

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

INTERAGENCY REPORT: ASTROGEOLOGY 19
STRATEGY FOR THE GEOLOGIC EXPLORATION
OF THE PLANETS

By M. H. Carr, Editor

with contributions from

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National Aeronautics and Space
Administration

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INTRODUCTION

Scope and Purpose

The geology of the planets bears directly on three basic aims of lunar and planetary exploration: determination of the origin and evolution of the solar system, determination of the origin and evolution of life and clarification of the nature of the processes shaping Man's terrestrial environment (Woods Hole Conference, 1965). The purpose of this document is to provide a guide to the orderly geologic exploration of the planets, to assign priorities to specific experiments and to suggest areas where supporting Earth-based research can be most profitably pursued. The kinds of data that are most relevant to geologic interpretation are specified and the sequence in which these data should be acquired is outlined. Lengthy theoretical arguments relating specific pieces of data to general problems of solar system evolution are avoided as are detailed considerations of the engineering problems involved in acquiring the data. Discussion is also constrained by what appears practical in view of present flight plans and probable future flight opportunities.

The document is the result of informal discussions between a large number of geoscientists mostly within the U.S. Geological Survey. Many of the people involved have had extensive experience in the planning and implementation of lunar missions and in interpreting the resulting data. Some have participated in other strategy sessions such as the Woods Hole and Santa Cruz conferences. As a result of these activities firm ideas have been developed as to how to explore other bodies in the solar system and the intent of this paper is to present these ideas within a coherent framework. The strategy is concerned almost exclusively with geologic problems; other topics are discussed only when they relate to geology and only insofar as they illuminate a particular geologic problem.

The term 'geology' is used here in its broadest sense and is considered to mean study of the solid portions of the planets.

Geophysics, geochemistry, geodesy and other sub-disciplines concerned with the solid planets are included in the general term geology. Planetary atmospheres are almost completely ignored, not because they lack relevance but because they are not normally studied by geologic techniques. While recognizing the importance of planetary atmospheres in modifying the surface of a planet and as an index to its outgassing history, some limit had to be placed on the scope of this discussion and atmospheres thereby received minimal attention. This limitation restricts much of the discussion to the terrestrial planets and to the solid satellites of the outer planets. Jupiter and Saturn in particular are difficult to consider in geologic terms since they may have no solid surface. Attention is also focused on the inner planets because they are closest to Earth and are easiest of access. Successful fly-by missions have already been made to Mars and Venus and several orbital missions to Mars are in advanced planning stages. In addition, preliminary plans for a Venus-Mercury mission are completed.

This strategy is intended as a supplement to previous more general documents. It has been written largely within the framework of recommendations of the Woods Hole Conference (National Academy of Science, 1966) and the McDonald Committee on Space Research (National Academy of Science, 1968). Heavy reliance has been placed on several previous documents, particularly those of the Space Science Division of the Jet Propulsion Laboratory (Adams and others, 1967a, 1967b, and Mackin and others, 1968). This document differs from the aforementioned largely in the emphasis given here on geologic problems.

A large number of Geological Survey personnel contributed directly or indirectly to this document. The chapter on stratigraphy and structure was written largely on the basis of discussions with Z. S. Altshuler, J. F. McCauley and D. E. Wilhelms. The cartography and geodesy section is a condensation of written recommendations from D. W. G. Arthur, R. M. Batson, W. T. Borgesson, A. P. Colvocoresses, and F. Doyle. R. R. Doell, J. H. Healey,

A. H. Lachenbruch, W. E. Lee, B. C. Raleigh, G. G. Schaber, and Kenneth Watson critically reviewed the section on geophysics, and the geochemistry section was written in collaboration with P. Toulmin and I. Breger.

Relevance of Geologic Studies

Before examining in detail what specific experiments best fulfill geologic requirements, the more general question of the importance of geology in planetary exploration must be examined. The role of geology in achieving each of the three basic goals of planetary exploration, formulated at the Woods Hole Conference and stated earlier, will be considered.

Origin and Evolution of the Solar System

Adams and others, 1967, examined the problem of the origin and evolution of the solar system and reduced it to five main questions:

1. Are the individual terrestrial planets and satellites chemically uniform or non-uniform?
2. Did final accretion result in the present array of planets or satellites, or in an array that was subsequently altered?
3. Was the cloud chemically homogeneous at the time of final accretion?
4. What was the state of the sun-cloud system when it first appeared as a recognizable unit?
5. Were there large-scale elemental and isotopic non-uniformities in the contracted nebula?

Since the above questions are all concerned with determination of the stage (or stages) in solar system evolution when chemical fractionation took place, answers must ultimately depend on chemical measurements. Many of the necessary measurements will be made on planets and their satellites and to interpret them we are confronted with the problem posed by the first question, that of chemical uniformity or non-uniformity. The general implication of any particular analysis cannot be assessed without knowing to

what extent the analysis is representative of the body being analyzed. It cannot be assumed a priori that the planet is chemically homogeneous and that a given analysis is representative of the whole planet. This is certainly not true of the Earth and it is highly unlikely to be true of the Moon (see p. 9). Planetary homogeneity or non-homogeneity must first be established by surface observations which will permit inferences regarding the structure of the interior. Furthermore, if general conclusions are to be drawn, it is not sufficient merely to establish non-uniformity; the nature of the non-uniformity must be defined.

To document non-uniformity, we cannot simply sample a planet's surface statistically assuming random variability because only a minute portion of the planet, the very near surface, is available for study and this may be totally non-representative of the planet as a whole. We must have a general understanding of the planet and this can be achieved effectively only by studying the processes that have caused and may yet be causing redistribution of materials within the planet. Only if the processes are understood can valid general conclusions be made regarding the significance of specific measurements. The sampling or type of measurement made on a planet should therefore be guided by geologic priorities based on need to understand geologic processes rather than cosmogonical considerations because we cannot proceed from the specific to the general without the geologic knowledge.

Geophysics is concerned largely with documenting internal heterogeneities and conditions. Chemical determinations on interiors cannot be made directly but inferences are possible from measurements of physical properties. Discontinuities of seismic properties and variations in internal densities, as determined from the figure of the planet and the rotational constants, may correspond to compositional differences. Magnetic measurements may reveal the presence of a core and heat flow measurements place limits on the distribution of radioactive elements. The value of any particular physical parameter is not important in itself since it depends on local conditions; its importance lies in the fact

that it places limits on chemical composition and internal conditions and provides data on internal processes.

One concern of stratigraphy is documentation of the heterogeneity of the crust. Even though the surface rocks constitute a minute portion of the total mass of the planet, it is the part on which virtually every measurement is made so that an understanding of these surface materials is crucial. We must know how variegated the surface rocks are and how they formed. Lateral variations can be delineated by direct observation; vertical variations are inferred from the distribution, attitude, age, and mode of formation of the observable rocks leading directly to consideration of petrological and tectonic problems. Determination of mode of formation is particularly important since different processes vary in the extent to which they cause chemical change. Consequently to understand the broader implications of surface analyses, the distribution and mode of formation of the rocks analyzed should be known, as well as the degree to which they typify all the materials of the planet.

Origin and Evolution of Life

The geology of planetary surfaces bears directly on the origin of life. This document has been written largely on the assumption that life will not be found anywhere in the solar system other than on Earth. This appears at present to be most probable but if life is found elsewhere then the significance of geology will be greatly enhanced and this strategy will need drastic revision. With life on a planet, the mode of rock formation, the physical conditions of deposition, and the relative age will take on new significance. Not only will they reflect past conditions and events but they will reveal the evolutionary path of life on that planet and the conditions under which life thrived. Paleontology, which has been totally ignored in this strategy, would become of paramount importance and different types of missions may be required to meet its needs.

Man's Terrestrial Environment

One important result of planetary exploration will be increased knowledge of the Earth. Many fundamental geologic problems could be solved by knowledgeable comparison of the Earth with other planetary bodies. The relative effects of size, original composition, and the presence of an atmosphere and hydrosphere on the evolution of the Earth are of particular geologic importance and comparison of the Earth with other bodies will allow these effects to be assessed.

Several theories of the formation and distribution of continental crustal material could be rejected or reinforced by finding similar material on other planets (Lowman, 1969). One possibility (Kay, 1951, Engel, 1963) is that the continents are essentially sedimentary in origin; they form by accretion of sedimentary materials on their margins and so are dependent on the presence of oceans. Other possibilities are that the continental crust is formed by igneous processes either as part of the mechanism of core formation or independently as the result of igneous processes in the mantle. A less widely held possibility is that the continental crust is the remnant of sialic meteorites that impacted the Earth early in its history (Alfven, 1963; Donn and others, 1963). The presence of continental crust on a planet with no present or past oceans or on a planet without a core will result in rejection of the ocean and core dependent theories and considerably narrow the number of possibilities for the Earth.

Similarly the relative importance of different mechanisms of oceanic crust formation could also be evaluated. Current theories of the formation of the oceanic crust emphasize the generation of new crustal material at the mid-oceanic ridges and its subsequent ingestion into the mantle in regions of crustal downturning (Deitz, 1961). The presence of oceanic crust on a planet devoid of linear structures, which presumably are indicative of mantle convection, would indicate that oceanic crust can form by non-convective mechanisms and that the case on Earth may be more complex than presently appears.

The mode of formation of mountains on the Earth is still in dispute. Convection in the mantle is widely believed to be the source of energy for mountain building on Earth (Blackett and others, 1965) but the role of continents and oceans in controlling the location and formation of mountains on the Earth is still imperfectly understood. Convection in the mantle could certainly occur on a planet with no ocean or continental crust. The effects of mantle movement on crustal rocks could be viewed on such a planet without the complicating effects of sedimentation at the continental margins, and this would lead to a clearer understanding of crust-mantle interactions on the Earth.

Probably the most important result of planetary exploration from the point of view of Man's terrestrial environment will be an improved understanding of the early history of the Earth. Features on the surface of the Earth are subject to relatively rapid destruction and modification largely as a result of the erosive action of water, but also as the result of tectonic and volcanic activity. Evidence of events and processes that took place early in Earth's history rarely survive so that very little is known of the first two billion years of the Earth's history. Mars, Mercury and the Moon on the other hand, have no oceans so that the erosive effects of water are virtually absent. Furthermore, because of their smaller size, we can expect less tectonic and volcanic activity than on Earth (Anderson, 1969). Primitive features are more likely to survive on these planets, thus allowing their early history to be defined. Analogy with these more primitive planets may be the only way to arrive at an understanding of the Earth's early history.

Geology will therefore play a vital role in achieving the three basic aims of planetary exploration and a detailed discussion on how best to pursue the geologic studies in concert with other types of investigations follows.

STRATIGRAPHY AND STRUCTURE

Stratigraphy is the study of rock sequences; structural geology is the study of rock deformation and the features it has produced. The ultimate aim of both is to determine the history of the planet and the mode of its formation. A planet is not static and unchanging; its constituents are constantly being rearranged to form new rocks with new distributions. The changes may be only surficial resulting from external mechanisms such as meteorite impact. Or the changes may result from internal processes such as volcanism and tectonism. Whatever the processes, a partial record of successive events is preserved in the surface rocks and structures. The role of stratigraphy and structural geology is to reconstruct from this fragmentary record the sequence and nature of the events that have affected the planet and to devise a model for the evolution of the planet that is consistent with the observations.

Applicability to the Planets

Geochemical, geophysical and petrological measurements on the surface of a planet cannot be reliably related to general questions concerning the evolution of the solar system unless the history and structure of the planet are partly understood. Correct interpretation of any surface measurement depends on knowledge of the heterogeneity of the planet, of the processes and sequence of events causing the heterogeneities, and of the local geologic environment at the site of measurement. One purpose of stratigraphy and structure is to provide this necessary background information and its relevance to the planets will be examined in this light.

Surface Heterogeneities

The immediate aim of stratigraphy and structure is to reduce the enormous complexity of a planet's surface to comprehensible proportions by dividing the near surface rocks into units and portraying their distribution and attitude on geologic maps. The complexity of the Earth's crust is well known and needs no further

discussion, but the variegated nature of other bodies in the solar system is less widely appreciated. The Moon is the only other body in the solar system whose surface has been studied in any detail and its heterogeneity is now well established. The basic distinction between mare and terra has been recognized ever since the Moon was first observed through a telescope by Galileo. Gilbert (1893), in pointing out the existence of a blanket of material surrounding Mare Imbrium, demonstrated that the terra is not homogeneous but is divisible into stratigraphic units. Several additional widespread terra units such as the Orientale blanket (McCauley, 1967) and the Cayley Formation (Morris and Wilhelms, 1967) have since been recognized and mapped from telescopic observations. Subtle differences in the color and reflectivity of the maria documented from telescopic observations (Whitaker, 1966, McCord, 1969) showed that the maria also are heterogeneous and susceptible to subdivision (Carr, 1966). The terra could locally be subdivided from telescopic photographs (Milton, 1968), but it was with the acquisition of Lunar Orbiter IV photography that different provinces of the terra could be fully recognized and differences in the maria adequately documented. Wilhelms and McCauley (1969) in a compilation of the geology of most of the front side of the Moon delineated terra regions that have specific characteristics distinguishing them from adjacent areas. One area has a unique crater frequency distribution, anomalously shaped craters predominate in another area, and a relatively uncratered plateau-like terrain is the dominant landform in yet another area. Wilhelms and McCauley ascribe many of the regional differences to volcanism, but whatever the cause of the differences, they are real and exemplify the heterogeneity of the terra. Similarly detailed but larger scale mapping of the Apollo landing sites (Trask, 1969) has shown that differences also occur within the maria and that the mare material cannot be treated as a single homogeneous unit. The Moon therefore shows considerable heterogeneity and stratigraphic studies are an essential prerequisite for its orderly scientific exploration.

Much less information is available on the surfaces of other planetary bodies but telescopic observations do reveal markings on all those with surfaces that can be observed. The surface markings of Mars, which probably result from albedo variations, are especially well known from the extensive observations of Lowell (1908), Antoniadi (1930), Slipher (1962) and DeVaucouleurs (1962). Recent Mariner photography has shown that the Martian surface is, in addition, topographically variegated. The Mariner Mars '69 experimenters have pointed to cratered areas much like the lunar highlands, to crater free areas such as Hellas, and to areas of "chaotic" terrain. Markings have also been observed on Mercury (McEwan, 1929; Antoniadi, 1930) and on the Jovian satellites Europa, Io, Ganymede, and Callisto (Katterfeld and others, 1968). Color differences have been detected on Mars and some Jovian satellites and the differences have been attributed to chemical heterogeneity (McCord and Adams, 1969). It thus appears that the surfaces of many planetary bodies are heterogeneous and it will therefore be necessary to establish the nature of the differences so that the events and processes leading to the present configuration can be understood.

Nature of Processes

Any data from the surface of a planet must be interpreted in light of the processes that resulted in the present configuration of the surface. Processes affecting a planet can be classified into two broad categories; those such as volcanism and tectonism that are related to internal forces and those, such as impact and erosion, that are related to external forces. If a planet is internally inert, and always has been inert, and if the geology of the surface is controlled exclusively by external processes, then stratigraphic studies will be of limited value. However, if the planet has experienced any internal activity, then chemical fractionation is likely and the significance of any analytical data will depend directly on the local geology. Stratigraphic studies are therefore required, firstly, to determine if internal

processes, particularly volcanism, have affected the surface, and, secondly, to document the geology in detail if internal effects are present.

The first close look at Mars provided by the Mariner IV photography indicated that Mars is more Moon-like than Earth-like. Meteorite impact appears to have played a prominent role in sculpting the surface and it is expected that the same is true of Mercury. This does not, however, imply that internal effects are absent. One result of impact on the Moon is to mask volcanic effects; nevertheless such effects have long been recognized from telescopic and orbital observations (Shoemaker and Hackman, 1962; Carr, 1965) and the volcanic nature of mare materials is now confirmed by direct measurements on lunar samples. The fact that volcanism has occurred on the Moon strongly suggests that it has also occurred on planets of comparable or greater size thereby greatly enhancing geologic interest in these bodies.

Sequence of Events

The significance of any event on the surface must be viewed in its historical context. If, for example, volcanism ceased 1 b.y. after the planet formed, the implications regarding bulk composition are far different than if volcanic processes are still active. Stratigraphy is concerned, in large part, with placing rock units in historical sequence and relating them to specific events in the past. This historical perspective distinguishes stratigraphy and the discipline of geology in general from most other natural sciences. In the absence of fossils and as a result of the difficulty of getting absolute ages, geometrical relations as observed by photography will be the principal source of data on relative ages. On the Moon, geometrical methods have been highly successful in establishing a global stratigraphy. Success has been possible largely because of the presence and recognition of extensive marker horizons by which other units can be dated. Two examples are the Imbrian blanket (Fra Mauro Formation) and the Orientale blanket which are both extensive deposits

that appear to have formed during a very short period of time. Structures have a similar importance for dating purposes and in some areas of the Moon the presence or absence of Imbrian sculpture is the dominant criterion for determining relative ages. The now well established techniques used on the Moon (Shoemaker and Hackman, 1962; Wilhelms, 1966) are directly applicable to planetary imagery and we can expect the same degree of success in unraveling crustal stratigraphy given photographic data of comparable quality. Definitive information on stratigraphic relations will however finally depend on surface-based observations; crucial relations inferred from the imagery must be checked at some stage by man, or by means of automatic roving vehicles or drilling techniques.

Geologic Framework

The stratigraphy and structure of a planet are of vital importance in that they provide the framework within which all other measurements must be evaluated. A chemical analysis, a heat flow measurement, or a seismic profile can be understood and correctly interpreted only if the geology near the place of measurement is known. A chemical analysis of a salt dome in Texas does not give the composition of the surface of the Earth in the south-central part of the United States, nor can a value for heat flow in Yellowstone National Park be extrapolated to the whole of the western United States. For any measurement to be understood, the geologic context must be known. This is so fundamental to geologic thinking that to state it appears trite and obvious, yet it is a concept that has found only limited acceptance with regard to the exploration of other bodies in the solar system. Without geologic analysis, the surface of the planet would of necessity be treated as a homogeneous unit; a chemical analysis would be considered as indicative of the chemistry of the whole surface and the mineralogy of one part would be considered as the mineralogy of the whole. Such interpretations are demonstrably nonsensical on the Earth, the Moon, and probably on Mars and there is little

reason to think that they will prove any more valid on other planets either. Measurements made on the surface of a planet must be interpreted in light of the local stratigraphy and to do otherwise could lead to the grossest errors in interpretation.

