Martian Landing Sites for the Voyager Mission

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A comprehensive study has been undertaken of the Voyager mission for landing scientific packages on the surface of the planet Mars. With the imposition of a variety of scientific and engineering systems constraints, the arrival windows at Mars have been computed for the entire Metonic cycle from 1969 to 1984. A 180-day effective lifetime for the scientific landing package has been assumed. Only certain fractions of the Martian year and only certain Martian latitudinal ranges are accessible in each launch opportunity. Since the existing astronomical evidence for life on Mars suggests a strong seasonal dependence of Martian biological activity, all launch opportunities are not equally promising for biological experimentation on Mars. The best opportunity for in situ studies of the wave of darkening exists in the 1969 opportunity. Equally good site selection is available for the favorable 1971 opposition if the extra launch capability is utilized to select a high-energy, short time-of-flight, transfer orbit. In the 1973 arrival window, the presumed seasonal biological activity is well past maximum. The post-1975 opportunities remain very unpromising until 1984. On the basis of their scientific desirability and engineering feasibility, a variety of Martian landing sites has been selected for the four biologically most interesting opportunities, 1969 to 1975. It is recommended that the first Voyager landings in 1969 or 1971 concentrate on Solis Lacus and Syrtis Major.

Introduction

THE technology of planetary exploration will soon permit direct scientific investigation of the surface of the planet Mars. Especially for biology, this capability represents an enormous and possibly unique scientific opportunity[1] which should be carefully and imaginatively prepared. The present body of scientific evidence suggests, but does not unambiguously demonstrate, the existence of life on Mars. In particular, the photometrically observed waves of darkening which proceed from the vaporizing polar caps through the dark areas of the Martian surface have been interpreted in terms of seasonal biological activity. Investigations of such phenomena are one objective of the Voyager project under study by NASA.

Avco Corporation's Research and Advanced Development Division has performed for the NASA a comprehensive design study‡ of the Voyager spacecraft for flights to Mars and Venus in the time period 1969 through 1975. This design study included a mission analysis, performed with the cooperation of the Geophysics Corporation of America, which considered both the scientific objectives of the program and the capabilities of the spacecraft to insure the most effective over-all design. This analysis led to a recommendation for landing sites on Mars which were selected with regard to the scientific objectives of the program and within the constraints of the system design. These results demonstrate that the effectiveness with which the exobiological questions can be answered is strongly dependent upon the over-all time schedule of the Voyager program. This paper reports the landing site analysis and includes the criteria for site selection, the constraints that limit that selection, and the resultant schedule of specific landing sites designed to attain the objectives of the exploration program. Although the specific selection of recommended landing sites has been performed only for the period 1969 through 1975, the analysis of the landing site constraints has been extended to cover the entire fifteen-year Metonic cycle. Thus, the detailed planning of Voyager missions can easily be extended to subsequent years under the same assumptions and by the same procedures used in this report.

Received April 22, 1964; revision received August 17, 1964.

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‡ Contract No. NASw 697.

Spacecraft Design

Some of the constraints on the selection of Martian landing sites are more or less independent of the spacecraft design and are dictated primarily by considerations of celestial mechanics. However, the net landing capabilities are of necessity affected by the design choices that enter into the spacecraft planning. Many details of the spacecraft design are dictated by considerations other than landing site selection. Therefore, only a brief description of the spacecraft will be given here so that the origin of the constraints may be understood.

The configuration selected is a split-payload spacecraft in which a lander is carried on an orbiter bus; it is launched by the Saturn IB with an S-VI upper stage. The sterilized lander is separated from the bus near the end of the interplanetary transfer orbit and is injected into a planetary impact trajectory. The bus is then placed in a polar planetary orbit by retrorockets. It there collects scientific information, including TV mapping of the surface, and acts as a relay for scientific and engineering information from the lander. The lander utilizes atmospheric braking on entering the planetary atmosphere, and then completes its descent to the surface by parachute. This lander design is capable of utilizing atmospheric braking and parachute deployment at Martian surface pressures as low as 10 mb. While descending, the lander takes TV photographs of increasing resolution of the terrain directly below and performs scientific measurements of the Martian atmosphere. After landing, it erects itself and carries out its biological, geophysical, and geological experiments over an expected 6-month operating lifetime.

The guidance accuracy of the Voyager spacecraft is such that each lander can be directed to a particular position on the planetary surface with an accuracy that makes worthwhile the careful selection of target sites. Therefore, the objective of this analysis has been to select, within the capabilities of the system, those landing sites that tend to enhance the likelihood of success of the biological experiments.

Constraints on Landing Sites

Although some constraints on the accessibility of landing sites are due to the relative geometry of Earth, Mars, and the sun, almost any such constraint could be removed if sufficient propulsive power were available. In practice, however, the constraints are determined by the specific transfer orbits actually chosen for the mission. The nominal trajectories used in the Voyager design study are not the usual minimum-launch-velocity, fly-by transfer trajectories. It was considered highly desirable that both the total payload injected into the transfer orbit and the payload carried into the Martian orbit be maximized. For a wide range of orbiter/lander weight ratios, the desired launch windows are very near the window defined by the requirement that the sum of the planetary approach velocity and the Earth escape velocity is a minimum. These minimum-sum launch windows have been used in this study, and differ in some cases by several months from corresponding minimum-launch-velocity windows.

