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RM-4437-NASA
APRIL 1965



# MARS ENVIRONMENTAL MEASUREMENTS IN SUPPORT OF FUTURE MANNED LANDING EXPEDITIONS

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PREPARED FOR:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

The RAND Corporation
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## PREFACE

This Memorandum is intended to identify the Martian environmental parameters that must be measured and the preferred techniques for measuring them, in support of the planning and design of a manned landing vehicle for Mars. The report contains a broad, early examination of the gross makeup and flight profiles of vehicles that could make the required measurements of the Martian atmosphere for a range of missions.

This is one of three Memoranda concerned with measurement of the density and composition of the Martian atmosphere; the others are RM-4434-NASA, Use of Radiation Gauging Methods to Measure Atmospheric Density During Martian Entry, by J. W. Ranftl, April 1965, and RM-4451-NASA, Instrumentation to Measure the Martian Atmospheric Composition, Using a Soft-Landed Probe, by R. O. Woods and J. W. Ranftl, April 1965.

All three Memoranda contribute to the Apollo Contingency Planning Study undertaken by The RAND Corporation for Headquarters, National Aeronautics and Space Administration, under Contract NASr-21(09).

## SUMMARY AND CONCLUSIONS

This Memorandum presents descriptions of some measurements that should be made prior to a manned expedition to Mars and comments on preferred techniques for making these measurements.

The measurements required to obtain data before undertaking various types of manned landing expeditions can be summarized as follows:

- For any manned landing: surface pressure and temperature, atmospheric composition, mapping, surface slope, and load-bearing capability.
- For a manned landing using aerodynamic braking from orbit: scale height at low altitude, surface atmospheric density, and winds.
- For a manned landing using aerodynamic braking from hyperbolic velocity: a relatively precise measurement of density as a function of altitude and, contingent on the terminal guidance system to be used, a precise measurement of the radius of Mars.
- For a manned landing using a Mars-orbit-rendezvous flight profile and having a significant inclination of the rendezvous orbit: measurement of the second harmonic of the gravity field in order to predict the rotation of line of nodes of the parking orbit.

Many studies of manned Mars expeditions have been based on propulsive braking to achieve orbit, presumably because of the lack of atmospheric data or the absence of plans to acquire such data. The acquisition of such data is of particular interest because of the possibility of using aerodynamic braking from hyperbolic velocity, which offers the advantages of (1) substantially smaller initial weight, and (2) either a direct-landing flight profile or a Mars-orbit-rendezvous flight profile (after establishing orbit by means of small propulsive corrections). Measurements that would permit aerodynamic braking from hyperbolic speed at Mars seem to require a substantially different probe flight profile than has been considered for the scientific (principally biological) probes like Voyager that have been studied heretofore.

The measurement techniques that seem desirable for unmanned probes in support of future manned landings can be summarized as follows:

- Atmospheric pressure and temperature: measurements by a lander vehicle during parachute descent and for about three days after landing.
- Atmospheric density: an X-ray backscatter gauge to function during the entire entry process of a lander vehicle, with decelerometers as backup for drag-deduced density measurements.
- Altitude measurements by a radio altimeter in the lander vehicle, to supplement density measurements. These measurements require descent from orbital velocity because of radio blackout. (This equipment can also be used before separation of the lander to measure the radius of Mars, in conjunction with DSIF* orbital data.)
- Composition: Mass spectrometer in lander vehicle to function during parachute descent and after landing, backed up by temperature instrumentation of heat shield and by filter radiometry to function during maximum-heating conditions.
- Surface load-bearing capability: Decelerometer with real-time data transmission on lander-vehicle leg or foot, supplemented by television pictures of foot after landing.
- Surface slope: television pictures (stereo) from lander vehicle during parachute descent and after landing.
- Winds: Anemometer on lander vehicle to function for about three months.
- Mapping: Stereo television pictures from orbiter.
- Radius of Mars: Radio altimeter from orbiter.
- Oblateness of Mars: DSIF tracking of orbiter for about 30 days.

The principal departure from previous probe studies necessitated by these measurements would be a change of the probe flight profile to one in which an entry/lander vehicle is ejected from an orbiter/bus after, rather than before, entering Mars orbit. This change in the

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*Deep Space Instrumentation Facility.

flight profile would be necessary to improve the accuracy of altitude and density measurements during entry. Although it would reduce the landed payload significantly, such a flight profile would have a number of subsidiary advantages: it could acquire atmospheric data without requiring successful parachute deployment or landing, entry conditions would be much less severe, and the power required for communications during entry would be substantially reduced.

Voyager could be modified to serve as such a probe, since most of the orbiter/bus equipment would be the same. Because the atmospheric data acquired would permit better design of unmanned as well as manned vehicles, this probe would be most useful as a first-generation Voyager. In general, the data and instrumentation requirements outlined here are more restricted in variety and less demanding in endurance than those proposed for Voyager, a factor that tends to make a modified Voyager economically more feasible.

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# I. INTRODUCTION

Past studies of manned Mars missions have been concerned primarily with the feasibility of specific types of missions. These studies (e.g., Refs. 1, 2, and 3) have considered possible flight profiles, hardware configurations, propulsion systems, combinations of trip year, flight time, and stay time, and other factors concerned directly with the flight and the flight vehicle. However, the need for preliminary measurement of Mars parameters prior to a manned landing has been indicated only incidentally, and no explicit statement is available of what data will be required.

Therefore, in this Memorandum we have examined the data requirements for various types of manned landing expeditions and have attempted to assess the capability of specific kinds of probes and instruments for acquiring the data.

It is difficult to determine unambiguously what data are necessary, because the requirements depend on many currently uncertain factors and because individual judgments will, of course, vary. Among these uncertain factors are (1) the flight profile to be used, (2) the magnitude of related parameters, (3) variations in the measured parameters, and (4) the length and season of the manned stay on Mars.

Flight Profile. The flight profile selected for a manned Mars mission will determine to a considerable extent the type of data that will be required. For instance, if aerodynamic braking is to be used only from circular velocity, fewer data on the Mars atmosphere are needed, and more accurate data on the radius of Mars may not be needed at all. However, it is our judgment that entry with aerodynamic braking from hyperbolic speeds should not be ruled out at this time because this mode of operation can have a significant favorable effect on the initial weight required for a manned mission.[4] Like lunar-orbit rendezvous, hyperbolic entry at Mars would represent a substantial advance beyond demonstrated capabilities, it requires a significant guidance-system development, and it results in a significant performance improvement. One view is that the capability for manned hyperbolic entry

> will be hard to develop because of the inaccessibility of the Mars atmosphere and the telemetry problems of probe experiments. A reasonable assumption is that early flights will use propulsive braking into Mars capture orbit and that aerocapture will be introduced later. The necessary experiments in the Mars atmosphere could be among the accomplishments of early manned missions.[5]

In this Memorandum a major issue considered is whether probe experiments can be devised which would permit aerocapture (hyperbolic entry) in early manned trips.

Magnitude of Related Parameters. The effects of the magnitude of related parameters can be shown, for instance, by the fact that the importance of wind velocity at takeoff increases as the magnitude of the surface pressure increases.

Variations in Parameters. Variations with time in parameters such as ground-level atmospheric density or wind velocity can affect the data requirements. The magnitude of variations must be determined, as well as the fraction of time these variations exceed certain values. For the first measurements, the important thing is to measure the parameter with sufficient accuracy and for sufficient time to detect variations. If unexpectedly large variations are found, further measurements may be indicated.

Length and Season of Manned Stay on Mars. The longer the planned stay on Mars, the more important it will be to have detailed data on meteorological conditions and their variations, on the radiation environment, and on the composition and density of the atmosphere, insofar as they may affect the design of life-support systems.

