LUNAR ORBITER MISSION PLANNING

January 25, 1965

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SUMMARY

The Lunar Orbiter is primarily regarded as part of a combined Lunar Orbiter/Surveyor team whose purpose is to find and identify at least one acceptable site for a manned lunar landing within a time frame consistent with the Apollo schedule. The approach recommended here is based on the first Lunar Orbiter taking contiguous high resolution photography (1 meter per optical pair) of areas large enough so that Surveyor could subsequently land in them. Such a mission mode offers the possibility of achieving a certified site even if only one Lunar Orbiter were successful. Contiguous areas 32 km x 32 km should be photographed to ensure at least 3 of Surveyor aim coverage. Each Orbiter can photograph 8 to 10 such areas.

Using ACIC base maps and lunar surface interpretation from other sources, a number of terrain types have been delimited separating out four most likely to contain suitable Apollo landing areas. These are:

1. Regional maria in Sinus Medii and Mare Tranquillitatus.
2. Highland basins.
3. Regional maria in S. Medii and M. Tranquillitatus containing wrinkle ridges and/or domes.
4. Regional mare in Oceanus Procellarum.

A distinction is made between Procellarum and Tranquillitatus because of the ejecta from large post-marial craters such as Copernicus.

A Lunar Orbiter mission can now be designed by assigning contiguous high resolution photography to the terrain types above. The eight to ten areas photographed can be supplemented by using the remaining photography on the same orbits accepting slightly inferior photographic conditions. In the event that there is a target of special interest, e.g., a landed Surveyor, the mission can be perturbed to include its photography.

The detailed design of the mission is influenced by a number of lighting and trajectory constraints. The most important of these are:

(a) width of the acceptable lighting band
(b) the tilt of this band due to the earth's motion and to gravitational precessional terms.
Two missions were laid out, one posigrade, one retrograde. From these it is clear that there are different ways of achieving nearly identical photography.

It is concluded that:

(1) The strategy of contiguous high resolution photography of multiple targets should be used. This allows successful Apollo site survey with only a single Lunar Orbiter.

(2) To allow the above, the camera sequencer control should be changed to include a quantity control for providing eight consecutive photographs.

(3) The quantity of gas made available for the attitude control system should be sufficient for a minimum of sixteen separate photographic maneuvers.

(4) To achieve at least 1 meter/optical pair resolution, photographs should be taken from a nominal height of 46 km or less.

(5) To avoid the possible problem of orbital instability for the above low altitude orbit due to the uncertainties in our knowledge of the moon's spherical harmonic terms, it is recommended that the orbit be inclined no more than 7° to the lunar equator.

The two sample mission profiles derived are representative missions based on present knowledge of lunar surface characteristics. However, the first mission profile to be actually flown should be based on all data (Ranger, Surveyor and earth-based) available prior to launch. Consequently it will be necessary periodically to update the detailed mission profiles, perhaps almost up to the actual launch date. As a corollary to this, it is important that data having a possible bearing upon the final configuration of the Lunar Orbiter mission profile be processed rapidly enough to be available for pre-launch consideration.
INTRODUCTION

The purpose of this report is to respond to a request from the Lunar Orbiter Program Office for a Lunar Orbiter Mission planning document which represents Apollo interests. Mission objectives have been provided so that suitable trajectory designs and operational procedures can be determined and hardware design modifications considered.

From an Apollo point of view, the Lunar Orbiter is primarily regarded as part of a combined Lunar Orbiter/Surveyor team, whose purpose is to find and certify at least one acceptable site for a manned lunar landing within a time frame consistent with the Apollo schedule. With this objective in mind, a general strategy has been derived from a detailed consideration of:

(a) Lunar Orbiter and Surveyor capabilities and the team interrelationships
(b) our present knowledge of the nature of the lunar surface
(c) our present knowledge of the moon's spherical harmonic terms
and (d) the probabilities associated with achieving various numbers of successful missions, given the presently funded five Lunar Orbiters.

The general strategy discussed herein should remain valid for at least the first Lunar Orbiter mission, irrespective of additional data obtained. However, it is anticipated that new data will undoubtedly influence the detailed mission plan which will eventually be flown. Thus, the general strategy proposed has sufficient flexibility to permit modification of the precise mission objectives shortly before an actual launch.
ALTERNATE STRATEGIES AND MISSION MODES

The working partnership of the Lunar Orbiter and Surveyor Programs has as its goal the certification of one or more Apollo sites.* It is necessary to select a strategy for employing these programs which will maximize the likelihood of achieving this goal. An almost infinite number of alternative strategies can be conceived, but most of these can be reduced to variations of a few basic alternatives.

All strategies previously considered have been based on the following three-phase sequence (for example, reference 1):

1. Selecting Surveyor aim points
2. Aiming of Surveyors at selected aim points
3. Overflying landed Surveyors.

The selection of the Surveyor aim points would be based upon all data available at flight time including that from the Lunar Orbiter and from Block I Surveyors. In this strategy the payoff comes when a Lunar Orbiter overflies a successfully landed Surveyor in contiguous high resolution mode, and the results of an analysis of the data obtained indicate that an Apollo site can be certified.

When the Lunar Orbiter Spacecraft hardware selection was initially made, the strategy assumed was of this class of strategies. Furthermore, the particular strategy assumed that the first phase, involving a selection of Surveyor aim points, would use broad area screening on at least the first Lunar Orbiter mission. Program assumptions were also made on quantities of Lunar Orbiters (ten) and Surveyors (eight) capable of site survey.

The approach recommended here for the first Lunar Orbiter mission is based on taking contiguous, high resolution photography of areas large enough so that a Surveyor could subsequently land in them. Such a mission mode offers the possibility of achieving the Lunar Orbiter mission goals if only one Lunar Orbiter is successful, without preventing the subsequent use of the above three-phase strategy should circumstances so dictate.

* See Appendix I for a description of the Lunar Orbiter and Appendix II for Apollo Site Survey Requirements.
Program Assumptions

There are five Lunar Orbiters presently funded. The assumption used in this report is that there will be no more than five Lunar Orbiters available for site survey.

A reliability goal has been set at .99 of achieving one successful Lunar Orbiter (out of five). This spacecraft goal has been converted to subsystem goals and these subsystem goals compared to expected subsystem reliability. This comparison indicates that the goal is difficult but obtainable. (12) This figure of .99 is therefore accepted as the expected reliability. A mission reliability of .6 (each mission), corresponds to a .99 probability of one successful spacecraft out of five (i.e., chance of 5 failures = \(0.45^5 = 0.01\)). From 5 planned spacecraft one can therefore expect 3 successful spacecraft missions (\(0.6 \times 5 = 3\)). Any strategy selected should therefore be examined with suitable emphasis placed on an expectation of 3 spacecraft missions. We need, however, be concerned with the possibility that we will be unlucky and only achieve two, or even one, successful spacecraft missions.

Lunar Orbiter/Surveyor Working Partnership

The function of a successfully landed Surveyor is to return detailed bearing strength and small-scale topographic data from an area on the lunar surface which is small compared to an Apollo landing site. The likelihood of achieving a successful Surveyor is a direct function of the probability of success of the Surveyor landing on the surface. Thus the merits of a strategy hinge on the Surveyors being sent to areas where they can land successfully.

The Lunar Orbiter, then, must perform the dual function of:

(a) pre-selecting Surveyor aim points to maximize the chances of a successful Surveyor landing

and (b) providing an extension of the Surveyor data to an area large enough to qualify as an Apollo site.

Proposed Mission Mode

As indicated in Table I, there is an 8% likelihood that only one spacecraft will be successful. An 8% likelihood is greater than can be ignored. It is therefore desirable that a strategy be selected which can result in a certified Apollo site even if only one Lunar Orbiter is successful.

* The probability of achieving no successful spacecraft mission is significant but is of concern to an analysis of Surveyor rather than Lunar Orbiter strategies.
With one Lunar Orbiter spacecraft we cannot both select a Surveyor aim point (and land a Surveyor on the basis of that selection) and then overfly that Surveyor. It is, however, possible to derive a mission strategy employing one Lunar Orbiter which may closely approximate the data returned by two Lunar Orbiters for at least one Apollo site.

The function of overfly missions is to extend our understanding of the surface features in the area directly observed by Surveyor to a larger area. This is most easily done if the exact position of the Surveyor in the overflown area is known. Notice that it is immaterial whether the Surveyor lands before or after the overfly mission if its position can be determined with the same accuracy in either case. The advantage in overflying a landed Surveyor is that, with this technique, the Surveyor position may be precisely determined in the Lunar Orbiter photographs. However, if the surface characteristics of importance to a landing LEM remain relatively constant over large areas, then the position of the landed Surveyor in the overflown area need not be known with great exactness in order to correlate Lunar Orbiter and Surveyor data. It may be possible, then, to achieve most, if not all, of the objectives of a post-Surveyor overfly mission by taking an area of high resolution photography large enough so that a Surveyor can subsequently land in it. If a block can be selected which is largely homogeneous and big enough so that a Surveyor can later be landed in this area, then it is possible that an Apollo site could be certified with as high a confidence as is associated with the Lunar Orbiter/Surveyor/Lunar Orbiter sequence. Since a number of such areas can be photographed in one mission, the aiming points for a Surveyor can be chosen within the area most topographically suitable. If the results of the first successful Lunar Orbiter mission demonstrate that the lunar surface is not homogeneous enough to warrant placing a high confidence in this technique, then the data may still be used for selecting a Surveyor aim point and a post-Surveyor overfly mission can be programmed.

The size of the blocks photographed in high resolution is based primarily upon a consideration of the Surveyor CEP. Assuming a Surveyor aim CEP of 5 km for two midcourse maneuvers, a 99 per cent confidence of hitting an area requires a circle of radius of 13 km. We can therefore place a square on a map of the moon of 26 km by 26 km and know that we can hit this with more than 99 per cent certainty, if a Surveyor is aimed at the center.

A mission mode in which square blocks of 32 by 32 km high resolution photographs are used is therefore recommended.* This requires a sequence of 8 high resolution photographs on each of two passes. For the first Lunar Orbiter mission, either eight,

* See Figure 1.
nine, or ten of these blocks should be photographed. Normally, each block requires two spacecraft maneuvers, and reliability considerations (plus a possible gas supply restriction) limit the advisability of larger quantities. Eight, nine, and ten 32 x 32 km blocks use 128, 144, and 160 frames respectively, leaving either 52, 36, or 20 frames for secondary purposes.

This mode is recommended solely for one reason - the possibility that this strategy can satisfy both the selection and certification functions in a single mission. Such a strategy optimizes the probability that five Lunar Orbiters will be a sufficient number. Since it possesses the capability of returning definitive information earlier than the three-phase strategy, it also optimizes the probability of certifying an Apollo site within a time framework consistent with the Apollo schedule.

The successful employment of this recommended mission is dependent upon the following factors:

(1) Since the number of successful Lunar Orbiters is assumed to be small, it becomes imperative to screen the area of interest, using pre-Lunar Orbiter data, to select those sections most likely to contain acceptable Apollo sites.

(2) It is important that the proposed strategy not only enables an optimum plan to be derived in the case of no more data than we have today, but that it be flexible enough to adapt to new data. Such new data may be returned from a successful Ranger, Surveyor, or even an initial Lunar Orbiter. Consideration must be given to all these possibilities in formulating a general strategy.