A second choice of transfer trajectories affecting the selection of landing sites is that of variable time-of-arrival rather than fixed time-of-arrival transfer orbits. Small injection and midcourse corrections are used to predetermine the time of day for arrival at the planet. However, daily minimum-sum launch conditions to orbits of varying time of flight have been selected which yield arrival windows at Mars varying from 12 to 50 days. As a result of this choice, the arrival dates at the planet are determined for each launch opportunity, and the seasons of arrival for subsequent experimentation are also determined. The specific results will be shown later in conjunction with the constraints on the landing sites.

The constraints taken into consideration in determining the range of possible Martian landing sites are the following: 1) approach asymptote orientation and relative velocity vector; 2) angle of entry of lander into the Martian atmosphere; 3) requirement for orbiter-lander communication during landing; 4) requirement for sunlit landing area; and 5) requirement for direct lander-Earth backup communications.

To best visualize the interactions among these constraints, consider a sphere centered at Mars but not rotating with the planet. Latitude can be defined for this inertially fixed sphere in a manner identical to the true Martian latitude. Longitude can be measured conveniently as a positive rotation about the North Pole of Mars (i.e., an angle measured in the Martian equatorial plane) with zero longitude being the projection on the equatorial plane of the vector from Mars to the sun. The latitude and longitude of the asymptotic approach velocity vector and the latitude of the vector to the sun can now be defined in this system throughout each arrival window.

The possible landing areas for a given asymptotic approach velocity vector are limited by constraints on the acceptable entry angles. The shallow angles $\gamma_E < -20°$ produce long times of passage through the atmosphere and unacceptable impact point dispersions due to atmospheric perturbations and entry condition uncertainties. Very steep entry angle $\gamma_E \simeq -90°$ may produce unacceptable heating limitations or deceleration loads for the higher values of the approach velocity. In addition to the degree of freedom provided by this choice of entry angle, a vehicle on an impact course with the planet has an azimuthal degree of freedom about the approach velocity vector. Small changes in the direction of the velocity vector by means of small normal velocity increments produce large changes in the orientation of the approach trajectory plane of the lander. In essence, then, at large distances from the planet, two degrees of freedom are available for the determination of the lander approach trajectory: 1) the choice of any plane that contains the asymptotic approach velocity vector and 2) the choice of entry angle in that plane within the constraints of heating minimization and landing accuracy. Thus, the locus of impact points for a given approach velocity and entry angle consists of a circle centered on the $-90°$ γ_E impact point on the inertial sphere of reference.

The choice of trajectories for the orbiter is considerably more restrictive. To provide adequate mapping coverage and daily lander-orbiter communication capability, a polar orbit is required. A nominal periapsis altitude of 1700 km was chosen to provide high resolution mapping while still maintaining, in the presence of approach and injection guidance errors, the long orbital lifetime (~50 yr) required to prevent biological contamination by the entering orbiter. Thus, the nominal approach hyperbola for any given date is specified since the magnitude and direction of the asymptotic approach velocity vector are known for the given date, and the polar orbital plane and periapsis altitude are system requirements.

Communication between the lander and the orbiter is constrained by a design limitation on maximum range (14,600 km) and a geometric limitation requiring the orbiter to be at least 30° above the lander's local horizon to avoid serious atmospheric attenuation. If the surface pressure is ~10 mb, this system requirement could be relaxed. To transmit engineering and scientific data gathered immediately upon landing, it is necessary also for the lander to be in communication with the orbiter for a minimum of 5 min after lander deployment. The landing sites that meet these requirements are contained in a corridor that has a complex shape on the inertially fixed sphere and that is symmetrical about the polar orbital plane and about the $-90°$ γ_E impact point.

A sunlit landing site is specified so that pictures of the area can be taken during descent without artificial lighting. In addition, it is desirable that the landing site continue to receive daily illumination at least 10° above the horizon for the proper operation of several instruments. The sunlit area can, therefore, be defined for a given date of arrival and also for the subsequent 6-month period as bounded by north and/or south latitudes on the inertially fixed reference sphere.

Communication between the lander and Earth can be examined in a similar manner. We assume a communications capability to within 10° of the horizon, and require backup communications directly with Earth during at least some portion of each Martian day for the entire 6 months of operating life. This imposes maximum latitude bounds for the landing sites. There are no corresponding longitude bounds, because the planet's rotation will cause the landing site to move within line of sight of Earth each day. It is worth noting, however, that the greater the separation in latitude between the Earthline and the landing site, the smaller will be the percentage of time available for direct communication with Earth.

The net effect of the simultaneous application of these constraints is the specification of a small portion of the reference sphere which is available to the lander. This is illustrated by the shaded areas in Fig. 1, where the various boundary curves have been plotted on a Mercator projection of the reference sphere for a launch date at the midpoint of each launch window. These detailed results are presented so that the constraints from which they are derived can be visualized and the over-all results modified as desired in future studies. From the previous discussion, it is evident that the limiting latitudes are in some cases determined by landing constraints during the arrival window, and in other cases by subsequent sun and Earth constraints over the 180-day lander lifetime. These two types of limits are shown in Fig. 2 for each launch opportunity.