The only Mars vehicle firmly programmed and funded is the Mariner family, the first of which is (as of March 1965) on its transfer trajectory to Mars. Substantially identical shots are scheduled to follow in about two years. Mariner, which is launched by an Atlas-Agena booster, is a flyby vehicle intended to measure interplanetary fields and particle concentrations, to transmit a limited number of television pictures of Mars (from a distance of several thousand kilometers), and to make initial measurements of atmospheric scale height and possibly of surface density* by radio occultation.**

A number of studies have been made of probes to be launched by Atlas-Agena or Atlas-Centaur boosters.[6,7] The purpose of these probes is to obtain data on the atmosphere of Mars by making a hyperbolic entry into the atmosphere. The landed equipment and instruments for these probes vary widely, but each probe uses a hyperbolic, high-angle entry at Mars, each will deduce the scale height from peak deceleration, and each will make approximate characterizations of the density/altitude structure of the atmosphere by deceleration measurements (and integrations thereof).

Studies have also been made of Voyager probes,[8,9,10] which are launched by a Saturn 1B*** and consist of an orbiter/bus and one or more lander vehicles. In the flight profile selected for the Voyager studies, the lander, which enters nearly vertically at hyperbolic velocity, is separated from the orbiter/bus and completes its landing before the orbiter/bus is maneuvered to go into orbit. Voyager is intended principally to make biological investigations, i.e., to search for life-forms on Mars, but because it can carry a substantial payload and because it incorporates both a lander and an orbiter, it can make a number of environmental measurements relevant to the manned expeditions to follow.

General characteristics of examples of these classes of probe vehicles are shown in Table 1. Different flight profiles will be examined to see if they might more reasonably satisfy the objective of acquiring data for future manned flights. It is also of interest to determine whether modifications of scientifically oriented probes will satisfy manned-space-flight requirements; however, a purely scientific probe program

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*Comments on the adequacy of these measurements (and of those to be made by other proposed probes) for various purposes will be given later in this Memorandum.

**This is an experiment in which the vehicle passes behind Mars, as seen from the Earth. The changes in Doppler shift and magnitude of radio signals as the vehicle passes behind the edge of Mars can give some information about the Mars atmosphere.

***Larger, but otherwise generally similar, probes to be launched by Saturn V have also been studied.

Table 1

CHARACTERISTICS OF EXISTING AND PROPOSED MARS PROBES

| Probe Designation | Flight Profile | Booster | Vehicle Mass (lb) | Principal Experiment | Status |
|---|---|---|---|---|---|
| Mariner C | Flyby | Atlas-Agena | 550 | TV pictures, radio occultation | In flight |
| Advanced Mariner (6) | Flyby and hyperbolic-entry vehicle | ........... | 70-lb entry vehicle plus Mariner bus[a] | Atmospheric scale height, density, and altitude | Study |
| Voyager (8) | Orbiter periapsis = 1000 km, apoapsis = 10,000 km | Saturn 1B | Orbiter = 1650 Lander = 800[b] or 2100[c] | Biological | Study |

[a] No provision for landing.

[b] Capsule separation after retrofiring.

[c] Capsule separation before retrofiring.

cannot be expected automatically to provide the data required for manned space flight.

It seems clear that measurements of the Mars environment can and should be made before a manned expedition to Mars is established. To wait until such a mission is formally initiated and announced seems inadvisable for several reasons: First, knowledge of the magnitude of effort required for the manned Mars mission depends critically on measurements; without them, only a very conservative or vague program could be initiated. Second, the lead time for Mars measurements is quite long because of the approximately 26-month interval between launch opportunities and because of the 6- to 9-month trip time, especially when the possibility of failures in probes must be faced realistically. Third, in order to be useful, data on the Mars environment must be available early in the development of the manned system because they can affect the design of virtually every major part of the system. And fourth, the cost of a Mars-measurement program as described here, while by no means trivial, would be small compared with the cost of a manned Mars mission.

Section II of this Memorandum discusses the reasons why certain data would be required and the instruments and techniques for measuring each parameter.

Section III discusses probe possibilities in terms of flight profile and the class of booster size required, as well as the communications concepts and the risks and advantages of some alternatives. The question of whether a totally different probe is needed for a measurement mission in preparation for a manned trip or whether a compromise with "scientific" objectives could be reached is also considered.

## II. MEASUREMENTS: REQUIREMENTS AND TECHNIQUES

In this section, measurements of Mars environmental parameters that are required for planning or designing manned Mars expeditions of various kinds are listed and techniques for measurement are discussed. These techniques range from remote (Earth-based or flyby) to direct *in situ* measurements. For the most part, the required measurements have been determined through a review of past studies of possible manned Mars expeditions. Most of these studies have not made explicit the required measurements, so we have deduced them, for a variety of expeditions. The required data fall into several categories: atmosphere, surface structure and winds, mapping, and Mars radius and oblateness.

### ATMOSPHERIC PARAMETERS

#### Surface Pressure and Temperature

Designers of life-support and heat-load-disposal equipment need to know surface pressure and temperature, and at least their diurnal variations, in order to achieve efficient designs. These data (as well as data on atmospheric density and composition, which will be discussed later) are also important for the design of the terminal landing system, because the temperature of the atmosphere must be considered when determining the suitability of materials and the Mach number and pressure distribution on the terminal braking system. Finally, the ground-level atmospheric temperature and pressure (together with the composition) can be used as a check on the accuracy of density measurements, or as a hedge against erroneous measurements; they are thus very important for this reason alone.

These measurements optimally would be made at the landing site of the manned Mars expedition scheduled to follow, and at the season of the (Mars) year of such an expedition; but neither of these will be known at the time of initial measurement. Studies of landing sites for manned expeditions have been made, of course, but they do not seem to have a very firm basis. Biologically oriented studies tend to favor low-latitude sites in or near a region where seasonal changes have been observed. However, continuous or nearly continuous communications can be achieved with a high-latitude landing site, although this does not seem to be an overriding consideration.

If a Mars-orbit-rendezvous mission mode (i.e., a mission in which the return stage is left in Mars orbit to rendezvous with the lander before return) is used and a high-latitude site is selected, the problems of energy management are complicated by the need to predict accurately the orbit precession (thus requiring additional data on Mars' oblateness). Also, additional constraints are placed on the choice of an orbit, in that significant propulsion penalties result if the satellite orbit plane does not contain the return initial-velocity vector at the time of return. A final consideration is that a near-equatorial landing site would minimize the takeoff propulsion requirements for return trips, whether a Mars-orbit-rendezvous mode is used or not. Therefore, a low-latitude landing site in a "desert" area which shows little seasonal change will probably be considered most favorable for landing, but the site should be near an area of observed change for biological investigation. However, the choice of landing site can be greatly affected by measurements of the type discussed here, and any early selection is subject to future change, especially as more data (e.g., Mariner pictures) are accumulated.

Although we speak here of "ground-level" measurements, it seems both possible and highly desirable to make these and other measurements during terminal parachute descent also, after the period of significant aerodynamic heating and dynamic pressure, both to obtain data on the variation of temperature (and pressure and composition) with altitude, and to hedge against the possibility of equipment failure in the final landing. After a successful landing, measurements should be continued for a period of at least three days in order to measure day/night effects, if any. For this purpose a measurement frequency of about every ten minutes seems reasonable, but this could be somewhat reduced. The power requirements for transmitting this type of data are much less than those for picture transmission.

The pressure and temperature measurements must be sufficiently accurate to achieve a redundant measure of ground-level density; especially high accuracy of individual measurements will not be required. The reproducibility of measurements must be very high in order to detect diurnal variations. To realize about 5 percent accuracy in density estimates (a range which represents probable density variations, and which would not require a significant increase in landing-system weight), more accurate data on temperature and pressure are required. Measuring instruments should cover a pressure range of 1 to 500 mb with an accuracy of about 1 percent and reproducibility to 0.1 percent. Temperature instruments should measure a range of from $150^{\circ}K$ to $300^{\circ}K$, with an accuracy of within $2^{\circ}K$. These are the approximate ranges of estimated values.