Methodology

Because of dependence on remote sensing data, the techniques of stratigraphic and structural analysis of the planets differ from those normally used on the Earth. In terrestrial practice rock units are defined on the basis of lithology, chemistry and mineralogy as seen at an outcrop. The relative ages of different units are determined largely by relations observed in vertical sections or in outcrop patterns; correlations are effected by comparison of successions of lithologies, by tracing specific horizons on the ground, by fossils and by absolute dating methods. In general the stratigrapher proceeds from particular observations seen at specific outcrops to a synthesis of general patterns. The reverse procedure must be used in studying the geology of a remote surface. General patterns are observed from remote sensing data and the significance of the patterns is later checked and supplemented by measurements and observations at a restricted number of ground sites. The procedure is similar to that used terrestrially in geologic exploration of remote regions, such as the Canadian shield where initial reconnaissance is by aerial photography, aerial gravity and magnetic surveys; areas of interest are located from the remote sensing data and a restricted number are checked on the ground.

The techniques used in analyzing the surface of the planets will be similar to those that have already been used on the Moon. For stratigraphic purposes photography has been the most valuable source of remote sensing information; nearly all the basic lunar stratigraphic units and relations have been determined from the visual imagery. Variations in gravity, emissivity in the infrared spectrum, radar reflectivity and color have had value largely

as interpretative aids, but not in defining and mapping units because they have not been determined with the same linear resolution as the visual black and white image. Since the external environment is almost the same everywhere on the Moon, variations in surface properties most likely result from differences in the materials exposed at the surface. These differences may result from age, composition, lithology, mode of deposition, and structural deformation, but whatever the cause they are intrinsic to the material at the surface and so have geologic significance. Some ambiguity does exist however because of the difficulty in discriminating between properties intrinsic to the regolith and those related to the underlying rocks. Surface properties have nevertheless been used to define rock units and from the variation in surface properties the distribution of different rock units has been documented. The relative age of adjacent units are determined by superposition and intersection relations and a Moon-wide chronology has been established by dating units with respect to extensive marker horizons such as the Fra Mauro Formation.

One reason for the success of the stratigraphic techniques on the Moon is that the lunar surface does not experience regional variations in external conditions. The surface of the Earth is greatly affected by external conditions such as those produced by weather patterns; as a result a specific set of surface properties may follow a climatic zone rather than the outcrop pattern of a rock unit. On the Moon the principal external process modifying the surface is meteorite bombardment and inasmuch as this is essentially isotropic differences in properties of the lunar surface must reflect differences in the properties intrinsic to the surface materials. A similar situation probably holds for Mercury. In the case of Mars, and Venus, regional climatic patterns may affect surface forms and geologic interpretation must be made in light of the possible climatic effects.

The techniques that have been applied to the Moon are directly applicable to Mars, Mercury and many planetary satellites, but

additional techniques may also prove useful. In particular, color, being partially dependent on mineralogical composition, may prove to be a valuable aid in identifying and characterizing geologic units on planetary surfaces. Color differences on the Moon are very subtle and have required special techniques for their detection (Whitaker, 1966; McCord, 1969). The differences have had only limited use for stratigraphic purposes, however, because the appropriate detection techniques have been in only a rudimentary state of development. With the development of more sophisticated techniques of multiband photography and photometry, color should play a prominent role in planetary stratigraphy, especially in the stages following the early exploratory work.

Once the geologic units have been defined and their relations to one another determined, the results can be portrayed on geologic maps. Although the geology of the Moon has been interpreted largely in light of surface landforms and albedo, the resulting maps are truly geological since they incorporate the three basic ingredients of a geologic map: rock units, age relations and geometrical positions. They are quite distinct therefore from topographic maps, terrain maps, and physiographic maps which are concerned exclusively with the surface form. Unless surface form is controlled exclusively by surficial effects such as wind action in a thick debris layer, we can similarly expect to make meaningful geologic maps of several of the planets.

Complete characterization of the rock units recognized from the imagery will require ground based measurements. A major purpose of a lander will therefore be to determine the lithology, texture, mineralogy, and petrology of the rocks at the landing site. An additional purpose should be to determine the vertical and lateral variations in these properties so that the stratigraphic relations at the site can be compared with those inferred from the vertical imagery. The choice of site for establishing ground control will clearly be critical. In the initial stages of exploration the sites should be located on geological units

that have a wide distribution and in areas where there is the minimum of stratigraphic ambiguity. Subsequently, sites may be chosen to clarify a specific scientific problem such as presence of volcanic activity or they may be located in an area where a vertical section is accessible, as near a fresh crater or steep vertical wall. In late stages of exploration characterization of surface units and their mutual relations will be most efficiently effected by some kind of traversing vehicle.

Data Requirements

The first stage in the geologic exploration of a planet is to identify and outline the distribution of the basic units of the crust from remote sensing data. Visual imagery will be the principal source of data, but this may be supplemented by data from infrared radiometry, radar reflectivity, gravity surveys, etc. The second stage is to establish "ground truth" at critical locations by obtaining chemical, mineralogical and petrological data from landers. It is vitally important that sufficient data be obtained in the first stage so that landing spots can be effectively chosen and the data obtained related to a regional framework. No matter how many landers are deployed, determination of the geologic environment at each site and interpolation between the sites will depend on the quality and coverage of the available regional imagery. If adequate imagery is lacking the whole subsequent exploration program could be prejudiced through lack of the basic information needed to interpret the in situ data. It is pertinent therefore to examine in detail what photographic data are needed to fulfill later exploration needs.

Fly-by Photography

The initial photographs of any planet will surely be from fly-bys. These missions will be reconnaissance in nature and no systematic coverage can be expected, the purpose being in large part to determine crustal style and identify general problems. For optimum utility, an early reconnaissance mission should

strive for imagery at a wide range of scales and broad coverage at low resolution. The ideal plan would result in photographs of the whole disc during approach and subsequent photographs each at a larger scale and nested within the previous frame. This has two advantages over a plan in which all photographs are taken at the highest resolution. First, because the broad geography of the body is established, and second the nature of the terrain at different scales is determined. The last is important as there is no way of knowing in advance at what scale meaningful information on critical landforms is obtainable. Systematic stratigraphic studies are however not possible from fly-by photography; orbital coverage is required.

Orbiter Photography

Orbital photography will be the single most important source of stratigraphic information and its usefulness for stratigraphic purposes depends on three main factors, resolution, areal coverage and illumination. In the very early stages of exploration color, polarization, photometric fidelity, and stereo overlap, though useful, are of secondary importance. Imagery is a source of information on two basic properties of the surface of a planet, topography and reflectivity; detailed information on both properties is necessary for stratigraphic work. Albedo differences are best seen at or near vertical illumination; topography is best observed at low angles of illumination when topographic detail is enhanced by the presence of shadows. Ideally, vertical photography at both low and high illumination should be obtained. Non-vertical photography on the other hand has very limited use for systematic work because of scale changes, and because distant features may be hidden by near features.

Resolution. --The term resolution as it is applied to visual imaging experiments often leads to confusion with regard to system capability. Photographic resolution has traditionally been given in terms of separable white and black line pairs per millimeter of the image. In vidicon imaging experiments, on the other hand, the

scale width of a single TV line, or in other cases the width of two TV lines, at a particular altitude, is often given as an index of system resolution. The size of the smallest objects about which something can be said either in a topographic or geologic sense is considerably larger than the width of two TV lines and is a function of overall target contrast. In any given television picture, small high contrast objects such as young fresh craters will be more detectable than larger, subdued, older craters. If, for example, one is interested in the frequency of craters near the resolution limit, the more numerous small smooth craters of an impact population cannot be seen, but small sharp craters of the same size are readily detectable. The measurable size-frequency distribution is thus biased as it approaches the limiting resolution of the system and cumulative crater counts show a "roll-over" or flattening at about four to six times the size of the smallest identifiable crater. In the ensuing discussion resolution is meant to imply the smallest relief element that can be recognized topographically. This is done with the realization that resolution is not fixed by the imaging system alone, but does depend also on illumination and the character of the surface being photographed.

The importance of resolution is easily understood, the finer surface details that can be seen at higher resolutions permit more refined stratigraphic analysis. The Zond III pictures of the far side of the Moon, with resolutions of 10 km allowed little more to be deduced than the location of mare areas and the largest craters. No stratigraphic work was possible because surface textures could not be seen. Stratigraphic work was possible from early telescopic photography of the near side, with resolutions of approximately 2 km, but only units, such as the Imbrian blanket (Fra Mauro Formation), that have very coarse surface textures, could be recognized. The big breakthrough in lunar stratigraphy came with the acquisition of the Herbig photography (taken with the Lick 120" reflector) with resolutions of approximately 200-400 m. This photography revealed the highly variegated nature

of the lunar uplands as well as differences in the mare. Lack of broad continuous coverage however prevented analysis of the whole front side at these resolutions. This was later rectified by Lunar Orbiter IV which provided coverage of nearly the whole Moon at even better resolutions. This latter mission was ideal from a stratigraphic point of view, since complete coverage at fairly constant resolution and illumination was provided. In the case of the Moon, improvement in resolution beyond 20 m does not significantly improve geologic interpretation because regolith variations rather than the underlying rock units control the fine-scale topography. The optimum resolution at which to systematically photograph each planet must be established from prior fly-bys but 0.5-1 km resolution appears to be a reasonable goal for early orbital imagery based on Moon and Mars experience.

Illumination.--The importance of illumination has long been understood from telescopic observations. The resolution limit of a telescope is essentially fixed by the optics yet in observing the Moon, the closer the area being observed is to the terminator, the smaller the topographic feature that can be identified. Keene (1965), in an empirical study prior to the Lunar Orbiter flights, was able to determine quantitatively the effect of variation in lighting angle on the resolution of a given system. Objects of varying size and shape with reflectance properties similar to those of the Moon were photographed at varying sun elevations. Observers' responses to the images were categorized into no detection, detection and identification, then plotted as a function of object size and illumination (fig. 1). The lowest curve shows the limiting size of objects that can be detected; the next curve shows the limiting size of objects which cannot only be detected but which can also be classified topographically, for example, a crater can be distinguished from a dome. The uppermost curve is based on U.S. Geological Survey experience in mapping from a wide variety of lunar photographs and shows the limiting size of objects that can be categorized geologically. In

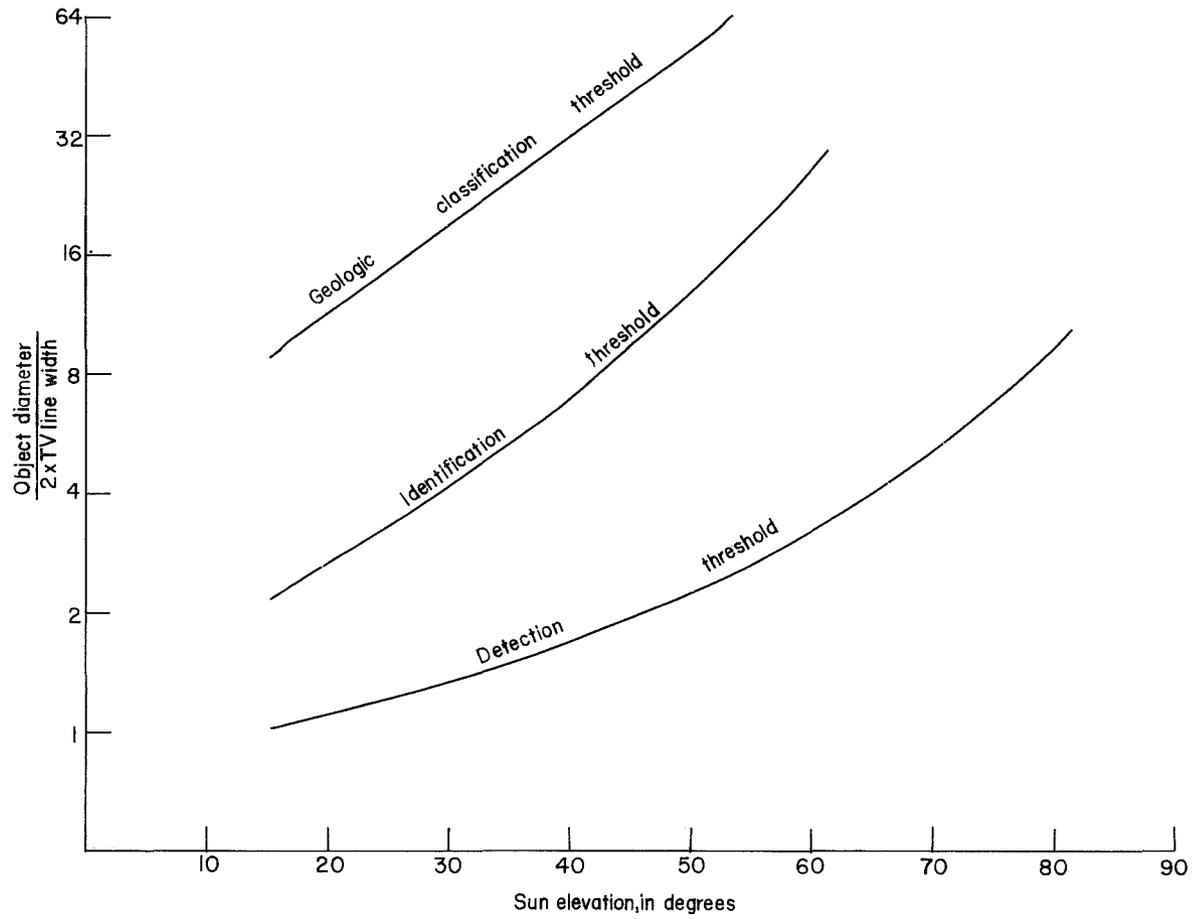


Figure 1. --Dependence of feature recognition on illumination angle (after Keene, 1965).

all cases recognition is best at the terminator and deteriorates with higher illumination because of diminished contrast. Near terminator photography is therefore necessary to take full advantages of available resolution.

Low illumination is desirable because shadows bring the surface topography into relief. At high angles of illumination, few shadows are cast and the nature of the relief is difficult to discern. Glancing illumination, on the other hand, is undesirable because too much of the area is in shadow. The optimum illumination angle depends on the roughness of the terrain and for lunar terrain illumination in the 5° - 15° range has proved best. In very smooth terrain, illumination at the low end of the range is desirable so that low relief elements can be discerned, whereas higher angles are necessary in rough terrain to prevent too much of the image being in shadow. The optimum angle must be determined from preliminary terrain analysis.

Photography at or near vertical illumination should be obtained in addition to that with oblique illumination. At high sun, no shadows are present so that variation in brightness of the image results from variation in albedo of the planet's surface. Albedo is a property intrinsic to the very near surface materials and is an additional criterion upon which mapping can be based. Also, many inferences can be made concerning the nature of the near surface materials from the albedo values. Albedo information is additionally necessary for photometric work and is essential for photoclinometric studies.

Areal coverage.--The study of stratigraphy and structure from aerial photography hinges on recognition of regional patterns. Broad regional coverage at resolutions such that surface patterns can be recognized is therefore essential. Photography of restricted areas, even if of excellent quality, has limited usefulness unless the general geologic context of the areas is known. The Mariner IV photography of Mars, for example, cannot be used for stratigraphic purposes because the individual frames cannot be

placed in regional context. The importance of areal coverage results from the importance of distributional patterns in the study of stratigraphy. The distribution of a rock and its relations with adjacent units often tells more about the origin and age of many rock units than does the surface morphology. The fact that the Fra Mauro Formation on the Moon occurs all the way around the Imbrium basin is far more indicative of its origin than is its surface texture. Similarly, very detailed photography of a particular fault scarp in the Southern Highlands might reveal very little concerning the origin of the scarp, whereas wide photographic coverage could show it to be part of a system of fractures radial to Mare Imbrium and therefore related in origin to the formation of the Imbrium basin. Distribution patterns are an essential geologic tool and to ignore them or to fail to acquire broad photographic coverage would be disastrous. Image analysis would be reduced to inefficient exercises in comparative geomorphology.

Wide areal coverage is also necessary to define the most important scientific problems and to permit judicious choice of landing sites. Telescopic photography of all the planets is so poor that no intelligent attempt can be made to assign scientific priorities to specific features. One purpose of early photographic missions should be to provide wide areal coverage at moderate resolution so that areas meriting further detailed inspection can be identified. Similarly, the success of a landing mission will depend in part on the scientific merit of the site and the suitability of the terrain; in order to make judgments on both these factors and to ensure that choice is made within the broadest range of possibilities, wide photographic coverage at moderate resolutions is required. Despite the importance of wide areal coverage, it is useful only if acquired at adequate resolution. Lunar experience suggests that increased coverage cannot justify degradation in resolution beyond 2 km and that the early photographic effort should be directed toward getting the broadest possible coverage at resolution of 0.5-2 km (6-8 TV line widths).

Color.--Despite the reservations stated above, information on color should be obtained on early orbital missions if coverage and resolution are not prejudiced. For example, in the Mariner Mars '71 fixed features mission, color photography can be obtained without loss of resolution and coverage, late in the mission after complete monochromatic coverage, by rephotographing with different filters. Color of this type is largely qualitative, but is nevertheless useful as a mapping aid. Spectral work that would provide information on mineralogical composition necessitates measurement of surface reflectance in a large number of wavelength ranges (McCord, 1969). This is better achieved photometrically than photographically and so cannot be considered as part of an imagery experiment. Multizonal photometry is discussed below in the geochemistry section.