The constraints discussed up to this point have been dependent upon vectors (i.e., the sunline, the Earthline and the approach asymptote) that vary only slowly with time. The position vector of a particular landing site, however, rotates with the planet relative to the inertially fixed frame of reference and therefore with respect to the three vectors of interest. If the latitude of a particular landing site falls within the latitude limits of the constraints previously discussed, that landing site can be attained by adjusting the time of arrival so that the desired site is, in fact, within the acceptable inertially fixed area at the time of arrival. This time of arrival can be predetermined by transfer orbit adjustments at injection and at each midcourse correction. This effect of the planetary rotation is illustrated in Fig. 3 where the 1969 footprint of Fig. 1 has been superimposed on the International Astronomical Union map of Mars. The longitudinal position of the footprint has been chosen arbitrarily for the illustration, but any area between the horizontal dotted lines will obviously appear within the inertially fixed footprint boundaries as the Martian globe rotates once each Martian day.

Exobiological Criteria for Site Selection

The photometric, colorimetric, and polarimetric observations suggestive of life on Mars point to a marked seasonal dependence of Martian biological activities.[2] Of these techniques, the greatest topographical resolution is obtained in the photometry of the wave of darkening, a progressive albedo decline that proceeds from the vaporizing polar ice cap, coursing through the dark areas on the Martian surface and becoming indetectable only some 20° beyond the equator.[3] The standard biological interpretation of this phenomenon invokes the seasonal response of small organisms to the increased availability of water vapor. Indeed, the wave of

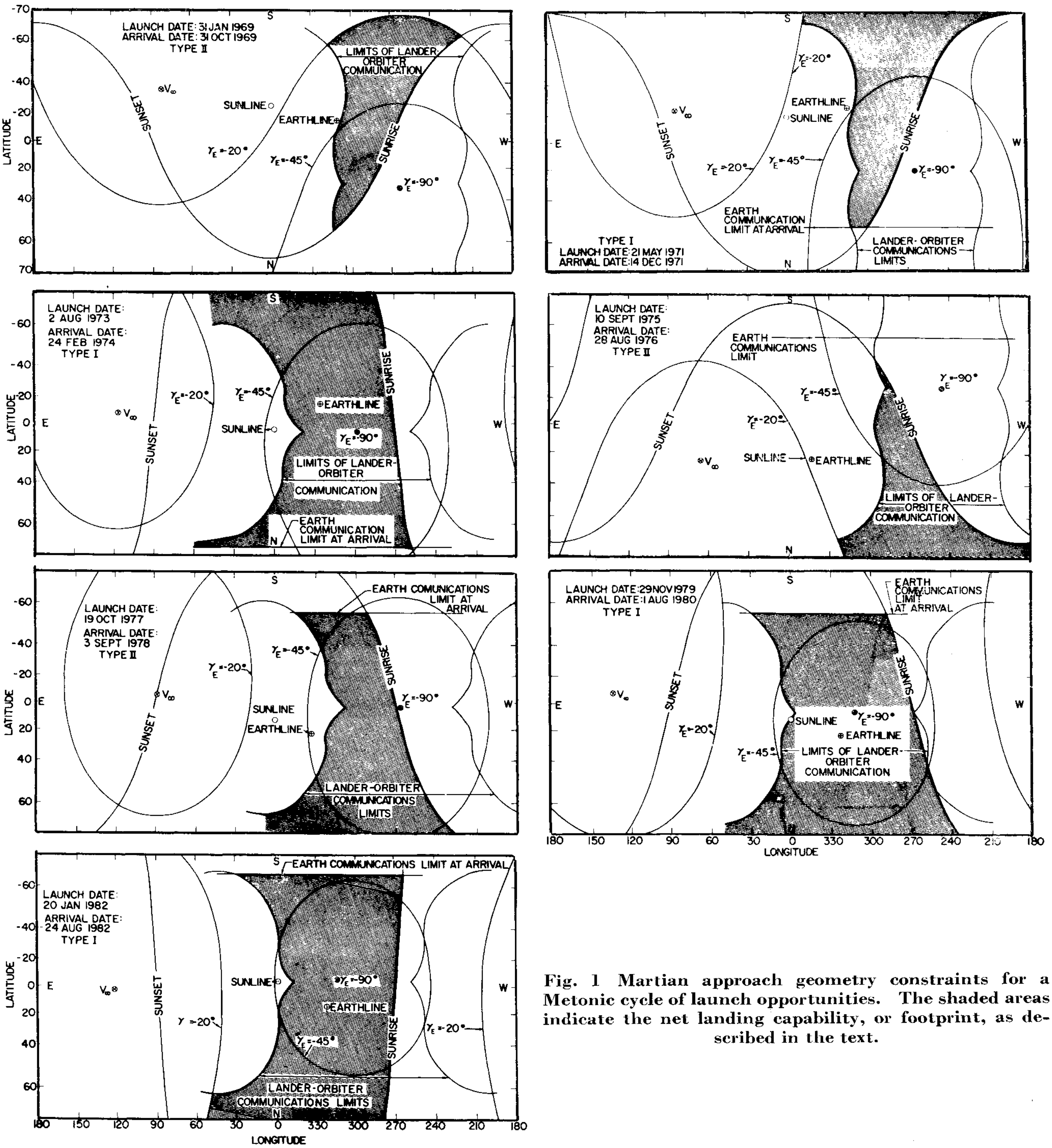

Fig. 1 Martian approach geometry constraints for a Metonic cycle of launch opportunities. The shaded areas indicate the net landing capability, or footprint, as described in the text.

