case, and that there is a conical cavity behind the Moon with a closure rate roughly appropriate to the particle thermal speeds.

Thus far, the Moon behaves like a poorly conducting, non-magnetic body with a negligible permanent magnetic field. It is generally concluded that the magnetic field lines thread through the Moon as though it were not there, that there is essentially no intrinsic magnetic moment and that its electrical conductivity is low. The magnetic moment is presently taken as $\approx 10^{20}$ cgs units, or $< 10^{-5}$ that of the earth. With this limit fairly well established, it is possible to draw further conclusions regarding the lunar interior by way of times involved in field perturbations carried through the lunar body. This leads to an estimate of its conductivity, which in turn establishes an interior temperature. This technique makes use of the dilation of a discontinuity time profile (change in field) due to the time required for the magnetic field to diffuse through the Moon's interior. The time constant for a conducting sphere is $\tau = \mu\sigma R^2/\pi^2$. With a measured value of τ = 56 sec, σ becomes $\approx 5 \times 10^{-5}$ mho/m. For an olivine Moon, T is then about 1000°K.

In interpreting data of this sort, it is common to consider the interaction of the solar wind with a lunar model consisting of an inner core surrounded by a crustal layer with electrical conductivity different from that of the core. Several possible implications of the apparent absence of a lunar bow shock have been considered. If the outer layer were of sufficiently high conductivity as to carry the bulk of induced currents, crust thicknesses of less than several tens of kilometers could be consistent with the observed absence of a bow shock. This case requires very low internal conductivities, however, much less than 10^{-5} mho/m. For the case where the core carries the bulk of the current, but where the outer layer was not insulating, it was found that the absence of a bow shock required core conductivities small compared with 2.6×10^{-5} mho/m. Finally, the case where the crustal layer had the effect of an insulator, thus shielding a conducting core, was considered. It was found that if a surface dust layer, 10 meters deep, is to prevent the formation of a lunar bow shock, its conductivity must be much less than 10^{-10} mho/m, while if the insulating layer was 10 kilometers thick, a bow shock would form if the conductivity were less than 10^{-7} mho/m. Such low conductivities do not seem likely, so the presence of a highly conducting core does not appear to be substantiated by present experimental data.

There is another interior property important to our overall consideration here and that is the lunar gravitational field. Doppler tracking has been performed in the past on the Lunar Orbiter and Apollo CSM spacecraft. However, spacecraft maneuvering, altitude control activities, and limited periods of continuous tracking resulted in less than ideal results.

Accurate measurement of a satellite's natural lunar orbit position over significant time periods allows definition of a lunar mass model. A subsatellite in near circular polar orbit with an altitude of 10-20 kilometers which remains in orbit for several years would provide valuable gravimetric data.

2.3 Particle and Field Interactions

In the absence of more definite knowledge about a lunar magnetic field, it appears that a lunar shock wave is very unlikely. In the relatively weak interplanetary magnetic field, the radius of gyration of a solar wind proton is comparable with the lunar radius. Table 1 presents representative values for the proton Larmor radius as a function of field strength and plasma energy (or velocity). It is likely that in the case of the Moon a collisionless shock wave analogous to the earth's may not always be present, if indeed it ever is. Whether or not such a shock develops depends very critically on the physical parameters in the interplanetary medium and the state of the lunar magnetic field. This point has been discussed by Gold in connection with the direct penetration of the solar plasma into the lunar body.

TABLE 1 PROTON LARMOR RADIUS AS A FUNCTION OF PARTICLE ENERGY (OR VELOCITY) AND MAGNETIC FIELD STRENGTH

Proton Energy	Velocity km/sec	Radius, km at 10 γ	at 5 γ	at 2 γ
4 kev	876	914	1828	4572
2 kev	619	646	1292	3232
1 kev	438	457	914	2286
500 ev	310	323	646	1616
250 ev	219	229	457	1143

A most interesting set of observations have been made relating to the field and plasma in the lunar wake. The major effect of the Moon on the solar wind plasma is the creation of a plasma cavity in the umbral region of the lunar shadow. In this cavity the magnitude of the magnetic field increases ; i.e., the field is observed to be stronger than the undisturbed interplanetary field. On either side of the umbral increase, the field decreases; i.e., the field becomes weaker than the undisturbed condition. These penumbral decreases occur at the location where the plasma density is about half of the undisturbed plasma density, and they are often bounded on the exterior by additional small increases in the field magnitude. As an example, an interplanetary field value of 7.5γ may increase initially to 8.5, drop to 6.5, and then return to slightly greater than 8.5 throughout the umbra. A positive correlation between the increase of the plasma flux, the plasma density,and the penumbral increase of field magnitude has also been observed.

From the overall experimental and theoretical results obtained thus far, it appears that the magnetic field perturbations in the lunar wake are of complex geometry depending critically upon the solar wind velocity, density, and temperature as well as the field orientation ϕ. The speed ratio,S, which measures the relative magnitudes of the solar wind velocity parallel to the field line, is a critical dimensionless parameter employed in the analysis. The parameter β is the ratio of material to magnetic pressures.