Polarimetry.--The usefulness of photography through polarizing filters has yet to be demonstrated in the case of the Moon, in the case of the Earth, or in the case of experimental surfaces, and no polarimetry should be attempted at the expense of other potentially more useful aspects of a mission.

Advanced orbital missions.--A strategy for advanced orbital missions cannot effectively be formulated without prior knowledge of the results of the early reconnaissance program. Certain needs can, however, be anticipated. After photographic coverage of most of the planet at a resolution of approximately 1 km, detailed photography will be required of limited areas. Specific sites would be chosen because they include features typical of a given class, or because the area is critical for the solution of some specific geologic problem. The detailed photography would be required to bridge the gap in scale between observations on the ground and the reconnaissance orbital photography and to provide a basis for extrapolation of the reconnaissance photography to finer scales. The mission would resemble in part the Lunar Orbiter V mission, but should have additional capabilities. In particular, the capabilities of convergent stereo and multiband photography should be included.

Following a Lunar Orbiter V type of mission, emphasis should shift away from imagery toward other remote sensing techniques, with particular emphasis on techniques that provide information on the chemical and mineralogical properties of the surface rather than those more dependent on physical properties. Possible remote sensing techniques are discussed in the sections on geophysics and geochemistry.

Lander Photography

A landed photographic system has three main geologic purposes:

1. To examine in detail the lithology, texture, and attitude of the surface rocks in a local area.
2. To determine the topography in the vicinity of the spacecraft.
3. To provide supplementary information for other experiments on the spacecraft.

Lithology, attitude and texture of surface rocks.--Since Mars and Mercury are not protected from meteorite bombardment by thick atmospheres, their surfaces are probably covered at least partly, by a debris layer or regolith similar to that on the Moon. The Martian regolith is of particular interest because processes other than impact are likely to have played an important role in its formation. Aerolian erosion and deposition, permafrost, carbon-dioxide "glaciation" and atmospheric weathering may all have left their imprint on the regolith. Detailed examination of the lithology, texture and structure of the regolith to determine what processes have been most active in its formation, will therefore be one of the main tasks of the imaging system.

On Mars, in contrast to the Moon, coherent rocks may be more accessible in place, for analysis and observation. The yellow clouds, which are widely interpreted as dust storms, may remove the regolith in places and expose bedrock for inspection. A lander might therefore be able to examine rocks in place, provided the site is carefully chosen. Coherent rock material will almost certainly be available for inspection, if not in place,

then as blocks in the regolith. The fine-scale texture and lithology of rocks reflect their mode of origin. Layering suggests a sedimentary process, either in a magma chamber or on the surface. A texture of interlocking crystal forms indicates a crystallization stage during rock formation, either as a result of derivation from a melt or as a result of postdepositional recrystallization. Euhedral phenocrysts point to a magmatic origin and rounded grains to a sedimentary origin. Textures of this type are generally visible at 1 mm resolution and cameras can achieve this resolution without special optics. The ability to discern these fine-scale textures will depend on lighting and repeated photography of the spacecraft environment at different lighting conditions will be necessary to bring out all the observable features.

The gross features of rocks in place are also related to origin. Bedding, cross-cutting relations, faults and folds are all necessary for understanding sequential relations yet they cannot be examined adequately from a stationary vehicle nor from an orbiter. Some mobility is required because of the scale of the features involved and because a sufficiently large number of relations must be observed to confidently interpret them. Automated roving vehicles are also needed to test the heterogeneity inferred from the orbital imagery and to sample a variety of geologic units for chemical and physical characterization. They should therefore be considered for advanced missions.

A landed imaging system is an excellent means for assessing the value of detailed colorimetric work on the planet. The same area can be photographed repeatedly with a wide variety of filters and over a wide range of lighting conditions. This information will be important for detecting different rock units, for recognizing different types of blocks in a regolith, for preliminary identification of mineral constituents in the rocks, and for evaluating potential orbital multiband experiments. A multiband filter system should therefore be included in the landed photographic package.

Surface topography.--The conditions necessary for topographic reconstruction from landed imagery is given in the section on Geodesy and Cartography. The topography of any planet's surface is likely to be constantly changing as a result of contending destructive and constructional processes and evidence of the character of the processes is probably preserved in the landforms. On Mars permafrost structures, formed either by H_2O or CO_2 , may show the results of freeze-thaw conditions at the edge of the ice caps; in other areas sand dunes and yardangs may result from wind deposition and erosion, and linear scarps could indicate tectonic activity. All these features will be modified by impact and their state of preservation will indicate something about the rate of landform development. Detailed photography of the surface therefore provides basic information on surface modifying processes. The effect of these processes on data from other experiments such as any chemical or mineralogical determinations can then be effectively assessed.

Analytical support.--One of the prime functions of a landed imaging system is to provide support for other analytical instruments. The geological environment around the spacecraft will almost certainly be geologically diverse. Rocks of various types may be present both on the surface and in place. An imaging system provides an essential means of monitoring what is being analyzed and what else is available. When used in conjunction with a surface sampler, the imaging system will greatly improve the versatility of many analytical instruments on board inasmuch as it changes the sampling from a random process to one of intelligent control and selection. This reasoning applies both to the geological instruments and also to the biological and engineering instruments.

Rock Properties

Many of the bulk properties of rocks such as compressibility, bearing strength, density, porosity, stress-strain characteristics, and grain-size frequency distributions are important from an engineering standpoint, but are of secondary geologic importance

because they are difficult to relate to formative processes. Whilst recognizing the value of engineering information, its significance lies outside the scope of this report and it will be discussed only insofar as it relates to geologic problems. The most important geologic properties of a rock are its age, chemistry, mineralogy, and petrography. Only petrography is discussed here; chemistry and mineralogy are discussed in the section on geochemistry. Optical microscopy is the most widely used petrographic technique. By no other method can a rock to be so completely characterized and it is the only means of acquiring essential information on rock textures. Petrographic microscopes have been successfully combined with TV systems and compact lightweight microscopes have been designed specifically for spaceflight programs so that petrographic work can be done remotely. However the utility of remote petrographic microscopy is likely to depend more on the effectiveness of sample preparation than on the ability to design flight qualified instruments. Thin section work is the most informative type of microscopy; examination of crushed rock or fragmental debris from the regolith are far less important geologically and alone would not merit an elaborate microscope experiment. Development of remote techniques of making thin sections must therefore be considered an essential part of the design of a petrographic microscope and since information on rock textures is so fundamental to understanding the rock genesis, development of both microscope and thin section techniques should be actively supported.

A less desirable alternative to remote microscopy is visual examination of a sawed surface, perhaps coated with a wetting agent to improve contrast. A device to cut a very small flat surface and a spray coater should not present great technological difficulties. If the material is reasonably coarse grained then in addition to textural relations modal analyses may be made by point counts of pictures of the surface. Provision for sampling selected areas on the surface for chemical and mineralogical tests would greatly enhance the value of the device.

The capability of drilling a hole and making in-hole measurements is of prime importance for stratigraphic studies. Holes are also needed for heat flow measurements, for detection of subsurface water, and for penetrating the regolith as well as for strictly stratigraphic purposes. Vertical sections may be observable on crater walls, or fault scarps, and may be accessible to roving vehicles but a section is always available to a stationary vehicle with drilling capability. A large number of in-hole measurements are feasible once a hole is dug. Resistivity, conductivity, porosity, and natural and induced radioactivity can all be logged to reveal stratigraphic discontinuities and existing logging techniques require only the minimum of adaptation for planetary use. The principal technological difficulty lies not in logging but in drilling since no satisfactory technique of remote drilling is available. A hole is so important that every effort should be made to develop drilling techniques so that advance systems will have a drilling capability.

General Conclusions

1. Stratigraphic studies are essential for documenting the heterogeneity of a planet's surface, understanding the processes controlling a planet's evolution, determining the planet's history and interpreting geochemical and geophysical data from the surface.
2. On a remote surface stratigraphic analysis is based largely on imagery. The basic requirement is planet-wide coverage at 1 km resolution, or better, supplemented by imagery of restricted areas at 50 m resolution or better. If visual imagery is impractical, radar imagery with equivalent coverage and spatial resolution should be obtained.
3. Mapping variations in the chemical and physical properties of the surface should follow acquisition of the imagery or be done concurrently, provided the imagery is not jeopardized. Mapping chemical and mineralogical variations, by means of multiband photometry for example, should take precedence over mapping physical properties of the surface, (porosity and dielectric constant,

for example) because the former are more readily related to formative processes.

4. Landers will provide in situ information on the texture, attitude, chemistry and mineralogy at a very restricted set of sites. The utility of the information will depend on how effectively the sites are chosen and how well they can be stratigraphically characterized. Early landings should be on geologic units of wide areal extent and in places susceptible to the minimum of stratigraphic ambiguity. Later sites may be chosen on the basis of a need to solve specific scientific problems.

5. Advanced landers should have both mobility and a drilling capability.

GEODESY AND CARTOGRAPHY

Definition of Objectives

The literal meaning of geodesy is to "divide the Earth." In application it has come to mean the determination of the size and shape of the physical Earth, and the location of a network of control points on the Earth's surface in fixed coordinate systems. Because of the instrumental techniques employed for measurements on the Earth's surface, geodesists have had to concern themselves with the positions of celestial bodies, and with the gravity field. Their activities and interests overlap with those of astronomers and geophysicists; and as a consequence geodesy has been divided into three nearly distinct subjects: geometric geodesy, geodetic astronomy, and gravimetric (physical) geodesy.

Cartography is the representation of the Earth's characteristics on charts and maps. In connotation with geodesy, it usually implies topographic mapping by means of photogrammetry, but in actuality includes any kind of thematic mapping--geologic, vegetation, hydrologic, geographic, and others.

For most of its history, geodesy has had to depend on observations made from the surface of the Earth. Their necessarily restricted range made possible the preparation of highly detailed and precise maps of localized areas, but expansion of dimensions and reference systems to continental and global areas was accomplished only with great difficulty and some unresolved ambiguities still exist. The capability of observing from and to artificial satellites--available only in the last ten years--has completely revolutionized geodesy. When applied to the planets, the new techniques will make feasible the scientifically preferable approach of proceeding from the general to the specific in an orderly fashion, with the possibility of review at each level before proceeding to the next.

Geodesy and cartography are intensely practical subjects. They provide an indispensable reference system for recording and correlating the observations and deductions of all other planetary sciences. Because of this general utility they are often

looked upon as an exercise in technology and the inherent scientific content of the data obtained is neglected.

With specific reference to the solar system planets, the techniques of geodesy, photogrammetry, orbit analysis, and cartography can provide information on the following:

- a. The basic planetary dimensions.
- b. A mathematical figure of reference.
- c. The orientation of the body in the celestial coordinate system.
- d. The rotational constants.
- e. A defined system of coordinates.
- f. The location of any number of surface points in the defined coordinate system.
- g. The gravity potential expressed in spherical harmonics.
- h. Topographic and thematic maps
 - . at small scales for synoptic coverage
 - . at intermediate scales for regional coverage
 - . at large scales for landing areas and other sites of particular scientific value.
- i. Surface albedo in various wavelengths.

The size, shape, and rotational constants contain geophysical information about moments of inertia, internal composition, and rigidity. The harmonics of the gravity field contain information about anomalous mass distribution within the body. Regional and local topography imply internal and external mechanisms of formation. Albedo measurements give information on regional and local differentiation and composition of materials. Coordinate systems and point locations are necessary for correlation of all other data, for specification of site locations, for navigation and guidance of eventual landers and surface mobile vehicles.

Geodetic studies are therefore essential for the study of any planetary body with a solid surface. In addition, photogrammetric techniques are applicable to the study of atmosphere in that features at different levels can be determined so much of the subsequent discussion is relevant to all planets.

Data Acquisition System

It makes sense to consider the commonality of geodetic and cartographic sensors with those employed for other planetary sciences. The basic sensors--imaging systems, tracking systems, stabilization systems--are essential to all disciplines, and minor concessions in optimization for one application can immeasurably increase the utility for another. An excellent example is the Lunar Orbiter Program which was designed essentially to provide surface photographic coverage at medium and high resolution. That function is performed beautifully, but when landmark positions, elevations, terrain slopes, and control geometry were required, the system was grossly inadequate. With full surface coverage plus many detailed area photographs it should have been possible to determine a coordinate system and a reference figure to accuracies approaching the surface resolution of the pictures. This cannot be done because the geometry was simply not considered in the basic system design. Imaging systems on future planetary missions must be designed and used in such a manner that accurate reconstitution of surface geometry is possible.

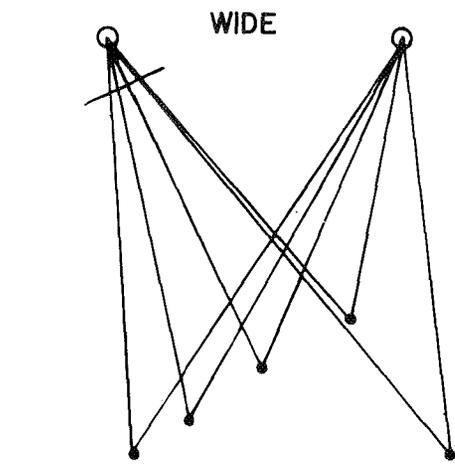
Cameras

Both geodesy and cartography depend in large part on scaled reconstruction of the surface by means of some form of imagery. It is appropriate therefore to review the conditions which are necessary for the photogrammetric reconstitution of models from photographs. In pure photogrammetry, only the photographs themselves are used, all external data are excluded. This is preferred since camera position and attitude errors may be encountered. A distinction must also be made between wide angle (usually 60° - 90°) and narrow angle photography; wide angle cameras are preferred for geodetic purposes because their greater geometric strength results in much less restrictive reconstitution conditions. For wide angle photography the necessary conditions for reconstitution are that five points must be identified on two photographs and no

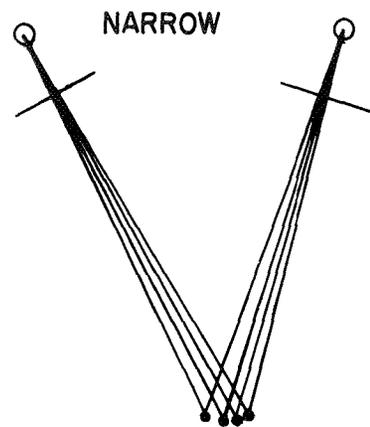
three of these should lie in one plane containing the two camera positions. This is the well known Fourcade correspondence theorem. Base height ratios of 0.2-1.5 are usable with 1.0 being about the optimum. The Fourcade correspondence theorem cannot be applied to narrow angle photography. Nevertheless, pure photogrammetric reconstitution is possible but a minimum of three pictures with considerable convergence ($>30^\circ$) is required, with the same four points measured and identified on all three pictures (fig. 2). Reconstitution is possible from two strongly convergent photographs provided accurate orientation and positional information on the camera is available so that the correspondence settings can be performed.

Despite their disadvantages for geodetic purposes, narrow angle cameras have been used on previous lunar and planetary missions and will be used on missions presently planned because only with these cameras can acceptable ground resolutions be achieved from normal orbital altitudes. Photogrammetrists can work with narrow angle systems but the pictures must be taken with adequate convergence ($>30^\circ$) and accurate orientation and positional data must be available. An additional factor of critical importance for any kind of photogrammetry is calibration of the camera system's internal geometry and this should be considered from the initiation of camera system design.

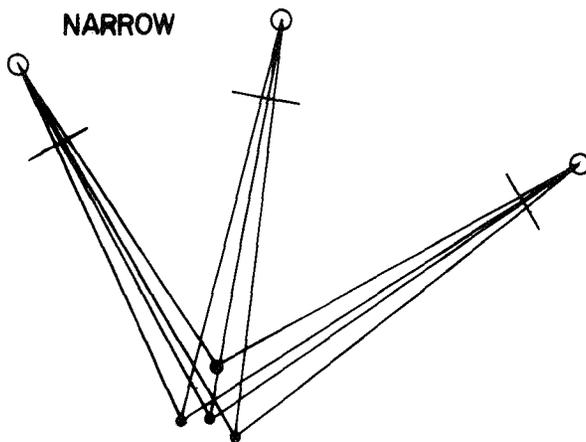
Given a choice, geodesists and cartographers will always opt for physical film return because of the inherently simpler and more accurate data reduction. However, physical film return, while not impossible, is unlikely for unmanned missions other than to the Moon. High resolution vidicon systems and combination film-scanning transmission systems such as on Lunar Orbiter can currently produce image plane resolutions approaching 300 lines per millimeter and development of such systems will certainly continue. The quality of the possible imagery is more likely to be restricted by transmission capabilities than camera design. A high quality terrestrial aerial photograph contains approximately



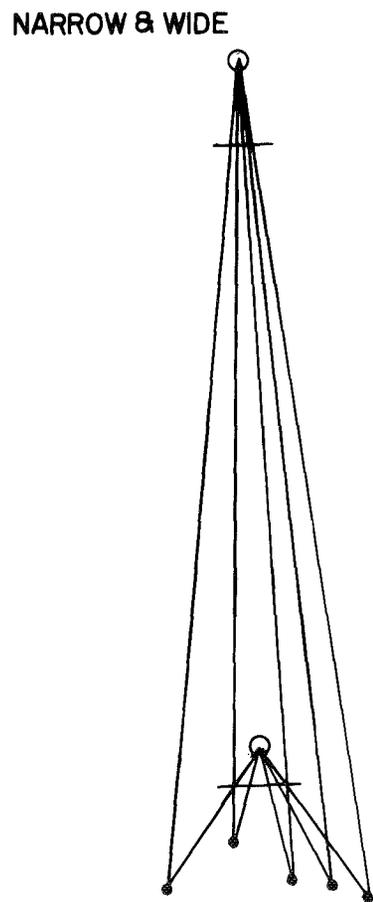
1. Reconstitution generally possible



2. Reconstitution not possible without external data



3. Reconstitution generally possible



4. Reconstitution generally possible

Figure 2.--Conditions for photogrammetric reconstitution.