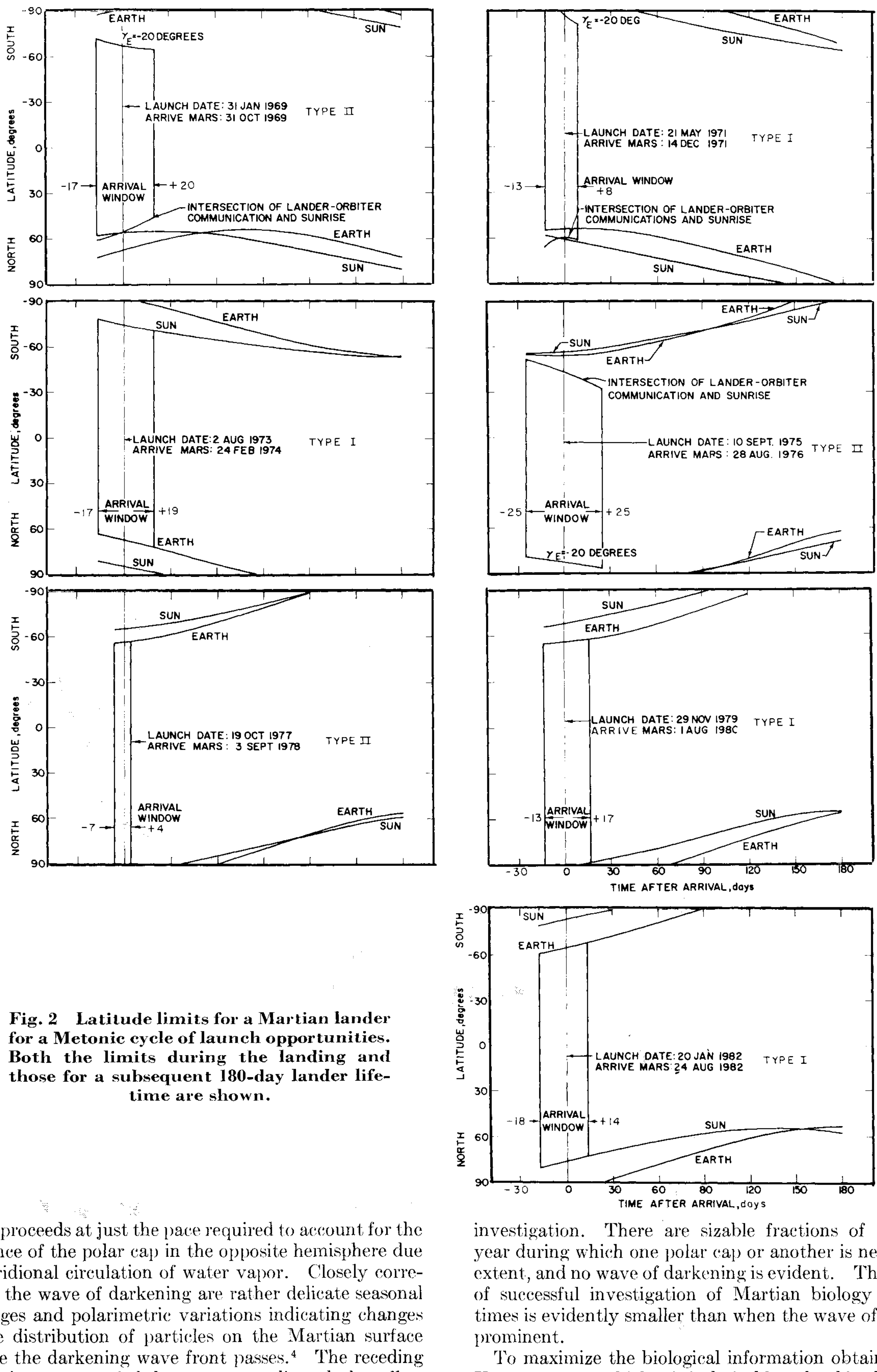

Fig. 2 Latitude limits for a Martian lander for a Metonic cycle of launch opportunities. Both the limits during the landing and those for a subsequent 180-day lander lifetime are shown.

darkening proceeds at just the pace required to account for the reappearance of the polar cap in the opposite hemisphere due to the meridional circulation of water vapor. Closely correlated with the wave of darkening are rather delicate seasonal color changes and polarimetric variations indicating changes in the size distribution of particles on the Martian surface at the time the darkening wave front passes.[4] The receding polar cap is accompanied by a surrounding dark collar, variously described as black, brown, or blue, which may be caused by the same factors that lead to the wave of darkening.

It is clear that spacecraft investigations of Mars should strongly emphasize biological studies; such a recommendation, made by the Space Science Board of the National Academy of Sciences,[5] has been adopted by the NASA. However, not all times of arrival at Mars will be equally favorable for biological investigation. There are sizable fractions of the Martian year during which one polar cap or another is near maximum extent, and no wave of darkening is evident. The probability of successful investigation of Martian biology during such times is evidently smaller than when the wave of darkening is prominent.

To maximize the biological information obtained from the Voyager entry vehicles, it is desirable to land in those Martian dark areas that are undergoing seasonal contrast variations attendant to the wave of darkening. At a given arrival time, there will generally be several areas undergoing contrast variations. Of these, some will be of greater biological interest than others because of previous reports of secular topographic changes or striking color changes, or because of infrared or polarimetric evidence suggesting the existence of life in these regions. A dark area at one longitude may be at maximum contrast in the seasonal darkening cycle, whereas areas at other longitudes, but at the same latitude, may be at times before or after their contrast maxima. Certain areas have much more pronounced contrast variations than others. Dark areas near the equator generally undergo a double darkening cycle each year because they are enveloped alternately by two waves of darkening proceeding from opposite poles.