It is tempting to conclude that higher-order iterations of the plasma and field equation will lead to a more self-consistent solution and thus will provide better agreement with observations. At present the absence of definitive plasma data precludes exact comparisons of the experimental results for those few existing cases in which the satellite orbit is approximately in the symmetry plane of plasma flow. The changing nature of the interplanetary medium on both short and long time scales precludes a statistical study. As additional experimental data are obtained, in particular, from simultaneous observations of the interplanetary medium by separate satellites, a more comprehensive comparison with theory will be possible.

2.4 Lunar Surface

The very rarified atmosphere of the Moon permits the use of an orbiting vehicle for exploration of the lunar surface through the observation of charged particles, neutrons, non-optical electromagnetic radiation, and mapping experiments. Synoptical observation of parameters in integrated experiment packages has greater selenological importance than single observations. The principal objectives are to conduct a compositional survey of the lunar surface. Differentiations will be evident down to scales of about 10 km. The experiments can discriminate between basaltic and granitic areas and are also sensitive to the presence of hydrogenous material near the surface and to the spatial distribution of natural radioactivity which is proportional to the concentration of uranium and thorium.

Prior to the Apollo lander missions, very little was known about the chemical composition of the surface. If the assumption is made that lunar radioactivity is similar to the natural radioactivity of the earth, the principal elements that contribute to the gamma radiation emitted by rocks are K^{40}, U^{238} and Th^{232}.

It was observed on earth that granite rock is richer in uranium than basalts and that granite therefore exhibits a high gamma activity. Terrestrial data also indicate that the concentration of uranium and thorium and their ratio increases with degree of differentiation.

In addition to natural radioactivities, gamma radiation can be induced by primary cosmic rays and solar flares. The mechanisms which can induce detectable gamma ray fluxes include primary nuclear reactions produced by high energy cosmic rays and solar particles, and the secondary processes of neutron capture and neutron inelastic scattering. If the instrument and experimental conditions are sufficiently good, it will be possible to observe characteristic gamma ray lines induced in a few selected elements of substantial abundance; namely, iron, aluminum, sodium and perhaps silicon. A program of simulation experiments and calculations is under way in this area.

If the processes by which radon diffuses to the surface on earth are similar on the Moon, the natural radioactivity on the Moon's surface will be considerably above that predicted by the natural distribution of uranium and thorium. It is expected that alpha particles can leave the Moon's surface without degradation and it will be thus possible to observe alpha particles with discrete kinetic energies. Monitoring of the alpha emission can also serve as an alarm for indication of sudden escape of gases from the lunar interior. These gases will presumably sweep radon and thoron out of the interior and enable the efflux to be located.

The extremely rarefied lunar atmosphere permits the detection of the surface emitted or scattered protons, alphas, and fission fragments, even at lunar orbital altitudes, using solid state detectors. The measurements of principal interest are the intensity and energy spectrum of alpha particles. In addition to measuring the alpha flux, the solid state detectors can also measure the flux of heavy fragments from nuclear fissions and the proton albedo. A monitor of charged particle flux input to the lunar surface is a necessary adjunct to these measurements.

The anticipated major source of alpha emitters on the lunar surface is diffusion of the radiogenic noble gas radon (Rn^{222} and Rn^{220}) through the upper few meters of surface layer. The radon decay and decay of its daughter products, which have coated the lunar surface, yield an effective thin source of alphas with characteristic sharp line spectra. This same mechanism will yield a comparably large quantity of gamma lines. The exceptional energy resolution and low background levels characteristic of solid state detectors, coupled with the expected energy distributions, will allow accurate identification of the alpha emitting species.

This, in addition, will assist the proposed gamma-ray experiment with its inherently lower resolution detector, to unfold the observed complex gamma spectrum and separate surface contribution from subsurface.

Two isotopes of radon are produced in the two decay chains of uranium and thorium. The rate at which they diffuse to the surface is determined by the diffusion coefficient in the lunar soil and, therefore, on its porosity. The isotope from the uranium decay series, Rn^{226}, has a half-life of a few days, and since nearly all the atoms emerging from the surface are trapped by the Moon gravitational field, the atoms of this isotope will bounce from the surface taking excursions up to altitudes of several kilometers before decaying. Thus, this isotope would be expected to be distributed over large areas of the lunar surface. The isotope from the thorium chain, Rn^{220}, has a much shorter half-life and most of its decay will occur in flight offering much better spatial resolution and permitting identification of high count rates.

The natural radiation of the lunar surface will also contribute to the alpha particle count rate and thus provide information on the chemical abundance and hence, the composition of the lunar surface. Information is available only for the top few microns of the surface; therefore, these measurements would be most useful in helping to confirm the results obtained from a measurement of lunar surface gamma radiation emission.

The purpose of the mapping experiments is to determine the lunar surface temperatures, to detect and study any anomalously hot or cold areas, and to study the heating and cooling rates of the surface layers.

In view of the many different types of surface details with which thermal anomalies have been identified, it seems quite probable that they are caused by an equally large number of different geological phenomena. Several possible explanations of the thermal enhancement of particular surface regions have been proposed. These proposed models include changes in thermal impedance, enhanced roughness, internal heat sources, variations in emissivity,and enhanced infrared surface transparency.

With the data presently available from earth observations, it is impossible to decide among the various possible mechanisms which could cause thermal enhancement of the lunar surface. Because of the low level of the radiated energy from the darkened lunar surface and the small collecting angle subtended even by the largest aperture telescopes, the measurements made using earth bound telescopes as radiometers have of necessity been of limited thermal sensitivity and low spatial resolution. Thus, only the most intense and extensive thermal enhancements of the lunar surface can be detected, and accurate estimation of error limits are difficult due to uncertanties introduced by internal radiation in the instrument and by the intervening atmosphere.