(3) There are certain crucial parameters which limit the permissible orbits and their associated good lighting bands. These parameters must be defined and their effects clearly delineated.

The above factors are thoroughly discussed in the following sections and form the ground rules used in deriving the two sample missions discussed in Section V.
TABLE I

Probability of achieving successful spacecraft assuming .6 probability of success of each craft:

<table>
<thead>
<tr>
<th>Result</th>
<th>Probability</th>
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<tbody>
<tr>
<td>5 successes 0 failures</td>
<td>.07776</td>
</tr>
<tr>
<td>4 &quot; 1 &quot;</td>
<td>.25920</td>
</tr>
<tr>
<td>3 &quot; 2 &quot;</td>
<td>.34560</td>
</tr>
<tr>
<td>2 &quot; 3 &quot;</td>
<td>.23040</td>
</tr>
<tr>
<td>1 &quot; 4 &quot;</td>
<td>.07680</td>
</tr>
<tr>
<td>0 &quot; 5 &quot;</td>
<td>.01024</td>
</tr>
<tr>
<td></td>
<td>1.00000</td>
</tr>
</tbody>
</table>
FIGURE 1 LUNAR ORBITER CONTIGUOUS HIGH RESOLUTION MODE
AN "8 x 2" BLOCK
(PRIME TARGETS)
SECTION II

TERRAIN CLASSIFICATION OF THE APOLLO LANDING BELT

Since the unmanned lunar reconnaissance program is unable to explore the entire permissible Apollo landing belt with the thoroughness necessary to determine the suitability of the terrain for an Apollo landing, it is desirable to be able to direct the unmanned probes to areas thought to contain the highest percentage of acceptable terrain. The use of the Lunar Orbiter as a screening tool for Surveyor has already been discussed. However, the Lunar Orbiter itself must be directed to areas which maximize its chances of performing the screening function. One approach to this problem is to determine the relative ranking of terrain types within the area of interest. In this section, two such previous classifications are briefly discussed. Based on these classifications and a consideration of the recent Ranger VII data, a third terrain classification, differing in emphasis and detail, is proposed.

The question of what constitutes suitable terrain for Apollo purposes is a pertinent one. A comprehensive answer, however, is complex and not completely germane to the present study. Suffice it to say, at this point, that the most desirable landing surface is that which exhibits the least amount of surface sinkage and small-scale relief and the lowest local and regional slopes. A detailed discussion of Apollo site survey requirements is presented in Appendix II.

BASES FOR TERRAIN CLASSIFICATION

Information which would enable us to infer the relative surface bearing strengths of the mappable units within the area of interest is not available. As a result, estimates of the relative acceptability of the various units rest on the small-scale topographic configurations inferred from earth-based observations and the Ranger VII pictures.

Earth-Based Observations and Mapping

The observable features of the lunar surface have been studied for many years, primarily as evidence bearing on the origin and history of the moon. The past few years have witnessed a great intensification of such lunar observations. Although these studies of lunar features have not resolved the origin and detailed history of the moon, they have made it possible to deduce a relative history of the lunar surface, the probable processes involved and, in a general way, the results of these processes. This relative history is briefly summarized as follows:
A. Premarial history - The earliest recognized period which has had a lasting effect on lunar topography, the premarial period, was one of intense or prolonged cratering and crustal faulting, probably culminating in the Imbrium event, which laid a thick ejecta blanket over a considerable portion of the older surface. In fact, toward the end of this period, virtually the entire surface of the moon must have been covered with a rubble layer produced by the throwout of countless craters. Direct observations show that the premarial processes resulted in a densely cratered, highly fractured and faulted surface, which was certainly very rough on a large scale. This period of lunar crustal development is represented today by the lunar continents or highlands.

B. Marial history - Over a period of time which was short relative to the total span of lunar time, the topographically depressed portions of the premarial surface were covered by material which most selenologists regard as magmatic in origin, leading to the formation of the lunar maria as we know them today.

These superimposed deposits were sufficiently thick to eliminate all of the pre-existing small-scale topography and most of the pre-existing large-scale topography in the areas which were covered. The new surface which was generated was essentially lacking in large-scale features. The types of magmatic activity which have been suggested as operative in the formation of the maria (from rhyolitic ash flows to fluid basaltic extrusions) could produce a wide range of unobservable surface features. Since it is probable that several types of magmatic processes were operative during this period, it has been widely assumed that the marial surfaces were indeed heterogeneous immediately after formation, exhibiting a wide range of small-scale topographic features from one area to the next.

C. Post-Marial history - The same processes which were active during the premarial history of the moon continued to modify the surface subsequent to the formation of the maria. But either the post-marial events were markedly reduced in frequency or the post-marial period has been relatively short. In any case, the large-scale modifications to the marial surfaces since their formation have been minor, except in the immediate vicinity of a few, large post-marial craters such as Copernicus.
Five-fold subdivisions of lunar history have also been proposed (4 & 5), but these somewhat more detailed breakdowns are no more informative than the three-fold subdivision described above for inferring small-scale surface features.

Certain inferences concerning the relative small-scale configurations of the general terrain types can be drawn from a consideration of the above history of the lunar surface:

A. Observable craters are caused by violent events which undoubtedly clutter the crater floors, rims, and surrounding surfaces with blocks of small-scale ejecta and secondary craters.

B. The processes which produced the observable features of the premarial surface most probably also produced an extensively fractured, rubbly and cratered surface on a scale of concern to a landing LEM.

C. The processes responsible for marial surfaces most probably produced initial surfaces ranging from very smooth (no small-scale relief; general slopes 3°) to as rough as the unmodified premarial surface on a small scale. Although quantitative estimates are not possible, presumed terrestrial analogies suggest that a significant percentage (>10%) of the lunar maria should have been smooth enough for a LEM landing immediately after formation.

D. It follows from the above inferences that marial regions well removed from post-marial craters should be relatively more promising for pre-Apollo reconnaissance than continental areas.

There is one additional factor which could conceivably change this conclusion. The small-scale features of the lunar surface have been continuously modified throughout their existence by meteoritic bombardment. Since the impacting meteorites are characterized by a size-frequency distribution, there will be both a tendency to roughen the surface by primary and secondary projectiles producing craters and rubble in the 3 ft. to 300 ft. class and a tendency to smooth the surface due to the "sandblasting" effect of the smaller projectiles. The net effect of these opposing tendencies is not predictable from earth-based data. The absolute acceptability of the surface is certainly dependent upon what this net effect is and there is the additional possibility that the relative acceptability of surface units is also so dependent. Consider that whatever the net effect is, it will be in the same direction over the entire lunar surface, since the impacting meteorites in the size range of interest interact in essentially a random fashion with the surface. Thus only the extent of smoothing or roughening will
vary for surfaces of different age. There are only two possibilities to consider. If the net effect is to roughen the surface, the continents will experience a greater roughening than the maria, since they are older. On the other hand, if the net effect is to make the surface smoother, the situation is not as clearcut. It is true that if a significant percentage of the maria is acceptable to begin with, a net smoothing effect makes them look even more attractive. But there exists the possibility that, if the continents are very much older than the maria and the original small-scale roughness difference between highlands and maria were not as large as suggested herein, the small-scale relief of continents could be much more drastically reduced than that of the maria. This possibility precludes the dismissal of continents from consideration for landing sites, but in view of the greater certainty that parts of the maria will be relatively smoother in either case, the highest priority for reconnaissance must remain assigned to marial regions.

While the foregoing analysis is thought to be generally valid, it is too broad to be of optimum value to a reconnaissance program. Clearly, it should be possible to subdivide both maria and continents into several units on the basis of the obvious variations in observable features. There have, in fact, been two such attempts to subdivide part of the equatorial region into several terrain units, both studies using ACIC LAC charts as base maps.

A. A U.S.G.S. terrain classification of part of the equatorial belt (10°N-10°S, 60°W-15°E) using the "median slope frequency" of measurable E-W slope elements as the determinative parameter (6). The region is divided into the following six units, in order of increasing "median slope frequency:"

1. general maria
2. rayed maria
3. maria in the vicinity of domes and wrinkle ridges
4. highland basins
5. areas in and adjacent to young craters
6. general highlands

B. An independent terrain assessment made by JPL, covering much the same region (10°N-10°S, 60°W-50°E). Nine terrain types are differentiated, using such features as "topography, orientation of topography, regional slopes, area density of certain features, albedo and spectral reflectivity" (3). On the basis of presumed correlations between observable and unobservable features, plus a consideration of the probable processes involved, the authors have attempted to roughly estimate the small-scale
terrain parameters of the different units. In order of increasing small-scale roughness within the two major divisions, these units are:

1. Maria
   (a) dark basin deposits
   (b) regional maria
   (c) ray-covered maria
   (d) dark rough deposits

2. Highlands
   (a) smooth highland basins
   (b) general highlands
   (c) rough highlands

Two additional units are young craters and young crater ejecta blankets, neither of which are seriously considered for possible Apollo landing sites.

The authors found it difficult to compare the relative small-scale roughness of the continental and marial subdivisions, but they do favor marial regions for initial reconnaissance.

Ranger VII Data

The last "P Camera" picture transmitted from Ranger VII has provided us with a "point" measurement in a lunar marial region lying somewhat outside of the area of interest to Apollo. This measurement is of direct applicability to the Apollo system in the sense that it actually shows the topography on the scale which is necessary to determine the hazard to a LEM. The area in question is located within a ray element and the surface is characterized by a reasonably high density of secondary craters. Nevertheless, intensive analysis of this last "P Camera" picture has demonstrated that the topographic configuration would be marginally acceptable for a LEM landing. Furthermore, the lower resolution "A Camera" and "B Camera" pictures indicate that immediately adjacent, non-rayed areas may be even smoother than the area shown in the last "P Camera" picture.

Quite apart from the direct observation of surface features in the crucial size range over a very small area, the Ranger pictures supply us with some strong evidence concerning the effects of certain lunar processes which were heretofore highly uncertain. First, although rayed maria have generally been given a lower priority than non-rayed maria for lunar reconnaissance, the evidence for this relative ranking has been rather tenuous. The nested "A Camera" pictures definitely show that rays contain large numbers of secondary craters and consequently do materially roughen the surface upon
which they are imposed. Secondly, unless we are being badly fooled, the demonstrated existence of small craters in all stages of modification, from fresh and sharp to almost totally destroyed, testifies to the efficacy of micrometeorite bombardment in modifying the moonscape toward a more hospitable surface. Although there is still some controversy over the maximum extent of surface erosion shown in the Ranger VII pictures, the gently rounded appearance of the surface indicates that at least one meter of material has been removed from the oldest topographic features in this area.

A final significant aspect of the Ranger VII data is that none of it was totally unexpected. In particular, the aim point was chosen because earth-based data indicated that there was a good chance the area was characterized by a minimum amount of surface roughness, and indeed it turned out to be reasonably smooth. The greater roughness of rayed areas, the increasing number of smaller primary craters, and the increasing importance of secondary craters were all predicted before the Ranger VII mission. Thus the pre-Ranger supposition that there are correlations between observable and unobservable lunar features and that it is possible to predict the unobservable from a consideration of the observable was supported by the Ranger VII data.