Some attempt has been made below to give a selection of landing areas in a range of longitudes, so that the scientific desirability of a landing area can be traded off against possible limitations that are imposed if three Deep Space Instrumentation Facility antennas, at approximately equally spaced intervals of terrestrial longitude, are not available at the time of the Mars landings. In such an eventuality, only certain longitude regions will face the Goldstone Facility at encounter, and alternate landing sites must be selected. For each of the four oppositions from 1969 through 1975, several landing areas have been chosen. Both the scientific desirability of the landing site and the constraints discussed previously were considered, and major attention was given to the acquisition of biologically relevant information. It is perhaps unnecessary to add that these evaluations have been performed on the basis of present knowledge, and that future observations, including those obtained in early planetary missions, may alter these priorities.

Recommended Landing Sites

The method of site selection can be clarified by reference to Fig. 4 where the loci for the wave of darkening are plotted against Martian latitude and time throughout one Martian year. Also shown in Fig. 4 are the net landing constraints from Fig. 2, which are bounded in time by the width of the arrival window and in latitude as previously discussed. The latitude constraints imposed by the 180-day lander lifetime are shown by dotted lines in Fig. 4. The dashed lines indicate the 180-day lander lifetimes that are currently envisioned.

Information on the wave of darkening was obtained from the photometric observations reported by Focas[3] and data on the topographical and color histories of various dark areas from an unpublished compilation by Horowitz and Sagan[6]. The southern polar cap boundaries are based on data presented by Slipher,[7] noting that the cap is centered at latitude $83\frac{1}{2}°$, longitude 30°. The northern polar cap edge has been plotted for longitude 240° based on drawings by Dollfus.[8] Latitudes and longitudes of landing areas have been taken from the International Astronomical Union Mars cartography.[9]

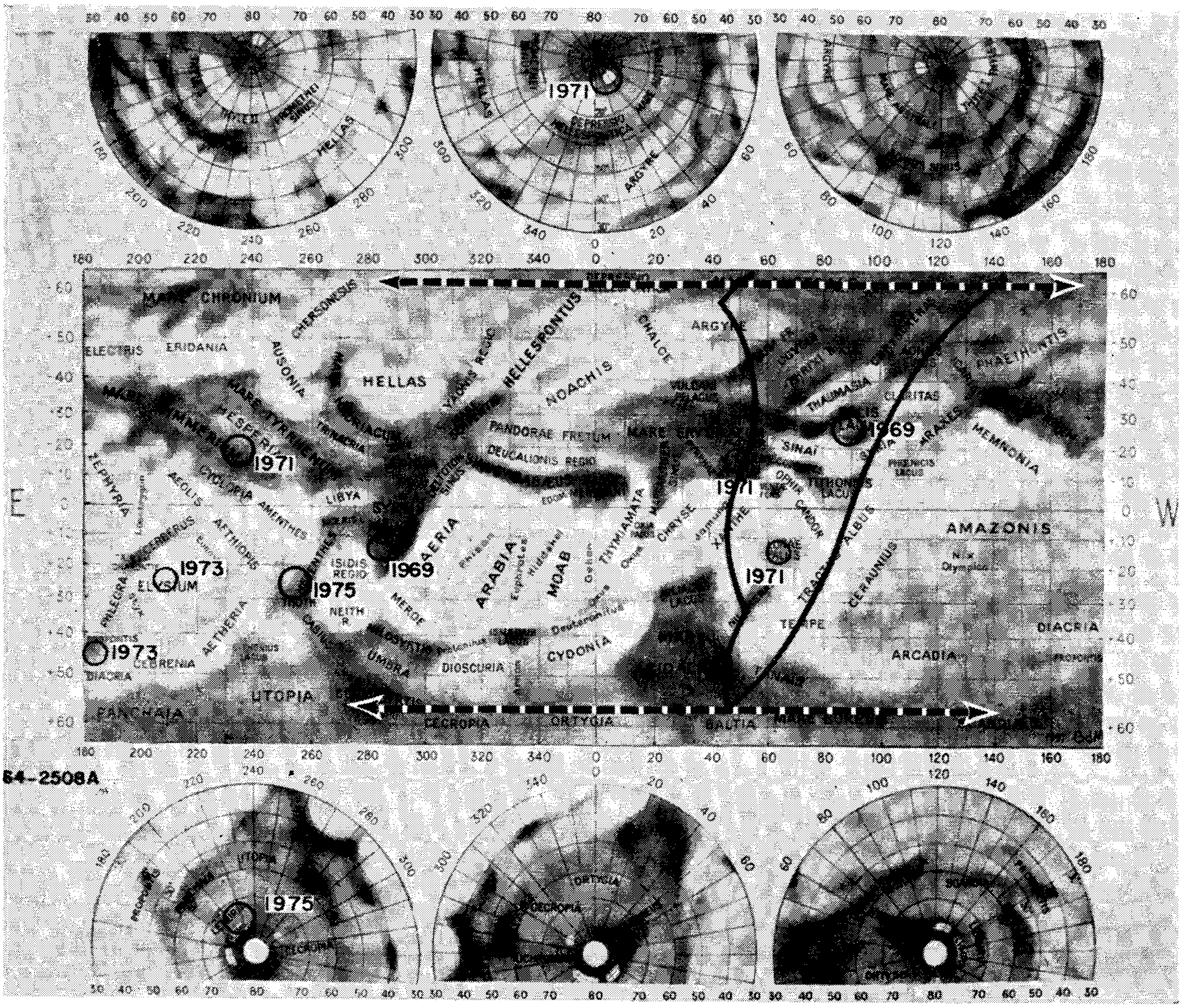

Fig. 3 The effect of planetary rotation on the inertially fixed net landing footprint for 1969. The dashed arrows indicate the longitude shifts, which are permissible. The footprint is superimposed on a map of the high-priority landing sites for 1969–1975.