10^7 to 10^8 bits so that to obtain wide coverage at comparable quality enormous amounts of data must be transmitted.

Other Imaging Systems

Infrared and microwave imaging systems may be useful for other planetary sciences but their inherent geometric problems and gross resolution make them undesirable for geodetic and cartographic applications. If, however, they are the only imaging sensors to be carried on a mission, their geometry should be analyzed and the system geometrically calibrated. Some useful geodetic information may be extracted under such circumstances.

Planets with a visually opaque atmosphere (Venus) may be amenable to radar imagery. Again geometric analysis and calibration beginning with sensor system design are required. Radar imagery is susceptible to the same kind of reduction as optical imagery but additional techniques are also available. In particular the ranging capability of radar may be utilized for reconstruction of surface topography.

Support Data

Timing.--Timing data is most useful to correlate image data with orbit data. As a general rule, the precision of time data should permit vehicle location with an accuracy comparable to the surface resolution of the image.

Attitude.--Usually sensor attitude can be determined to nearly an order of magnitude better than the sensor can be aimed. Such data provides a valuable constraint for subsequent computations. A particularly useful reference for attitude is the stellar field recorded either photographically or by star trackers. Properly time coupled and calibrated with surface photography this may permit measurement of the celestial orientation of the pole and the rotational constants of the body.

Orbit tracking.--Tracking transponders are required for spacecraft control. Orbit analysis based on tracking data is the fundamental source of gravity data about the planet. In addition, when coupled with time and attitude data, it makes

possible a much more rigid solution for surface point locations that can be obtained from photogrammetric conditions alone. Orbit position accuracy comparable to surface resolution is a desirable objective.

Altimetry.--Altimeter data (laser or radar, depending upon planetary conditions) provides a scale restraint for photogrammetric solutions, and in the absence of geometric imaging systems can, when coupled with orbit data, provide the size and shape of the planetary body.

Fly-by and Approach Photography

The most useful photography for geodetic purposes is that which encompasses all or most of the disk and is best achieved during approach photography are:

1. Measurement of the profile of the disk to determine ellipticity,
2. Determination of the relative three-dimensional positions of surface markings,
3. Fitting of the surface markings to an oblate spheroid and fixing the axis of rotation with respect to surface markings,
4. Determination of the position of the axis of rotation with respect to the celestial sphere.

The aims are pertinent to all sizeable bodies in the solar system except these that have no solid surface. Two situations are encountered. Mars yields an example of the first, in which the planet rotates relatively rapidly; Mercury is an example of the second, where the planet rotates relatively slowly. For rapid rotation it is possible to make good use of the long-focus characteristics likely to be enforced by the requirements of other fields of study and depend on the planets rotation to provide a baseline. The preferred geodetic photography for such a planet is whole-disk photography taken at such distances that the disk is somewhat less in diameter than the field of view of the camera. Note, however, that aiming problems may be appreciable since we are talking

here of disks of the order of one degree diameter. If at all possible the photographic period should be extended to obtain photographs intermediate in resolution between the geodetic and close-up photography. If this is neglected, there may be uncertainties in the correlations between the points identified on the two types of photographs.

The fly-by photography has peculiar importance for the planet Mars as the optical and dynamical figures are widely discordant. The discordancy may be real, with important implications for the internal structure of the planet, or the optical figure may be incorrect because of the limitations of Earth-based methods. A solution of this problem is important for the geophysics of the planet Mars.

The inclination of the vehicle trajectory to the plane of the planet's equator needs consideration; in geodetic photography that utilizes the planets rotation for establishing a baseline it is the mean latitude of the spacecraft during the photographic period which decides the nature of the triangulation. Clearly if the spacecraft is on the polar axis in this period then, as viewed from the surface of the planet it is not displaced by rotation. The spacecraft's position remains fixed and a three-dimensional triangulation is not possible. Thus, simple considerations favor a trajectory in the equatorial plane of the planet although this may be counter to the requirement of photographing areas adjacent to the polar cap.

To establish a baseline for triangulation on a slowly rotating planet, the planet's rotation is of no assistance and image displacement must be caused entirely by spacecraft motion. Since this is directed almost directly toward the planet, the position in the sky, as seen from the planet, will change only slowly so that poor geometry will result until near encounter. At encounter the direction of spacecraft motion is at a significant angle to the line joining the spacecraft and the planets center and so the spacecraft moves rapidly across the planet's sky and good geometry is possible.

A similar geometric problem is encountered in establishing the position of a rotation axis with respect to the celestial sphere from approach photography. The approach trajectory is almost a straight line and the position of the spacecraft on the line alone is insufficient to define the geometry since the planet and the cameras can be rotated as one around the trajectory without violating the tracking data or the photographic measures. To rigidly define the geometry, the orientation of the camera must be known. This can be determined from the spacecraft orientation provided the geometric relation between spacecraft and camera has been previously determined. The precision of the measurements will then depend on the precision that the spacecraft orientation can be determined. For successful geodesy the relation between camera orientation and spacecraft orientation must be precisely determined (in gravity-free environment to offset flexing of structural members) and the inflight orientation of the spacecraft to the stars must be accurately known.

Orbital Photography

Systematic mapping of fixed surface features is necessary for guidance and navigation, for location of landing sites or sites for more detailed orbital examination, and to provide a base for portraying and correlating other analytical data. In order to achieve the appropriate resolutions this systematic mapping must be done from orbital altitudes. In the case of the Moon, a map series was recommended by the Geology Panel at the 1967 Conference on Lunar Science and Exploration at Santa Cruz.

- a. Orthographic, Mercator, and Polar Stereographic projections of the whole Moon at scale 1:5,000,000.
- b. Complete topographic coverage of the Moon at scale 1:1,000,000.
- c. Coverage of approximately 20 areas of scientific interest for landing sites and traverses at scale 1:250,000.
- d. Coverage of central parts of 20 areas of special interest at scale 1:50,000.

- e. Coverage of landing locations in the central portion of science sites at scale 1:5,000.

This series may be considered representative of what might be desired for other planetary bodies although the requirements may vary in detail according to size and surface configuration.

Standards exist for the positional accuracy of maps at various scales, for the surface resolution required to produce the necessary content, and for the elevation accuracy required for various contour intervals.

Map Accuracy Requirements

| Map Scale | Horizontal Std. error (meters) | Optical Resolution (meters) | Contour Interval (meters) | Vertical Std. Error (meters) |
|-----------|--------------------------------|-----------------------------|---------------------------|------------------------------|
| 5,000,000 | 1520 | 250 | 1000 | 300 |
| 1,000,000 | 300 | 50 | 500 | 150 |
| 250,000 | 76 | 12.5 | 100 | 30 |
| 50,000 | 15 | 2.5 | 25 | 8 |
| 5,000 | 1.5 | 0.25 | 3 | 1 |

For camera systems with strong geometry, the accuracy of positions and elevations established photogrammetrically will be 1 to 3 times the surface resolution. This means that a planimetric map having compatible resolution and horizontal positional accuracy as listed in the above table can be produced from camera systems of relatively weak geometry.

Elevation Determinations

Although accurate planimetric maps are possible with weak geometries, the conditions for determination of elevations are more restrictive and should be considered in more detail. Photogrammetry is the only rigorous photographic method of determining elevations. With camera systems presently being flown, useful vertical resolutions can be achieved with convergent stereo but those achievable by vertical stereo are marginal. Because of the difficulty of systematic coverage by convergent stereo other methods of measuring elevations, such as photogrammetry or the

traditional shadow analysis technique, must be considered.

Vertical stereo.--In vertical stereo, the optical axis of the camera remains vertical and the base line is fixed by the viewing angle of the camera and the overlap. Typical camera systems used so far on lunar and planetary missions incorporate a vidicon tube with a 10 mm square format and optimally 35 optical resolution elements/mm (corrected from the number of TV line pairs according to Keene, 1965). The smallest elevation difference that can be measured is given by:

$$\Delta H = \frac{H\Delta\theta}{\sin \alpha} \quad (\text{Borgeson, 1966})$$

H = height of camera

$\Delta\theta$ = angle in radians subtended at the lens by the smallest resolution element in the image

α = intersection angle at ground point formed by two homologous rays from two cameras.

For a camera with a focal length of 50 mm

$$\Delta\theta = \frac{1}{35} \times \frac{1}{50} = \frac{1}{1750}$$

For vertical cameras with 50 percent overlap

$$\sin \alpha \approx 0.1$$

Therefore

$$\Delta H \approx \frac{H}{175} .$$

The smallest differences in elevation that can be measured are 5.7 km for an orbital altitude of 1000 km and 11.4 for a 2000 km orbit. These figures are independent of camera focal length if the overlap remains the same, since maintaining the overlap keeps the base/height ratio constant. The measurable differences are inadequate for most mapping purposes. Systems with wider angle lenses or higher resolutions than previously used, must be flown if useful vertical stereo is to be obtained.

Convergent stereo.--Photogrammetrically useful stereo pairs can be obtained by convergent stereo even if the camera system is

inadequate to provide useful vertical stereo. Instead of taking overlapping vertical photographs, the camera is tilted and multiple oblique photographs are taken of the region of interest. In the case of vertical photographs the base/height ratio is fixed by the viewing angle of the camera and the overlap. With convergent stereo, the base/height ratio depends on the tilt of the camera and some leeway is possible in choosing an appropriate ratio.

Consider the case of two photographs of the same area, one vertical and the other taken with a tilt angle, t :

As before
$$\Delta H = \frac{H \Delta \theta}{\sin \alpha}$$

$\Delta \theta$ remains the same being $\frac{1}{1750}$ for a 50 mm lens. α , the intersection angle at the ground formed by homologous rays from each camera position is now the tilt angle t ,

Therefore
$$\Delta H = \frac{H}{1750 \sin t}$$

For a 1000 km orbit $H = 2.2 \text{ km } 15^\circ \text{ tilt}$

$H = 1.1 \text{ km } 30^\circ \text{ tilt}$

The vertical resolution improves proportionately with the focal length of the camera since $\Delta \theta$ becomes smaller without a corresponding decrease in α as in the vertical case. The increased resolution is of course accompanied by a decrease in the area covered.

The disadvantages of convergent stereo with long focal length cameras are that a high pointing accuracy is needed and that systematic coverage requires a large number of frames to cover a relatively small area. The technique may be practical only for limited areas such as landing sites or sites of unusual scientific interest.

Photoclinometry. -- Photoclinometry is a method of extracting topography for nonstereoscopic photography obtained from orbiting vehicles (Watson, 1968). It is based upon the assumption that, if surface albedo is constant, variations in photographic density are functionally related to the surface slope. The relation is

expressed by the photometric function which is required before the technique can be applied. Slope data is acquired on profiles across the photograph and integrated to provide elevations from which contours can be interpolated. While theoretically attractive because it does not impose severe restraints on angular field or stereoscopic overlap, the method is not truly practical because the normal albedo is not constant, the photometric function is not adequately known (particularly in the case of planets) and the data reduction effort is enormous. Whilst photoclinometry has been successful in characterizing different types of lunar terrain by statistical slope analysis (Rowan, McCauley, and Holm, 1969), the technique has had only limited success in terrain reconstruction to form topographic maps. The technique should be regarded as a stop-gap measure to be used where other methods have failed. Since the data required for its implementation (zero phase and oblique illumination photography) coincide with requirements for other purposes, no specialized photography is required. The only special requirement is that of photometric fidelity and this also coincides with other scientific needs.

Radar altimetry.--One possible way of making elevation measurements over wide areas is by means of radar altimetry. Profiles of the surface can be determined to accuracies of 10-100 meters with existing systems which have only modest weight and telemetry requirements. A simple radar altimeter experiment would also provide valuable calibration data for photogrammetric purposes.

Soft Landing Missions

Imaging systems on soft landed planetary probes present a "man's eye" view of the landing site, and provide a frame of reference for the various measurements made by other instruments in the probe. A landing site can be reconstructed from pictures, provided that the imaging system is specifically designed for making photogrammetric measurements and that the optical geometry of the system has been precisely calibrated. However, the difference in ground resolution between pictures taken from orbit and

pictures taken from a planetary surface is so great that the meaning of much of the information in pictures taken by a landed system is lost, unless the location of the lander is precisely known and photographed from orbit. If an orbiter is present, a symbiotic relationship between orbiter and lander can be developed from which highly detailed interpretations of planetary surfaces can be made. Even without support from an orbiter considerable topographic information can be extracted from the lander imagery. Because the soft lander is stationary during data acquisition, the photographic problems are generally simpler than for orbiting spacecraft.

Photography

Imaging systems for planetary landers fall into two main categories:

- a. Slow-scan television.
- b. Optical-mechanical scanners.

Slow-scan television pictures are geometrically similar to pictures taken by conventional film cameras. Panoramas can be taken with a slow-scan camera by rotating it about its perspective center some angle less than the field of view between each picture until the entire panorama has been covered. The resulting pictures can be pieced together as a mosaic.

Optical-mechanical scanners are similar to the facsimile systems used by news services to transmit photographs from one facility to another. A camera of this kind suitable for surface planetary exploration incorporates a small mirror which rotates about vertical and horizontal axes, and which reflects images into the lens of the system. A tiny hole in the image plane, on the axis of the lens, admits light to a photosensitive device which converts luminous flux to an electrical signal for processing and transmission to receiving stations. As the mirror rotates about one of its axes, the focused image of the landing site moves across the pinhole above the photosensor. The luminance along a narrow band of the scene is thus transmitted. A picture is taken by

making adjacent sweeps with the mirror until the complete panorama has been transmitted. Entire panoramas or segments of panoramas are recorded as single pictures, without making mosaics.

There are several advantages in using facsimile cameras on planetary landers. Their design is so much simpler, mechanically and electronically, than slow-scan television cameras that they are inherently more reliable. Optical design is simplified because the pinhole is on the lens axis and optical aberrations outside the paraxial region need not be considered. They are capable of producing very high resolution from relatively small systems.

Stereoscopic coverage, permitting topographic mapping of the area photographed, requires photographs from two different points of perspective. This can be achieved:

- a. By moving the imaging system physically from one station to the other.
- b. By photographing the object space directly and then photographing its reflection in a mirror appropriately located.
- c. By providing two imaging systems separated by an appropriate baseline.

Stereoscopic baselines may be either vertical or horizontal. Horizontal baselines present the most natural view of the scene, but vertical baselines are equally useable from a geometric point of view.

In all cases the accuracy and extent of mapping depend on the length of the baseline and the height of the perspective centers above the planetary surface. If the baseline is calibrated in advance, it will permit the establishment of a local coordinate system and map scale without reference to external control provided by orbiter photography. Under certain circumstances the lander imaging system can photograph identifiable stars from which azimuth and perhaps position can be established.

Spacecraft shadows provide data from which topographic measurements can be made. The location with respect to the imaging

system of a shadow on a planetary surface can be computed as a function of the known size and orientation of the part casting the shadow and the angle the shadow subtends from the imaging system. A second method of spacecraft shadow measurement is the computation of shadow location as a function of the illumination angle, the angle subtended at the imaging system between the shadow point and the spacecraft part casting the shadow, and the distance between the imaging system and the spacecraft part.

Statistical slope information can be gathered by measuring shadows of natural features, and theoretically, systematic slope measurements could be connected to provide map data. The geometric conditions for mapping by this method are so varied and complicated, and the number of observations required are so great that this approach should be considered as an emergency solution rather than a primary procedure.

A mapping method called "Phototrig" may be used when the same surface features can be identified in pictures taken by both lander and orbiter. Feature heights relative to the imaging system are computed as a function of distance from the lander (measured on orbiter pictures) and vertical angle (measured on lander pictures). Contour lines are then interpolated between the spot elevations thus computed.

As with all imaging systems from which map data are to be produced, geometric analysis and system calibration are indispensable.

Data Reduction

The camera focal lengths and picture formats useful for planetary exploration from spacecraft--whether fly-by, orbiter, hard or soft lander--will generally be different from those employed in conventional aerial or terrestrial mapping. They may therefore be expected to be more or less incompatible with the photogrammetric procedures and equipment generally available. In addition, information about camera position and attitude--available through orbital tracking and attitude sensors--provides

geometric constraints on triangulation not available to usual aircraft situations. This means that computer programs designed for conventional aerial control extension will be inadequate for planetary missions.

It is therefore necessary that consideration be given from the very initiation of a planetary exploration program to the complete system design which includes not only the spacecraft, the sensors, and the mission, but also the hardware and software for extracting the maximum geodetic and cartographic information from the records obtained. Unfortunately this has not been the case through the lunar program and the pending planetary flights.

Conclusions

Geodesy and cartography, in addition to providing indispensable support for other planetary sciences, can contribute essential scientific information relating to the origin, history, and present status of bodies in the solar system. Fly-by, orbital, and landing missions can each make contributions to the basic problems.

Among the data obtainable from an integrated program of geodetic and cartographic exploration are:

- a. Basic planetary dimensions.
- b. Mathematical reference figure.
- c. Celestial orientation of the body.
- d. Rotational constants.
- e. Defined surface coordinate system.
- f. Location of surface features in the defined coordinate system.
- g. Gravity potential.
- h. Topographic and thematic maps.

Attainment of these objectives requires consultation of geodesists and photogrammetrists at the initiation of planetary exploration programs, careful analysis of the system geometry, precise calibration of the sensor systems, and adequate consideration of the data reduction problems.

Geodetic and cartographic objectives are not incompatible with those of other planetary sciences, and good planning and coordination will result in superior systems for all concerned.

GEOPHYSICS

Geophysics is concerned with the study of the planets by the methods of physics and includes consideration of the structure, dynamics and physical conditions of planetary interiors. Detection of radial sub-divisions such as core, crust and mantle, characterization of seismic activity, measurement of heat flow, and mapping the gravity and magnetic fields are of fundamental importance because they can be related very directly to processes involved in the history and evolution of the planet. Of lesser importance, but still of geologic significance, are measurements of the physical properties of near surface materials. Abundant ground based data cannot be expected from any planet since relatively few ground stations will be established. However, even very few surface geophysical measurements will enormously improve our knowledge of the planet because so little is known of the interiors of any planet other than the Earth. Many geophysical parameters such as size, shape, dynamical figure, surface reflectivity and emissivity at various wave lengths can be determined remotely, either from spacecraft or from the Earth and these are the measurements on which most data will be obtained early in the exploration program.