In this consideration of measurement techniques, primary interest is in determining which techniques permit unambiguous interpretation with a minimum of assumptions or auxiliary data, rather than in describing specific types of instruments to be used. For measurements of atmospheric pressure and temperature at the surface, a number of Earth-based techniques have been proposed and used, with widely varying results. One such measurement, that by Kaplan et al.,[11] is given as an example.*

Kaplan et al. have measured a Mars surface pressure of 25 ± 15 mb; this is the most recent measurement available. We may and do look forward to improved refinements of the technique used, at the next opposition. It is instructive, therefore, in assessing the probable accuracy of future Earth-based measurements, to review the analysis made by Kaplan and to list the necessary assumptions and/or auxiliary data used in the analysis of observational data. Most of the uncertainty in Kaplan's measurement was attributed to the observations, which were near the limit of sensitivity of the then-available equipment, and uncertainties were not explicitly assigned to other assumptions or auxiliary data.

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*This discussion is representative also of the difficulties encountered in making other remote measurements.

According to Ref. 11, Kaplan's method is based on simple physical principles, rather than on diverse assumptions that are practically impossible to verify observationally. First, the equivalent width of certain spectral (absorption) lines of $CO_2$, which are pressure-independent, is obtained from a spectrogram of Mars; then an estimate of the amount of $CO_2$ in the Mars atmosphere is obtained, using an assumed atmospheric temperature and laboratory measurements of strength of the spectral lines, taking account of the average path traversed by light into and back out of the atmosphere. These data, in combination with measurements of strongly pressure-dependent bands of $CO_2$ (correcting for the effect of the type of pressure-broadening gas), enable an estimate to be made of the surface pressure on Mars.

The following assumptions and auxiliary data are used in deducing the surface pressure on Mars:

- Line equivalent width, which is measured by light coming from the southern one-third of the planetary disc*
- Absolute value of equivalent width of lines, by comparison with Fraunhofer lines
- Atmospheric temperature
- Variation of laboratory line and band strength with temperature
- Effective path length in the Mars atmosphere
- Effectiveness in broadening of various gases
- Types of broadening foreign gas (other than $CO_2$)
- Uncertainty and fluctuations in absorption of 2-$\mu$ bands
- Spectral reflectivity of Mars versus the Moon
- Half-width at standard pressure

These assumptions or the sensitivity of the result to them will not be discussed in this Memorandum; however, it is evident that even in the absence of any measurement error in the Mars spectrogram, many

*This is significant when estimating the effective depth listed later and effectively rules out measurements of variations with space and time.

opportunities for errors are present, even for this relatively straightforward approach. Probably the most important of the assumptions is that of atmospheric temperature. Substantial variations in temperature are possible with height and with geographic position in the Mars atmosphere, and these could have a significant effect on the deduced surface pressure, because of the effect of temperature on line strength.

It is unlikely that temperature variation with altitude in the Mars atmosphere can be measured by Earth-based methods, and we must anticipate a substantial (i.e., 20 percent or more) uncertainty in measurements of surface pressure or density even with much improved ground-based techniques.

This does <u>not</u> mean that ground-based planetary astronomy should not be pursued further; indeed, the improvement of such techniques is very important, and although we do not believe that they can yield sufficient data for planning a manned Mars expedition, they are extremely useful in the design of unmanned probes, since more risk is acceptable in unmanned probes, and contingency allowances can be designed into them with much less penalty.

Earth-satellite-based astronomical observations of Mars have limitations similar to those of Earth-based observations. Although such experiments can eliminate filtering by the Earth's atmosphere, thus providing a wider spectrum for investigations, difficulties in interpretation will still exist. Of course, from a practical standpoint, the difficulties in pointing, exposure time, spectral sensitivity, and resolving power for an Earth-satellite-based measurement would probably make such an experiment less valuable than an Earth-based measurement.

Similar difficulties in interpretation and in instrument design will limit the accuracy of data obtained from flyby probes which make spectral measurements, using reflected light from Mars. The accuracy of occultation measurements of surface pressure and temperature that can be made by a flyby vehicle using transmitted light is limited because the light may be cut off by mountains or dust clouds, so that the altitude at which a measurement is made will be uncertain. Occultation measurements also share some of the difficulties of interpretation listed previously.

Finally, none of these relatively indirect techniques can provide measurements throughout a diurnal cycle on Mars, and none promise the level of accuracy that will be required for design of a manned landing system.

Therefore we feel that a direct surface-pressure measurement is needed to support the planning and design of a manned system, and although this measurement is not one of high priority, the measuring equipment can easily be put on a lander vehicle (which is necessary in any case), and the weight and data-transmission requirements of the instruments should be trivial in comparison with those for other required measurements.

The temperature of the atmosphere is generally more difficult to deduce by ground-based astronomy or other remote techniques than is the pressure.[11] Moreover, because of the spatial and temporal variations which must be anticipated, nothing more than a gross average could be expected. Nighttime temperatures of the Mars atmosphere would not be available at all.

Limited temperature data could perhaps be obtained by a flyby probe, as was done for Venus (although difficulties in interpretation make that measurement somewhat ambiguous). However, it would be very unsatisfactory, compared with data that could be obtained from a lander, in terms of low-altitude temperature, accuracy, and variations with altitude (near the surface, during parachute descent) and with time. Measurement of temperature and pressure by a lander vehicle should not present a serious problem.

## Density and Its Variation With Altitude

If an aerodynamic braking device is to be used, density at the surface and at least an approximate scale height must be known, or a substantial penalty in braking-system weight must be accepted. Furthermore, the higher the speed at which aerodynamic braking is initiated, the more must be known about the density-altitude relationship. Many studies[1,4,12] have shown the favorable effect that aerodynamic braking from hyperbolic speed at Mars has on the initial weight of manned systems. They further have shown that for a certain range of atmospheric models (and other assumptions) the "feasibility" of such operation is not a serious problem. But if manned entry is to be made at hyperbolic speeds, it is vitally important to know in considerable detail the atmospheric density as a function of altitude, in order to know precisely where the entry corridor lies. (If the vehicle overshoots the corridor, it will fail to be captured by Mars; an undershoot results in excessive g-loads.)

Interest in hyperbolic entries at Mars is almost certain to continue, since entry from parabolic or circular velocity would require that the initial gross weight of the vehicle be greater by a factor of about 1.5 to 3, depending on propulsion system, year of attempt, etc., and since, in general, entries at Mars are substantially easier than at Earth (assuming that Mars has an adequately dense atmosphere, that enough is known about it, and that adequate guidance is available).[(12)]

A manned landing is almost certain to be carried out on the sunlit side of the planet (to permit visual selection of a precise landing site); therefore, the first unmanned probe to measure the atmospheric density as a function of altitude should also land on the sunlit side. But since aerodynamic braking into an orbit might well occur at any time of day, it seems desirable to make two or more measurements of density and altitude at widely spaced times of day, to get an indication of the density variations to be encountered in the upper atmosphere.

The accuracy in altitude that is required for a given density depends on the hyperbolic approach velocity[(2,4)] but ultimately is limited by the guidance accuracy that will be possible in manned entry systems. (This accuracy is presently not known with high confidence.) Hyperbolic-entry corridors about 30 km in depth (i.e., tolerance on the periplanet altitude) have been estimated by Sohn.[(1)] Uncertainties in Mars radius, variations of atmospheric density as a function of time, and variations in the scale height of the atmosphere all could reduce the effective corridor depth to about 10 to 15 km, thereby increasing the guidance accuracy required. Since inaccuracies in measuring the altitude at which a given density is present directly reduce the effective corridor depth, altitude measurements must be accurate to within about 1 km to retain a significant margin for guidance error. There will probably be diurnal and seasonal variations in density which a vehicle must be able to accommodate, and this tends to lessen the required accuracy.

Detection of significant density variations requires an accuracy of about 5 percent. A dynamic range of from $10^{-8}$ to $10^{-3}$ $gm/cm^3$ is required, since, depending on the amount of atmosphere present and therefore the ballistic coefficient, densities in this range can have a significant braking effect. Measurements should be made at altitude intervals of 1 km or less to determine whether there is significantly different density from constant-temperature or constant-composition models. For these measurements, Earth-based astronomy can be ruled out at once, because it has insufficient resolving power to give an adequate picture of the density variation with altitude. A decision to include equipment for several time-phased measurements on an early probe will depend on the payload available and the other instrumentation to be carried, among other things.