PROPOSED TERRAIN CLASSIFICATION FOR LUNAR ORBITER PLANNING

Based on presently available information, flat, non-rayed, general marial regions most probably contain a high percentage of possible LEM landing sites and such areas should be given the highest priority for reconnaissance. Marial areas containing wrinkle ridges and/or domes may be slightly rougher on a small scale than featureless regions. Rayed maria should be avoided and since it is apparently not possible to distinguish all the rayed areas from earth, areas which are more accessible to throwout from large post-marial craters must be given a lower priority, even if they appear featureless. In terms of the area of interest, this means that general, "non-rayed" marial regions in Oceanus Procellarum, which are within easy reach of ejecta from two major post-marial craters (Copernicus and Kepler), are not as favorably regarded as similar areas in Sinus Medii and Mare Tranquillitatus.

Two additional marial terrain types have been distinguished, one apparently rougher and the other apparently smoother than general maria. Both types occupy much less than 1% of the area of interest and consequently do not merit further consideration.

There are good reasons for believing that continental areas were considerably rougher than comparable marial areas at some period in their history. It is certainly true that they are rougher on a large scale today, whether roughness is measured in terms of observable topographic features or median slopes over resolvable
distances. There is, however, no direct evidence bearing on the actual small-scale surface configurations of continents today. Certainly there are many continental areas where the general surface slopes do not exceed values commonly found in maria. Since continents may be much older than maria and the erosive effects of micrometeorites appear to dominate the shaping of the smaller land forms, it is possible that at least portions of the continents are as smooth as or smoother than nominal marial terrain. This possibility is not considered large enough to warrant giving continental areas a high ranking as potential Apollo terrain but neither can these areas be dismissed from consideration, and some small part of an initial reconnaissance mission should be devoted to selected portions of the "general highlands" terrain type.

A final major terrain type which may be suitable for Apollo constitutes the floors of old, large craters and other depressed areas in the continents. Although this terrain is a subdivision of the highlands, it should be considered a marial terrain type, as its probable origin and small-scale surface configuration seem to be comparable to marial terrain. It is considered to be somewhat less suitable for Apollo because of its slightly greater "median slope frequency".

The various terrain units, as they can be presently differentiated, are tabulated below in the probable order of their increasing hazard to a landing LEM:

<table>
<thead>
<tr>
<th>Terrain Unit</th>
<th>Map Symbol and Rank</th>
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<tr>
<td>Regional maria in Sinus Medii and Mare Tranquillitatus</td>
<td>1</td>
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<td>Highland basins</td>
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<td>Regional maria in S. Medii and M. Tranquillitatus containing wrinkle ridges and/or domes</td>
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<td>Regional mare in Oceanus Procellarum</td>
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<td>Rayed maria</td>
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<td>General highlands</td>
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<td>Rough highlands</td>
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<td>Young craters and vicinity</td>
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</table>
Areas larger than a Surveyor 3 σ aim capability in the area of interest are plotted in Foldout A for the first four of these types. Actually there is little to choose between these four at the present time. The centers of fifteen 1° X 1° areas recommended as "lunar landing areas" in an MSF Program Directive (14) are also shown in Foldout A.

It cannot be emphasized too strongly that this terrain classification is somewhat arbitrary and very crude. The relative small-scale topographic differences between certain units are largely inferred and there is currently no possibility of estimating relative bearing strength.

It is anticipated that more definitive, earth-based observations and early unmanned probes will do much to improve terrain classification before the first Orbiter mission. The classification proposed herein, then, should be recognized as tentative, to be revised as additional observations dictate.
SECTION III
MISSION OBJECTIVES

MISSION OBJECTIVES FOR THE FIRST LUNAR ORBITER

The first mission should be designed by locating primary targets in the terrain units discussed in the previous section. The weighting of the number of targets in each terrain type should be based on the ranking of the terrain types using the total information at the time of mission design. If a maximum of sixteen maneuvers is assumed, eight primary targets can be chosen.

Modification of Objectives due to Special Targets

If, prior to the Lunar Orbiter mission, there has been, for example, a successful Surveyor mission which indicates a suitable Apollo site, then this Surveyor would be a target of special interest and would become a primary objective for high resolution photography. The Lunar Orbiter mission would then be modified to include this special target.

The following special targets should be considered for primary or secondary emphasis if they are within the Apollo area of interest:

(a) Ranger impact points, if there is a good chance the impact point can be found and identified

(b) Landed Surveyors, whether successful or unsuccessful, whether indicating acceptable or unacceptable terrain

(c) Landmarks suitable for navigational purposes

Table II rank-orders the above special targets and assigns block sizes to each.

Secondary Targets

The mission should be designed on the basis of primary and special targets. Remaining photography can be assigned to secondary targets. Perturbations which optimize secondary photography without compromising the primary mission can be allowed, however. For example, if there were a choice of two identical primary targets and the one leads to better photography over a secondary target, then the perturbation may be made.
The secondary targets used herein are:

(a) Samples of \((1 \times 4)\)* in high resolution
(b) Samples of \((1 \times 4)\)** in low resolution stereo.
(c) Additional samples \((8 \times 2)\)** in high resolution

Secondary targets may be used to examine interesting terrain with a view toward furthering our knowledge of lunar surface processes or they may be employed to examine areas that may be suitable for Surveyor aim points.

MISSION FOLLOWING A FIRST MISSION FAILURE

It should be emphasized that the mission plan for the first Lunar Orbiter must be followed until an initial success is achieved, even if this takes all five Lunar Orbiters. The only modification to this would be if some partial success were achieved. For instance, if the moon's spherical harmonic terms were determined but no other data were received, then the second Orbiter to be flown could make a different angle of inclination if the spherical harmonic terms justify that course of action.

MISSIONS FOLLOWING A SUCCESS

The value of information that will be obtained from one successful Lunar Orbiter mission makes specific target planning of a subsequent Lunar Orbiter mission prior to that time completely useless (except perhaps as a training device). No such specific target planning is therefore made in this report for any mission following a successful Lunar Orbiter mission.

Two comments need to be made, however:

(1) The Lunar Orbiter capabilities required to perform missions of the type described in the examples are considered sufficient for all subsequent missions of the first five Lunar Orbiters (with the possible exception of an ability to photograph from lower altitudes).

(2) Because the data obtained from the Lunar Orbiter's first successful flight will be used to determine the mission plan for subsequent flight, the analysis of the data is interwoven with the flight schedule. For example, if the successful Lunar Orbiter is launched on day 0 and data return completed on day 30,

* See Figure 2
** See Figure 3
*** See Figure 4
in order for a new flight to take place on day 90, the data must be analyzed (as far as this purpose is concerned) and the optimum new flight plan derived from this data in 60 days.

Following a successful Lunar Orbiter mission or a successful Surveyor mission, the terrain analysis must be re-examined to determine whether or not the terrain unit emphasis should be changed for the next mission.

LUNAR ORBITER FLIGHT SCHEDULE

The approach taken in this mission planning document is that the first Lunar Orbiter should under no circumstances be held back because of a situation existing in the Surveyor Program. That is to say, the first Lunar Orbiter flight should occur at a time which is independent of whether there have been Surveyor flights or whether any are about to occur or what the results of any of those Surveyor flights have been. However, one can conceive of a decision following one or more successful Lunar Orbiter flights, to hold back the remaining Lunar Orbiters until several attempts have been made to achieve a successful Surveyor.
TABLE II

RANKING OF LUNAR ORBITER TARGETS*

<table>
<thead>
<tr>
<th>PRIMARY TARGETS</th>
<th>Comment</th>
<th>Rank</th>
<th>Picture Sequence Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveyor Site (Not Yet Tested with Surveyor)</td>
<td>Untested</td>
<td>2</td>
<td>&quot;8 x 2&quot;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECONDARY TARGETS</th>
<th>Comment</th>
<th>Rank</th>
<th>Picture Sequence Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveyor Site (Not Yet Tested with Surveyor)</td>
<td>Untested</td>
<td>2</td>
<td>&quot;4 x 1&quot;**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPECIAL TARGETS</th>
<th>Comment</th>
<th>Rank</th>
<th>Picture Sequence Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operationally Successful Surveyor</td>
<td>Positive</td>
<td>1</td>
<td>&quot;8 x 2&quot;</td>
</tr>
<tr>
<td>Indicating Acceptable Spot</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operationally Successful Surveyor</td>
<td>Negative</td>
<td>3</td>
<td>&quot;4 x 1&quot;</td>
</tr>
<tr>
<td>Indicating Unacceptable Spot</td>
<td>Data</td>
<td>6</td>
<td>&quot;4 x 1&quot;</td>
</tr>
<tr>
<td>Engineering Test Surveyors</td>
<td></td>
<td>7</td>
<td>&quot;4 x 1&quot;</td>
</tr>
<tr>
<td>Area Photographed by Ranger (VIII or IX only)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operationally Unsuccessful Surveyor</td>
<td>Negative</td>
<td>4</td>
<td>&quot;4 x 1&quot;</td>
</tr>
<tr>
<td>Deployment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landmarks for Navigational Mapping</td>
<td>Desired</td>
<td>5</td>
<td>&quot;4 x 1&quot;</td>
</tr>
</tbody>
</table>

* If within Apollo area of interest

** Possibly in low resolution stereo (with samples) mode

Note: If two interests can coincide, RANK automatically upgrades to highest rank of the two interests.

Note: "+" indicates that under certain circumstances it may be worthwhile covering a bigger area.
KEY

--- HIGH RESOLUTION
-- --- LOW RESOLUTION
* APPROXIMATELY

FIGURE 2 LUNAR ORBITER CONTIGUOUS HIGH RESOLUTION MODE
A "4 x 1" BLOCK
(SECONDARY TARGETS)
FIGURE 3 A "4 x 1" IN STEREO MODE
(SECONDARY TARGETS)
KEY

- - - - - - HIGH RESOLUTION

- - - - - - LOW RESOLUTION

* APPROXIMATELY

FIGURE 4 LUNAR ORBITER CONTIGUOUS HIGH RESOLUTION MODE
AN "8 x 2" BLOCK
(SECONDARY TARGETS)
SECTION IV

CRITICAL FACTORS AFFECTING THE METHOD OF CARRYING OUT THE PLAN

A number of factors are critical to the method of carrying out the mission plan. These are discussed in this section and amplified in Appendix III and IV. A definitive mission plan should take all of these factors into account.

Requirements for One Meter Resolution

The requirements for data in support of Apollo necessitate the detection of objects of 50 cm high or less (see Appendix II). This can be converted to a need for the Orbiter to fly at an altitude of 46 km or less (see Appendix I). This defines the orbit as having a periselene, \( r_p \), of 1738 + 46 or 1784 km or less.

It is assumed that on the first flight that a nominal mission at 46 km altitude will be flown rather than attempting a lower altitude. However, on later flights, for instance when a Surveyor has indicated a possible Apollo site, it is very much desired that better resolution pictures be obtained and that all possible techniques for achieving such an improvement should be considered.

Period and Other Parameters of the Final Lunar Orbit

It is understood that the period of the orbit will need to be sufficiently large to enable the presently planned battery to be recharged. Thus the period time of 3.45 hours presently proposed by Boeing (12) is accepted. Assuming a periselene of 1784 km and a period of 3.45 hours the aposelene is approximately 3588 km (see Appendix III).