Size, Shape, Mass and Rotational Constants

Size, shape, mass, and rotational constants are of interest because they place constraints on two important properties of a planet, the internal mass distribution and internal viscosities. The internal distribution of mass may reveal compositional differences implying that differentiation has taken place and internal viscosities are important in that they place limits on the temperature and pressure conditions in the interior. Information on these parameters is derived largely from deviations from radial symmetry and the rotational response of the planet to these deviations.

The radius and geometrical figure can be determined from radar measurements, approach photography and occultation experiments (Ash and others, 1967). Radius is important as a constraint on the internal mass distribution and from deviations of the geometrical figure from hydrostatic equilibrium viscosity estimates are made.

The dynamical figure of a planet is the shape of its gravitational field as determined from the orbital parameters of satellites. If the rate of rotation of a planet is large enough to cause significant polar flattening then the moments of inertia can be determined from the dynamical figure, assuming hydrostatic equilibrium. Since the moment of inertia severely constrains values of internal densities, precise determination of the dynamical figure is of fundamental importance. Very accurate determination of the dynamical figure requires tracking of several satellites, preferably in tight orbits with different inclination, but determination of the lower order harmonics results from normal tracking of an orbiter around a planet and will follow from any orbiter program.

Higher order harmonics of the dynamical figure, similar to those encountered on the Moon (Müller and Sjogren, 1968), can result from near surface anomalous mass distributions and may have important implications concerning the structure of the crust. These anomalies can be determined only by precise tracking of satellites unaffected by drag. For this purpose, a tracking transponder, preferably incorporating a nul-type accelerometer, should be placed in orbit around the planet.

Moments of inertia can be derived from the dynamical figure only if the rate of rotation is large enough to cause significant polar flattening. If the rotation rate is too slow then the moment of inertia must be determined from the response of the planet's motion to torques. The principal response is a librational or precessional motion and precise determination of these motions is needed for moments of inertia calculations. Location

of axes of rotation by approach photography and extended terrestrial radar observations will aid in defining the planet's motion.

Anomalous internal mass distributions may occur especially in the case of Venus and Mercury which exhibit spin-orbit coupling. Non-radial symmetry would be revealed by non-coincidence of the centers of the geometrical and dynamical figures and by comparing their deviations from sphericity. This can be achieved by radar altimetry from an orbiting vehicle. Since radar altimetry is also needed for accurate topographic analysis, inclusion of a radar altimeter should be considered in advanced missions.

Although of great interest from a dynamical point of view because of its spin-orbit coupling (Goldreich and Peale, 1967), the moments of inertia of Mercury are difficult to determine because of the slow rotation. However, refinement of figures for the mass and radius will result from a fly-by and extended observation of an orbiter will give precise information on the geometrical and dynamical figures. Full disk photography should be undertaken from all spacecraft so that the axis of rotation can be accurately located and any librational motion defined.

The slow rotation of Venus also prevents direct determination of the moment of inertia from the flattening. However, determination of the dynamical figure is still extremely useful for analyzing gravity anomalies and other indications of dynamic imbalance. Because the atmosphere of Venus will cause significant drag on a satellite, consideration should be given to using a tracking transponder which incorporates a nul-type accelerometer for precise determination of the dynamic figure. Determination of the libration of Venus is necessary for determination of the axial moment of inertia and this appears possible from extended radar observations of the planet from Earth. The moment of inertia of Venus is of particular importance because of the similarity in mass and size of the planet with the Earth. Analysis of the internal mass distribution will reveal how different the evolution of their interiors has been.

Mars rotates fast enough to cause significant polar flattening. At present the geometrical flattening is not well known and the best figure conflicts with the dynamical flattening which has been determined from the orbits of Deimos and Phobos. Precise values of the optical flattening and radius will be obtained from the far encounter photography and occultations of the '71 orbiters. Tracking of these orbiters will lead to more precise determinations of the dynamical figure and, as a result, of the moment of inertia and the internal mass distribution. Later orbiters containing a nul-type accelerometer and tracking transponder should be flown to analyze local gravity anomalies and the general structure of the Martian crust.

Seismology

The seismicity of a planet provides indirect evidence concerning the thermal and dynamical state of its interior. Seismology provides the most effective way of measuring the dimensions of a core, crust or any other subunit of the interior and is the most simple and direct way of locating internal discontinuities and internal movement. This information is of such fundamental importance in determining the origin and evolution of a planet that a seismic experiment should be given a very high priority and included early in any exploration program.

The ideal seismic experiment requires a global network of seismic stations each with a wide variety of seismic detectors and the necessary power and data handling facilities. The possibility of establishing such a network on any planet other than the Earth is exceedingly remote, but this does not rule out a meaningful scientific experiment. Much can be learned from a relatively simple seismic experiment. The simple experiment not only provides basic scientific data but enables subsequent more complex and comprehensive systems to be better designed.

The simplest experiment involves placing a single seismic detector on the surface of the planet. This detector should be a

short period (1 second) single axis seismometer, or if telemetry and weight restraints permit, a short period 3-axis type. From such a detector the seismicity or aseismicity of the planet could be established and estimates could be made of the magnitude and frequency of seismic events. The general level of seismic noise could be measured and from the separation of the S and P waves approximate distances of events from the station could be inferred. Apart from its intrinsic scientific worth the data would permit an accurate assessment of the advisability of future more complex seismic stations and provide design constraints on such systems. The experiment is of such fundamental importance that it should be carried on either the first or second lander to any planet.

A second-generation seismic station should include both long and short period three-component seismometers. From such a station a far more complete picture of the seismic properties of the planet can be obtained than from records of a single short period instrument. Comparison of the amplitude and separation of surface and body waves enables distances and focal depths to be estimated. Distances and directions can be established with far greater accuracy than with a single short period instrument and better determinations of attenuation rates are possible. In addition, the seismic properties of the "crustal" materials can be deduced from the dispersion of surface waves that results from the wave guide effect (Press and others, 1960).

The effectiveness of a seismic station is vastly enhanced by the simultaneous operation of a duplicate station. Many of the ambiguities of interpretation are removed by having duplicate records and seismic events can be more accurately located by using widely spaced stations. Far better estimates can be made of the variation of seismic velocity with depth than from a single station and under certain conditions shadow zones can be detected and the presence of a core determined. Consideration, therefore, should be given to the simultaneous operation of two distantly spaced stations early in the exploration program. Gravity, tilt

and strain variometer experiments to examine free oscillations, tidal effects and secular deformation should be deferred until at least two six-component stations have been established on the planet.

The internal constitution of Mercury is of special interest because of the planet's high density. Although no landers are presently planned, a lander is feasible and a simple seismic experiment should have high priority on the first lander.

The interest in Venus stems from its similarity in size to the Earth, and a thorough evaluation of the similarities and differences between the two planets is essential to understanding what controls the evolutionary path of a planet. It is of prime importance to determine if Venus is divided into core mantle and crust as is the Earth. This is a problem readily soluble by seismic experiments and the feasibility of designing a seismic experiment to survive in the 700° C temperature and 100 atm pressure that prevail on Venus should be explored.

A successful Mars seismic experiment appears particularly promising. Mars landers are planned for '73 and '75. A simple seismic experiment should be carried on the '73 lander, preferably a 3-axis short period seismometer capable of operating for six months. This should be followed by a 6-component seismometer on two separate landers in '75. The two landers should be placed at a substantial distance from one another for accurate epicenter location.

Development of lightweight, compact, low-noise seismometers is well advanced. Instruments have been designed that weigh less than 5 lbs. and which can withstand loadings of up to 25 g. Such instruments developed for operation on the Moon can be adapted for planetary purposes with little modification. The principal problem in establishing a seismic station is not in detecting and recording the signal but in transmitting the information. Most of the presently planned seismic experiments for the Moon are based

on technology of data analysis which is derived from our earth-based experience. To obtain relatively few numbers we analyze thousands of data bits from a seismogram. There are many possible ways to reduce the quantity of information required for transmission and these ways should be explored. One possibility is an event triggered mode of operation. Initial operation could be continuous to determine the general seismic noise and appropriate trigger level; long term operation would be event triggered.

A seismic station must of necessity operate for a considerable length of time before a statistically significant number of events are recorded. No estimate can be made of this time until the level of seismicity of each individual planet is obtained. A minimum 6-month operation time should be aimed for and the appropriate power sources for such lengthy operation should be developed.

Active seismic experiments are normally used to study near surface discontinuities and near surface seismic velocities. These are of considerably less importance than analysis of natural seismic events and this type of active seismic experiment is given only low priority on a seismically active planet. However, active seismic experiments can be used to study the interiors of planets that do not have an adequate number of natural seismic events. Very little effort has been expended in attempting to define realistic active experiments for the Moon and other planetary bodies and it may be possible to carry out these experiments perhaps by using abandoned delivery vehicles. In anticipation of some planets being aseismic, study of possible active experiments should be undertaken.

Heat Flow

The most significant geothermal measurement is that of the internal heat flow. From its value much can be deduced concerning the thermal regime of the planet's interior and the thermal evolution of the planet (MacDonald, 1964; Lee, 1967). The measurement is, however, particularly difficult on a remote surface because the measuring devices must be placed in a hole drilled in

the surface. Temperatures and thermal conductivities must be measured in the natural state at depths sufficiently far below the surface to avoid appreciable diurnal and seasonal temperature variations. The required depth depends on the surface temperature variations, the length of days and seasons and on the local drilling of a hole at least 5 to 10 meters deep is required. Because of the likelihood of strong lateral gradients in temperature and near-surface properties, measurements in such holes may be contaminated by strong lateral flux components, therefore, several heat-flow measurements may be needed to evaluate the significance of these shallow observations. Drilling of the hole provides the greatest technical difficulty in making the heat-flow measurements since the actual measuring devices are already developed and are lightweight, compact, draw very little power, and have very modest telemetry requirements. Such a hole would be useful for a wide variety of experiments other than heat flow, and the feasibility of drilling on different planetary surfaces should be vigorously explored. Until drilling is a practical possibility, attempts to make in situ heat-flow measurements should be deferred.

Monitoring of the near-surface temperature regime by emplacement of temperature sensing devices at shallow depths can give information on diurnal and seasonal temperature variations. From the damping of these variations as a function of depth, and from the phase lag, local values of thermal diffusivity can be estimated. Although these shallow thermal measurements do not have the same fundamental importance as the internal heat flow, they can yield very useful data on the thermal environment for other experiments and on the heat-exchange process at the planetary surface.

Determination of near-surface thermal properties at a landing site can be used to calibrate IR radiometric measurements from an orbiting spacecraft. However, because of the likelihood of lateral inhomogeneity, a number of measurements should be made, and they must be used with caution in the interpretation of radiometric data.

Magnetics

Detection of a planetary magnetic field significantly larger than that of the interplanetary medium indicates the presence of an electrically conducting and convective core within the planet. The existence of such a core would show that the planet has undergone some differentiation in the past and that the present conditions of the core are such that mobility of the core materials is possible. If the presence of a core is demonstrated by seismic methods yet no magnetic field is detected then we can infer that either the core is non-conducting or that conditions in the core are such that motion of the materials is not possible or that the forces necessary to cause motion within the core are absent. Should remanent magnetism be detected in surface rocks in spite of the present lack of a field then the conditions within the core must have been different in the past. Magnetic measurements therefore have important implications concerning both the past history of the planet and the present conditions deep in the interior.

Magnetic field measurements are relatively simple and can be made remotely from fly-bys or orbiters with sensitivities limited only by the magnetic properties of the supporting vehicle. The simplest magnetic experiment is measurement of total field strength with a three-axis magnetometer from a fly-by. The experiment has very modest weight, power and telemetry requirements and should be included on all first-looks at a planet. Subsequent strategy will depend on the results of the first look. If a field is detected then follow up experiments will be concerned with mapping the structure of the field since this will reflect the flow pattern within the core. If no field is detected then consideration should be given to methods of improving the sensitivity of the measurements.

Jupiter is the only planet on which a magnetic field has been detected. An early spin stabilized fly-by or preferably a "tight" orbiter should carry a 3-axis magnetometer to map the

magnetic field. This would provide sufficient information for harmonic type analysis which would reveal details of the core magnetohydrodynamics and the possibility of other magnetic sources. The appropriate instruments are available so no new developments are needed. Should strong fields be detected on other planets then a similar program of magnetic mapping should follow.

Magnetic fields have not been detected on Mars and Venus from fly-bys (Fawcett and others, 1965; Brandt and Hodge, 1964), and if fields are present on either planet then more sophisticated magnetic experiments are required than have been tried in the past. The possibility of using de-magnetized spacecraft to make more sensitive magnetic measurements and place more stringent limits on the magnetic fields should be explored. In the case of Mars, where a series of landers is planned, the feasibility of making magnetic field measurements at some distance from a landing vehicle by projecting the magnetic experiment away from the spacecraft, should be studied. However, detection of magnetic fields of very low intensity is of secondary importance and should not pre-empt more fundamental and less risky experiments such as seismic and chemical measurements.

The absence of a magnetic field at present does not preclude the existence of a field in the past. Evidence of the past field will be preserved in the surface rocks and a simple experiment to determine to what extent surface rocks are magnetized should be carried on an early lander to all planets. The simplest experiment would require a single axis magnetometer and a sampler similar to the one carried on Surveyor. Magnetometer readings are taken as samples are moved toward it. Since the experiment is being conducted in the absence of a field, changes in magnetometer readings would indicate some rock magnetism and hence that a magnetic field existed in the past. Success of the experiment would imply the existence of a core and would further imply that present conditions within the core are static.

Physical Properties of Near Surface Materials

Several remote sensing techniques are available for measuring the properties of near surface materials. These techniques have had only limited applicability to terrestrial geologic problems largely because the appropriate measurements can commonly be made more accurately on the ground. However, because of the limited availability of ground based information on planets, the importance of remote sensing techniques as geologic tools is greatly enhanced. Some of the parameters susceptible to remote measurement, e.g., porosity, density, and thermal conductivity are difficult to relate to mineralogy and petrology of the underlying rocks so that the absolute values of these properties have limited geologic significance. Nevertheless, the measurements are geologically useful since their variation across the planet's surface can be used for mapping and for interpolation between ground measurements. Placing undue reliance on the optical response of the surface is thus avoided. Furthermore, although remote sensing measurements rarely offer unique solutions, they do add to the bank of data with which any interpretation of the surface must be consistent.

Infrared Radiometry

Infrared radiometer measurements on the Moon (Shorthill and Saari, 1966) have proven extremely useful in interpreting the nature of the lunar surface and the relative age of craters. Systematic radiometric mapping will be similarly useful on Mars and Mercury. Of particular interest is the detection of thermal anomalies and correlation of these anomalies with optical features. Anomalies detectable on the nightside result principally from differences in the rates of decay of surface temperatures because of local differences in thermal inertia. Since thermal inertia is dependent on lithology, variation in nighttime temperatures are related to variations in the rocks. Although unlikely, thermal anomalies could result from internal heat sources and

anomalies of this type would be most readily observed just to the darkside of the morning terminator where surface temperatures are lowest. Systematic radiometric mapping of nighttime surface temperatures, including the temperatures immediately before dawn, from an orbiter is therefore recommended for Mars and Mercury, and should follow acquisition of broad photographic coverage at useful resolutions (≈ 500 m) in the visible. Mapping should be from a vehicle in polar orbit with a lifetime sufficient to cover the whole planet and with a detector capable of measuring temperatures as low as 30° K. Measurements should ideally be made concurrently with passive microwave measurements preferably at more than one wavelength.

Microwave Emission

A planet experiences both diurnal and seasonal variations in surface temperature. A thermal wave communicates these temperature fluctuations to subsurface layers, but with depth the wave becomes progressively damped in amplitude and retarded in phase. Because the overall microwave opacity of solids generally decreases toward longer wavelengths, microwave radiometers tuned to lower frequencies can observe at progressively greater depth (Pollack and Sagan, 1965). With increasing wavelength we should therefore expect a decrease in the amplitude of the diurnal temperature oscillations and an increase in the phase lag. Furthermore, if the sole source of heat is the sun and if the albedo is constant then the mean surface temperature should be the same for all wavelengths. If the mean surface temperature is not the same then discontinuities in thermal properties with depth or an internal source of heat can be inferred.

The geologic interest of passive microwave measurements results from the possibility of determining internal heat flow and from determination of near surface properties. Theoretically the internal heat flow can be measured from the variation in mean surface temperature as measured at different wave lengths, provided the thermal conductivities of the near surface materials are

known. Preliminary measurements on the Moon are consistent with a near surface temperature gradient since the mean surface temperature appears to increase with increasing wavelength. However, the variability of apparent mean surface temperature more likely results from calibration errors (Kaula, 1968, p. 283). Clearly more definitive work is necessary but in view of the importance of internal heat flow, development of microwave measuring techniques and possible applications to planetary problems should be supported. Measurement of microwave emission at several wavelengths and comparison with the infrared measurements will remove some of the ambiguities in interpreting emission measurements and allow changes in thermal properties with depth to be determined. These depth effects will be especially important if the planet's surface is covered with a debris layer. The preliminary results from the Moon (Drake, 1966; Kaula, 1968) have resulted in placing constraints in the porosity, thermal inertia and dielectric constants of near surface materials, but no systematic mapping of microwave emission similar to the radiometric measurements of Shorthill and Saari (1966) has been attempted. The practicality of systematic orbital mapping of apparent nighttime surface temperatures of Mars and Mercury at several wavelengths in conjunction with infrared measurements should be explored. The systematic mapping will allow thermal anomalies to be located and measurements at several wavelengths will permit the variability of thermal properties with depth to be mapped.