The 1964-1965 Mariner radio-occultation experiment, however, is intended to obtain an indication of (average) scale height* of the Mars atmosphere and, if successful, will yield very important data for the design of unmanned probes. But as a measuring device for support of future manned hyperbolic-entry systems, the Mariner experiment has several important limitations:

1. Mariner will not provide an absolute altitude scale (in terms of fixing the density at a given altitude) because cutoff of the signal will not be sharp and may be caused by a number of things other than the mean surface of Mars, e.g., mountains, dust clouds, or ionosphere. (This is a difficulty shared by all occultation experiments.)

2. Interpretation of the results will depend on the index of refraction for radio waves of the constituents of the Mars atmosphere, which are substantially unknown. No index-of-refraction measurements

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*The scale height is the altitude interval over which the density changes by a factor of e. It is variable within a given atmosphere, depending on temperature and composition changes with altitude.

have been made of gases that may exist at Mars at the frequencies of interest. It has been assumed, reasonably, that the index of refraction of the Mars atmosphere at a given density will be like that of the Earth.

3. The effective path width of radio waves through the Mars atmosphere will be measured in kilometers, and for this reason the "resolving power," or the ability to measure changes in scale height with altitude, will be very limited.

4. Uncertainty in the location of the occultation path can result in substantial uncertainties in the deduced scale height, especially for near-grazing paths.

It should be emphasized that these comments, and earlier comments on pressure measurements made by Earth-based astronomy, must not be interpreted as criticisms of the experiments; indeed, a great deal of very ingenious thought has gone into them, and within the existing constraints, they represent near-optimum utilization of techniques. Our point is that the data they will give are valuable and necessary but not sufficient for planning manned missions.

Two principal methods have been considered here for density measurement: deduction from known mass, area, velocity, and drag coefficient, and the use of radiation-scattering measurements.

Drag-deduced density measurements are highly attractive, because they are relatively simple, require very small power, and are readily mechanized. But they are limited in the following ways:

1. Accuracy will be poor at very high and at very low altitudes (on either side of the maximum-deceleration region) where the acceleration is low. Because future entry vehicles may have very different deceleration altitudes, it is desirable to expand the range of density measurements.

2. During hyperbolic entries, the mass of the vehicle will change due to ablation by an amount that is difficult to measure or predict, and drag estimates will be correspondingly in error.

3. For all except spherical bodies, drag is sensitive to angle of attack, which is difficult to measure in itself. Spherical bodies require greater mass for structure and heat protection,[13] and a

spherical body with offset center of gravity, as described by Beuf,[6] will oscillate, which may result in spurious cyclic accelerations that are difficult to measure when a limited number of readings are taken.

4. The probe must survive past the maximum acceleration point in order to obtain an indication of the scale height. Depending on blackout effects and data-transmission rate, some data may be lost in the processes of storage and transmission.

Because of these limitations, it is desirable to examine other density-measuring methods, of which radiation backscatter seems most promising. This is more fully discussed in Ref. 14, which concludes that (1) it appears feasible to measure density over the range of $10^{-8}$ to $10^{-3}$ gm/cm$^3$ using X-ray backscatter techniques; (2) the expected accuracy is about 10 percent at the lowest density, and it improves very rapidly as density increases and as the entry angle is reduced, permitting longer integration time; (3) the power requirement is fairly high--about 100 w during the entry period; and (4) X-ray backscatter techniques are insensitive to shock layers surrounding the vehicle, angle of attack, velocity, and the composition of the atmosphere.

Such a technique should not replace drag-deduced density measurement entirely, because of its relative novelty. However, we do feel that with drag methods as a backup, it represents the preferred method of density measurement because of its wide dynamic range and capability to produce accurate and unambiguous data at high and low altitudes.

Altitude measurement during entry is a more difficult problem, and it seems not to have received adequate attention. Seiff[7] and Beuf[6] have proposed measuring altitude by making a double integration of acceleration. This method depends on the probe surviving entry all the way to the surface, in order to get an indication of a zero altitude,* and since acceleration-data acquisition and transmittal are relatively poor, as is the accuracy with which initial velocity and

*The Deep Space Instrumentation Facility (DSIF) alone cannot determine its pre-entry position with the required accuracy.

entry angle could be known, this method could result in significant errors in the altitude at which a given density would be present. Roberts,[13] for example, points out that an error of 0.5 percent in accelerometer measurement could lead to an error of 100 percent in the density at high altitude. Since Beuf[6] limits the accuracy to about 1.5 percent, in order to limit the transmission rate, the accuracy in altitude would not appear to be very good. More direct methods of altitude measurement must therefore be considered.

Alternative methods of altitude measurement are (1) radio altimetry from the lander during entry, and (2) radio-ranging (plus trajectory analysis) by a transponder link between the lander and an orbiter of known altitude. Both methods require communication with the entry vehicle during entry for measurement of altitude, and therefore the radio-blackout problem which may exist during the period when the more valuable data are being acquired must be considered. If the lander is ejected after orbit is established, then no blackout is encountered at practical frequencies, and there is no problem. On the other hand, radio altimetry from a hyperbolic-entry vehicle must communicate through or near the stagnation region, where the electron concentration can approach $10^{15}$ per cubic centimeter[15] and the critical transmission frequency would be $2.7 \times 10^{11}$ cps, which is inaccessible to current electronic techniques. Even for transmission out the side or back of the vehicle, an order-of-magnitude increase of frequency above the 2300 Mc DSIF value would be required, and techniques for such frequencies are in an unsatisfactory state of development[16] for implementation in a space vehicle. Moreover, blackout predictions are very uncertain because, among other things, little is known of atmospheric constituents and of the recombination rate of electrons in an expansion. Methods for avoiding blackout (other than frequency change) have also been discussed,[17] but they do not seem practical for use in the stagnation region, as they are largely unproved and require a substantial complication of the entry vehicle.

For these reasons, to make precise measurements of altitude with high confidence (i.e., where the vehicle does not have to survive through landing) requires entry at substantially less than the (nominal)

27,000 ft/sec that results from a minimum-energy transit. The velocity need not be as low as orbital velocity to avoid blackout; depending on the altitude-measurement scheme and the entry angle, reduction of the entry speed to about 16,000 to 20,000 ft/sec would be adequate. But other considerations, which are discussed in Section III, suggest that it would be preferable to achieve orbit before retrofiring of the lander.

Both of the radio-ranging schemes described above (i.e., radio altimetry from the lander, and radio-ranging between the lander and the orbiter) require radio altimetry, and in order to get an idea of the power requirements of such a system, rough estimates of a radio altimeter intended to be used for the more difficult of the cases have been made (from the standpoint of the power required); that is, the determination of altitude from an orbit of approximately 1000 km. An operating frequency of 2300 Mc has been assumed (since an orbiter will have such a power supply, not because it is necessarily optimum). A 1-ft-diam antenna has a 34-deg beam width and a gain of 14.5 db. A ground-reflection factor of 0.1 has been assumed (this is probably conservative, since, for example, dry sand has a reflection factor of about 0.25), a signal/noise ratio of 20 db, a combined noise temperature of detector and background of 600°K, and a bandwidth of 3 Mc. The resulting peak transmitted power is about 160 w in 1-μsec pulses. A duty cycle of about 1/1000 gives abundant measurements, so that the average power is quite low and would be dominated by heater power, which is estimated to be about 4 w. Such a design would not be entirely suitable for an entry vehicle, because a still less directive beam would be required (because of changes in attitude of the vehicle), and a shorter range would be required. In either case, radio altimetry does not seem to place unreasonable demands on the state of the art in electronics or on the vehicle power supply. Thus, radio altimetry on board the entry vehicle is the preferred method of measuring altitude, since it would give the most direct results. This, of course, requires propulsive retrofiring for the lander or entry from circular velocity. If the probe makes a high-speed entry, accelerometer-derived altitude measurements seem the only practical possibility, in spite of the problems previously noted.