Lighting Conditions

Although it is true that the Lunar Orbiter can achieve useful photography throughout a broad range of lighting conditions it's ability to detect those items of interest to Apollo, that is to say, slopes, depressions, or protuberances, is maximized by taking photographs within a limited range of sun angles.

For vertical photography, the sun should be between 15° and 40° from the terminator.* This provides suitable contrast and illumination for optimum photography (7).

*Sunrise photography is considered desirable due to power requirement during photo readout.
At any given instant, there is an annular ring of good lighting 25° wide as shown in Figure 5. The Lunar Orbiter will pass across this ring and while passing across will be able to take satisfactory photographs.

For orbits other than equatorial, the orbit crosses the good lighting ring moving in latitude an amount which is dependent upon the angle of inclination of the orbit. For example, for an orbital inclination of 7.0°, the change in latitude during one orbital pass across the ring is 25° tan 7.0°, i.e., 3.07° (Fig 6).

As the moon turns beneath the Lunar Orbiter, a new area of the moon is brought into suitable lighting condition and this band is moved across the face of the moon defining on the moon a strip running approximately east-west. For any given mission, therefore, there is only one band of the moon 3° wide (for 7.0° inclination orbit) in which we can take good photography. This band does not necessarily have to be centered about the equator. The position of the lighting band depends on the relative position of the orbital node and the terminator.

The latitude of the area of photography is further restrained to plus or minus the angle of inclination of the orbit about the equator. On a 7.0° inclination orbit, the spacecraft does not rise above 7.0° north or south and near 7.0° the lighting band is no longer 3° wide but approaches zero.

**Angle of Inclination of Orbit**

(a) **Contiguous Photography Requirement**

Because of the need for contiguous photography of high resolution samples taken on different orbits, a limitation is placed on the possible choices of angle of orbital inclination.

The size of the high resolution pictures perpendicular to the direction of travel is 16 Km at an altitude of 46 Km (see Appendix I). To provide assurance that contiguous photography is met, some overlap of the photographs should be planned. It is recognized that considerable detailed examination is necessary in order to precisely determine numerical effects resulting from an evaluation of all the trades which affect the setting of the appropriate distance. For the purpose of this report, a distance between photographs of 15 Km is used in the calculation of the angle of inclination of the orbit.

For this given requirement of 15 Km and recalling the requirement for a 3.45 hour orbit, the angle of inclination of
the orbit can be computed (Figure 7). The appropriate angles can be derived from the formula

\[
\sin i = \frac{15}{n \times D}
\]

where D is distance that a point on the equator moves in one orbital period = 62 Km

n is any integer

and i is the angle of inclination of the orbit to the equator.

The results are shown in Figure 6. Orbital inclinations of 14.1°, 7°, 4.6°, etc. can be flown.

Any one of these will satisfy the contiguous photography requirement. Several factors influence the choice of which of these should be used.

One factor is the confidence in achieving contiguous photography. The angular error introduced by inaccuracies of thrusting do not increase in proportion to the angle of inclination attempted. Thus, larger angles can be achieved with greater percentage accuracy and, therefore, less side overlap need be provided.

A second factor is in the advantage with low inclination orbits of more guarantee that some orbit will be within a few kilometers of the desired photographic orbit.

The side distance between orbits is 15 Km to achieve contiguous photography on every orbit, so that any point on the moon's surface must be within 7.5 Km of some orbit. If, however, contiguous photography is achieved while flying at 7° the photography takes place every other orbit and the orbits are 7.5 Km apart so that any point on the moon's surface must be within 3.75 Km of some orbit. This gain to low inclination orbits assumes that the flight operational technique used is one of selection of photographic orbits after final burn. A capability to control the position of the orbits to high accuracy is not assumed.

A third factor, which is considered dominant, is the effect of the moon's gravitational pear shape term.
(b) Moon's Gravitational Pear Shape Term ($J_3$)

The moon's gravitational irregularity is expected to contain an appreciable pear shape term ($J_3$)* which will vary the altitude of the spacecraft at periselene with time. This effect is significant in two respects. First, it will change the altitude during photo taking which will affect the resolution and the area covered (and possibly the contiguous photography requirement). Second, it might change the altitude to such an extent that the mission is terminated by an impact with the lunar surface prior to the completion of readout.

The effect of $J_3$ on the altitude of the Lunar Orbiter at periselene can be expressed as $K_y$ where $K$ can be treated as a constant and corresponds to the rate of change of periselene altitude.

$$y = \sin i (5 \cos^2 i - 1)$$

where $i$ is the angle of inclination of the orbit (see Appendix III).

A computer plot of $y = \sin i (5 \cos^2 i - 1)$ is shown in Figure 8.

For angles of $15^\circ$ or less, the effect of $J_3$ is roughly proportional to the angle of inclination of the orbit.

If the magnitude of $J_3$ is such that the effect is significant then low inclination orbits must be flown, certainly on the first mission and possibly on all missions to avoid degradation of the mission. It is strongly recommended that the approach of flying at low inclination orbits be taken rather than choosing a final ellipse with a higher periselene and the subsequent loss in resolution.

It is clear that for $J_3$ terms of the magnitude being estimated by Goudas and Kaula (11), that a drop below a $14.1^\circ$ orbit to a $7.0^\circ$ orbit is required, and to a $4.6^\circ$ orbit very much desired.

It is recommended that analysis of this problem should continue to receive emphasis.

*See Appendix III.
(c) Handicap to Finding Suitable Targets

As the angle of inclination of the orbit is decreased, the band of good lighting conditions across the moon is reduced and eventually the band becomes sufficiently narrow that it is a considerable handicap in selecting a suitable set of targets on the moon's surface.

An angle of inclination of \(4.6^\circ\) or less may cause planning difficulties. An angle of inclination of the orbit of \(7^\circ\) is recommended for the first mission.

Direction of Travel

One of the variables available to the Lunar Orbiter program is the direction of travel around the moon.

There are four possible alternate directions of travel (Figure 9). These are:

- Posigrade - Ascending node
- Posigrade - Descending node
- Retrograde - Ascending node
- Retrograde - Descending node

There are several factors which will influence the selection of the most suitable direction of travel. These include:

1. Desire for telemetry during deboost
2. Time available for Canopus lock
3. Waiting time to first target
4. Angle of tilt of good lighting band
5. The moon's surface characteristics.

(1) Telemetry at Deboost

It is clear that telemetry during the deboost (that places the spacecraft into initial orbit) can only take place if the spacecraft is in line-of-site of the earth. Line-of-sight of earth is available for posigrade orbits; it is not for retrograde orbits.

Telemetry at this time is desirable but not considered an absolute requirement.
(2) Canopus Lock

It has been indicated by Boeing (Reference 12) that there is more time for Canopus lock if ascending node photography is used. It is not clear, however, that there is insufficient time if descending node photography is used. This needs checking.

(3) Waiting Time to First Target

The actual waiting time in initial orbits is a function of many things including earth moon trajectories, spacecraft plane change capability, position of initial target to be photographed and direction of travel. It appears that the choice of direction of travel is significant for certain initial targets, e.g. 60° West or if outside + or -5°. However, for the initial targets expected for the first Lunar Orbiter mission, i.e. within + or -5° and between 20° and 45° East, it is not expected that the choices of direction of travel will be restricted by a desire for a short waiting time.

It is to be noted that sufficient waiting time in initial orbit need be planned so that a suitable accuracy of determination of gravitational field terms can be made prior to the deboost into final lunar orbit.

(4) Tilt of Good Lighting Band

For a 7° angle of orbit inclination, there is a band of good lighting that runs approximately east-west and is 3° wide (see earlier discussion). However the band is not exactly east-west, it is in fact tilted.

The tilt is due to two effects:

(a) The effect on the annular lighting ring of the rotation of the earth and moon about the sun

(b) The precession of the node of the final Lunar Orbiter ellipse, particularly that due to the moon's north-south oblateness - gravitational spherical harmonic term \( J_2 \).

The edge of the annular good lighting ring is moved 1° per day eastwards due to the rotation of the earth and moon about the sun. The effect of the precession of the node is to modify the rate at which the position of the edge of the annular good lighting ring moves relatively to the node. (see Appendix IV).
These effects either add or subtract depending upon the direction of travel of the spacecraft. The magnitude of the tilt of the band due to the combined effects is as follows:

For posigrade orbits 1.2° in 66°;
For retrograde orbits 0.3° in 66°
(see Appendixes IV and III)

The resultant direction of tilt of the lighting band is shown in Figure 10.

For retrograde orbits the tilt of the band is small enough that primary targets selected for either ascending or descending node photography are applicable to both.

Posigrade orbits, however, produce a tilt significant to mission planning. Ascending node photography produces a north-west to south-east tilt of 1.2° in 66°; descending node photography produces a north-east to south-west tilt of 1.2° in 66°. These different tilts have a definite effect upon which sections of the moon's surface can be photographed in any one given mission.

(5) Moon's Surface Characteristics

The moon's surface characteristics have a significant bias that affects the possible directions of travel through the need for good lighting.

The effect of Copernicus and Kepler is to cause a desire for the band of good lighting to be placed to the South. If the possible lighting bands are placed such that they are suitably covering this section, the direction of travel for the posigrade - ascending node tends to prevent a suitable examination of the eastern terrain types.
FIGURE 5 ANNULAR RING OF GOOD LIGHTING CONDITIONS
LIMITS OF GOOD LIGHTING

DIRECTION OF FLIGHT

SPREAD OF BAND
$25^\circ \tan i$

EQUATOR

\[ \text{ANGLE OF INCLINATION } i \quad \text{tan } i \quad 25^\circ \text{ tan } i \]

<table>
<thead>
<tr>
<th>ANGLE OF INCLINATION $i$</th>
<th>tan $i$</th>
<th>$25^\circ$ tan $i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6°</td>
<td>0.0831</td>
<td>2.02°</td>
</tr>
<tr>
<td>7.0°</td>
<td>0.123</td>
<td>3.07°</td>
</tr>
<tr>
<td>14.1°</td>
<td>0.251</td>
<td>6.27°</td>
</tr>
<tr>
<td>35.5°</td>
<td>0.713</td>
<td>17.8°</td>
</tr>
</tbody>
</table>

FIGURE 6  BAND OF GOOD LIGHTING
CONTIGUOUS HIGH RESOLUTION PHOTOGRAPHY CONSECUTIVE ORBITS

OR 16 km SIDE PROGRESSION
\[
\sin i = \frac{16}{62} = 0.258
\]
\[i = 15.9^\circ\]

FOR 15 km PROGRESSION
\[
\sin i = \frac{15}{62} = 0.243
\]
\[i = 14.1^\circ\]

CONTIGUOUS HIGH RESOLUTION PHOTOGRAPHY EVERY OTHER ORBIT

FOR 16 km SIDE PROGRESSION
\[
\sin i = \frac{16}{124} = 0.129
\]
\[i = 7.4^\circ\]

FOR 15 km PROGRESSION
\[
\sin i = \frac{15}{124} = 0.121
\]
\[i = 7.0^\circ\]

FIGURE 7 ORBITAL INCLINATION

FOR 3.45 HOUR ORBIT
MOON SHIFT IN 24 HOURS IS 13.2°
MOON SHIFT IN 3.45 HOURS IS 1.9°
1.9° x 32.5 km/° = 62 km
$Y = \sin i \left(5 \cos^2 i - 1\right)$

**FIGURE 8** VARIATION OF EFFECT OF $J_3$ AS A FUNCTION OF ANGLE OF INCLINATION OF ORBIT
(1) POSIGRADE ORBIT ASCENDING NODE (ON EARTH SIDE)

(2) POSIGRADE ORBIT DESCENDING NODE (ON EARTH SIDE)

(3) RETROGRADE ORBIT ASCENDING NODE (ON EARTH SIDE)

(4) RETROGRADE ORBIT DESCENDING NODE (ON EARTH SIDE)

FIGURE 9 FOUR ALTERNATE ORBIT DIRECTIONS (FOR GIVEN $i$, WHERE $i$ IS ANGLE OF ORBIT INCLINATION)
SECTION V

SAMPLE MISSIONS

In the previous sections, mission objectives and restrictions and a preferred mission mode have been delineated. Additionally, a preliminary screening of terrain in the lunar equatorial belt has been performed. Based upon a consideration of all these factors, several equally acceptable Lunar Orbiter missions could be derived. The foldout attachments at the end of the document illustrate the derivation and characteristics of two possible missions—one example for a retrograde orbit (X - 1) and one example for a posigrade orbit (X - 2).