Measurements made using earth telescopes have been limited to spatial resolutions on the lunar surface of 1/250 of the diameter. This is approximately 14 Km at the subearth point and increases toward the limb. Significant improvement in the spatial and thermal resolution capabilities would require larger telescopes and higher infrared detector sensitivities than are currently available, and would still be limited to near side studies of the lunar surface.

In order to determine the mechanisms causing the thermal enhancements, radiance maps with significantly improved thermal and spatial resolution are required. The obvious method to obtain this information is to place the mapping radiometer on a lunar orbiting spacecraft.

3. IMPORTANT SCIENTIFIC QUESTIONS

The following scientific questions indicate the need for further knowledge of the Moon.

1. What is the spatial distribution of the density and composition of the transitory lunar atmosphere?

2. What is the nature of the solar wind-lunar surface interaction and what sort of bright side "boundary layer" (if any) exists?

3. What are the details of the solar wind flow around the body, particularly at the limbs?

4. What is the precise cause of the field pattern and particle distribution on the wake?

5. What are the physical processes at the wind-wake interface?

6. What is the exact magnitude and configuration of a possible intrinsic lunar magnetic field?

7. What is the surface temperature distribution and how does it relate to observable features?

8. Are there areas on and beneath the lunar surface containing moisture?

9. What is the nature of the lunar interior? Does a distinct core exist?

10. What are the important selenodetic properties, such as the precise value of mass, principal axis, moments and products of inertia?

11. What is the thermal history and age of the Moon? Has substantial melting ever occured?

4. MEASUREMENT REQUIREMENTS

The set of measurements which we wish to consider here are established by the preceding scientific questions and the data which have been obtained thus far by the way of the Explorer Satellite program. They may be loosely categorized in the following three classes, which are given along with some typical specific measurements.

(i) Particles and Fields Measurements - Determination of possible existence of shock fronts, physical processes at the interface, existence of waves and their modes, etc.

(ii) Lunar Atmosphere and Surface Environment - Detection of transitory atmosphere, characterization of the bright side boundary layer, possible detection of subsurface anomalies and interior structure. These measurements should be made down to altitudes as low as are consistent with stable orbit characteristics.

(iii) Surface Mapping - Analysis of lunar surface and subsurface layers, surface mapping, temperature variations, etc.

4.1 Experiment Constraints

For either the conceptual or the actual design of the experiments, numerous constraints must be satisfied. These constraints are concerned with the structure and configuration of the spacecraft, individual instruments, instrument-spacecraft and instrument - instrument interfaces, and the temporal and orbital requirements. We have tabulated in Table 2 a reasonably comprehensive list of possible instrument and experimental constraints in several distinct categories.

TABLE 2 POTENTIAL CONSTRAINTS

A. General Constraints

1. Lifetime of operation
2. Launch vehicle requirements
3. On-board calibration requirements
4. Port requirements
5. Reliability/Compatibility

B. Mechanical Parameters

1. Dimensions and shape
2. Weight
3. Location (appendages?)
4. Power
5. Thermal operating range
6. Packaging and mounting requirements

C. Orbital Parameters

1. Apolune
2. Perilune
3. Inclination
4. Period
5. Pointing (?)

D. Shielding

1. RF
2. Magnetic
3. Mechanical
4. Particle Radiation
5. Outgassing

E. Data Handling

1. Format
2. Rate
3. Transmission

Some additional considerations regarding these constraints are worth noting. First of all, it appears reasonable to assume that the lifetime requirements would vary between one month and one year. The low limit is that which would be required for mapping the entire lunar surface; the upper limit is an estimate for the case where the capability for changing orbits enables measurements to be made throughout a broad range of altitudes and environmental parameters.

Scientific cleanliness is another important requirement. This is particularly significant for magnetic and electric field measurements and for determining the flux of low energy particles. Stray fields as well as any flux from radioactive sources could not be tolerated where magnetic fields of a few gauss and electric fields down to μ-volts/cm^3 must be measured, and where particles with energies down to 100 ev must be observed.

Polar or high inclination orbits are generally required for the mapping experiments and are just as satisfactory, if not superior, for many of the other measurements. The mapping measurements favor circular orbits with altitudes less than 500 km. Some of the anticipated particles and fields measurements require eccentric orbits, so that the wake out to 4 or 5 radii as well as the bright side boundary layer near the surface can be investigated. A controlled spin rate as well as controlled vertical pointing are the two anticipated attitude constraints. In addition, it is expected that simultaneous measurements will sometimes be required, either on the lunar surface or on another satellite. This need arises due to the changing properties of the solar wind.

4.2 Particles and Field Measurements

4.2.1 Magnetometry

The magnetometry experiments are designed to reveal information about both the lunar interior and the lunar environment. The principal goals concerning the interior are to refine the estimate of the bulk electrical conductivity, determine the structure of the lunar interior, to search for subsurface anomalies, and to attempt to distinguish between any intrinsic lunar field that may exist and one caused by diffusion of the interplanetary field into the Moon.