Composition of the Atmosphere

The design of a heat-protection system for the entry vehicle can depend critically on the composition of the atmosphere.[3] In addition, measurement of composition is important in that it provides two independent methods for the ground-level density measurement (deducing density from pressure, temperature, and composition, as well as from the radiation-backscatter method discussed earlier); it aids in analysis of the temperature structure of the atmosphere; and it is of use in the design of the surface life-support system. The composition at the surface should receive primary attention, although it will be of interest to analyze the atmosphere at high altitudes also, because of the important problem of entry heating. Monitoring the temperature of the heat-protection system could provide an indirect indication of special heating problems, although such data would be very difficult to interpret in terms of the atmospheric composition. Although a complete quantitative analysis of the atmosphere that will be encountered during entry does not seem possible because of contamination by ablation products, spectrometric observations at one or a few bands should be possible. In any case, such backup measurements should definitely be made.

The ground-level composition should be measured at the landing site just prior to landing, with positive identification of species having atomic or molecular weights of from 1 to 150 (to include all inert gases). The amount of constituents whose densities are as low as $10^{-6}$ gm/cm$^3$ should be measured with an accuracy of within 5 percent, to indicate the possibility of special heating problems, as well as to provide data to be used in the design of life-support equipment. All measurements should be repeated about 6 and 12 hr after landing, in order to detect diurnal variations in composition.

Because some of the major constituents of the atmosphere of Mars may be impossible to measure spectroscopically, an actual penetration of Mars seems necessary. Measurement techniques are discussed in Ref. 18, which emphasizes soft-landed instrumentation. The principal results of that study can be summarized as follows:

While Earth-based astronomy can contribute significantly to our knowledge of atmospheric composition, it is limited by atmospheric attenuation and the radiating bands of possible species. Flyby or Earth-orbital measurements may be possible, but they cannot be shown to be adequate, because of the unknown transmission characteristics of the Mars atmosphere. In addition, quantitative spectroscopic analysis places very severe requirements on instrumental techniques and on data transmission and is of questionable feasibility, especially when the constituents are not known. The same limitations apply to occultations of stars by the planet which are observed from a flyby vehicle. Spectrometric analysis of the shock layer of an entry vehicle does not seem adequate either, since it presents similar problems, in addition to those caused by contamination of the shock layer by ablation products. Detailed measurements of composition could be delayed until after significant heating had occurred, possibly until after parachute deployment. But certain limited measurements related to composition should be made during peak entry loading: temperature instrumentation of the heat shield and measurements of shock-layer radiation in one spectral region, or possibly a very few, would give rather direct indications of special heating problems due to composition, although they would not give composition data of significant value for other purposes. A radiometer filtered to admit radiation of the CN (cyanide) band to pass appears to be the most important type of early-entry composition instrumentation.

Mass spectrometry is the best available technique for measuring the composition and density of the Martian atmosphere from a soft-landed instrument package, and gas chromatography is a fairly close second. The short measurement time possible with mass spectrometry makes its use during parachute descent particularly attractive.

A mass spectrometer of the magnetic-deflection type might weigh about 5 lb, would require 4 to 5 w of power, and could produce a scan of the entire m/e (mass/electronic charge) range in 1 to 3 sec.

## SURFACE FEATURES AND RADIATION ENVIRONMENT

### Load-Bearing Capability and Slope

Load-bearing capability and slope must be measured to assure that a manned vehicle will be able to land on the surface without toppling over or sinking. A successful unmanned landing and at least photographic or television pictures of the surface taken after landing will be required to gain even reasonable assurance of adequate load-bearing capability. These pictures should range from the close-ups of surface immediately under the vehicle (photographed with a resolution of about 1 mm to get an idea of the nature and amount of soil consolidation) to panoramic views of the surrounding territory, with special provisions such as incorporation of stereo pictures for quantitative estimates of slope distribution. Pictures should also be taken before landing, in order to extend the area covered and to perhaps reveal presently unanticipated problems.

One or a few point measurements are essentially without value for measurements of surface slope. Two kinds of measurements seem necessary: (1) pictures taken of the area surrounding an unmanned-landing site (which at present we can only hope will be that of a manned landing), during parachute descent and after landing, and (2) global mapping for detection and mapping of mountains, valleys, or other irregularities. A landing site cannot be finally chosen at this time, but measurements should not be delayed on that account, since they are necessary to make such a choice. But it must be anticipated that a number of landers will eventually be required for this purpose, as well as for a repeat of density/altitude measurements. This discussion does not include details of television-camera design or picture-storage techniques, some further discussion of measurement techniques for the low-altitude and surface pictures is in order.

Because of the absence of familiar objects from which to get an indication of range, it seems necessary (for quantitative estimates of slope) to use stereo cameras for at least some of the pictures. It is desirable to provide a 360-deg coverage of the horizon, say by eight cameras, each with a field of view of approximately 50 deg, and to make every other picture a stereo pair. During parachute descent, a set of such pictures should be taken at an altitude (from radio altimeter) of 3 to 5 km. The precise altitude depends on details of the vehicle design and the power available; lower altitude would give more detail but less time for data transmittal. If energy for data transmission is not limited, two or more sets of such pictures should be taken at decreasing altitudes. All or as much as possible of the data taken by a lander should be transmitted before landing because of the substantial risk of landing failure due to terrain strength, slope, or surface winds.

The load-carrying capability can be measured at only one (or at most, a few) points by a probe. Experience on Earth suggests, however, that there are relatively few kinds of surface that would cause trouble, and most of these are not expected to exist on Mars, at least not in "desert" areas (e.g., liquids, forests, marshes, thin ice). Speculations about the moon have suggested some additional possibilities such as very deep, loose dust or a very porous and compressible surface. In any case it does not seem appropriate to make detailed chemical analysis of the crust, or to make measurements of particle and rock size. Most of the questions about the local surface would be adequately answered by a successful landing, and it is questionable whether any further measurements (aside from pictures) would be necessary.

The load-bearing capability of the surface and its gross structure could be found by either of three methods: (1) by mechanical penetrations of the surface after landing, such as by drills, spikes, or ploughs, in which the penetration as a function of load would be recorded; (2) by a picture taken of the leg or supporting structure of the vehicle, together with data on the terminal velocity; or (3) by detailed measurements of the deceleration of an impacting body as a function of time during impact.

Of these methods, only the last could be used in case of a vehicle failure during the landing operation. Possible variations include use of a device shot or ejected from the primary lander vehicle and (depending on the vehicle configuration) measurements of deceleration of a leg or impacting part of the vehicle. Because of the difficulty of predicting altitude or impact time accurately, the latter arrangement seems the more practical. With this technique, the deceleration and time data must be transmitted during impact but before failure of the lander transmission system. Because a surface structural problem (i.e., a low load-bearing strength) would result in low, rather than high, values of deceleration on impact, the possibility of successfully obtaining data with such a device seems very good. Until the general arrangement of the landing vehicle and its expected touchdown velocity are known, very little can be said about specific details of instrumentation.

If the landing is successful, much more valuable data could be obtained from a picture taken of the impacting part after landing, because an indication of penetration depth and of the makeup of the surface would thereby be obtained. Again, details depend on the lander configuration, which is as yet unknown.

All these surface-measurement techniques and others we have considered are capable of measuring characteristics at only one or a few points. A broader coverage would be desired, and to some extent, depending on the initial findings, some indication of surface characteristics over a significant area could be supplied by television pictures, as discussed previously.

## Winds

The magnitude of winds present must be considered in the design of the landing system and the takeoff system of vehicles for manned missions. For example, very high wind velocities could introduce entirely new landing-engine requirements. Because temporal and spatial variations in winds are to be expected, a long observing period would be desirable to get a reasonable idea of the fraction of time winds exceed a certain magnitude. Moreover, measurement of wind velocity during descent of an unmanned lander would not be statistically significant, although it could be useful in diagnosing a possible failure of the lander. An indication of wind velocity could be obtained from pictures of the surface taken during descent (as discussed previously) or from terminal-deceleration data, and this indication should suffice for diagnosis of possible failure.

For takeoff systems the dynamic pressure level and wind shear are of greatest interest. But their importance depends strongly on the atmospheric density, and for most estimates would not present a significant problem. Therefore we feel that measurements of dynamic pressure and wind shear are not in themselves of as high priority as are measurements of surface wind velocity.