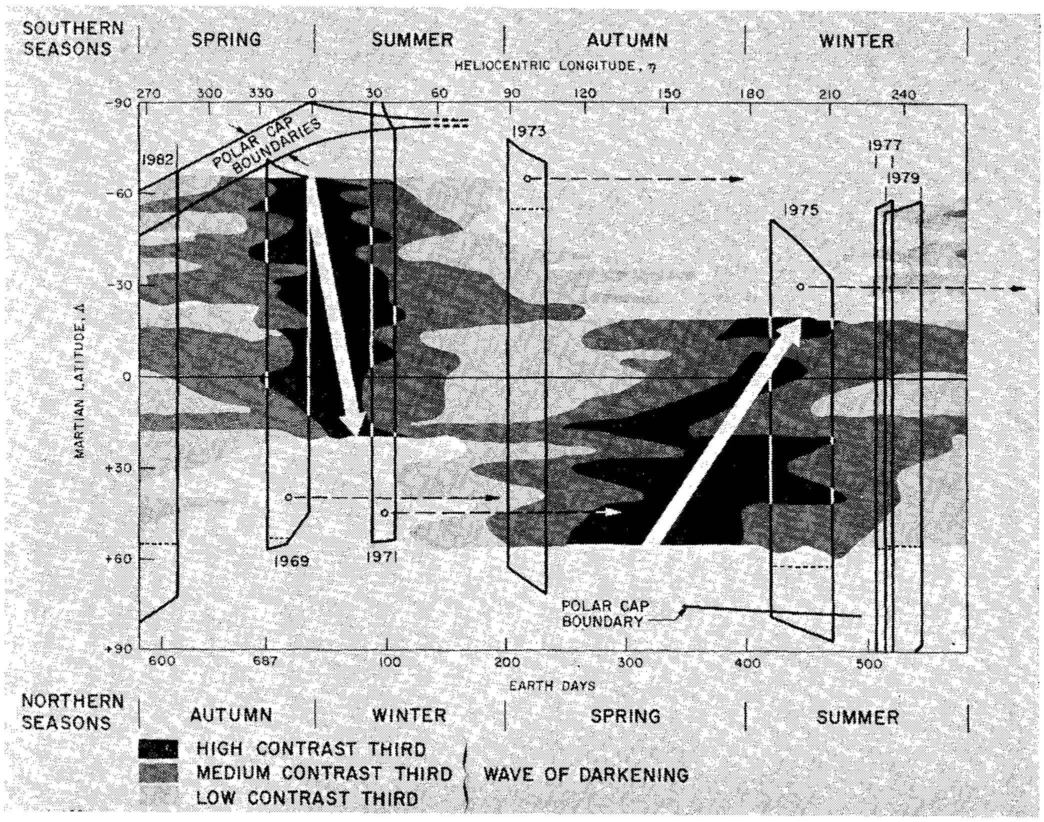

Fig. 4 Voyager landing footprints and Martian seasonal phenomena.

The results of this study are shown in Table 1. For each opposition from 1969 through 1975 the table shows the arrival window in heliocentric longitude, the latitude constraints from Fig. 2, the recommended landing sites in order of priority with their areocentric coordinates, the predicted mean daytime surface temperatures at these sites during the arrival window,[10] and remarks intended to clarify the reasons for the choices. The locations of the higher priority landing sites are shown in Fig. 3, where the circles indicate the size of the 3σ landing dispersions. Relatively few Martian dark areas are covered by the front of the wave of darkening during any given entry window, and the choice of landing site is fairly well dictated by the spacecraft trajectory and the information desired. The last column of Table 1 also lists reported observations of possible biological relevance which Voyager landing vehicles may help to clarify.

Primary sites have been suggested for two landers at each launch opportunity for each of which two identical launch vehicles and spacecraft are proposed. In addition, for the 1971 launch window, payload capability exists to carry two landers on each spacecraft bus. Therefore, four landing sites are specified for that year. A promising alternative mission design for 1971 is discussed below. No attempt has been made to present alternate schedules for landing sites in the eventuality that one or more launch attempts fail. The number of possible permutations is too great to make such an exercise worthwhile at the present time.

From Fig. 4, it is apparent that the best opportunity throughout the entire Metonic cycle for in situ studies of the wave of darkening exists in 1969 (or 1984). In those years, a lander may be placed in one of several locations in the southern hemisphere of Mars, just before the wave of darkening has its maximum effect. The wave of darkening is much more pronounced in the southern than in the northern hemisphere. In 1969, it will be possible to observe the darkening, through its maximum and well into its subsequent decay, within a time span of no more than 50 days. By comparison, in 1973 well over 100 days will be necessary and the phenomena to be observed will be much less striking because they will be restricted to the northern hemisphere wave of darkening. In the 1975 arrival window, the wave of darkening contrast maxima will have passed in both hemispheres. An opportunity will exist for observation of the wave of darkening maximum in only one region, that near Solis Lacus, and even this will require 180-day lander lifetimes.