In addition, the experiments will provide for studying the effect of the incident plasma on the lunar surface and atmosphere. They will also contribute to an understanding of the wake structure and the physical processes at the solar wind-wake interface.

Triaxial sensors will be used to avoid any possible confusion in regions characterized by irregular fields. Both a D.C. and an A.C. magnetometer operating out to about 10 KHz would be required to meet the above objectives. The D.C. device is necessary for most of the work pertaining to the interior, and the A.C. device is required for detecting plasma and wave phenomena in the environment and particularly in the tail.

An extended period of time (at least several months) is required in order to permit adequate mapping and to record data for a variety of solar conditions. This experiment would benefit greatly from the ability to change orbits from a low level circular orbit to an eccentric orbit out to 4 or 5 radii for wake studies. The times and amounts of each change would be determined by the data already obtained. A boom mount would be required to avoid interference by spacecraft instrumentation. Table 3 gives the measurement specifications for magnetometry.

TABLE 3 SPECIFICATIONS FOR PARTICLES AND FIELDS

MAGNETOMETER MEASUREMENTS

	DC MAGNETOMETER	AC MAGNETOMETER
MEASUREMENT	Interior Fields for Structure	Fields in Wake for Lunar & Plasma Phenomena
LOCATION	Boom Mount	Boom Mount
ORBIT CHARACTERISTICS	Polar (Eccentric) Perigee-low as possible Apogee-4 to 5 radii	Polar (Eccentric) Perigee-low as possible Apogee-4 to 5 radii
LIFETIME	1 year	1 year
EXP. RANGES	0-100γ	0-100γ
EXPERIMENTAL BIT RATE	25 BPS	100 BPS
TEMPERATURE	$\pm$ 50°C	$\pm$ 50°C
WT. (LBS.)	3	5
P (w)	2	2
VOLUME (in^3)	< 1800	< 1800
REMARKS	Requirement for Additional Simultaneous Measurements	1-10^3 Hz response

4.2.2 Plasma Probes

The plasma probe experiment is intended to monitor solar wind parameters, study the interaction of the solar wind with the Moon, and determine information about the lunar atmosphere and possibly the boundary or transition layer near the surface. The basic set of measurements is the determination of the velocities and positions of the plasma protons and electrons as functions of time. These are determined from measurements of the particle fluxes within limited ranges per unit charge (E/Q) and direction.

The ideal detector would continuously measure the flux of positive ions and electrons versus energy and direction. While it is likely that this cannot be achieved completely, a good compromise is offered by the use of different kinds of detectors: monitors and analyzers. The monitors would measure the total particle flux and perhaps the total energy flux as functions of time and direction of incidence. The analyzers would concentrate their measurements in directions at those energies which are predominant. A satisfactory combination would include a quadrispherical analyzer for a broad energy range of positive ions, an electron-proton electrostatic analyzer, and a solid state energetic electron detector.

The plasma probes should likely be grouped with the D.C. and A.C. magnetometers, and of course require a spinning satellite. Table 4 gives the measurement specifications.

4.2.3 Potential Probes

Electric fields near the Moon are commonly associated with phenomena such as lunar "boundary layer" or "surface" processes as well as interactions of the lunar body with the geomagnetic tail. Another very important aspect of electric fields involves the structure of and the physical processes in the wake and at the wake-solar wind interface.

In the most general case, measurements of electric fields near the Moon could help to provide an understanding of the interaction of the solar wind with the Moon, the state of the plasma, and the acceleration processes occurring in the plasma. More particularly, it may be possible to learn some details of the processes at the limbs, which give rise to the complex wake-plasma interface. In addition, it is important to establish the characteristics of any waves that are propagating, since they depend on the properties of the medium and are a potential source of information about the solar wind-moon interaction. It is particularly important to study interactions between the waves and charged particles which contribute to the acceleration of particles and their possible diffusion into the wake.

Measurement techniques would likely be either potential probes or ion or electron beams. The probes would likely be a pair of conductors mounted on booms and separated by a distance of several meters. The potential difference divided by the separation distance is equal to the component of the electric field along the direction of the antenna in the coordinate system of the antenna. An extendable - retractable type of antenna would likely be required.

The most important regions for study are the sunlit side and the limbs at low altitude, and the wake from very near the surface out to about four lunar radii. A polar orbit with variable eccentricity would be the first choice. Table 5 gives the measurement specifications.

4.3 Lunar Atmosphere and Surface Environment

4.3.1 Mass Spectrometry

A mass spectrometry experiment is essential for examining the lunar atmosphere before contamination becomes a severe problem. Because the lunar atmosphere is so tenuous, it is particularly

TABLE 4 SPECIFICATIONS FOR PARTICLES AND FIELDS MEASUREMENTS

PLASMA PROBES

MEASUREMENT	Quadri-Spherical Analyzer	Electron-Proton Electrostatic Analyzer	Solid-State Detectors
LOCATION	Not critical	Same	Same
ORBIT CHARACTERISTICS	Polar(Eccentric) Perigee-low as possible Apogee-4 to 5 radii	Same	Same
LIFETIME	1 year	1 year	1 year
EXP. RANGES	(+ ions) (50-10000 ev/charge)	(e + p) (100 ev - 9 Kev)	e(30-300 Kev)
EXPERIMENTAL BIT RATE	1000	1000	1000
TEMPERATURE	$-15 < T(°C) < +50$	Same	Same
WT. (LBS.)	5	2.5	5
P (w)	3	2	2
VOLUME (in^3)	400	200	≈ 1800
REMARKS	Shielding from spacecraft backscatter		