Pollack and Sagan (1965) have discussed in detail microwave effects on Venus. By combining Earth-based emission measurements at different wavelengths with radar reflectivity measurements, they have determined limits for the chemical composition and several physical properties of the Venus near surface materials. The measurements permit a wide range of interpretation, however in view of the difficulties of obtaining any useful information on Venus surface materials the terrestrial microwave measurements should continue both to obtain as much information as is possible

from Earth-based observations and to evaluate the feasibility of orbital measurements. Systematic orbital mapping of the surface temperatures of Venus appears, at this time, to have little geologic application. Atmospheric effects probably prevent wide variations of surface temperatures at any particular point on the surface and so anomalies analogous to those detected on the Moon are unlikely.

Bistatic Radar

Study of planetary surfaces by means of bistatic radar methods has been suggested by Fjelbo (1964) and Tyler (1966), and were applied to the Moon in a preliminary manner during the Lunar Orbiter I and Explorer 35 missions (Tyler, 1968). In the bistatic mode, radar signals transmitted from the Earth are received by an orbiting spacecraft after the signals are reflected from the planet's surface. The nature and intensity of the signal depend on the configuration and properties of the near surface materials. Surface roughness is particularly important in controlling the signal since it affects the proportions and intensities of the specularly and diffusely reflected components. Surface roughness in the radar sense could be mapped bistatically with resolutions of several hundred wavelengths (Tyler, 1966) which is considerably better than what is possible by totally Earth-based systems. An early vehicle to Venus should test the feasibility of mapping in the bistatic mode by using the S-band radio system. If mapping appears feasible in this mode then a spacecraft of the Pioneer/Imp class should be devoted exclusively to bistatic mapping of the Venusian surface.

Radar measurements of the surface roughness of Mars and Mercury are of less importance than for Venus because their topography can be better described from visual observation. Radar reflectivity measurements are, however, of interest on Mars and Mercury because of the possibility of mapping dielectric constants and because of the possibility of detecting subsurface discontinuities. Furthermore radar measurements, combined with microwave

emissivity measurements, place constraints on several other properties of the surface. The dielectric constant is of particular importance as a means of detecting water. Dry materials rarely have dielectric constants in excess of 10, yet values can be much greater than 10 if moisture is present. A radar receiver could therefore detect and map near surface water and, if the vehicle had an extended lifetime, the changes in the distribution of near-surface water with the seasons could be followed. The wavelength should be as long as is compatible with instrument design (10^5 to 10^7 Hz) since penetration is a function of wavelength and surface roughness is of lesser interest.

Detection of subsurface discontinuities is also of geologic interest especially if the surface is covered with a debris layer. The surface configuration of the debris layer on Mars, for example, may be in part controlled by atmospheric effects so that geologic mapping from the visible alone may be difficult. Since radar signals penetrate to much greater depths than optical signals, radar measurements will be useful for detecting variations in the properties of rocks below the debris layer and variations in the thickness of the layer. The feasibility of bistatic mapping of Mars and Mercury at various wavelengths should therefore be examined.

Radar Topographic Mapping

From a geological viewpoint, the most important aspect of radar is that it provides a means of mapping the topography of a planet whose surface is obscured by the atmosphere. This is particularly important in the case of Venus which is very similar in radius to the Earth and so might reasonably be expected to have followed a similar evolutionary path. We know, however, that the atmosphere of Venus is drastically different from the Earth's and it is essential to know whether the solid portions of the planets exhibit comparable contrasts. Comparison of the topography of Venus with that of the Earth is an essential first step in evaluating the nature and causes of difference between

the two planets. Presence of orogenic belts, rift zones and sedimentary basins on Venus similar to those on Earth will have particular geologic significance. The necessary imagery could be obtained either from terrestrial measurements or from orbital measurements.

Terrestrial observations

Radar imagery, with spatial resolution comparable to telescopic optical photography (≈ 2 km), has already been obtained of the Moon. There is no theoretical reason why radar imagery of comparable quality should not be obtained of Venus from terrestrial observations. The hemisphere ambiguities problem has already been solved and rudimentary imagery has been obtained with existing techniques. Resolution is presently limited only by the ratio of signal to noise and there is every expectation that this ratio can be significantly improved in the near future. Every support should be given to terrestrial radar observation of Venus with particular emphasis on improving spatial resolution. This has higher priority than any other measurement of Venus and is comparable in priority to obtaining orbital photography of Mars. As support to this work every effort should also be made to improve knowledge of the rotation and orbital constants of the planets and particularly of Venus.

Coherent side-looking radar

Side looking radar is the only means of obtaining high resolution (100 m) imagery of the surface of Venus, or any other planetary body obscured by clouds. A side-looking radar system measures the reflectivity of the scattering medium as a function of position and uses the information to construct an image of the surface. The transmitter and receiver are both within the spacecraft and a signal is transmitted to the target surface at a fixed angle (generally $45-60^\circ$). The reflected signal varies in intensity largely according to the relationship between surface slopes and the spacecraft and the signal is measured as a function of track position, azimuth and range. The positional and intensity information are combined to construct a radar image, which

strongly resembles an optical image of the surface under oblique illumination. Use of synthetic aperture techniques permits high resolution images to be formed from orbital altitudes without need of physically impossible antennas (Brown, 1969). The imagery can be interpreted by standard optical techniques, including stereo, provided the appropriate imagery is obtained, but several additional techniques unique to radar can also be applied. Since the side-looking radar is a ranging device as opposed to the angle measuring device, as is a standard camera, topographic information can be extracted from the range data. It is not yet possible to determine elevations exclusively from range data on a single radar image, however ranging techniques are being developed for construction of topographic maps (LaPrade and Leonardo, 1969). In addition, depth effects can be discerned with the use of multi-frequency systems and imaging at different radar wavelengths.

Utilization of side-looking radar will depend on rate of development of terrestrial radar techniques. Moderate resolution (≈ 2 km) radar imagery of Venus must be obtained during the next decade. If this appears not likely from terrestrial measurements then side-looking radar imagery must be obtained even if this requires all the payload of a Mariner class vehicle. Side-looking radar of Mars and Mercury is not recommended for the foreseeable future unless obscuration of surface features from atmospheric effects proves to be more of a problem than anticipated.

GEOCHEMISTRY

One important concern of geochemistry is the bulk composition of each of the planets. Since chemical differences between the planets may reveal the nature of chemical heterogeneities in the original solar nebula and the mechanism of planetary accretion, it is important to acquire the data necessary for evaluation of the bulk composition of the planets. Present evidence of chemical abundances in the solar system is derived from study of the Earth's crust, the photosphere of the Sun, and meteorites. Because of the similar relative abundance of non-volatile elements (except Fe) in the Sun and Type I carbonaceous chondrites, it has been widely assumed that chondritic material is the basic stuff of the solar system and that the planets are also chondritic in composition. The assumption of uniform chondritic composition is now being questioned; the terrestrial Rb/Si and Cs/Si ratios appear to be lower than the chondritic ratios and the Earth appears to be depleted in In, Hg, Cs, Cl, Tl, and Pb and enriched in U and Th relative to the chondrites (Gast, 1969). A chondritic composition for the Earth and, by extension, for the other planets is therefore in doubt. Differences in uncompressed densities of planetary bodies, particularly the Moon, Earth, and Mercury also rule out uniform composition. Determination of the nature and cause of the chemical differences between the planets must therefore be one of the basic aims of scientific exploration of the solar system and this chapter is concerned with how best to achieve this aim.

Obviously there is no way to chemically analyze a body as large and heterogeneous as a planet at a single gulp. Chemical homogeneity cannot be assumed. The earth is certainly not homogeneous and most evidence points to a heterogeneous Moon. By analogy therefore there is every reason to assume that other planetary bodies are also heterogeneous. If this is true the overall bulk composition can be determined only by devising a sampling and analytical program designed to evaluate and allow for compositional variability. To do this statistically on the

assumption of random variability is both inefficient and, because only the very near surface can be sampled, subject to great errors. A plan must be devised that is based on an understanding of the geochemical regularities and geologic relations among the various rock types of the body. We should begin by determining the mineralogic and petrologic relations so that the processes by which the major rock units have been formed can be inferred and so that relative proportions of different rock types can be deduced. Although the processes of formation of surface rocks may seem trivial and far removed from solar system evolution, if we are to arrive at any meaningful estimate of bulk composition we must be concerned with rock forming processes. Only when we have a fairly detailed understanding of the geochemical and petrogenetic processes that have operated on the planet and the history of their action, and a satisfactory model for the internal structure of the planet, probably derived largely from geophysical experiments, will we be in a position to arrive at a reasonable estimate of the bulk chemical composition of the planet.

The most effective strategy for the geochemical study of a planet is to proceed systematically with the mineralogical and chemical characterization of its materials in accordance with geologically determined priorities. It is insufficient merely to chemically analyze the surface rocks. Determination of mineralogy, texture, lithology and any other property of the rock that might be relevant to origin is also necessary. Mineralogic composition is particularly important. The mineral assemblage reflects both the chemical composition and conditions of formation and is far more diagnostic of rock type and formative processes than chemical composition alone. Mineralogy has been greatly neglected in the exploration of the Moon but it must be included as a major aspect of the exploration and scientific study of the planets. Indeed if a choice must be made between a mineralogic and a chemical analysis, the geologist will generally opt for the mineralogic analysis because the latter contains much of the

chemical information and a great deal more besides. Hopefully such a choice will not be necessary since mineralogical and chemical experiments can be readily integrated to provide a complete analysis.

The exploration strategy for the planets must be more comprehensive than that for the Moon. Exploration of the Moon has been conducted with the expectation of early return of lunar samples to the Earth. Difficult experiments could therefore be conveniently deferred until a sample was available on Earth. Return of samples from any of the planets presents far greater technological difficulties than from the Moon and we cannot anticipate having planetary samples on the Earth for complete analysis in the foreseeable future. The in situ measurements therefore must be far more complete than in the case of the Moon. Difficult experiments such as age determinations, petrologic characterization, isotopic and trace element analyses cannot be held in abeyance until samples are returned to Earth; the instruments necessary for performing these experiments remotely must be developed and deployed.

The success of any geochemical exploration program will depend to a large extent on how intelligently sites are chosen for analysis. A chemical analysis on the surface of a sand dune on Mars for example will not reveal much about Martian petrological processes. The site must be chosen so as to bring the maximum return in geologic knowledge. Information from orbiters will be crucial in making these choices; photography is likely to be most valuable but other techniques, more specifically chemical in nature, such as multizonal photometry should also be used. The usefulness of these techniques depends not so much on the precision with which they can determine surface chemistry, but on their ability to detect differences. Orbital measurements will also give areal dimension to specific surface analyses since they will delineate the areas over which the analyses are likely to have validity. The orbital and landing programs must therefore be

planned in concert and strategies employed such that each mission plan can be modified by information gained from the other program.

To summarize, data from a lander should include both chemical and mineralogical information supplemented by information of petrologic importance such as texture, lithology and structural position. The general significance of such information gathered at a restricted number of landing sites should be evaluated in light of all available geologic information including geophysical measurements on properties of the interior and orbital measurements of the variation in surface properties. The following sections contain more specific discussions evaluating different methods of acquiring the necessary fundamental data.

Elemental Composition

Sampling

Some of the broader aspects of the sampling problems were discussed in the previous section but additional problems are encountered in the immediate vicinity of the spacecraft. Because of possible local variations any analytical instrument must have the capability of making measurements on any nearby object of interest and of visually monitoring such measurements. This requires that a sampling tool be available and that the analyses be conducted in close conjunction with the imaging system as was done successfully with Surveyor. Analysis without visual support is of very limited value because to interpret the results it is essential to know, for example, whether a soil or a coherent rock is being measured, whether it is in place or an exotic block, and what sort of variations in rock type are at the site. Drilling is an additional desirable capability and its value has been stressed previously. Besides presenting fresh unweathered samples for analysis it opens the door to a wide variety of analytical techniques and may enable different stratigraphic units to be analyzed from a stationary vehicle. Surface mobility is another obvious asset on a chemically variegated surface and the geochemical versatility of advanced vehicles will be greatly enhanced if they can move over the surface.

Accuracy and Precision

It serves very little purpose at this time to specify accuracies and precisions for possible chemical determinations. This will depend on what is technologically feasible and also on the variability in surface chemistry of the planet under consideration. Efforts to achieve extreme precision with relatively few analyses would be justifiable in the case of a homogeneous planetary surface whereas more analyses with lesser precision might be desirable on a planet with variable surface composition. In the table below the precisions listed are those adequate to characterize most terrestrial rock types. For even the most homogeneous of terrestrial rocks the natural chemical variability is generally in excess of the listed precisions (Landy, 1961) so that to more accurately define the chemistry of the rock, multiple analyses are required in addition to increased analytical precision. This is somewhat academic in the case of the planets because the presently achievable precisions fall far short of those listed in the table and we are not likely to be presented with the choice between extreme precision on few analyses or moderate precision on many analyses early in the exploration program.

Highest priority

| Element | Expected range (Percent) | Precision needed to define most terrestrial rocks (Percent) |
|------------------|-----------------------------|--|
| Na | 0.5 - 4.5 | 10 |
| Mg | 0.5 - 20 | 10 |
| Al | 2.5 - 20 | 10 |
| Si | 15 - 35 | 3 |
| K | 0.5 - 5 | 5 |
| Ca | 0.5 - 6.5 | 10 |
| Fe | 0.5 - 20 | 5 |
| H ₂ O | -- | -- |

Second priority

S, Ti, Mn, Ni, Cr, U and Th

Third priority

Ba, Sr, Cu, Pb, Li, P, B, Cl, F, and Zn.

Priorities have also been assigned to elements in the table. This could be done in a more sophisticated way if available chemical data were more carefully evaluated. A wealth of chemical data is available in terrestrial rocks yet little systematic work has been done in organizing the data to separate natural variations from analytical errors and to determine what abundances or what elemental ratios are most diagnostic of specific rock types or meteorites. The Geochemistry Group at the Santa Cruz conference suggested that intensive study be made of existing data with the intent of evaluating the diagnostic value of specific abundances and ratios. They stated that "The K/Ca ratio (may be) a much better index by which to classify chemical variations than analysis for Al, Mg, Si, and Fe. The K/Ca ratio varies by a factor of 500 in common rock types, where Mg/Si or Mg/Fe ratios vary by less than a factor of 10. Similarly, the Al/Si or Ca/Si ratios are a much better index for distinguishing chondritic material and ultramafic rocks from other rocks than the Mg/Fe or (Mg or Fe)/Si ratios. Probably the most distinctive chemical characteristic of chondrites is the Ni content or Ni/(Mg or Fe) ratio."¹ Such a study should be made to avoid expending excessive undue effort in making chemical determinations of limited diagnostic value.

The importance of specific elemental ratios as indices of bulk differentiation of the planet or heterogeneities in the solar nebulae should also be explored. Adams and others (1967a) have approached this problem and have pointed to the importance of the Fe/Si ratio in determining homogeneity of the original nebulae, internal uniformity of the planets and formation of pre-planets. Other ratios may have comparable significance.

Analytical Techniques

A detailed evaluation of different analytical techniques is beyond the scope of this report and the following discussion is

¹Natl. Aeronautics and Space Adm. Spec. Pub. 157, p. 239.

included more to illustrate problems than to suggest solutions. No one technique can be used to determine all the necessary major elements satisfactorily so different techniques may need to be combined if we are to have an adequate analysis. Furthermore since a mineralogic analysis is absolutely essential for understanding any chemical analysis, compatibility with phase detecting devices should be of prime importance in evaluating the relative merits of the different techniques.

The alpha-backscatter is the only fully flight qualified instrument available at the time of writing (fall, 1969) and it has been used successfully on the Surveyor program. The technique gives good results for light elements, especially O, Mg, Al, and Si which constitute most of any likely rock, but it has poor precision for heavier elements. Lack of precision for the heavy elements is particularly detrimental in the case of the highly diagnostic elements Ca, K, and Fe. The technique will encounter problems on Mars and Venus because of atmospheric absorption but it might be appropriate for Mercury.

X-ray fluorescence is a versatile technique with a high degree of compatibility with various methods of phase analysis and, depending on the excitation source, both light and heavy elements can be examined. The standard technique of using a high energy primary X-ray beam to excite the sample is sensitive for all elements heavier than Al; to determine the lighter elements, advantage can be taken of the rising alpha particle excitation function with decreasing atomic number and an alpha-emitter such as Cm²⁴² or Po²¹⁰ used to excite the sample. The excited X-rays may be detected dispersively by means of goniometers or non-dispersively with the use of solid state detectors. Continuing development of small multi-channel analyzers and higher resolution detectors makes the non-dispersive methods potentially very attractive because the instruments are mechanically simple and the resolution of present detectors (<250 ev)

already permits unambiguous determination of adjacent elements heavier than Mg. An important advantage of fluorescence techniques over the alpha-backscatter is the low atmospheric absorption of X-rays from all but the lightest elements so that fluorescence is particularly relevant to planets such as Mars that have a significant atmosphere.

Neutron activation may be of value in determining elements not possible by one of the more general techniques or in low level determinations of specific elements. The technique is particularly sensitive for Na, Al, Si, Ca, K, Mn and Be and could be conveniently combined with an X-ray fluorescence unit using the same analyzer and the same detector (appropriately biased). The only additional requirement would be some form of neutron source. The sensitivity of neutron activation depends on the particular element and on the flux available to excite the sample but potentially the technique can be used for trace element analysis which is not possible by either α -scatter or X-ray fluorescence.

Optical emission spectrometry is the traditional method of trace element analysis and holds considerable promise for remote applications. The development of linear arrays of closely spaced photo-detectors may have provided the key to space utilization of this technique, however, photography and subsequent photometric scanning is still a possibility. The method is sensitive to a large number of elements, can deal with very small samples and has a wide range of response. Calibration to provide quantitative data may be the greatest problem with the technique.