In 1971 the southern cap is accessible, but considering lander dispersion circles, it will be difficult to land on the dark collar that surrounds the polar cap. However, it should be possible to land beyond the collar, on the cap, and observe the dark collar as it passes. This is the best opportunity to investigate the southern cap and should receive high priority that year. Although all of the Martian dark areas will have passed their contrast maxima for the 1971 arrival window, a few of the regions will be not very far past their peaks. It is likely that many useful biological experiments still can be performed by the second lander on each spacecraft directed to these areas.

In 1973 there will be a good opportunity to study the desert areas and the so-called canal features, since the Southern hemisphere wave of darkening will be essentially inaccessible. One "canal" region in the Northern hemisphere, Propontis, will be undergoing the maximum of its darkening wave cycle, and is an obvious candidate for study. If the 1969 and 1971 missions abort, some Northern hemisphere dark areas, including Syrtis Major, can be observed near their contrast maxima, but site selection is restrictive.

In 1975 the northern polar cap and its dark collar will be accessible to the lander. At the time of arrival on the planet, the edge of the polar cap at 220° longitude will be at about 78° N latitude and should be receding at approximately 1 km/day as determined from published photographs.[8] It is recommended that special consideration be given in the 1975 launch to reducing the lander dispersion (perhaps by late separation from the bus) so that the probability of performing in situ observations of the dark collar can be increased.

In the 1977, 1979, and 1982 launch opportunities, the arrival times are grouped around the least desirable time of the Martian year, the time of maximum extent of the southern

Table 1 Landing sites and objectives[a]

Landing site long., lat., deg	$\bar{T}_d$, °K	Remarks
1969: 336° ≤ η ≤ 359°; −65° ≤ Λ ≤ +45°		
Primary objective: wave of darkening; two landers		
Solis Lacus 90, −28	300	History of striking secular topographic changes. Wave of darkening near maximum during arrival window.
Syrtis Major 290, +10	290	Darkest of the Martian dark areas; reports of characteristic color changes. Biologically implicated both by infrared spectroscopy and by polarimetry. Region of double peaking of darkening wave.
Mare Sirenum 140, −30	300	Reports of marked seasonal color changes. Wave of darkening near maximum during arrival window.
Lunae Palus 65, +15	285	In recent years, dark area with greatest changes in photometric contrast. Marked double cycle of seasonal albedo changes; different peaks can be studied in 1969 and in 1973.
Trivium Charontis 198, +20	280	Reports of striking anomalous color changes.
1973: 92° ≤ η ≤ 110°; −71° ≤ Λ ≤ +63°		
Primary objectives: deserts and canals; two landers		
Propontis 185, +45	275	Region of typical Martian "canal" of the earlier literature. Area of Mars undergoing greatest photometric contrast at season of landing. Striking secular topographic changes.
Elysium 210, +25	270	Near circular anomalous bright region of "pinkish" coloration. Assigned high priority since it is assumed that the more standard bright areas will have been studied previously to some extent in conjunction with dark areas.
Hellas 290, −40	240	Bright area of anomalous "yellowish" coloration and anomalously high albedo.
Nix Olympica 128, +16	270	Bright area of standard coloration suspected to be plateau, because of tendency for cloud formation here.
Ismenius Lacus 330, +40	275	Reports of striking anomalous color changes near arrival window.
Mare Acidalium 30, +45	275	Biologically implicated both by infrared spectroscopy and by polarimetry. Near primary maximum of darkening wave ~60 days after arrival window.
1971: 32° ≤ η ≤ 44°; −82° ≤ Λ ≤ + 54°		
Primary objectives: Southern polar cap and ark areas; four landers		
Polar Cap 40, −82	280	Only opportunity for southern polar cap. Possible observations of dark polar collar. Moisture measurements and search for permafrost indicated.
Mare Cimmerium 235, −18	290	Reports of characteristic seasonal color changes. Double peaking of darkening wave; second peak observable in 1975 opportunity.
Lunae Palus 65, +15	285	Wave of darkening maximum past, but albedo still low. See comments for 1969.
Aurorae Sinus 50, −15	295	Reports of characteristic seasonal color changes.
Solis Lacus	295	See comments for 1969. If no Solis Lacus landing is performed in 1969, priority would increase for 1971 landing. Also likely candidate if two landings at one location are desired.
Mare Serpentis 315, −30	295	Orifice of main (Hellespontus) channel of darkening wave; however, not near contrast maximum during arrival window.
1975: 191° ≤ η ≤ 214°; −32° ≤ Λ ≤ +79°		
Primary objectives: northern polar cap and dark areas: two landers		
Polar Cap in Olympia-Lemuria	270	Exact location dependent on detailed study of recession of cap, extent of dark collar, and dispersion of lander. Attempt should be made to land on cap at position such that dark collar passes lander during its lifetime; other longitudes may be preferable. Possible shadow mountains and permafrost features.
Mare Cimmerium	260	Peak of northern hemisphere darkening wave early in arrival window. One of few sites of contrast maximum at fairly low temperature for this arrival window. See also comments for 1971.
Nepenthes-Thoth	285	Site of unusual secular changes in the 1940's. Former location of a so-called "canal" system.
Mare Acidalium	290	Biologically implicated both by infrared spectroscopy and polarimetry.