TABLE 5 SPECIFICATIONS FOR PARTICLES AND FIELDS MEASUREMENTS

POTENTIAL PROBES (ANTENNAS)

MEASUREMENT	Plasma Structure
LOCATION	Extendable
ORBIT CHARACTERISTICS	Polar (Eccentric) Perigee-low as possible Apogee-4 to 5 radii
LIFETIME	1 year
EXP. RANGES	μ volts/cm - m volts/cm
EXPERIMENTAL BIT RATE	30 BPS
TEMPERATURE	$-10 < T(^\circ C) < +65$
WT. (LBS.)	10
P (w)	3
VOLUME (in^3)	900
REMARKS	0.05 Hz - 100 KHz response

susceptible to such contamination from flight operations, which will obviously alter or destroy the present situation which reflects the history of the lunar environment. The sources for formation and maintenance of a lunar atmosphere include volcanism, meteoric impact and volatilization, the solar wind, radioactive decay, and an original atmosphere. The attenuation of the atmosphere is caused by gravitational escape, the solar wind, chemical transformation, and chemical interaction with the surface. While present estimates of atmospheric parameters may well be in error, it appears that the surface pressure may be near 10^{-11} torr and the total mass of the atmosphere lower than 100 tons.

The experiment is intended to determine the composition and variations of the intrinsic lunar atmosphere, examine the source and escape mechanisms in some detail, and to study diffusion mechanisms. The effect of solar activity on the lunar atmosphere as well as possible outgassing at the surface may be detected as well if the proper orbits can be selected. While some of this information may be obtained from instruments placed on the surface, the synoptic information that is required would need such an extensive network of surface stations that it would be impractical. A polar circular orbit at a low altitude or an eccentric orbit which allows for a portion of the observing time to be at low altitudes would be most desirable. Entrance aperture shielding would be required along with a minimum of outgassing. Table 6 gives the suggested measurement specifications.

4.3.2 X-Ray Detection

The objective of the experiment is to obtain a gross analysis of the principal elemental composition of the lunar surface layer. The solar flux will produce a substantial x-ray albedo that should consist primarily of K&L lines from the more abundant elements. These lines can be resolved using proportional counters and filter techniques to determine amounts of elements.

The measurements should be able to provide discrimination between granitic, basaltic, or meteoritic regions. This is due largely to the difference in uranium amounts present in these

TABLE 6 SPECIFICATIONS FOR LUNAR ATMOSPHERE AND SURFACE ENVIRONMENT MEASUREMENTS

MASS SPECTROMETER

MEASUREMENT	Atmos, Wake, and Boundary Layer Composition
LOCATION	Boom Mount
ORBIT CHARACTERISTICS	Polar Perigee-low as possible Apogee-4 to 5 radii
LIFETIME	1 year
EXP. RANGES	3 mass ranges with 1 - 4 Simultaneous 12 - 28 amu Scanning 40 - 160
EXPERIMENTAL BIT RATE	One 8 Bit Word per Minute
TEMPERATURE	$-20 < T(°C) < +70$
WT. (LBS.)	22
P (w)	13
VOLUME (in^3)	720
REMARKS	120 volts required for ion source potential; stray field $\approx$ 0.1 gauss

different materials. Both the K-shell radiation and the instantaneous solar x-ray spectrum would be measured to determine the chemical composition so as to compare the incident radiation to the fluorescent radiation.

The actual experiment could consist of a set of proportional counters and filters with different band passes. A collimator would be used to limit the field of view. Since the softer x-rays would come from a more shallow depth, comparison with the γ-ray flux may then provide information regarding composition versus depth near the surface. Table 7 gives the measurement specifications.

4.3.3 γ-ray Detection

The interaction of cosmic rays and energetic solar particles with the Moon will produce some secondary x-rays, γ-rays, and neutrons, so that a detailed set of measurements can provide information on the composition of surface and near-surface material.

In addition to the induced γ's, there is of course some natural radiation. If the assumption is made that lunar activity is similar to the natural radioactivity on earth, the principal elements that contribute are K^{46}, U^{238}, and Th^{232}. The main contribution, however, is expected to come from cosmic ray interaction. Thus it should be possible to observe characteristic emissions from a few selected elements of substantial abundance; namely iron, aluminum, sodium, silicon, etc.

The γ-ray flux will be detected by means of a scintillation detector coupled to a PM tube. The scintillator could be a crystal of thallium-activated sodium iodide with a shell of plastic scintillator to shield out charged particles. The system must be mounted on a boom to minimize counts due to production of γ's from cosmic particle - spacecraft interactions. Table 8 gives the measurement specifications.