The examples were derived in the following manner:

(1) The preferred terrain areas were outlined on ACIC charts of the lunar equatorial region (Foldout A).

(2) The surface traces of each orbit and their associated bands of good lighting (Foldouts B & D) were superimposed on the base map. For any given mission, the band delineating good lighting conditions may be moved somewhat north or south of the equator as mentioned in Section IV. In the absence of any good reason for doing so, both bands were placed symmetrically about the equator since this is the most desirable area for Apollo.

(3) Eight Primary Targets were then placed in the selected terrain units in a manner which did not violate any of the mission constraints.

(4) Finally, the Secondary Targets were placed before and/or after the Primary Target, in all cases within 3° of the associated Primary Target. The end results, with the surface traces of the orbits removed for clarity, are shown in Foldouts C and E.

**As drawn, the orbital traces are only accurate near the equator.**

*Assuming nadir at the center of the Primary Target, a 3° displacement of Secondary Targets does not result in undue resolution deterioration. (See Fig. 11 and Ref. (8).)*
In selecting the Primary Targets, it was arbitrarily assumed that the spacecraft would be capable of a maximum of sixteen separate maneuvers, allowing eight 32 x 32 Km high resolution chunks to be photographed.

Although the four preferred terrain types are ordered in terms of presumed relative acceptability to Apollo (Section II), the emphasis given each type in these example missions does not correspond to this order. This discrepancy is more or less dictated by the availability of suitable areas and certain operational considerations of both the Surveyor and Apollo systems. Successful Surveyor landings become more difficult as the aim point shifts eastward on the lunar surface, so the easternmost regions of the area of Apollo interest were largely excluded from consideration as possible Primary Targets. It is desirable to spread the Primary Targets across the remainder of the area of interest rather than concentrating them in (presumably) the most acceptable terrain types for two reasons:

1. This spaced coverage is considered a better method of assuring that at least one acceptable area will be found.

2. In case more than one acceptable area is found, the separation of the areas on the surface allows the Apollo launch window to be opened to a greater extent than bunched sites would allow.

The optimum distribution of Primary Targets within the confines of a narrow band of acceptable lighting conditions does not leave a great deal of leeway in target selection.

In both examples, the distribution is:

<table>
<thead>
<tr>
<th>Terrain Type</th>
<th>No. of Primary Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Actually there is presently little basis for choosing between these four terrain types, which is why the arguments for spreading the Primary Targets as evenly as possible across the belt dominate target placement. Terrain type 4, in particular, is desirable from a Surveyor standpoint, and if it should prove possible subsequently to differentiate between rayed and non-rayed areas with high confidence, then at least some of these areas would become equivalent to terrain type 1.
One Primary Target was placed in a general highlands area that appears to be relatively smooth on a large scale. Although highlands have been uniformly ignored as possible Apollo sites, the authors feel there is a chance that parts of the highlands may be more hospitable than much of the maria. The probability of this is not considered large enough to warrant assigning a higher priority to highland areas at this time, but it does warrant assigning one Primary Target to a "smooth" highland area. In this way, even if we are completely mistaken in putting most of the primary emphasis on marial regions, there is still a chance that one Lunar Orbiter mission can fulfill both site selection and overfly requirements.

It should be noted that both example missions cover almost the same Primary Targets. This was done deliberately to demonstrate that terrain considerations need not affect the selection of a specific orbit.

Although there is no requirement placed on the unmanned lunar program for navigational data at this time, it is recognized that one function of the Lunar Orbiter may be to provide data on the moon that Apollo needs to get to any selected site. A major consideration is the provision of positional information about the landing site with respect to other points on the moon within 5°N - 5°S latitude and 60°E - 60°W longitude which can themselves serve as landmarks for navigational purposes. To this end, care was taken to include at least two surface features, easily visible from earth, somewhere within the area covered by low resolution stereo photography associated with every Primary Target.*

In addition to eight Primary Targets, the Lunar Orbiter has the capability of taking 52 additional pictures, which may be used for Secondary Targets. The strategy chosen here is to distribute most of these pictures in groups of four, before and/or after a Primary Target. Since there is no maneuver capability for Secondary Targets, these "targets of opportunity" must always be closely associated with Primary targets, so that the Primary spacecraft maneuver can be utilized to keep the resolution degradation due to image motion at an acceptable level. Because of the position and/or spacings of certain Primary Targets, it was not possible to utilize all thirteen 4's available in an optimum manner. Thus, one of the Secondary Targets is composed of a 32 x 32 Km high resolution block, leaving nine sets of 4 to distribute. Seven of

* Apollo is also interested in the relationship between the moon's surface and its center of mass. Both the low resolution stereo photography and V/h sensor data from the nominal type of mission recommended herein can provide this information.
these sets are composed simply of 4 contiguous high resolution pictures (16 x 16 Km) and two are composed of an extended sequence of 4 pictures (see Figure 3) giving a broader sampling at high resolution and maximum stereo coverage at low resolution. The distribution between these two secondary modes is more or less arbitrary. We prefer to use the 16 x 16 Km block for most of the Secondary Targets because of the greater area of contiguous high resolution coverage (greater than a Surveyor 1 CEP) and the greater flexibility possible in placing the high resolution coverage.

The examples discussed here are neither unique nor definitive. They are, however, representative in the sense that other mission plans, using the same ground rules, would not be expected to differ from these two examples in any significant respect. Further, as additional data become available and the ground rules consequently change, the specific mission plans will surely require modification but the general strategy illustrated by these two examples should remain valid.

*The Coordinates of the Primary Targets are listed in Table III (for Sample 1) and Table V (for Sample 2). The Coordinates of the Nadir Points for the Primary Targets and the Centers of Secondary Targets are listed in Table IV (for Sample 1) and Table VI (for Sample 2) showing the orbits where photographic activity needs to be programmed.
FIGURE 10  COMBINED EFFECTS OF SOLAR AND GRAVITATIONAL PRECESSION


TABLE III

LIST OF PRIMARY TARGETS

Coordinates

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0° - 5'S, 30° - 50'E</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0° - 35'N, 24° - 5'E</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0° - 30'N, 21° - 27'E</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0° - 40'N, 17° - 9'E</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0° - 10'S, 12° - 50'E</td>
<td></td>
</tr>
<tr>
<td>6*</td>
<td>0° - 2'N, 1° - 25'W</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1° - 5'S, 31° - 17'W</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0° - 47'S, 44° - 6'W</td>
<td></td>
</tr>
</tbody>
</table>

*An associated secondary "8x2" is centered at 0° - 10'N, 0° - 20'W.
### Table IV

**List of Primary Target Nadir Point Coordinates and Associated Centers of Secondary Targets**

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Target</th>
<th>Nadir Point</th>
<th>B-Before</th>
<th>Type</th>
<th>Center of Secondary Target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A-After</td>
<td>of &quot;u&quot;</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0° - 20'S, 30° - 52'E</td>
<td></td>
<td>Hi Res.</td>
<td>0° - 2'S, 29° - 0'E</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0° - 15'N, 30° - 48'E</td>
<td>A</td>
<td>Hi Res.</td>
<td>0° - 2'S, 29° - 0'E</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>0° - 22'N, 24° - 8'E</td>
<td></td>
<td>Hi Res.</td>
<td>1° - 10'N, 26° - 5'E</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>0° - 42'N, 24° - 2'E</td>
<td>B</td>
<td>Hi Res.</td>
<td>1° - 10'N, 26° - 5'E</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>0° - 20'N, 21° - 30'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>0° - 48'N, 21° - 25'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>0° - 30'N, 17° - 10'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>0° - 58'N, 17° - 8'E</td>
<td>B</td>
<td>Hi Res.</td>
<td>1° - 20'N, 19° - 18'E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>Hi Res.</td>
<td>0° - 55'N, 14° - 56'E</td>
</tr>
<tr>
<td>9*</td>
<td>5</td>
<td>0° - 22'S, 12° - 52'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>0° - 10'N, 12° - 48'E</td>
<td>A</td>
<td>STEREO</td>
<td>0° - 12'S, 10° - 30'E</td>
</tr>
<tr>
<td>17</td>
<td>6</td>
<td>0° - 8'S, 1° - 28'W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>6</td>
<td>0° - 20'N, 1° - 22'W</td>
<td>A</td>
<td>STEREO</td>
<td>0° - 1'S, 3° - 37'W</td>
</tr>
<tr>
<td>28</td>
<td>7</td>
<td>0° - 50'S, 31° - 20'W</td>
<td>B</td>
<td>Hi Res.</td>
<td>0° - 30'S, 28° - 53'W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>Hi Res.</td>
<td>1° - 5'S, 33° - 28'W</td>
</tr>
<tr>
<td>30</td>
<td>7</td>
<td>1° - 20'N, 31° - 15'W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>8</td>
<td>0° - 59'S, 44° - 3'W</td>
<td>B</td>
<td>Hi Res.</td>
<td>0° - 45'S, 42° - 20'W</td>
</tr>
<tr>
<td>38</td>
<td>8</td>
<td>0° - 30'S, 44° - 9'W</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* This is the second primary on the same orbit. This situation will require a second attitude adjustment. However, there may be insufficient time to acquire a second Canopus lock. If a second Canopus lock is considered essential, the photography specified above should be replaced by photography on orbit #13.
TABLE V.