[a] Alternate sites are listed in decreasing order of priority for each launch opportunity.

polar cap. Thus, no minimum-sum launch opportunity between those of 1969 and 1984 permits so definitive a study of the wave of darkening. However, an alternate approach to the choice of the 1971 transfer orbit circumvents the practical difficulties of achieving a Voyager mission as early as 1969. As noted previously, the 1971 opposition is so favorable with respect to payload as to make possible the launch of a spacecraft with two landers. If, instead, it is desired to utilize this added launch capability to select a higher-energy transfer orbit, then a single lander can be carried on a shorter time-of-flight trajectory. By this approach, the seasonal arrival time of the 1971 window can be set earlier to coincide exactly with that of 1969. Thus, the exobiologically highly desirable arrival characteristics of the 1969 arrival can be completely duplicated in the 1971 launch period.

The preceding discussion has been restricted to the Voyager mission, and to the Saturn IB launch vehicle. If the Saturn V booster were available for similar Martian missions, it is clear that superior site selection could be performed. The lander lifetime could be prolonged, or higher-energy trajectories assumed, which would place the post-1971 arrival windows more opportunely for investigations of the wave of darkening. Although we have not performed a comprehensive study of the Saturn V superiority in this context, preliminary calculations indicate that the landing footprints for all post-1971 opportunities may be made to superimpose on the 1969 footprint of Fig. 4 if the Saturn V is used.

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JAN.-FEB. 1965 J. SPACECRAFT VOL. 2, NO. 1

Spacecraft Propulsion Requirements for Lunar Missions

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This paper considers spacecraft propulsion requirements for lunar orbiting and landing missions, including requirements imposed by flight path, accelerometer errors, altitude determination errors, and impulse errors, with particular attention to minimizing the number of maneuvers, number of engines, and throttling requirements. It appears that a single fixed-thrust engine will satisfy the requirements for an orbiting mission. For landing from lunar orbit, a single regeneratively cooled engine with a throttling range as low as 3.5:1 appears acceptable; alternatively, if the system has a separate landing engine, a throttling range as low as 2:1 appears to be acceptable.

Nomenclature

g = gravitational acceleration at earth's surface
g_l = gravitational acceleration at lunar surface
H_h = hover altitude
H_0 = lunar orbit altitude
I_{sp} = specific impulse
M_0 = initial total mass of spacecraft
M_{pay} = payload mass
R_T = throttling ratio, T_{max}/T_{min}
T = thrust
T_{min} = minimum thrust
T_{max} = maximum thrust
V_∞ = hyperbolic excess velocity relative to the moon
W_{ll} = spacecraft lunar weight at landing
ΔV = characteristic or effective velocity increment
ΔV_0 = impulsive velocity increment

Introduction

ALL lunar missions are likely to involve midcourse corrections, and they may require various other maneuvers for entry into lunar orbit, landing, and return to earth. Questions of reliability (e.g., redundancy of engines and start-stop requirements) also enter, and for manned missions, abort (return to earth) capabilities must be included. Total impulse requirement and mass of the spacecraft propulsion system vary with all of these factors. This paper attempts to collate and summarize the various maneuver requirements, to assess their effect on the propulsion system design, and to determine the effect in terms of over-all system performance of minimizing propulsion-system requirements.

Maneuver Requirements

Midcourse Corrections

For either trans-earth or trans-lunar phases of flight, one to five midcourse corrections (totaling 100 to 500 fps) may be required. Since these maneuvers are relatively small, efficiency is usually secondary to reliability. Acceleration has little effect on efficiency (due to the small gravity gradient involved), but it may significantly affect maneuver accuracy. The minimum acceptable thrust is often determined by the null offset error of an integrating accelerometer used for shutoff control. Maximum thrust levels are often determined by the uncertainty in the impulse delivered after the shutdown command caused by uncertainties in propellant-valve response time and in the shutdown thrust transient. A fairly large range of accelerations can be used with relatively small impulse-magnitude errors. For example, if a 20-fps trajectory correction were required in a situation where the allowable error is $\pm 2\%$, the accelerometer null offset error is 0.0005 g, and the shutoff impulse uncertainty is equivalent to ± 0.05 sec of full-thrust operation, the range of usable accelerations would be 0.025 to 0.25 g. Subsequent discussion will show that the acceptable range of acceleration is important, because for most applications it is desirable to perform trajectory corrections with a propulsion system sized for additional spacecraft maneuvers.

Direct Landing from Trans-Lunar Trajectory

A direct landing maneuver can be considered in two parts: the main descent to a hovering position, and the subsequent soft landing on the lunar surface. The curves in Fig. 1 show the variations of hyperbolic excess velocity V_∞ with transit

Presented as Preprint 63-76 at the IAS Annual Meeting, New York, January 21–23, 1963. This paper presents the results of one phase of research carried out under NASA Contract No. NAS 7-100. The author wishes to acknowledge that the data for Fig. 7 were developed by Rocketdyne under contract NAS 5-916 to NASA; the data for Figs. 10 and 12 are from the analyses of A. V. Zimmerman.[1] A. D. Harper and J. R. Wrobel of the Jet Propulsion Laboratory also performed analyses that have been used in the preparation of this paper.

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