Determining the duration of wind measurements by initial probes is a serious problem; these measurements are almost unique in that they require a significant active life for the lander. On the other hand, the power requirements for measurement and transmission should be very small (compared, for instance, with Voyager requirements). An active duration of at least several months is necessary to obtain statistically significant data. Ideally, measurements would be taken at the site planned for the manned landing and during the season of the Mars year when the manned landing will be made, but it is unlikely that the landing site or season will be known at the time of initial measurement. Nevertheless, we do not believe that the measurements should await program definition; rather, they should precede it, even at some cost in terms of strict interpretation of the data. Measurements of wind velocity of from about 10 to 150 kn (the range estimated heretofore) with about 10 per cent accuracy and a frequency of about one every 10 min would be sufficient. For statistically significant data giving the fraction of time the wind exceeds specific velocities, measurements should be made for roughly three months.

Instruments for long-term, intermittent measurement of winds present a novel design problem. The direction of the wind is of little or no interest. Preferred techniques would measure wind velocity more or less directly, rather than dynamic pressure, which would put very severe demands on the dynamic range of a detector; the data obtained would also require additional interpretation.

No development work has been done on anemometers for use on Mars, and we must expect that a significant amount of experimentation and calibration on possible techniques would be required. In general, it seems desirable to avoid mechanical (windmill) anemometers such as have been used on Earth because they tend to be heavy and otherwise unsuited to space application; and careful correction must be made for ambient conditions when hot-wire techniques are used, which would increase the required data rate. A relatively direct measurement of wind velocity, and one for which the instrumentation could be rugged and compact, might be devised as follows:

In the center of a substantially horizontal plane, spark electrodes would be placed which would ionize an element of "air" on discharge. Wind in any direction across the plate would cause the element of ionized "air" to move and encounter two other electrodes in the form of circles (centered on the first electrodes) that are close to each other and charged to a potential just below that required to discharge them. When the ionized element of "air" reached these electrodes, it would cause them to discharge because of its higher conductivity. The wind speed could then be found by measuring the distances from the central electrodes to the outer-ring electrodes and the time interval between the two current pulses. The distance between the pairs of electrodes would be set by the minimum wind speed to be measured and by the recombination rate of the ionized "air." A substantial amount of experiment would be required to verify the possibility of such an instrument working over the range of atmospheres now postulated. In view of the uncertainty about atmospheric pressure and composition, a self-correcting system to set the potential on the second pair of electrodes would be necessary. This might be done by making the gap and shape of the primary electrodes such that they would discharge at slightly lower voltage than the secondary electrodes and feeding them from the same supply (with suitable switching and auxiliary circuits). This technique is one on which laboratory work seems appropriate.

It cannot be said that this technique is the best, or even that it would work, but at the same time we do feel that with ingenuity and experiment a simple and rugged anemometer (possibly even of a mechanical type) could be devised to meet these novel requirements.

Radiation Environment

Ultraviolet, X-ray, and radiation measurements must be made on the surface of Mars before protective equipment for personnel can be designed. Since this is a well-known problem area, these measurements will not be discussed in detail, other than to indicate that a rather low sampling rate (perhaps 2 or 3 per day) should be adequate, since solar-radiation flares are of longer duration. Also, only data above a background level not requiring shielding would need to be transmitted. Here, however, it would be desirable to make measurements for a significant duration (e.g., several months), especially in the hope of detecting the effects of solar storms on Mars' surface radiation. To determine whether Mars' magnetic fields or atmosphere provide substantial radiation shielding, similar data simultaneously taken by an orbiter would be of great interest. A number of probes for measuring interplanetary and Mars-neighborhood radiation and particle flux are already planned. Therefore, requirements for such measurements have not been discussed.

TOPOGRAPHY

An initial mapping effort should be undertaken to get an indication of the presence and location of mountains and valleys and to discern the surface slope on a global or nearly global basis, as a further aid in selecting sites for manned landings. Since measuring probes will undoubtedly land at or near a proposed manned-landing site, in order to investigate slope and surface strength, extremely good resolution of space and height is not required. Data obtained from mapping should be adequate to permit navigation for a manned landing (by locating prominent features) and should resolve many questions about the surface configuration, such as the depression of canals, the elevation of particular features, and the general homogeneity of the desert areas.

Camera and television subsystems have been studied in detail for Voyager,[10] and that effort will not be reproduced here. A stereo system with a ground resolution of about 1 km and a height resolution of about 350 m can be used for mapping. Such a system will not in itself discern whether slopes are suitable for manned landings; this will require a significant amount of photo-interpretation, as well as lander pictures.

An orbiter carrying a mapping system must have a high orbital inclination for global coverage, and a minimum altitude (limited by sterilization considerations) over the sunlit side of the planet to give the best ground resolution.* For optimal illumination, the angle between the orbital planes and the Mars-Sun line should not be less than about 30 deg or more than about 70 deg, to avoid either poor contrast or surface darkening.

A conflict arises in orbit-inclination requirements because a polar orbit, which would give complete mapping coverage of the planet, would not permit a determination of the second harmonic of the gravity distribution. (This will be discussed in more detail later.) Because mapping has a low priority among the measuring efforts and because it is unlikely that a very high-latitude landing site will be selected, it seems reasonable to compromise the orbit inclination to a lower value and forgo mapping of the polar regions, at least for the first orbiter.

## RADIUS AND OBLATENESS OF MARS

### Radius

If a manned hyperbolic entry is made at Mars, using a terminal guidance system based on angle measurements between stars and the (deduced) planet center, it is necessary to know not only the altitude at which the entry corridor exists, but also the radius of Mars, because the present uncertainty (about 30 km) in estimates of the radius of Mars equals or exceeds the depth of corridors for manned hyperbolic entry. Terminal guidance systems of the type described above are the only ones which have received study (and that only in a somewhat idealized way).[2] It may be possible to design a terminal guidance and correction system that uses altitude information acquired during approach (from optical observations of the planet limbs or from radio

*The effect of orbit period on the efficiency of coverage has been extensively discussed in Voyager studies.[9,10]

altimeters, for example) to correct the approach trajectory. System designers would have to determine whether sufficient time would be available for propulsion corrections, the magnitude of propulsion corrections required, and the orientation time required for propulsion corrections and to prepare for entry.

Thus, depending on the results of more detailed guidance-system study, the radius of Mars may not have to be measured accurately for a hyperbolic manned entry. More realistic studies must be made of the problems of the more conventional guidance scheme also, particularly the determination of the center of a partially illuminated and possibly irregular planet. The guidance problems presented by manned hyperbolic entry at Mars are for the most part the same as those of hyperbolic re-entry at the Earth,* which is generally considered feasible (although the entry velocities and heating problems at Earth demand substantial development of protection equipment).

Because of possible variations of flight profile and guidance equipment, a firm requirement to measure the radius of Mars cannot be established. However, a significant penalty could be incurred if the radius is not measured, whereas if it is measured and later not used, only the relatively small penalty resulting from its incorporation in the payload of a probe would have been incurred. Instruments for the preferred method of radius measurement, radio altimetry from orbit, can be incorporated into equipment installed for another purpose (measurement of altitude during aerodynamic braking and descent), so that the penalty can be small.

The estimated width of entry corridors and the probable accuracy of guidance systems[(1)] suggest that a measurement of Mars radius to within 1 to 2 km is desired. Because of the possibility of mountains and other irregularities on the surface of Mars, radius measurements in at least three nearly perpendicular directions are necessary and a more extensive investigation is highly desirable.

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*Except as modified by the presence of active transmissions from the Earth.

Earth-based astronomical measurements of Mars radius (which have many experimental sources of error) are limited ultimately by the resolving power of telescopes. For a 100-in.-aperture telescope operating at a wavelength of 2 x $10^{-5}$ in., the resolving power, neglecting atmospheric turbulence (such as would occur in an orbital or lunar observatory), is about 1/20 sec of arc,* or, at Mars distance, about 15 km. Optical measurements are, of course, further made uncertain by the atmosphere (both of Mars and Earth), limb darkening, nonnormal illumination, and other factors. Atmospheric turbulence on Earth limits resolution to about 1/2 sec of arc, or about 150 km at Mars. This possible error is larger than the allowable corridor width for hyperbolic entry (about 30 km, or about 15 km for a low-pressure, lower-scale-height atmosphere).(1) Thus, this uncertainty by itself could cause a simply guided spacecraft to miss, or come dangerously close to missing, the entry corridor. In view of the many other uncertainties, such as the altitude at which the atmosphere has a specific density, the possible variations of density with time, and guidance accuracy, it clearly is desirable to make the radius-measurement uncertainty small in comparison with the entry corridor.