LIST OF PRIMARY TARGETS

<table>
<thead>
<tr>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6*</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>

*An associated secondary "8x2" is centered at 0° - 10'S, 0° - 20'W.
**TABLE VI**

**LIST OF PRIMARY TARGET NADIR POINT COORDINATES AND ASSOCIATED CENTERS OF SECONDARY TARGETS**

<table>
<thead>
<tr>
<th>Orbit #</th>
<th>Target #</th>
<th>NADIR POINT</th>
<th>B-Before</th>
<th>Type of</th>
<th>Center of Secondary Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2° - 18'N, 37° - 56'E</td>
<td>B</td>
<td>Hi Res.</td>
<td>2° - 30'N, 35° - 30'E</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1° - 48'N, 37° - 53'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>2° - 10'N, 23° - 10'E</td>
<td>A</td>
<td>Hi Res.</td>
<td>1° - 52'N, 25° - 45'E</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>1° - 40'N, 23° - 15'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>1° - 33'N, 21° - 35'E</td>
<td>B</td>
<td>Hi Res.</td>
<td>1° - 50'N, 19° - 20'E</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>1° - 3'N, 21° - 30'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>1° - 50'N, 17° - 10'E</td>
<td>B</td>
<td>Hi Res.</td>
<td>2° - 12'N, 14° - 45'E</td>
</tr>
<tr>
<td>13</td>
<td>4</td>
<td>1° - 20'N, 17° - 5'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>5</td>
<td>0° - 20'N, 12° - 50'E</td>
<td>B</td>
<td>STEREO</td>
<td>0° - 38'N, 11° - 10'E</td>
</tr>
<tr>
<td>21</td>
<td>5</td>
<td>0° - 15'S, 12° - 48'E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>6</td>
<td>0° - 18'N, 1° - 20'W</td>
<td>B</td>
<td>STEREO</td>
<td>0° - 30'N, 3° - 45'W</td>
</tr>
<tr>
<td>28</td>
<td>6</td>
<td>0° - 20'S, 1° - 25'W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>7</td>
<td>0° - 40'S, 31° - 15'W</td>
<td>B</td>
<td>Hi Res.</td>
<td>0° - 12'S, 33° - 28'W</td>
</tr>
<tr>
<td>44</td>
<td>7</td>
<td>1° - 10'S, 31° - 22'W</td>
<td>A</td>
<td>Hi Res.</td>
<td>0° - 50'S, 29° - 0'W</td>
</tr>
<tr>
<td>47</td>
<td>8</td>
<td>0° - 32'S, 44° - 5'W</td>
<td>A</td>
<td>Hi Res.</td>
<td>0° - 50'S, 41° - 33'W</td>
</tr>
<tr>
<td>49</td>
<td>8</td>
<td>1° - 10'S, 44° - 20'W</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SECTION VI
CONCLUSIONS

A strategy has been evolved to optimize the possibility of accomplishing all the objectives of the program even if only one successful Lunar Orbiter flight is achieved. This strategy is based upon the high resolution contiguous photography mode of sampling the most promising areas of the lunar surface, as determined by pre-Lunar Orbiter terrain analysis, which are accessible to both Apollo and Surveyor. The blocks of photography are composed of sets of sixteen, contiguous high resolution pictures (giving a $32 \times 32$ km area) which can be used to both screen the general area for a subsequent Surveyor landing and to extend the effective area of the Surveyor measurements. The strategy requires only minor modifications to presently proposed Lunar Orbiter hardware and permits the launch schedule, at least through the first successful mission, to be essentially independent of the Surveyor launch schedule.

In order to carry out the strategy evolved, the following specific recommendations are made for hardware modifications and operational procedures to be followed on the first mission:

1. The camera sequencer control should be changed to include a quantity control for providing eight sequential photographs.
2. The quantity of gas made available for the altitude control system should be sufficient for a minimum of sixteen separate photographic maneuvers.
3. Photographs should be taken from a nominal height of 46 km (and no equipment changes should be made that would preclude photography from a lower altitude on a later flight).
4. To avoid the possible problem of orbital instability for the above low altitude orbit due to the uncertainties in our knowledge of the moon's spherical harmonic terms, it is recommended that the orbit be inclined no more than 7° to the lunar equator.

The two sample mission profiles derived are representative missions based on present knowledge of lunar surface characteristics. However, the first mission profile to be actually flown should be based on all data (Ranger, Surveyor, and earth-based) available prior to launch. Consequently it will be necessary to periodically update the detailed mission profiles, perhaps almost up to the actual launch date. As a corollary to this, it is important that data having a possible bearing upon the final configuration of the Lunar Orbiter mission profile be processed rapidly enough to be available for pre-launch consideration.
ACKNOWLEDGEMENTS

The authors wish to particularly acknowledge the extensive contribution made to this paper by D.B. James. The critical evaluation of G.T. Orrok and the dedication of Mrs. S.P. Moore in the correction of numerous manuscript errors are also greatly appreciated.

D.D. Lloyd
R.F. Fudali
APPENDIX I

THE LUNAR ORBITER

In a nominal mission, the Lunar Orbiter is injected into its translunar trajectory by the Atlas/Agena with a guidance system essentially identical to that used by the Mariner and Ranger Programs. The 3 axis attitude guidance and control system aboard the Lunar Orbiter is used to control the attitude of the spacecraft and direction and magnitude of thrust of its engine for all other velocity changes. Midcourse corrections as required are commanded by SFOF and DSIF regular facilities. The spacecraft is deboosted into an initial elliptic orbit above the moon's surface. It will be the first spacecraft to achieve a lunar orbit and will therefore need to operate despite a lack of pre-flight information on the moon's gravitational non-uniformities.

A few photographs may be taken while in this initial elliptic orbit but to obtain the detail needed for Apollo site survey the Lunar Orbiter needs to be brought nearer the surface of the moon. The engine is again fired to slow the craft into an elliptic orbit with a periselene of 46 km. The firing is timed to bring the Lunar Orbiter to where it can cover the first pre-selected target while that area is illuminated by sunshine from a sun at an optimum illumination angle.

PHOTOGRAPHIC OPERATION

The Lunar Orbiter takes pictures much like a commercial camera. The negative is, however, read out electronically and reconstructed on the ground. The major control over the camera, for its nominal altitude, is therefore the frequency with which photos are taken. Actually two photographs are taken

---

* I.M.P. #D is scheduled to achieve a long elliptic orbit anchored on the moon shortly after the first scheduled Lunar Orbiter.
simultaneously low resolution picture - at 8 meter resolution and covering 38 X 32 Km plus a high resolution picture - at 1 meter resolution covering 16 X 4 km in the center of the low resolution picture (Figure 14). The center of each is directly below the spacecraft. The line of flight is perpendicular to the 16 km and the 38 km edges.

The normal choice lies between taking pictures timed such that either

(1) the high resolution pictures are contiguous; or
(2) the low resolution overlap 55% to achieve stereo with the low resolution pictures; or
(3) completely separate single photographs are taken.

Each Lunar Orbiter takes 180 low resolution pictures (each with a high resolution picture in its center). If five perfectly working Lunar Orbiters were achieved, then 5 X 180 = 900 low resolution photographs would be taken. Each photograph covers about one square degree for a total of 900 square degrees. This is equal to an area of interest of ±45° in longitude and ±5° in latitude. To achieve the desired stereo photographs reduces the area so that only half the area of interest can be photographed.

Five successful Lunar Orbiters will provide detailed information in high resolution on about 1/20th of the 900 square degrees. The fineness of detail provided in these pictures will correspond to a resolution of one meter (about equal to the final 60 m X 60 m Ranger frame). Contiguous high resolution photography needed for site certification is an alternate mode to contiguous low resolution photography and is in competition with it for the limited film availability.

PHOTOGRAPHIC DETAIL OBTAINED

The Lunar Orbiter has a capability to determine slopes by an analysis of the quantity of light coming from a surface. This data is extracted from the high resolution photographs and is checked against the slope information obtained from the low resolution stereo pairs. A considerable quantity of information about local slopes is obtainable from this data. Objects of about 1 meter diameter can be detected from this data. A 2 meter diameter object in the shape of a cone 1/2 meter high will produce a signal to noise ratio of better than 3 to 1 and will be detected. Similarly, a crater 2 meters wide, 1/2 meter deep would be detected. Numerical analysis of the distribution of such hazards can be carried out by semi-automatic processes.
PICTURE SEQUENCE

The picture taking sequence is flexible to the following extent:

1. Single shots whenever wanted but not closer than 5 seconds apart (equivalent to 10 km)

plus 2. Any one of three quantities of photographs can be taken in a group at any one time, for example, 4, 8, 16*. Under no circumstances can there be more than 20 photographs per orbit.

NOTE: This grouping must apply to both high resolution contiguous and low resolution stereo modes, (with the low resolution stereo mode time interval adjusted by multiplying by 4).

PHOTOGRAPHIC MANEUVERS

A restriction is imposed on the number of possible photographic maneuvers. The Lunar Orbiter presently has a capability of 12 photographic maneuvers. This can be increased by allocating gas supply presently unassigned. However, reliability considerations reduce the advisability of planning on large numbers of maneuvers. A capability to perform 16 photographic maneuvers is assumed.

IMAGE MOTION COMPENSATION

The image motion compensation is such that a resolution of 1 meter can be obtained at an altitude of 46 km. The image motion compensation instrument has an operating range of 6 in altitude.

PRESENTATION OF RESULTS

The photographs obtained can be used to provide topographic maps of the lunar surface. Fine detail will be shown of areas considered to be suitable landing sites. Photo-geological analysis will also be made which in conjunction with Surveyor data will enable geological maps to be produced showing surface types. These presentations will be provided to appropriate Apollo program personnel so that a decision can be taken on which sites should be chosen for the first LEM landings.

* The present sequence is 4, 14, 20. A change to 4, 8, 16 was recommended in Reference 18.
APPROXIMATE

32 km

16 km

4 km

38 km

ACTUAL

31.63 km

16.55 km

4.15 km

37.38 km

FIGURE 12 LUNAR ORBITER
ONE PICTURE PAIR (AT 46 km)
This Appendix has been designated CONFIDENTIAL and will therefore be distributed under separate cover entitled "Lunar Orbiter Mission Planning - Appendix II - Apollo Site Survey Requirements", by D. D. Lloyd and R. F. Fudali, Bellcomm TR-65-211-1 (Confidential), dated January 25, 1965.
APPENDIX III

FINAL LUNAR ORBIT - FLIGHT MECHANICS

Introduction

During the photographic portion of the Lunar Orbiter mission, the Lunar Orbiter flies in an elliptic orbit, one focus of which is the center of the moon's gravitational field. It is necessary to consider the relative position of the Lunar Orbiter to the surface of the moon. Consideration must be given to a considerable number of effects some of which are interrelated to the overall problem in several ways.

Relative Position of Lunar Orbit to Moon

The dominant factor influencing the relative position of the Lunar Orbiter (at periselene) to the lunar surface is the rotation of the moon on its axis. The rotation of the moon takes place in inertial space and is about the moon's axis of maximum inertia. This axis is defined as running North-South, and the moon's equator lies in a plane perpendicular to this axis. The moon rotates about this axis once every 27.32 days* (which is identical to the rotation period of the moon about the earth). If we consider the moon's 360 degrees of longitude, then the rotation in degrees of longitude per day is 360 divided by 27.32 or 13.2 degrees per day, which is .55 degrees per hour. If we had an orbit whose periselene were at the node with photography taking place at this point, i.e., directly above the equator, then the position of the equator would move relative to the orbit periselene, .55 degrees per hour (which, at the equator, is .55 x 32.5 kilometers). Irrespective of where periselene is or where photography is taken, the shift of the moon's surface relative to the node is .55 degrees per hour. On the moon's surface the subnodal point moves East to West across the moon along its equator. Similarly the path of the orbit appears to move East to West across the moon's surface (see Figures 15 & 16).