TABLE 7 SPECIFICATIONS FOR LUNAR ATMOSPHERE AND SURFACE ENVIRONMENT MEASUREMENTS

X-RAY PROPORTIONAL COUNTER

MEASUREMENT	Gross Analysis of Lunar Surface Layer
LOCATION	Solar Monitor
ORBIT CHARACTERISTICS	Polar Circular $\leq$ 500 km
LIFETIME	$\geq$ 1 month
EXP. RANGES	< 10 Å
EXPERIMENTAL BIT RATE	30 - 100 BPS
TEMPERATURE	0 - 50°C
WT. (LBS.)	45 (with shield) 9 (solar monitor)
P (w)	10 7
VOLUME (in^3)	2000 20
REMARKS	2000 volts for proportional counter; Resolution - 50 x 50 km

TABLE 8 SPECIFICATIONS FOR LUNAR ATMOSPHERE AND SURFACE ENVIRONMENT MEASUREMENTS

γ-RAY SCINTILLATION DETECTOR

MEASUREMENT	Composition of Surface and Near-Surface Material
LOCATION	Boom Mount (20 ft.)
ORBIT CHARACTERISTICS	Polar Circular 30 to 50 km height
LIFETIME	$\geq$ 1 month
EXP. RANGES	0.1 to 10 Mev
EXPERIMENTAL BIT RATE	3KB/sec
TEMPERATURE	$15 < T(°C) < 75$
WT. (LBS.)	16
P (w)	8
VOLUME (in^3)	400
REMARKS	1500 volts for PM tube; Pointing to within $\pm$ 10° of vertical.

4.3.4 Neutron Detection

The measurement of the induced neutron albedo could determine whether or not there is hydrogen in the form of water near the lunar surface. Those neutrons generated near the surface which are scattered by the lunar nuclei are those that result in the albedo. Since energy transfer occurs in these scatterings, and since the amount of the energy transfer depends upon the kind of nuclei doing the scattering (transfer is most effective for light nuclei), the energy spectrum of the neutron albedo will reflect the presence of hydrogen. Hence it is sufficient to know the ratio of slow to fast neutrons.

The slow neutrons can be detected with proportional counters filled with BF_3, while the fast ones will be detected with an organic liquid scintillator using a xylene base. To reduce background counts, the detectors should be mounted on a boom. Table 9 gives the measurement specifications.

4.3.5 α-Particle Detection

It is expected that the major source of alpha emitters on the Moon is the radiogenic noble gas radon (Rn^{222} and Rn^{220}) diffusing through the top layers of Moon. Radon is produced in the decay chains of uranium and thorium. The isotope from the uranium decay series has a long half life (a few days) and would likely be distributed uniformly in the atmosphere. The isotope from the thorium chain has a much shorter half life and so may provide the spatial resolution to detect cracks and fissures.

The α-particles emitted have energies between 5.3 and 7.7 Mev. A silicon surface barrier detector, having already been flight tested, would be the most appropriate detector. Table 10 gives the measurement specifications.

TABLE 9 SPECIFICATIONS FOR LUNAR ATMOSPHERE AND SURFACE ENVIRONMENT MEASUREMENTS

NEUTRON PROPORTIONAL COUNTER

MEASUREMENT	Near-Surface Hydrogen Content
LOCATION	Boom Mount
ORBIT CHARACTERISTICS	Polar Circular $\approx$ 100 km
LIFETIME	$\geq$ 1 month
EXP. RANGES	Two ranges < 10 kev 1 < E < 10 MEV
EXPERIMENTAL BIT RATE	1 BPS
TEMPERATURE	20°C - 30°C
WT.(LBS.)	16
P (w)	3
VOLUME (in^3)	900
REMARKS	

TABLE 10 SPECIFICATIONS FOR LUNAR ATMOSPHERE AND SURFACE ENVIRONMENT MEASUREMENT

α-PARTICLE DETECTOR

MEASUREMENT	Radon Detection Rate of Evolution from Lunar Surface
LOCATION	Not critical
ORBIT CHARACTERISTICS	Polar Circular ≈ 100 km
LIFETIME	≥ 1 month
EXP. RANGES	5 to 7 Mev
EXPERIMENTAL BIT RATE	5 BPS
TEMPERATURE	$15 < T(°C) < 35$
WT. (LBS.)	37 (with shield)
P (w)	11
VOLUME (in^3)	1200
REMARKS	

4.3.6 S-Band Transponder Experiment

The objective of this experiment is to track the sub-satellite in Lunar orbit by means of S-band doppler measurements during periods when the spacecraft is unperturbed by maneuvers, attitude control or other activity, and then reduce these data for enhanced gravity field determination. A better lunar mass model, when correlated with lunar shape information, will enhance and support future lunar activities (both visible and farside) by permitting greater surface landing accuracy, more accurate orbit determination, and will give the scientific community a basic model for such considerations as lunar origin and subsurface structure. This experiment is identical to present flight control doppler tracking techniques, except that non-gravitational movement of the spacecraft is rigidly controlled. A polar orbit with approximately a 10 km altitude is required. With a lifetime of a year or more, a very detailed gravimetric study could be accomplished; satellite-to-satellite tracking for the occulted zone on the farside could be employed.

4.4 Surface Mapping

4.4.1 μ-Wave Radiometer

The general microwave properties of the lunar surface are fairly well understood, theoretically. The property of the Moon measured by the electrically scanned microwave radiometer will be the brightness temperature, T_b, which for the case of a totally transparent atmosphere is a function of the microwave emissivity of the surface, the subsurface temperature regime within a few units of optical depth, the electromagnetic absorptivity of the lunar material, and possibly the dielectric constant. Measurement of the surface and subsurface temperatures permits estimates to be made of the electromagnetic and thermal parameters of the Moon.