It is evident from this brief discussion that no single technique will fulfill all geochemical needs. Emphasis should be placed on integrating various methods and exploring the commonality of different components so that a complete geochemical package can be assembled, similar in concept to the ALSEP package for the Moon.

Isotopic Composition and Age Determinations

The principal interest of isotopic compositions of the condensed portions of a planet is that they provide a means of determining ages. Sequence and age are of fundamental geologic concern. Only by placing rocks in proper sequence can we achieve some order out of the complexity of a planet's surface and arrive at some understanding of the processes that resulted in its formation. It is of obvious geologic importance to know whether the surface of a planet that formed 4.5 billion years ago has been dead ever since--or whether the surface is still undergoing endogenous change. Each alternative has vastly different implications concerning the chemistry and conditions of the interior.

The isotopes of most interest are those of Rb, Sr, A, U, and Pb and the only satisfactory technique of determining isotopic compositions of these elements is mass spectrometry. Instruments are under development that utilize a sputtering ion source and a double focusing system but presently achievable precisions enable only the crudest of geochronological measurements to be made. Mass spectrometry is potentially a very versatile analytical instrument since it can be used for measuring elemental abundance as well as isotopic abundances and a major effort should be expended in obtaining flight qualified instruments.

Mineralogic Composition

The importance of mineralogic composition has been emphasized above and is restated here. Only if its mineralogy is known can a rock be unambiguously identified and only if the rock is identifiable can its mode of formation be inferred. Mineralogic analysis is therefore of prime importance. This is not to deny the utility of elemental analyses; the emphasis should be placed, however, on correct phase identification and the major elemental analyses should be directed toward this end.

X-ray diffraction is the only satisfactory technique for determining mineralogy. No other technique can provide the same combination of generality, specificity and quantitative data. X-ray diffraction patterns of polycrystalline material can be interpreted (1) to identify most phases present with little or no ambiguity (2) to determine quantitatively the composition of most solid solution series and (3) to determine quantitatively or semi-quantitatively the modal proportions of phases in aggregate. The phase compositional data can be recalculated into an elemental analysis which, though somewhat less precise than that obtained by direct methods, is nevertheless useful for most interpretative purposes. (Interpretation of an elemental analysis involves, at least implicitly, calculation of a hypothetical mineralogical composition.)

Several different diffraction techniques are possible. The usual way is to change the angular position of a detector with respect to the sample and X-ray source and measure the intensity of X-rays at different angular positions. Although this technique has been adapted for space flight applications, the instruments are delicate and mechanically intricate and several simpler alternatives are feasible. One promising approach is to use a curved position-sensitive proportional counter (now being developed at IITRI). The counter is in a fixed position, subtending a substantial angle with respect to the sample, so that X-rays from the sample hit the counter in different positions according to the angle through which they are diffracted. The resulting pulses are attenuated by the central wire of the detector with the result that pulse height depends on where the X-ray entered the detector and hence on the diffraction angle (monochromatic X-radiation is assumed). D-spacings in the sample can therefore be derived from the pulse height distribution in the detector output. The chief advantages of the system are that there are no moving parts and sample preparation is minimal. Photographic methods are also possible; film could be wound

through an appropriate camera then developed and scanned by methods analogous to those used in the Lunar Orbiter program. One problem of film techniques on extended flights is protection of the film from fogging. This could be solved by using a xerographic technique whereby the detecting medium becomes photosensitive only after receiving a high electrostatic charge. Another possible diffraction technique is to have a non-dispersive detector in a fixed position with respect to the sample and source. The diffracted X-rays are then dispersed electronically with a multi-channel analyzer rather than mechanically by means of a goniometer. All the above alternatives should be explored to avoid placing undue reliance on goniometer systems.

One additional technique of mineralogic determinations deserves mention. Although of limited use for systematic mineralogy, differential thermal analysis (DTA) can provide very useful mineralogical data. It is particularly important for identification of clay minerals, carbonates and other minerals that undergo low temperature transformations. The devices are compact, lightweight and have low power and transmission requirements; they may therefore be still feasible when a more comprehensive mineralogical experiment is not possible.

Organic Radicals

A major objective of planetary exploration will be the search for extraterrestrial life. Although other groups are concerned with the detection of actual life processes, efforts of the organic geochemists will be primarily devoted to recognition, identification, and analyses of organic matter on the planetary surface or in its atmosphere. Should living substances not be detected, then such organic material might provide clues as to extinct life processes, or might reflect compounds formed abiotically. These latter substances may in turn provide evidence, by analogy, of substances similarly formed on Earth which ultimately were the progenitors from which life arose on our own planet. Abiotically-formed compounds could also

provide information on the chemical radicals that exist within the space of our solar system.

The organic geochemist cannot ignore the environment in which the organic matter he has under study has been formed or found. Problems involving mineralogy, catalysis, and radiation chemistry, as well as the condensation or polymerization of organic compounds, are all interrelated. The following suggestions are made with this point in mind.

(1) Organic matter may be formed biogenetically or may represent the abiotic products derived from condensed fragments such as C, CH, CH₂, CH₃, CO, N, NH, NH₂ and other radicals interacting in planetary atmospheres or on planetary surfaces. The occurrence of high fluxes of cosmic radiation (Mercury and Venus in particular) or of ultraviolet radiation could readily provide the energy necessary to create the radicals in the vicinity of the planet or to convert low-molecular-weight compounds to high polymers on the planetary surfaces. Search for compounds containing C, H, N, and O probably must be conducted by alpha back-scattering. The possibility that such compounds may interact with clays must also be considered, and could probably best be detected by techniques involving thermal degradation.

(2) Differential thermal analysis (DTA) is useful for the detection of bonded water, in establishing the presence of carbonates by the elimination of carbon dioxide, and in the identification of clay minerals. Evolved gases could be analyzed, quantitatively if desired, by infrared absorption or mass spectrometry with or without gas-liquid chromatography. Infrared techniques are also available for determining C^{13}/C^{12} ratios in carbon dioxide that may be eliminated. Establishment of the C^{13}/C^{12} ratio would be significant in determining if the organic matter had the same ratio as that of the atmospheric carbon of the planet; a significant variation would lead one to suspect that the organic matter was produced by a chemical of "biochemical" reaction accompanied by isotopic fractionation.

Microscopic examination will be necessary to permit determination of the association between minerals and organic matter, and to provide information as to whether the organic matter was deposited in situ, or whether it was fluid at some time and flowed into its present location, where it then condensed or polymerized.

Most of the techniques suggested above have already been developed for adaptation to landers, or are now under development. A package containing gas-liquid chromatography, differential thermal analysis, mass spectrometry, and microscopy, with, possibly, an infrared analyzer, would provide a powerful set of tools for evaluation of the nature of the organic matter, its source, and its relationship to other constituents of the planet being examined. It could also provide complimentary information as to isotope ratios and mineral species.

Orbital Measurements

Precise chemical and mineralogical determinations are not possible from orbiting vehicles; nevertheless extremely useful geochemical information can be gained from orbital programs. Only a restricted number of landers will be deployed on any planet so that precise geochemical measurements will be possible at only a few places. To evaluate the general implications of these few precise analyses, we must have some knowledge of the geochemical variability of the planet's crust and this can only be practical from orbital vehicles. Utilizing a variety of remote sensing devices geochemical variations can be mapped, geochemical anomalies identified and limits placed on chemical and mineralogical compositions over wide areas. Unique chemical and mineralogical determinations cannot however be expected from orbital measurements; the results will be more akin to terrestrial gravity and magnetic maps and subject to a limited set of interpretations. Nevertheless orbital geochemical measurements of some kind are necessary to obtain a general picture of the chemistry of a planet's surface.

Multi-band photometry in the visible and near infrared is particularly promising as a technique for mapping surface chemical and mineralogical differences. The technique is based on the fact that the color of light reflected from crystalline material depends on the elemental and mineral species in the material. Color differences have been detected on the Moon (McCord, 1969). The method has several limitations, some practical and some theoretical. One practical limitation is that its utility is dependent on areal resolution and the number of wavelength channels in which measurements are made. Each spot measurement requires a large number of bits--because of the large number of channels--so that to build a mosaic of a planet's surface with useful resolution, say 5 km, would require enormous transmission capabilities. This limitation also applies to other spectral measurements discussed below. A theoretical limitation of the method is that the characteristic peaks are very broad and so are not very specific and any given spectrum is susceptible to a wide number of possible interpretations. Despite these reservations, development of the method should be supported, certainly for telescopic work, but also in anticipation that orbital measurements will be practical.

Infrared spectroscopy has essentially the same limitations as multi-zonal photometry. In fact the two techniques are very similar and differ only in the wavelength range under examination.

γ-ray spectrometry from orbiting vehicles is particularly attractive in the case of a planet where gross differentiation of the crust is suspected. Because of atmospheric absorption however the technique is relevant only to Mars and Mercury. Measurements are made of surface variations in natural γ-ray activity, which is the result largely of variations in the U, Th, and K contents. These elements are particularly diagnostic of "oceanic" and "continental" rocks on Earth and will have similar diagnostic importance on other planets. Other major elements may also be detected as a result of γ-ray activity induced by

radiation from the sun. This is particularly likely in the case of Mercury.

X-ray spectrometry may be possible on Mercury from an orbiter because of the high solar flux and thin atmosphere. The purpose of such an orbiter would be to map compositional differences as revealed by the differences in X-ray spectra as a result of excitation of the surface by the sun's radiation.

Atmosphere

Detailed analysis of the dynamics and chemistry of the atmosphere is beyond the scope of this report but the atmosphere impinges so directly on some geologic problems that some aspects must be discussed. The concentration and isotopic composition of the noble gases are of particular importance. "Inventories of He^4 and Ar^{40} in the terrestrial atmosphere have been valuable indicators of outgassing of radioactive rocks. These inventories will be similarly important for the other terrestrial planets. The kind and amount of rare gas isotopes in a planetary atmosphere are functions of the original entrapment of those isotopes within the planet and of its subsequent outgassing history. As such these determinations can set useful boundary conditions on theories of the planets origin. Differences, if they exist, in isotopic composition between planetary matter and terrestrial matter are probably most easily detectable in the rare gases; and all the gases from neon through xenon can probably be included in the search because background interference in mass spectrometer measurements tends to fall off more rapidly with increasing atomic mass than does the abundance of the rare gases. In the case of xenon, special anomalies in isotopic composition due to extinct radioactive I^{227} and Pu^{244} have been prominent in the meteorites"^{1/} and may be visible in other planets. If so,

^{1/} Planetary Exploration 1968-1975. Report of a study by the Space Science Board, June 1968. National Academy of Sciences, Washington, D. C. p. 20.

it may be possible to infer when the different planets formed. A mass spectrometer capability should therefore be developed to measure the concentration and isotopic composition of the noble gases.

Supporting Earth-based Research

The first and most obvious earth-based activity is in the field of instrument development and this has been discussed above. As previously stated, the main thrust should be toward exploring the commonality of components between different techniques and toward producing an integrated package for elemental and mineralogical analysis.

The second--and in a sense more fundamental--kind of ground-based study should be devoted to acquiring basic scientific data needed to interpret the experiments performed at the planets. In part, this consists of the obvious direct calibration of instruments and simulation of experiments under conditions similar to those to be encountered on the planet's surface. The DTA response of a dehydration or decarbonation reaction, for example, may be quite different in the Martian environment than in a terrestrial laboratory. Effects of this sort may be evaluated in much the same way that flight hardware must be tested for operation under expected conditions. This work is properly part of the development procedure for specific instruments and experiments, and can be done only in conjunction with experimental design.

A thin line separates these from other research programs that are designed to gain a better understanding of the conditions and processes on the planetary surface so as to predict and define the most significant measurements, as well as to aid in their interpretation. For example, we need much more extensive data on the stabilities of phases that are curiosities on Earth but may be important constituents of the surface materials of other planets. We need especially to study minerals whose stabilities may be greatly enhanced or restricted by atmospheres very different from ours in composition, pressure, oxidation potential, content of H_2O , CO_2 , CO , NH_3 , and others.

To take a specific example, we know that the Martian atmosphere, with a surface pressure of 15 mb, contains major amounts of CO_2 , measurable CO and H_2O , and a large fraction of spectroscopically non-detectable gases. Such an atmosphere is so different from our highly oxidizing, wet one that we cannot predict with certainty the nature of the weathering products that would result from its interaction with even common terrestrial rocks. We can predict that the mineral phases in equilibrium with the Martian atmosphere are likely to be more reduced and perhaps more carbonate-rich than their terrestrial counterparts, but we are not in a position to make any quantitative predictions. A program of direct experimentation in low-temperature reactions between common terrestrial rock types and simulated Martian atmospheres is one desirable route of attack, but it should be supplemented by systematic measurement, compilation, and evaluation of equilibrium data on the low-temperature regions of pertinent simple systems under similar reducing conditions. Carbonyl compounds and oxalates, quite rare in terrestrial occurrences, may be much more common on Mars; the properties and stabilities of these containing the major rock-forming cations should be investigated. Stability studies for conditions on other planets, especially Venus and Mercury, should be similarly pursued.

The extent to which the atmosphere may have influenced more deep-seated rock-forming processes depends to large extent on the overall history of the planet. If a mobile interior and sedimentation on a large scale have allowed sedimentary accumulations of weathered debris to sink to sufficient depth to be metamorphosed, or partially or completely melted, the character of the weathering products will obviously affect the resulting metamorphic or igneous rocks. Even if this has not occurred, volcanic rocks interact directly with the atmosphere in the process of their formation and the resulting mineral assemblages of the volcanic rocks may show the effects of the volatile

constituents, especially those affecting the oxidation states of the magma. Again, both direct simulation and carefully controlled studies of selected key systems are called for; fortunately the effect of F_{O_2} on the crystallization of basaltic melts is of great terrestrial importance, and studies recently completed or currently underway may suffice, but their status should be evaluated from a planetologic point of view and supplementary work supported as needed.

STRATEGY

Mars

Plans for the exploration of Mars are well advanced; two orbiters are planned for the 1971 opposition and orbiter-lander combinations are planned for 1973 (Viking Missions). The emphasis during early exploration will be on life detection and this will in large part govern the choice of experiments and the strategy followed. There is little conflict between geologic and biologic needs in the area of orbital measurements but some conflict does arise in the case of landers. The instruments presently conceived for early landers are chosen largely from biological considerations and, though useful, are not those that are best for geologic purposes. More geologically relevant experiments must await later landers. If no evidence of life is detected by the early mission then emphasis should shift away from life detection toward unraveling the geologic history of the planet and the strategy and instruments carried on subsequent missions directed more toward this end.

Mariner Mars '69

Only a limited increase in our geologic knowledge of Mars can be expected from the Mariner Mars '69 data although the mission was essential for future planning purposes. Many of the experiments on Mariner Mars '69 were directed toward studying the atmosphere and T-P conditions at the surface are related only indirectly to geologic problems. Visual imagery is the source of most geologic information but the utility of the Mariner Mars '69 photography is limited because coverage and resolution are inadequate for systematic stratigraphy so the geologic interpretation of surface features must be based almost exclusively on geomorphologic rather than stratigraphic reasoning. Nevertheless, despite restrictions, the Mariner Mars '69 photography very clearly demonstrates the geologic heterogeneity of Mars, the feasibility of doing stratigraphy and the ability to acquire adequate imagery

from orbital altitudes with the minimum of atmospheric interference. In addition Mariner Mars '69 has provided essential terrain, surface albedo, and atmospheric information for optimization of the 1971 missions especially as regards resolution, lighting conditions, exposure settings, filters, and type of coverage. The Mariner Mars '69 mission has therefore been a vital link in the ongoing program.

Mariner Mars '71

Two orbital missions to Mars are planned for 1971 and the importance of these missions for the success of the ongoing exploration of Mars cannot be overstated. The objectives of the mission cannot be considered in isolation but must be examined in light of an overall plan. If an appropriate strategy is followed, the 1971 missions will provide data on the geology and geography of Mars that is essential for the orderly planning and execution of future missions; if the missions fail or the wrong strategy is used then subsequent exploration of Mars is severely jeopardized. For the success of future missions most of Mars must be systematically photographed in 1971 at the highest resolution that is consistent with broad areal coverage. This reconnaissance photography is required for the following purposes:

Stratigraphic analysis.--The necessity of interpreting data from the surface in light of its geologic context has been emphasized throughout this report. Geochemical and geophysical data has only limited value if the geologic units on which the measurements were made cannot be identified. Stratigraphic analysis is an essential prelude to any data-taking at the surface, and since moderate resolution photography is so essential for stratigraphic studies, this should be acquired before the landings are made. The same reasoning is true for orbital measurements. Any orbital measure of the physical and chemical variations of the surface must be interpreted in light of the local stratigraphy and supplemented by appropriate photography.

Terrain analysis.--Future landers will be restricted to areas with specific terrain characteristics and wide photographic

coverage at 1 km resolution will be needed to block out areas of the planet on which landing is possible.

Site selection.--Because only a limited number of landings will be made on a planet, the effectiveness of the program will depend partly on how well landing sites are chosen. Similarly future orbiters will have the capability of acquiring detailed information on limited areas and site selection will partly control the usefulness of the returned data. Choice of sites for future more detailed work will be of necessity almost wholly based on the 1971 reconnaissance photography so every effort must be made to insure this is of the highest quality.

Problem definition.--The present telescopic and fly-by information on Mars is inadequate to evaluate the relative importance of specific scientific problems such as the wave of darkening or diurnal albedo variations. Such problems may turn out to be trivial or not soluble by the techniques available so that a mission specifically committed to resolving a particular problem involves high risk. Early missions should be directed toward systematically assembling fundamental data on the geography, geology, and physiography of the planet with the minimum of redundancy so that priorities can be more knowledgeably assigned to unsolved problems. A photographic mission aimed at covering most of the planet at 1 km resolution is best designed for providing such fundamental documentation. The most logical sequence is to proceed from the general to the specific, acquiring broad areal coverage first and then concentrating on areas of interest.