* "Day" will be used to mean "earth mean solar day" in this report.
The path of the Lunar Orbiter around the moon follows that of a perfect ellipse for a moon free from perturbation effects. If the moon were of uniform density and a perfect sphere, and if the gravitational field of the earth and the sun and other masses did not influence the orbit, then it would be a perfect ellipse with a focus at the center mass of the moon. This is a satisfactory model for most photographic considerations. In those cases where this is not a satisfactory model the differences are discussed.

PARAMETERS OF A FINAL ELLIPTIC LUNAR ORBIT

There is a definite relationship between the period of the orbit, $T$, the periselene radius $r_p$, and the eccentricity $e$, of the orbit. This relationship is defined by the following equations.

\[(1) \quad T^2 = \frac{4\pi^2}{\mu} \frac{a^3}{P} \quad \text{(from Kepler's laws)}\]

For a given $T$ and $\mu$, $a$ is determined

\[(2) \quad r = \frac{p}{1 + e \cos \phi} \quad \text{and} \quad p = a(1 - e^2) \quad \text{from the definition of an ellipse} \]

At periselene,

\[r_p = \frac{p}{1 + e \cos \pi} = \frac{p}{1 + e} \]

\[r_p = \frac{a(1-e^2)}{1+e} = a(1-e) \]

Thus all other parameters of the ellipse are specified completely. The resulting final elliptic orbit is shown in Figure 17.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$</td>
<td>PERIOD OF ORBIT</td>
</tr>
<tr>
<td>$a$</td>
<td>SEMI MAJOR AXIS OF ELLIPSE</td>
</tr>
<tr>
<td>$\mu$</td>
<td>NEWTONIAN CONSTANT TIMES LUNAR MASS</td>
</tr>
<tr>
<td>$r$</td>
<td>RADIAL VECTOR TO ANY POINT ON ELLIPSE FROM THE FOCUS CORRESPONDING TO THE MOON'S CENTER OF MASS</td>
</tr>
<tr>
<td>$p$</td>
<td>SEMILATUS VECTUM</td>
</tr>
<tr>
<td>$e$</td>
<td>ECCENTRICITY OF THE ORBIT</td>
</tr>
<tr>
<td>$\phi$</td>
<td>ANGLE MEASURED FROM MAJOR AXIS OF ELLIPSE</td>
</tr>
<tr>
<td>$r_p$</td>
<td>PERISELENE</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>ARGUMENT OF NODE</td>
</tr>
<tr>
<td>$\omega$</td>
<td>ARGUMENT OF PERISELENE</td>
</tr>
<tr>
<td>$\tau$</td>
<td>SUFFICE NOTATION SPECIFYING &quot;PER ORBIT&quot; (e.g., $\Delta \Omega_h$ IS CHANGE IN $\Omega$ IN ONE ORBIT)</td>
</tr>
<tr>
<td>$i$</td>
<td>ANGLE OF INCLINATION OF ORBIT TO EQUATOR</td>
</tr>
<tr>
<td>$R$</td>
<td>MEAN RADIUS OF MOON</td>
</tr>
<tr>
<td>$J_2$</td>
<td>MOON'S SECOND HARMONIC - OBLATENESS TERM</td>
</tr>
<tr>
<td>$J_3$</td>
<td>MOON'S THIRD HARMONIC-PEAR SHAPE TERM</td>
</tr>
</tbody>
</table>

![Diagram showing celestial mechanics terms and symbols](image-url)
EVALUATION OF EFFECTS OF J₃

The J₃ term of the moon will affect the lunar orbits in several ways. The principle concern is over its affects on the altitude of the spacecraft at periselene.

Effect on Altitude

This effect is significant in two respects. First, it will change the altitude during photo taking which will affect the resolution and the area covered (and possibly the contiguousness requirement). Second, it might possibly change the altitude to such an extent that the mission is terminated by an impact with the lunar surface prior to the completion of readout.

Tolerance Requirements

The tolerance requirements during photo taking are tight, say 46 Km ± 5%, but the time period is short, say 5 days.

The tolerance requirements for the total mission are more relaxed, 46 Km downwards and no direct restriction upwards, but the time period involved is of the order of 30 days.

These tolerances are more pertinently expressed as:

\[ \text{periselene} = (1738 + 46) \text{ Km} ± 2 \text{ Km (5 days)} \]

\[ \text{and periselene} = (1738 + 46) \text{ Km} - 46 \text{ Km} + >460 \text{ Km (30 days)} \]

Evaluation of Effect on Altitude at Periselene.

The effect of J₃ on the altitude at periselene \( \Delta r_p \) can be expressed in terms of the change in orbit eccentricity as follows:

\[ \Delta r_p = \Delta a (1-e) = -a \Delta e_{3h} \text{ when } a \text{ can be treated as constant} \]

and

\[ \Delta e_{3h} = \frac{-3\pi}{4} \frac{J_3 R^3}{p^3} (1-e^2) \cos \omega \sin i (5 \cos^2 i - 1) \]

Ref. (9) I. I. Shapiro

(adjusted by R³ to bring to non-dimensional definition of J₃)
Significance of Angle of Inclination of the Orbit

It is constructive to examine the significance of the variable $i$. To isolate the effect of variation in $i$ we can simplify the equation by making certain approximations.

Over a short period of time, $p, e,$ and $\cos \omega$ can be treated as constant and $\cos \omega$ can be treated as equal to 1, for this consideration of the effect of the angle of inclination.

It is therefore possible to rewrite

$$\Delta e_{3h} = \frac{-3\pi}{4} \cdot \frac{J_3 R^3}{p^3} (1-e^2) \cos \omega (\sin i (5 \cos^2 i - 1))$$

as

$$Ky$$

where $K$ can be treated as a constant

and $y = \sin i (5 \cos^2 i - 1)$

where $i$ is the angle of inclination of the orbit.

A computer plot of $y = \sin i (5 \cos^2 i - 1)$ is shown in Figure 8.

For angles of $15^\circ$ or less, the effect of $J_3$ is roughly proportional to the angle of inclination of the orbit.

If the magnitude of $J_3$ is such that the effect is significant, then either the Lunar Orbiter altitude at periselene must be made considerably greater than 46 Km or a low inclination orbit must be flown. It is the authors' opinion that the former course of action is virtually equivalent to wasting a Lunar Orbiter and this report strongly urges that the alternative procedure of flying a low inclination orbit be adopted for at least the first mission.
Numerical Evaluation of $\Delta e_{3h}$

$$\Delta e_{3h} = \frac{-3\pi}{4} \frac{J_3 R^3}{p^3} (1-e^2) \cos \omega \sin i (5 \cos^2 i - 1)$$

$$= \frac{-3\pi}{4} \frac{J_3 R^3}{a^3 (1-e^2)^3} (1) \sin i (5 \cos^2 i - 1)$$

Approximately

$$\Delta e = -2 \cdot \frac{(10^{-4}) R^3}{a^3} (1) \sin i (5 \cos^2 i - 1)$$

for $|J_3| = 10^{-4}$ (Ref 11)

for $i = 7^\circ \sin i (5 \cos^2 i - 1) = 0.4$

and $R = 1738$ Km, $a = 2686$, Km

$$(\frac{R}{a})^3 = 0.125$$

$\Delta e = 1 \cdot 10^{-5}$

$a\Delta e = a \cdot 10^{-5}$

$$2,686 \cdot 10^{-5} \text{ Km}$$

$$= 2.7 \text{ Km in 100 orbits or 15 days.}$$

This effect is significant.

The primary unknown is accuracy of the value of $J_3$. 
There has been considerable detailed analysis of this subject including, in particular, Boeing's memorandum (11) to the Lunar Orbiter Project Office dated September 9, 1964 in which the effect of the angle of inclination of the orbit on the change in the altitude of periselene is evaluated.

This work is in part based upon a document (15) by C. L. Goudas of Boeing's Mathematics Research Group. This document contains numerical values for $J_3$ and $J_4$ terms that assume a constant density moon and make use of earth-based telescopic measurements of the surface on the front face of the moon. A weakness of this approach is the assumption of constant density. It seems equally likely that those areas of the moon that bulge (e.g., at 30° North) are due to the presence of low density material that has risen and formed a bulge precisely because of its low density. If Goudas' method had been used to evaluate the Earth the northerly land masses of the earth would have resulted in a $J_3$ pear shape term of opposite sign to that which actually exist. Kaula of UCLA has used a different method in which he infers knowledge of the moon from geophysical considerations. Kaula computes a similar numerical value to Goudas but with the sign of $J_3$ undetermined.

It is clear that for $J_3$ terms of the magnitude being estimated by Goudas and Kaula (11), that a drop below a 14.1° orbit to a 7.0° orbit is required.

It is recommended that analysis of this problem should receive emphasis.

Direct Effect of $J_3$ on Angle of Inclination of Orbit

There is need to note the effect of $J_3$ on the angle of inclination of the orbit. The effect is

$$
\Delta i_{J3h} = \frac{3\pi}{4} \frac{J_3 R^3}{p^3} e \cos \omega \cos \iota (5 \cos^2 \iota - 1)
$$

Ref. (9) I. I. Shapiro

(Adjusted by $R^3$ to bring to non-dimensional definition of $J_3$)
Numerical Evaluation of $\Delta 1_{3h}$

For

\[
\begin{align*}
\text{ae} &= 902 \text{ Km} \quad \text{(see Fig 17)} \\
a &= 2686 \text{ Km} \quad \text{(see Fig 17)} \\
e &= \frac{902}{2686} = .335 \\
R &= 1738 \text{ Km} \quad \text{(see Fig 17)} \\
\frac{R}{a} &= \frac{1738}{2686} = .52; \ (.52)^3 = .125
\end{align*}
\]

\[
\Delta 1_{3h} = \frac{3\pi}{4} \frac{J_3 R^3}{\rho^3} e \cos \omega \cos i (5 \cos^2 i - 1)
\]

\[
\Delta 1_{3h} = -2 \frac{J_3 R^3}{a^3(1-e^2)} \frac{1}{3} \cdot 4.
\]

\[
= 3 \frac{J_3 R^3}{a^3(1-.1)^3}
\]

\[
= 3 \times \frac{10^{-5}}{.7} \frac{R^3}{a^3}.
\]

\[
\Delta 1_{3h} = .5 \times 10^{-5}
\]

In 100 orbits $\Delta 1_3 = .5 \times 10^{-3}
\]

$= .03^\circ$

This effect is too small to affect the general plans but large enough so that it affects the detailed operational techniques and therefore needs detailed evaluation.
EFFECTS OF NORTH-SOUTH OBLATENESS, $J_2$

Effect on Tilt of Lighting Band

The moon's north-south oblateness causes significant effects in several ways. The two principal perturbation effects are on the angular movement of the node $\frac{\Delta \Omega}{\Delta t}$ and on the angular movement of the argument of periselene $\frac{\Delta \omega}{\Delta t}$.

The angular motion of the node (along the equator) is given by

$$\Delta \Omega_{2h} = -3\pi \frac{J_2}{\mu} \frac{R^2 \cos i}{a^2 (1-e^2)^2 T}$$

Ref 9 I. I. Shapiro (adjusted by $R^2$ to bring to non-dimensional definition of $J_2$)

where $p = a(1-e^2)$.