It may be possible to obtain radius data from a Mariner radio-occultation flyby, provided that the location of the flyby path behind the planet could be known with high precision, the radio cutoff could be distinguished from atmospheric effects, and reacquisition of signal was not delayed for any reason. Because of problems in interpretation, this type of measurement seems insufficiently accurate, as do television pictures of an illuminated limb. On the other hand, an orbiter with radio altimeter and a communications link to Earth can produce relatively accurate data. Radio tracking and analysis alone can provide very precise data on the orbital elements of such an orbiter, with the exception of the size of the orbit. The accuracy with which the size of the orbit can be known depends on the accuracy of knowledge of the

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*The definition of resolving power is based on the ability to separate two stars out of their diffraction patterns, and a diameter measurement is somewhat different. Nonetheless, it is a useful indication of the order of accuracy to be expected.

mass of Mars, which is known to about 1 part in 1000, through observations of the period and size of natural satellite orbits. (Here again, the accuracy depends, in effect, on the resolving power of telescopes, but the distances of satellites from the center of Mars can be measured with better accuracy when they are much greater than Mars' radius, so improved accuracy can result.) The uncertainty in radius of an artificial Mars satellite at a low altitude (nominally 4000 km from the center) thus would be about 4 km.

The radius of the planet could be found by a radio altimeter from an orbit of known dimensions, as described previously, with an error in altitude that could be made small in comparison to the uncertainty in radius of the orbit. With this method, limited information could also be obtained on the actual shape of Mars, and this would be of interest in planning a manned expedition.

Optical methods of determining radius from orbiters or near-flybys do not seem to be competitive with the above method in accuracy or in ease of practical realization. Various methods using a lander are possible, but they promise no greater accuracy and they require accurate knowledge of latitude of the lander.

## Mars Oblateness (Flattening)

If a Mars-orbit-rendezvous profile is used for the manned mission (which is probable) and the Mars orbit chosen has a significant inclination, the oblateness of Mars must be known. The Mars departure velocity requirement depends on the extent to which the Mars orbit plane (at the time of departure) can be made to contain the departure velocity vector. For this reason it is necessary to be able to predict the precession rate of an orbit that is caused by Mars oblateness.

Flattening* can result in a significant rotation of the line of nodes, as shown in Ref. 2. For a case with an orbital inclination of 148.5 deg, flattening results in a rotation of the line of nodes by

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*As used here, "flattening" refers to asymmetries in the gravitational field rather than in the planet's surface.

47.8 deg in 20 days, or almost 2.5 deg/day. The flattening used in calculating this example was arrived at by observations of the natural satellites of Mars and by an analysis of their orbital perturbations due to the Sun and to flattening. Although this analysis and the observation accuracies have not been examined in detail, it seems clear, because of the very low inclinations of the natural satellites and because of their relatively great distances from Mars, that such observations cannot yield values of very high accuracy. Theoretical models for the internal structure of Mars have been proposed which have flattening ranging from 0.0049 to 0.0057, a sufficiently wide range to cause a significant mismatch of orbit plane and desired departure direction, especially for stay times longer than 20 days.

To measure the rate of rotation of the line of nodes, an orbiter should have as low an altitude as is consistent with sterilization rules* and should have neither an equatorial nor a polar inclination. The rate of precession is proportional to the cosine of the inclination, but for zero inclination the precession rate is indeterminate and would be difficult to measure even for low inclinations (e.g., less than 10 deg). Because mapping in particular seems to call for high orbit inclinations, it is reasonable to consider inclinations as high as about 60 deg for flattening measurements. Rotation of the line of nodes should be measurable (and predictable) to an accuracy of within about 0.1 deg/day (or better, depending on the length of the manned stay), since a nominal stay time of 40 days would result in an uncertainty in orientation of about 4 deg, and this would not seriously penalize the return velocity requirement. The present uncertainty in oblateness is large enough that a change in Mars stay time by a factor of 2 or more might have to be made if this measurement were not made.

For an orbiter active life of 30 days, assuming an angle between the orbital plane and the line to Earth of 45 deg or less and an orbital inclination of about 45 deg, to measure the orbital rotation to within 0.1 deg/day would require that the orbiter velocity (relative to Earth) be measured by Doppler methods with an accuracy of about 0.03,

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*Past orbiter studies[(8)] indicate that an altitude of 1000 km or more would be required to give an orbiter lifetime sufficient to avoid contamination of Mars by an unsterilized orbiter.

or within about 300 fps. This value is well within the capability of the DSIF system. Therefore, on-board optical angle measurements[19] do not seem necessary for this measurement, unless the orbit is nearly perpendicular to the Earth-Mars line or is nearly equatorial, and both of these cases should be easy to avoid.

A summary of required measurements is given in Table 2, which indicates accuracy, range, duration, etc. Preferred techniques are summarized in Table 3.

## TIMING

The timing required for measurements in support of a manned Mars landing depends on the flight profile to be used, among other things. If full advantage is to be taken of aerodynamic braking at Mars, the density/altitude measurements discussed here would be necessary to verify the possibility of hyperbolic entry and to supply design data. This in turn would establish the size of a new booster and/or stages for a manned mission; and since present indications are that nuclear rockets could be used, a significant development time for engines and stages must be anticipated--say, eight to ten years between sizing of the stage and operational flight. If three probe flights are planned to measure the Mars parameters, the first probe should precede the manned mission by 14 to 16 years. Of course, different flight profiles (such as entry at Mars at less than hyperbolic velocity) could relax the urgency of some measurements significantly, as could allowance of large design size margins (such as allowing enough margin to permit either hyperbolic or circular entry at Mars).

Table 2

MEASUREMENTS REQUIRED TO SUPPORT A MANNED EXPEDITION

| Item Measured | Desired Accuracy | Range | Location or Occurrence | Duration | Frequency | Priority |
|---|---|---|---|---|---|---|
| Surface pressure | 1% | 1 - 100 mb | Landing site[a] | 3 days[b] | 10 min | Low |
| Surface temperature | $2^{o}K$ | $150 - 300^{o}K$ | Landing site[a] | 3 days[b] | 10 min | Low |
| Density | 5% | $10^{-8} - 10^{-3}$ gm/cm$^3$ | During entry | ...... | 1 sec | First |
| Altitude | 1 km | 0 - 100 km | During entry | ...... | 1 sec | First |
| Composition | (c) | At. or mol. wt. of 1 - 150 | Landing site[a] | 12 hr[b] | 6 hr | Third[d] |
| Surface slope | 5% | 1:20 - 1:5 | Landing site[a] | ...... | ...... | Second[e] |
| Winds | 10% | 10 - 150 kn | Landing site[a] | 3 months | 10 min | Second |
| Topography | (f) | ..... | Global | ...... | ...... | Low |
| Mars radius | 1-2 km | ..... | 3 at rt. ∠'s | ...... | ...... | Fourth |
| Oblateness[g] | $\sim 0.1^{o}$/day | ..... | ............ | ...... | ...... | Fifth |
| Surface radiation | ...... | ..... | Landing site[a] | 3 months | ...... | Low |

[a] Low-latitude desert area.

[b] And during parachute descent.

[c] Less than 5% on components as scarce as $10^{-6}$ gm/cm$^3$.

[d] Plus temperature instrumentation of heat shield.

[e] Large area coverage desired.

[f] Resolution sensitivity of 1 km to 1:5 slopes.

[g] Precession rate of orbit.