The unusual importance of the 1971 missions stems from the unlikelihood of obtaining the necessary regional moderate-resolution photography of the planet on any mission now planned for after 1971. If 1971 fails or the wrong strategy is used then many subsequent missions are seriously affected. As presently conceived each 1971 orbiter will be employed in a different mode. One will be placed in an orbit that precesses slowly around the planet (Mission A) so that most of the planet can be covered

photographically; the other orbiter is to be placed in a sub-synchronous orbit (Mission B) to repeatedly photograph the same areas under similar viewing and lighting conditions. Mission A is most likely to fulfill the objectives outlined above in that it will acquire moderate resolution photography of a large portion of the planet. In addition stereo and color information will be obtained on restricted areas. As presently planned (12 hr orbit) the Mission A vehicle completes one longitudinal pass every 18 days. Although periapsis is continually shifting northward, each successive pass will result in some overlap with the previous pass. These areas of overlap provide an excellent opportunity for obtaining color and convergent stereo photography of the surface without losing areal coverage and should be used for these purposes. Because of the importance of Mission A in the planning and operation of subsequent missions, it is imperative that contingency plans be made to ensure that the Mission A objectives are met in the event of one spacecraft failure.

Geologic mapping should follow acquisition of the wide coverage photography because of its relevance toward understanding the evolution of the planet and because of its pertinence in establishing the geologic environment at 1973 Viking landing sites. All the areas photographed in 1971 should be mapped geologically at a scale of 1:5,000,000 to establish the general stratigraphic framework of the planet and to determine the nature and sequence of major historical events. Areas of unusual interest both from a biological or a geological viewpoint should be mapped at a scale of 1:1,000,000. Once orbital and terrain constraints on the Viking lander have been established then areas of Mars must be blocked out according to their position and the suitability of their terrain for landing. Possible landing areas should be evaluated according to their scientific interest and a set of potential sites chosen and mapped geologically at a scale of 1:1,000,000.

Topographic maps at scales of 1:5,000,000 and 1,000,000

with appropriate aerographic control should be prepared of all the areas photographed. In the areas of no overlap between successive 18-day passes on Mission A the maps will be essentially planimetric with relative elevations determined at a few specific points by shadow analysis. In the area of overlap, convergent stereo may allow contour maps to be made of restricted areas.

Viking Mars '73

As presently conceived the Viking vehicle is a lander-orbiter combination; the lander will operate on the surface while the rest of the payload remains active in orbit. The main emphasis of the mission will be directed toward detection of extra-terrestrial life and most of the payload will be devoted to this end. There is, however, considerable overlap between biological and geological needs and a strategy optimal for geologic return can be followed without prejudicing the biological experiments.

The value of the orbiter for geological purposes will depend on the extent to which the lander and orbiter are used independently of each other. Geologically it is preferable that the orbiter operate to a large part independently of the lander. The orbiter can be used in a mode completely subservient to the lander, passing over the site every day to monitor activity at the site and to relay information from the lander to Earth. In this mode the orbiting vehicle would continually retrace the same ground track and so would be able to photograph only a restricted area of the planet. Alternatively and preferably for geological purposes, the orbiter can be largely independent of the lander, passing over the site only at infrequent intervals. In this mode much of the planet will be accessible for detailed photography and a Lunar Orbiter V type of mission plan can be followed in which a large number of preselected sites of unusual interest are photographed in detail, the sites being chosen from the Mariner Mars '71 coverage. This detailed sampling of the surface is the logical sequel to acquiring the planetwide coverage at 1 km resolution in 1971 and if followed would largely eliminate the

need for further photography of Mars. It is premature at this time to specify what resolution will be required but it probably will be in the range of 5-50 meters. Higher resolution will result in too great a loss of coverage and lower resolution will result in loss of usefulness. Provision should also be made for convergent stereo and multiband photography. Detailed photography of a large number of sites in different areas of Mars will also provide the basis for choice of landing sites for subsequent missions.

The penalty of following a strategy in which the orbiter only infrequently passes over the site of the lander is (1) a reduced transmission capability of the lander and (2) an inability to closely monitor any variations in the physical environment of the spacecraft. Since most of the transmission capability of the lander is taken up by the imaging system, the choice is largely between repeated photography from the lander and photography of different areas from an orbiter. Daily panoramas of the terrain in the vicinity of the lander cannot be justified geologically if gained at the expense of detailed orbital photographs of several different areas. However much of the lander photography will be in support of lander experiments most of which are biological. Evaluation of the relative merits of the biological experiments and additional detailed orbital photography is preferable. The likelihood of variable phenomena in the vicinity of the lander and the need to monitor it from an orbiter will be better assessed after the results of the 1971 missions.

The lander instrumentation is largely biologically oriented but the lander will yield substantial geological information. The imaging system will reveal the lithologic nature of the surface materials, the size frequency and shape of soil particles, the frequency and shape of blocks and the presence or absence of a soil or regolith. The granularity and layering of the rocks will be determined and the presence or absence of vesicles, phenocrysts and other macroscopic features. In conjunction with

the sampler, engineering properties such as cohesion, bearing strength and porosity will be determined. The photography will also allow detailed topographic analysis of the surface in the immediate vicinity of the spacecraft, especially if coupled with orbiter photographs. The climatic conditions at the site, including temperature, pressure and wind velocity will also be monitored. All this information is essential for an understanding of the processes of formation of the surface rocks and the nature of the processes modifying the surface.

The lander will also carry instruments to determine water and to detect organic radicals. Water is of special geologic importance in affecting phase relations and reaction rates among materials at the surface. The significance of organic radicals has been discussed in the section on organic geochemistry below. A DTA unit may also be included for expelling gases and this also will yield geologically important information on mineral phases. However none of these instruments has a high priority on geologic grounds. Geologically the most important instruments for a lander (after the imaging system) are a seismometer and an X-ray fluorescence-diffraction system or equivalent. One or both of these should be included in the Viking instrument package if we are to achieve an appreciable increase in our understanding of the geological evolution of Mars from the mission.

Advanced Missions

The course of Martian exploration beyond 1973 will depend on whether life is detected on the planet. If life is detected then geologic considerations will initially be of secondary importance in the design of subsequent missions and all efforts will be directed toward determining the nature of Martian life. In the more likely event of life not being detected, then emphasis should be shifted toward designing more geologically rewarding missions. Mars oppositions occur at two year intervals and advantage should be taken of each one. Exploration should continue to employ both orbital mission to monitor regional

variation in surface properties and landers to make in situ measurements in order that the orbital measurements are reliably interpreted.

The type of orbital instrumentation needed subsequent to 1973 will be governed by the quality of the information received by that time. More imagery will be needed unless both 1 km resolution coverage of the whole planet and 5-50 meter resolution coverage of critical areas with convergent stereo has been attained by that time. Once this type of coverage is in hand then emphasis should shift away from imagery toward mapping variations in surface properties other than optical response although wide angle photography may still be needed for areodetic purposes. At present the most attractive experiments appear to be:

1. Bistatic radar mapping of the surface.
2. Multiband photometry in the visual and infrared.
3. Infrared radiometry of the dark side of the evening and morning terminators.
4. Determination of the dynamical figure from a low orbit using a nul-type accelerometer.
5. Topographic mapping by radar altimetry.

Some type of orbital measure of variations in the chemistry of the surface to provide a basis for interpolating chemical data from landers is of prime importance. Because of atmospheric restrictions, only multiband photometry or photography appears feasible at present so this should have high priority.

After 1973, instrumentation of landers should be chosen on the basis of geological priorities. 1975 is the earliest opportunity for a sound geological payload and of highest priority are:

1. Imaging system.
2. Seismometer.
3. X-ray fluorescence-diffraction or equivalent.
4. H₂O and CO₂ detector.
5. Remanent magnetism.

The imaging system should incorporate the optics and filters necessary for examining surface rocks in color with a resolution of 0.01 mm so that the textures and crystal structures can be examined in detail. A mirror system or an extendable mount for the camera should also be provided for stereoscopic examination of the surrounding topography (also in color). The seismometer should be a six component type designed to operate for at least six months. If power or data transmission rates do not permit a 6-component system then a simpler system, although much less desirable, should be flown. It is essential that some seismic detection device be sent to Mars at the earliest possible opportunity. X-ray fluorescence/diffraction is specified above but a more comprehensive package to determine the chemistry and mineralogy of the surface is preferable. An integrated package analogous to the ALSEP package for the Moon should be developed to determine all major elements, major mineral species, and if possible the isotopic abundances of important heavy elements such as U, Pb, Rb, Sr, and others. The H₂O and CO₂ detector should be capable of making measurements several inches below the surface. For seismic triangulation and to obtain representative chemical and mineralogical samples, three or more landers should be deployed and should be designed to operate simultaneously.

Beyond 1975, development of landers should take place along the lines of (1) increasing analytical versatility and (2) increasing the sampling capability. Landers should be able to determine the following on any rock sample

- (i) major element composition
- (ii) trace element composition
- (iii) isotopic composition
- (iv) mineralogical composition
- (v) rock texture
- (vi) magnetic properties.

The lander should also include a seismometer to operate in both active and passive modes and provision for heat flow measurements.

Mobility is essential if full use is to be made of a landed instrument package. Because of the probability of surface heterogeneity, far more can be learned from many good analyses than from one analysis of extreme precision. Mobility allows many rock formations to be sampled and enables the chemical variability within each formation to be assessed. Mobility is therefore necessary for any comprehensive geologic exploration program. Drilling is also desirable; it is essential for any heat flow measurement and in addition enables measurements to be made on a vertical succession of rocks so should be included as part of an advanced lander's capability.

Venus

Venus is of special interest to geologists because of its similarity in size to the Earth. Although the obscuring atmosphere and inhospitable conditions at the surface make measurements of surface properties particularly difficult, much can still be learned about the planet with the use of existing techniques. Surface topography and variation in some physical properties of the surface can be mapped from radar and these techniques should be fully exploited pending development of an analytical instrument that can survive on Venus' surface. Terrestrial radar measurements will result in a significant increase in our knowledge of Venus during the 1970's and the strategy to be followed will depend largely on their success. Should images with 2 km resolution be feasible in the near future, then this would obviate the need for orbital radar reconnaissance imagery. Orbital radar imagery would be needed only for detailed imagery of selected areas, the type of coverage provided for the Moon by Lunar Orbiter V. A mission of this type could safely be delayed several years without jeopardizing the exploration program. If, however, 2 km resolution is not possible from Earth-based measurements in the next five years, then serious consideration should be given side-looking radar imagery of Venus from

orbiters even if this would require all the payload of a Mariner class vehicle. If imagery by side-looking radar is not possible then the surface should be mapped bistatically with the maximum possible spatial resolution. In addition, passive microwave measurements of surface emission should be made at several wavelengths to map variations in the properties of the surface and near surface materials.

Any orbital program will result in better definition of the dynamical figure. The lower the orbit, the greater the precision with which the figure can be determined provided that the compensation is made for atmospheric drag. Use of a null-type accelerometer in a high inclination orbit to accurately determine the dynamical figure, is strongly recommended. This will lead to greatly increased understanding of the internal mass distribution and possible near surface "mascons."

Development of analytical instruments to survive in the conditions at Venus surface must be started. The following are of highest priority:

1. Imaging system with appropriate light source.
2. Seismometer.
3. X-ray diffraction/fluorescence, or equivalent.

It serves little purpose at this time to look beyond deployment of the above three instruments.

Mercury

Interest in Mercury stems from the possibility that it represents an extreme of planetary evolution. Its unique high density suggests a composition different from the other terrestrial planets and this could have resulted from chemical fractionation of the material from which Mercury formed because of its proximity to the Sun. Mercury is also of interest in that, of all the planets other than Mars, it is the most accessible for geologic exploration. The atmosphere is extremely thin (<1 mb) and unlikely to interfere with measurements on the surface made from an orbiter. γ -ray, X-ray and infrared absorption by

the atmosphere is minimal and clouds will not obscure the surface. A comprehensive orbital program coupled with relatively few landers could therefore give a reasonably complete picture of the composition and internal and surface variability of the planet.

The extreme difficulty of telescopic observation makes it unlikely that any significant improvement of our knowledge of Mercury will come from terrestrial optical observations unless from earth-orbital platforms. Although radar measurements will almost certainly result in better definition of surface features and planetary dimensions, major advances in our knowledge must ultimately come from a spaceflight program. A Venus-Mercury fly-by is already proposed for 1973 and another opportunity to utilize the gravity field of Venus occurs in 1975. Missions to Mercury after 1975 must go direct, at least until 1991.

Venus-Mercury Fly-by '73

From a geologic point of view, the most useful information from the proposed Mercury fly-by will be derived from imagery of the surface. This 'first look' will allow the crustal style to be established so that the processes that have dominated the evolution of the surface can be inferred. The photography will also allow the photometric properties of the surface to be determined and this is essential for optimum design of subsequent photographic missions. From the fly-by trajectory we can expect a more accurate determination of the mass of Mercury and under very optimum conditions some measure of the differences in the principal moments of inertia may be possible. Significant improvement in the optical figure will result from approach photography and from occultations. Limits will be placed on the magnitude of the magnetic field strength and on the thickness of the atmosphere. These data, in addition to enormously improving our present meager knowledge of the planet, will be of vital importance in the design of subsequent orbital and landing missions.

The photographic strategy to be followed by the fly-by should be to characterize the terrain at a wide range of scales. Approach photography should encompass the whole disk and each successive frame should be nested within the previous one; moreover the difference in scale should be small enough that some features can be recognized on both frames. This strategy requires a more sophisticated camera platform than was carried on Mariner IV for example, but the increased utility of the photography over that obtained from a mission that attempts to cover as much of the planet as possible at the maximum resolution justifies a more elaborate system. Such a fly-by mission would allow the trade-offs between resolution and areal coverage to be evaluated and permit determination of the best lighting conditions for subsequent systematic high resolution orbital photography.

Orbital Missions

Any attempt to map variations in the chemistry and physical properties of the surface of Mercury, the variations in its gravity and magnetic fields and to correlate them with features identified from photographs will result in a substantial increase in our knowledge of the planet, particularly of internal mass distribution, internal viscosity and the chemical and physical evolution of the surface. The orbital information is essential for success of landers in that it provides information necessary for optimizing the choice of landing sites and interpreting the resulting data. Early orbiting vehicles to Mercury, possibly utilizing the 1975 Venus-Mercury alignment, should provide information on the following, in the order or priority.

1. Surface topography by means of high resolution (<2 km) contiguous photography of most of the planet.
2. Optical figure and geodetic control from approach photography and occultation.
3. Dynamical figure from tracking.

4. Magnetic field, if previously detected by fly-by.
5. Composition and chemical variability of the surface by γ -ray or X-ray spectrometry (activity induced by solar radiation).
6. Variation in physical properties of the surface by infrared radiometry on the dark side of the evening and morning terminators or by bistatic radar studies.
7. Mineralogic variation of the surface by visual and near-infrared spectrometry.
8. Variation of physical properties with depth and possibly internal heat flow by mapping passive microwave emission at several wavelengths.

The order of priority is based on feasibility of measurement as well as desirability of the data. A heat flow measurement, for example, although of high scientific priority is listed in eighth place because the measuring techniques presently available are of dubious accuracy and precision. Furthermore as measuring techniques develop priorities may change. If the techniques of infrared and visual spectroscopy significantly improve in their diagnostic value then they should take precedence over techniques for measuring physical properties.

Lander Missions

Assignments of priorities to specific experiments on possible Mercury landers has little meaning in view of our present limited knowledge of the planet and in view of the difficulty of anticipating what developments might take place in analytical instrument design during the next several years. However, for geologic purposes a lander should perform the following functions, not in order of priority:

1. Monitor internal seismic activity.
2. Determine internal heat flow.
3. Analyze the surface rocks, determining the abundance of all major elements and some trace elements, and the isotopic composition of critical elements such as U, Pb, A, Rb, Sr.

4. Determine phase compositions of the surface rocks.
5. Determine, by imagery, the lithology, texture and attitude of the surface rocks.
6. Determine the remanent magnetization, if any, of surface rocks.

The landing program must be preceded by a comprehensive orbital program so that landings can be made in areas least susceptible to ambiguous interpretation and so that the data from the lander can be confidently extrapolated to areas of the planet away from the lander.

Outer Planets

Favorable alinement of the outer planets in the late 1970's makes multiplanet missions at this time very attractive. The applicability of geologic studies to the outer planets is difficult to assess within the framework of our present knowledge since we know nothing of the solid portions, assuming that a solid gaseous interface even exists. A multiplanet mission will do much to remove some of the present ambiguities and should include radar ranging and occultation experiments to detect and measure the depth of any solid surface. If solid surfaces are detected then orbital radar techniques could later be used to explore topographic variability and variation in surface properties.

Planetary satellites

The chemistry and evolution of planetary satellites are as relevant toward understanding the evolution of the solar system as are the properties of the planets themselves so that satellites should not be ignored in any exploration plan. Study of satellites is of special importance in the case of the outer planets whose solid portions are inaccessible to direct observation. Their satellites will provide a means of assessing conditions that have pertained in the more distant parts of the solar system as well as indicate the chemistry and physical conditions in the distal portions of the original solar nebula.

A photographic mission to Jupiter should provide for photography of at least one of the regular and one of the irregular satellites. Photography will define diameter and hence density and should make it possible to establish whether a particular satellite is essentially rock or ice. The presence or absence of an atmosphere would also be determined. In addition, the topography of the surface will indicate what processes have resulted in its formation and modification and the photometric properties will provide a measure of the physical properties of the surface materials. From multiband photography or infrared spectroscopy some assessment of the mineralogical and chemical variability of the surface could be made but in situ chemical and physical measurements must ultimately be made for definitive data. The magnetic fields of the satellites should also be monitored, especially that of Io which modulates decameter radiation from Jupiter.

Photography and some form of spectroscopic examination of the surfaces of the satellites of Saturn, Uranus and Neptune should also be included in missions to these planets, and the feasibility of applying bistatic radar techniques to these bodies should be explored.

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