TABLE 11 SPECIFICATIONS FOR SURFACE MAPPING MEASUREMENTS

μ-WAVE RADIOMETER

MEASUREMENT	Thermal Emission Map	Sub-Surface Temps.
LOCATION	Not critical	
ORBIT CHARACTERISTICS	Polar Circular $\leq$ 100 km	Polar Circular $\leq$ 100 km
LIFETIME	> 6 months	> 6 months
EXP. RANGES	20gHz	1.2gHz
EXPERIMENTAL BIT RATE	200 BPS	
TEMPERATURE	$-65 < T(°C) < +85$	
WT. (LBS.)	45	45
P (w)	20	20
VOLUME (in^3)	700	700
REMARKS	Penetration from 3 to 10λ	

When used in conjunction with an IR radiometric imager, results will yield information on the thermal environment of the near subsurface lunar material. The IR radiometer measures the kinetic surface temperature while the microwave radiometer can measure subsurface temperatures which will allow the determination of emissivity profiles. Utilizing known signatures of materials previously identified, it should then be possible to identify the materials on the lunar surface. The observations should reveal regions of anomalous emissivity and regions of different thermal properties. Table 11 gives the measurement specifications.

4.4.2 IR Radiometer

The purpose of this experiment is to map the lunar surface temperatures, to detect and study any anomalously hot or cold areas, and to study the heating and cooling rates of the surface layers.

It is possible that a large number of different geological phenomena cause thermal anomalies which have been identified with different types of surface details. With the data presently available from earth observations, it is impossible to decide among the various possible mechanisms which could cause thermal enhancement of the lunar surface. Measurements using earth bound telescopes as radiometers have very limited thermal sensitivity and low spatial resolution. The obvious way to obtain the required increased sensitivity is to place a mapping radiometer in lunar orbit.

It is proposed to perform an experiment to produce a map to a resolution of 1 km. Successful completion of this task would give a better than 10 fold increase in spatial resolution over present thermal maps and extend it over the lunar far side. Study of this map would give a meaningful basis on which to plan subsequent measurements such as high resolution maps of selected anomaly regions. Mission parameters require a polar orbit and an operational time of at least one lunar period. Table 12 gives the measurement specifications.

TABLE 12 SPECIFICATIONS FOR SURFACE MAPPING MEASUREMENTS

IR RADIOMETER

MEASUREMENT	Thermal Emission and Surface Temperature
LOCATION	Not critical
ORBIT CHARACTERISTICS	Polar Circular $\leq$ 100 km
LIFETIME	> 6 months
EXP. RANGES	1 - 40 μ 0.5°K thermal resolution
EXPERIMENTAL BIT RATE	10 bits per resolution element
TEMPERATURE	≈ 150°K
WT. (LBS.)	150
P (w)	150
VOLUME (in^3)	2400
REMARKS	

4.4.3 IR Spectrometer

The objectives of this experiment are to determine mineralogical characteristics and composition variations across the surface of the Moon using spectral reflection of the near IR solar illumination.

Three different measuring techniques that can be employed are:

a) Prism spectrometer - reflected energy is collected using reflective optics. The spectrum is separated using a quartz prism and detected with any array of lead sulfide detectors for the entire 0.6 to 3 micron range. The prism spectrometer is less complex than the grating spectrometer.

b) Grating spectrometer - the same energy collection technique as the prism spectrometer is used. The spectrum is separated by using a grating and then detected using PbS detectors for the shorter wavelength and Pb Se for the 3-5 micron range. The grating spectrometer is more sensitive and has a wider bandwidth than the prism spectrometer. Where increased sensitivity is required, cryogenically cooled iridium arsenide detectors can be employed. Spectral reflectance experiences only second order effects due to phase angle and therefore measurements need not be made at different angles. Table 13 gives measurement specifications.

c) Interferometer spectrometer (Michelson type).

TABLE 13 SPECIFICATIONS FOR SURFACE MAPPING MEASUREMENTS

IR SPECTROMETER

MEASUREMENT	Surface Characteristics and Variations
LOCATION	Not critical
ORBIT CHARACTERISTICS	Polar Circular $\leq$ 100 km
LIFETIME	$\geq$ 6 months
EXP. RANGES	10 meter resolution 0.6 - 30 μ (≈ 300 Å resolution)
EXPERIMENTAL BIT RATE	$\simeq$ 200 Bits per Resolution Element
TEMPERATURE	
WT. (LBS.)	30
P (w)	15
VOLUME (in^3)	3600
REMARKS	Requires cooling

5. SUBSATELLITE MISSION PROFILES

Consideration of the required measurements illustrates the fact that several different mission and vehicle types must be considered if significant data are to be obtained for any of the experiment classes. The measurements to be made are:

Particles and Fields	Magnetometry Plasma Detection and Analysis Electric Field Detection
Mapping	IR radiometry μ-wave radiometry IR spectrometry
Atmosphere and Surface Environment	Mass spectrometry γ-ray detection x-ray detection Neutron detection α-particle detection UV spectrometry
Selenodetics	Gravity field determination

The principal objectives here, as mentioned earlier, lie in the areas of particles and fields, lunar environment, geodesy, and surface mapping. The objectives can be achieved, to varying degrees of success, by way of a variety of mission types. Since the Apollo program offers a possibility in some of the areas, it seems reasonable to consider it as a starting point, examine it for usefulness from a scientific standpoint, and then to proceed to more complex plans, if needed, in order to achieve the desired results.