Table 3

SUMMARY OF PREFERRED MEASUREMENT TECHNIQUES

| Measurement | Technique |
|---|---|
| Atmospheric pressure | Transducer (type unspecified) on lander, to function during parachute descent and after landing for about three days. |
| Atmospheric temperature | Transducer (type unspecified) on lander, to function during parachute descent and after landing for about three days. |
| Density | X-ray backscatter gauge, to function during entire lander entry process. Backup by drag-deduced density measurements (accelerometer). |
| Altitude[a] | Radio altimeter in lander. Requires descent from orbital speed to avoid blackout. |
| Composition | Mass spectrometer in lander, to function during parachute descent and after landing. Temperature instrumentation of heat shield and filter radiometry to make composition-sensitive measurements during entry. |
| Surface load-bearing capability | Accelerometer with real-time transmission on lander leg or foot. Television picture of foot after landing. |
| Surface slope | Television pictures (stereo) from lander during and following landing. |
| Winds | Anemometer (type unspecified) on lander, to function for about three months. |
| Mapping | Stereo television pictures from orbiter. |
| Radius of Mars | Radio altimeter from orbit. |
| Oblateness of Mars | DSIF tracking of orbiter for about thirty days. |

[a]To go with density data.

## III. PROBE FLIGHT-PROFILE POSSIBILITIES

The confident design and implementation of a hyperbolic, manned entry vehicle for use at Mars depends on obtaining accurate and direct measurements of the Mars atmosphere. As evident from the discussion in Section II, this requires a probe flight profile different from those previously studied (and discussed briefly in the Introduction). To avoid radio blackout at practical frequencies and permit altitude measurements during entry, the entry velocity should not exceed about 16,000 fps.[12] However, all probes considered previously have a near-vertical hyperbolic entry at a nominal velocity of 27,000 fps. On the other hand, a low-angle entry from orbit would result in a nominal velocity of about 11,000 fps. This would make possible longer integration times (or smaller altitude intervals) for the density-measuring instrument considered here (X-ray backscatter) and would permit a longer data-transmission time--both desirable, if not necessary, features. This section briefly discusses several flight-profile variations that could be used within the radio-blackout limitations.

One possibility is a profile like that of Voyager, with separation of the lander before establishment of orbit, and with a second propulsive maneuver given to the lander just before it enters the atmosphere. While this profile could permit an entry velocity low enough to prevent radio blackout, it would require that the lander have an attitude-sensing and control system and would make still more critical (because of the longer entry time) maintainance of line of sight to the bus. It also would require an additional velocity increment, would require precise timing of the retrofiring (possibly by means of a radio altimeter), and would result in a near-vertical entry. This mode seems to raise enough critical problems that the small saving in propulsion (compared with the modified Voyager described below) does not seem worthwhile.

In another mode of operation investigated, the lander was to be separated from the bus before it went into orbit and given sufficient retrovelocity to decrease its entry velocity to 16,000 fps (to avoid radio blackout) in a single propulsion maneuver. It was desired to find if there was any location for this maneuver that would permit entry before the bus passed perifocus (and was maneuvered for orbital attainment) and keep the bus in the line of sight. No such location could be found, because the resulting lander velocity was much lower than the bus velocity and the lander had to travel almost as far.

While the scope of this study does not encompass vehicle design, on the basis of earlier Voyager studies, it seems likely that Voyager could be modified to have an entry from Mars orbit rather than from hyperbolic speed. (Early Voyager studies showed that two landers, each with a large scientific payload for biological experimentation, could be carried.) It can be pointed out that the reduced entry velocity and angle of such a modified-Voyager flight profile result in some redeeming features as far as payload capability is concerned, since they would permit a higher $W/C_DA$ for a given atmosphere. The fact that communication distance between the bus and the entry vehicle tends to be minimized for this mode of operation makes possible a relative saving in entry-vehicle power required. (The communication distance during descent from orbit is of the order of the orbit altitude, or about 1000 km. Depending somewhat on the site chosen for hyperbolic entry, the communications distance from the entry vehicle to the bus is of the order of the planet radius, or about 3300 km. A reduction in communications power by an order of magnitude would thus be possible with entry from orbit.) A reasonably detailed study of a complete design would be required to show the effects of variations in entry angle, ballistic coefficient, and communications concepts on the weight of an entry vehicle.

Although the concept of a modified Voyager could utilize a Voyager bus with little modification other than an increase in propellant, the lander and virtually all its major subsystems would be different. Without a design study of such a probe one cannot be sure that all the instrumentation discussed in Section II could be carried, though there is good reason to believe so on the basis of early Voyager studies. The power supply for the lander of such a probe would have different requirements than that of a long-term biological probe. In particular, the power requirements would peak during parachute descent if it is attempted, as seems desirable (pending detailed design study of antenna breakdown and time available for transmission), to transmit television pictures before landing. Throughout descent a smaller steady-transmission load of atmospheric data would exist. After landing, about ten more pictures would constitute the main load, followed by a very low data rate for wind and radiation data for a period of weeks or months. The high peak powers seem to call for chemical rather than nuclear power supplies, and in view of the long-term storage and sterilization problems encountered with fuel cells, perhaps a chemical dynamic system (basically a rocket chamber driving a turbine and generator) could be used. The long-term low-power-level requirements might be met by solar cells or by batteries, if sterilizable solar cells prove infeasible.

The emphasis that has been given here to vehicles of the Saturn 1B-launched Voyager class is due to the fact that none of the measurements in the form we have discussed can be carried out by smaller available vehicles. But a different form of one of the more important measurements, that of density as a function of altitude, might be carried out by a modified Mariner.[9] Since this measurement is behind our interest in a modified Voyager, some explicit comparison of the two approaches is warranted. There are two sorts of reasons why we feel a modified Voyager is more desirable ; one deals with achievable accuracy of the altitude and density measurements and the other with the (avoidable) risks of the hyperbolic-entry probe.

The accuracy of the deceleration-derived data acquired by a hyperbolic-entry probe, as described by Beuf[6] is limited both on the density, because of an unknown amount of weight loss due to ablation, and on the altitude, which is obtained by a double integration of the acceleration.[13] Moreover, the range of densities in which accurate measurements can be made is limited to a fairly narrow interval. If successful, however, such measurements would unquestionably be of value to future entry designs, but they would not fulfill the stringent requirements for a manned hyperbolic entry, which will have a relatively narrow entry corridor whose altitude must be known accurately beforehand.

The flight profile considered for probes of the type studied by Beuf[6] (i.e., a substantially vertical entry at hyperbolic velocity) also introduces significant risks, or makes more serious those present in all systems: the entry heating and g-loading are much higher than for low-angle entry at circular velocity; maintaining the line of sight to the vehicle demands more of the guidance system; and the line-of-sight distance between the entry vehicle and the flyby bus will be substantially longer. The existence of radio blackout delays communications of data and introduces additional possibilities for failure. All these problems are alleviated by entry of the lander from orbit rather than from hyperbolic velocity.

From this discussion, it is evident that to support the design of a manned hyperbolic-entry vehicle, a "modified Voyager" will be desired to get more accurate data on density and altitude, whether a probe as suggested by Beuf is successful or not. On the other hand, a successful probe as suggested by Beuf, or later success with an unmodified Voyager, which has much the same problems, <u>together with</u> a decision not to use manned hyperbolic entry at Mars, could eliminate need for a "modified Voyager" (but would require that the rest of the measurements described here, other than the density/altitude and Mars-radius measurements, be incorporated in Voyager).

In pointing out the limitations of small vehicles for use in measuring atmospheric density and altitude, no criticisms of the work done or the concept are intended. Indeed, as has been noted, measurements with such probes might suffice for some possible programs. The limitations of such systems are inherent in their size and the present state of the art. Although it is not strictly a concern of this study to evaluate such probes, it is believed that they have a substantial risk, but even so, the relatively low cost of the approach proposed by Beuf should be accepted--certainly before a Voyager (unmodified) entry is attempted. On the other hand, building a new space vehicle for launch by Atlas-Centaur for instance, does not seem appropriate, since the costs would be significant and the additional capability marginal. Vehicle-development funds would be better devoted to a Voyager bus (the part of a Voyager which is active in transfer trajectory and Mars orbit), since indications are that it will be necessary for substantial progress in the exploration of Mars.

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