Obviously the simplest procedure for performing orbital science is to put an experiment package directly on board the CSM and perform limited experimentation in that configuration. Unfortunately, this option provides only limited data for reasons of current staytime limitations, scientific cleanliness, orbit altitude, and/or orientation.

It is in the context of these constraints that the following subsatellite mission profiles have been developed; the concepts are summarized in Table 14.

1. Simple CSM Release

This is a true subsatellite and involves only a mechanical release from the CSM. In its simplest form, the subsatellite would consist of an experiment package, power to operate the experiment, and an antenna for transmission of data. In this configuration, capability exists for performing the selenodesy experiment and the craft may be likened to the TETR satellite.

2. CSM Release - Spin Stabilization

This is the same as case 1, with the addition of spin stabilization, communications, some data handling capability, and more power. Now the magnetometry experiments could, in principle, be performed and the overall configuration is somewhat like that of the Pioneer satellite. However, it is felt that proper utilization of the experiments could not be made from the CSM orbit in which this vehicle must operate.

3. CSM Release - 3-Axis Stabilization

This has the same sort of capabilities as case 2, but provides 3-axis stabilization which is necessary for all of the surface mapping experiments as well as the high energy measurements and the nuclear particle detection. This configuration rather resembles the early Mariner craft. Because of the orbit limitations (low inclination), however, insufficient coverage is obtained to warrant serious consideration of this mode.

4. <u>Launch from CSM Orbit to Eccentric Orbit</u>

This is essentially the configuration described in case 2, but there is now the necessary propulsion to change the eccentricity of the orbit to provide for a 4 to 5 radii apoapse through the wake and a periapse of a few kilometers on the sunlit side. This meets rather well most of the desired parameters for the particles and fields measurements and as such should be given a high priority. If a lifetime of from six to twelve months can be provided, the magnetometry can also be used at low altitudes in the void to detect the existence of local magnetic anomalies. This configuration can be likened to a rather sophisticated Explorer 35 spacecraft.

5. <u>Launch from CSM Orbit to Polar Orbit</u>

This is essentially the instrumentation and equipment of case 3 with sufficient propulsion to effect a change in inclination. 50% of the total weight must be added for propulsion in order to achieve a polar orbit which, with 3-axis stabilization, makes possible all of the surface observation measurements previously discussed.

6. <u>Cislunar Launch to Polar Orbit</u>

This is the second method for obtaining polar orbit and is achieved with a propulsion weight ratio of 33%. With a 3-axis stabilization, this mode of operation appears to be the optimum choice for performing the IR and μ wave mapping, the high energy measurements, and the nuclear particle detection measurements.

7. <u>Earth Orbit Launch to Polar Orbit</u>

This is rather equivalent to case 6, except that now in addition to being able to provide the appropriate inclination and polar orbit, the orientation and phase angle can be selected. Thus the proper illumination conditions can be obtained initially, and a much shorter lifetime can provide all the desired results.

6. CONCLUSIONS

While all of the mission profiles given above are distinct possibilities, three of these (Cases 1, 4, and 7) are considered superior to the other candidates.

Case 1, the TETR - type concept is certainly a simple mission, can accomplish all of its functions in the most simple configuration, and therefore should be strongly considered. Case 2 (spin stabilized) and Case 3 (3-axis stabilized) are examples of missions of very marginal value insofar as the value of data return is concerned. In neither case are the orbits optimized; they are mentioned, however, in that they are simple CSM releases and they are logical steps along the way toward more complex missions.

Case 4 (spin stabilized, eccentric orbit) is a mode where certain experiments can be performed under optimum conditions. Here, from a CSM inclined orbit and with an eccentricity which permits measurements out to 4 or 5 radii, the particles and field measurements can be ideally performed. Case 5, (3-axis stabilized, polar orbit) similar to 4, begins with a CSM powered release, but changes inclination rather than gaining eccentricity so as to perform the mapping and high energy experiments. This is not quite as good as Case 6, (3-axis stabilized, polar orbit, cislunar release), however, since a savings in fuel is afforded by way of a cislunar launch. Case 7 (3-axis stabilized, polar orbit, earth orbit release) provides the same ultimate conditions as 5 and 6; however, since orientation and phase angle can be immediately selected, the lifetime need not be as long in order to achieve the proper illumination conditions.

In summary, it appears that Case 1 is best suited for the selenodetic experiment, Case 4 for the particles and fields and experiments, and Case 7 for all of the mapping and high energy experiments.

TABLE 14 ROLE OF SUB-SATELLITES

ORBIT	ATTITUDE	SEPARATION	CANDIDATE EXPERIMENTS
1. CSM	None	Lunar Orb.	Geodetics
2. CSM	Spin	Lunar Orb.	Particles and Fields? Mass Spectrometer?
3. CSM	3-Axis	Lunar Orb.	Particles and Fields? Environment? Mapping?
4. CSM $e > 0.3$	Spin	Lunar Orb.	Particles and Fields Environment?
5. Polar and Circular	3-Axis	Lunar Orb.	Environment Mapping
6. Polar and Circular	3-Axis	Cislunar	Environment Mapping
7. Polar any Orientation	3-Axis	Earth Orb.	Mapping

? = Limited value in performing experiments from given orbits

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