The rate of angular motion is

$$\frac{\Delta \Omega_{2h}}{\Delta t} = -3\pi \frac{J_2}{\mu} \frac{R^2 \cos i}{a^2 (1-e^2)^2} \frac{1}{T}$$

c/day

using:

$$T = \frac{4\pi^2 a^2}{\mu} = 2\pi \left( \frac{a^3}{\mu} \right)^{1/2}$$

This can be rewritten as

$$\frac{\Delta \Omega_{2h}}{\Delta t} = -3\pi \frac{J_2}{2 \mu} \frac{R^2 \cos i}{(a^2)(1-e^2)^2} \left( \frac{\mu}{a^3} \right)^{1/2} \ c/day$$

or

$$\frac{\Delta \Omega}{\Delta t} = -3\pi \frac{J_2}{2 \mu} \frac{R^2 \cos i}{(a^2)(1-e^2)^2} \left( \frac{\mu}{a^3} \right)^{1/2} \ c/day$$
and for:

\[ \mu = 4.90 \times 10^3 \]  
(Ref. 10)

\[ J_2 = 2.1 \times 10^{-4} \]  
(Ref. 10)

\[ \frac{\Delta \Omega}{\Delta t} = (-\cos i) \frac{3(2.1) \times (10^{-4})}{2(2686.10^3)(1-.34)^2} \frac{2}{(2.686 \times 10^3)^3} \]  

= \(-\cos i\) \cdot 0.60°/day

**Effect of Direction of Spacecraft Travel (see Appendix IV)**

For a posigrade orbit, the procession is westward, so that the combined effects of 1°/day solar change and this \( J_2 \) procession are additive to 1° + 0.60° (cos i)°/day.

For a retrograde orbit the effects subtract to

1° - 0.60 (cos i)°/day.

For low inclination orbits, cos i = 1.

Thus for posigrade orbits, total effect = 1.60°/day.

For retrograde orbits, total effect = 0.40°/day.
Shift in Periselene Due to Moon's Oblateness ($J_2$)

The angular motion of periselene along the orbit is given by

$$\Delta \omega_{2h} = \frac{3\pi}{2} \frac{J_2 R^2}{p^2} (5 \cos^2 i - 1)$$

Ref. (9) I. I. Shapiro

(adjusted by $R^2$ to bring to non-dimensional definition of $J_2$)

where $p = a(1-e^2)$

The rate of angular motion is

$$\frac{\Delta \omega_{2h}}{\Delta t} = \frac{3\pi J_2 R^2 (5 \cos^2 i - 1)}{2 a^2 (1-e^2)^2} \frac{c}{day}$$

$$T^2 = \frac{4\pi^2 a^2}{\mu} \text{ or } T = \frac{2\pi (a^3)}{\mu} \frac{1}{2}$$

This can be rewritten as

$$\frac{\Delta \omega_{2h}}{\Delta t} = \frac{3\pi J_2 R^2 (5 \cos^2 i - 1)}{2(2\pi) a^2 (1-e^2)^2} \left[\frac{\mu}{a^3}\right]^{1/2} \frac{c}{day}$$
or

\[ \omega = \frac{3J_2(5 \cos^2 i - 1)}{4(a/R)^2 (1-e^2)^2} \left( \frac{\mu}{a^3} \right)^{1/2} \text{ c/day} \]

For low angles of inclination \( \cos^2 i = 1 \), this reduces to

\[ \omega = \frac{3J_2(4)}{4(a/R)^2 (1-e^2)^2} \left( \frac{\mu}{a^3} \right)^{1/2} \text{ c/day} \]

or = +1.2°/day along the path of the orbit in the same direction as the movement of the spacecraft (see Fig. 18).

In 5 days periselene moves 6° along the path of the orbit. In N-S direction displacement = 6° \( \sin i \)

- for \( i = 7° \)
  - \( \sin 7° = .13 \)
  - N-S shift = .13 x 6° = .8°

The position of periselene moves North for ascending nodes (regardless of whether posigrade or retrograde orbit). The tilt of the path of periselene is in the same direction as the tilt of the lighting band for posigrade orbits and in opposition for retrograde orbits, (see Fig. 18). This effect must be taken into account when determining the change in altitude at nadir due to nadir not occurring at periselene.

Selection of Optimum Path of Periselene

The change in altitude at periselene (Fig. 19) as a function of angular distance along the orbit is shown in the computer plot (Fig. 20). The effect is significant enough that an optimum path of periselene needs to be selected that minimizes the loss of resolution due to the increased altitude. An optimum path for periselene is achieved by selecting one with a best fit (RMS) to the prime targets only.
Interdependence of Effects of Several Terms

It is necessary to note that the effects of the various Spherical Harmonic Terms are interdependent. For example:

\[ \Delta \omega \text{ is a function of } J_2 \text{ and } J_3. \text{ The effect of } J_2 \text{ was discussed earlier. The effect of } J_3 \text{ is:} \]

\[ \Delta \omega_{3h} = \frac{3\pi}{4} \frac{J_3 R^3}{p^3} (1 + 4e^2) \sin \omega (\sin i (5 \cos^2 i - 1)) - \cos i \Delta e_{3h} \]

Similarly

\[ \Delta \Omega \text{ is a function of } J_2 \text{ and } J_3. \text{ The effect of } J_3 \text{ is:} \]

\[ \Delta \Omega_{3h} = \frac{3\pi}{4} \frac{J_3 R^3}{p^3} e \sin \omega (\cot i (15 \cos^2 i - 1)) \]

Here attention is drawn to \( \cot i \) which approaches infinity as \( i \) tends to zero. Thus for orbits close to equatorial a large effect of \( \Delta \Omega \) results.

The numerical effect of interdependence can be handled by updating the value of the effected variables each orbit using an iterative process as implied by I. I. Shapiro's approach; however, other techniques are possible.

Such interdependences indicate a need for considerable detailed evaluation of all the effects prior to flight operations. Fast analysis of the Spherical Harmonic Terms during the initial lunar orbit will only be possible if considerable software preparation intended for this analysis has been carried out in advance.

Other Orbital Effects Produced

It should be noted that the above analysis does not cover all the effects that deserve evaluation. For example, it ignores the effect of periodic terms in the perturbations, and the perturbations due to the gravitational field of the Earth and the Sun.

These effects are not expected to modify either the comment that the \( J_3 \) effect should be treated as significant nor the general position of primary targets through a change in the angle of tilt of the lighting band. However, this intuition should be checked.
FIGURE 15 FLIGHT MECHANICS OF LUNAR ORBIT
IN MOON CENTERED
INERTIAL SPACE

Node in fixed position (approximately)
Periselene
Crater on Moon's surface moves eastwards*.55°/hour

EQUATOR
Orbit

IN RELATION TO
MOON'S SURFACE

Crater on Moon's surface fixed

Orbit and node appear to move westward .55°/hour

"EAST IS WHERE THE SUN RISES (APPROXIMATELY)"

FIGURE 16
MOON RADIUS = 1738 km
PERISELENE = 1784 km (Alt p = 46 km)
APOSELENE = 3588 km (Alt A = 1850 km)

SCALE: 1:50.106
PERISELENE DISTANCE, \( r_p = a(1-e) \)

ALTITUDE = \( a(1-e)-R \)

DIRECT EFFECT OF J3 IS ON \( \Delta e \)

IF \( a \) IS TREATED AS CONSTANT

THE \( \Delta \text{ALT.} = -a \Delta e \)

IF \( e \) INCREASES PERISELENE DISTANCE DECREASES

FIGURE 19 EFFECT OF J3 ON ALTITUDE AT PERISELENE
POSIGRADE

(a) Ascending Node

(b) Descending Node

RETROGRADE

(a) Ascending Node

(b) Descending Node

FIGURE 18 PATH OF PERISELENE
(PRECESSION OF PERISELENE DUE TO $J_2$)
FIGURE 20 COMPUTER PLOT OF CHANGE IN ALTITUDE AT PERISELENE AS A FUNCTION OF ANGULAR DISTANCE ALONG ORBIT.
APPENDIX IV

TILT OF BAND OF GOOD LIGHTING

To a first approximation that part of the moon which is in suitable lighting conditions for photography is a band running east-west the height of which is $25^\circ \tan i$ where $i$ is the angle of inclination of the orbit. However, this band is not exactly east-west, it is in fact tilted.

The tilt is due to two effects:

(a) The effect on the annular ring of good lighting of the rotation of the earth and moon about the sun.

(b) The precession of the node of the final Lunar Orbiter ellipse, particularly that due to the moon's north-south oblateness - gravitational spherical harmonic term ($J_2$).

It is convenient to first describe the effect of the rotation about the sun and to then superimpose the effect of $J_2$.

Effect of Rotation About the Sun

Although the dominant shift of the annular lighting ring on the moon is due to the rotation of the moon on its axis, a secondary effect arises as follows.

Consider the Lunar Orbiter at a node during photography. At some point in the mission (about half way through the photo taking part of the mission) this node will be centered in the lighting band $12 \ 1/2^\circ$ from each edge and $27 \ 1/2^\circ$ from the terminator. Let us call this time $t = 0$ (arbitrarily) then the conditions are as shown in Figure 21.

Figure 21 shows the earth-moon-sun system viewed from the north perpendicularly to the ecliptic plane.

After 10 days, the moon has moved $132^\circ$ to the position marked $t = 10$. If we ignore precessional effects, then the Lunar Orbiter crosses the equator (node) at the same position in moon centered inertial space as shown.
If we now take into account the movement of the earth and moon about the sun, the ring of good lighting has, however, shifted 10° due to the 10 days of rotation at 1° per day.

The Lunar Orbiter is now 10° nearer the edge of the ring of good lighting condition. In fact, by $t = 12\ 1/2$ days the node will correspond to the edge of good lighting conditions. How this looks on the moon is shown in Figure 22.

Effect of Precession of the Node

A significant additional effect arises out of the north-south oblateness - spherical harmonic term ($J_2$). One effect of $J_2$ is to precess the node. The magnitude\(^2\) of this precession is of the order of .6°/day. (Appendix III)

The effect of this term is added algebraically to the effect due to the rotation of the earth about the sun.

Combined Rotation and $J_2$ Precession Effect

Figure 23 and 24 show the combined solar and precessional effects. Figure 23 shows the effect for posigrade orbits. The rotation of the earth and moon about the sun moves the edge of the band of good lighting eastwards (+Ve) 1° per day; at the same time the node is precessed westward (-Ve) - .60°/day. (See Appendix III)

The Lunar Orbiter and the edge of good lighting are, therefore, brought together at a rate of $(1 + .6)°/day$. To move from the center to the edge requires a loss of $12\ 1/2°$. Thus, it takes $12.5/1.6 = 7.8$ days to lose $12\ 1/2°$. In this period, the band has dropped half its height or $\frac{3.1°}{2}$ for a 7° inclined orbit.

For convenience of preparing a mission plan, it is useful to compute the north-south change in 5 days. (5 days is equivalent to 66° of rotation of the moon). The north-south change is $\frac{3.1° \times 5}{2} = 1.2°$. The line has a tilt of magnitude $\frac{1.2°}{7}$ in 66°.

Similarly Figure 24 shows the effect for retrograde orbits. In this case, the solar and the precession effects are both eastwards. The net effect is, therefore, reduced. The line has a tilt of magnitude $\frac{.3°}{66°}$.

The direction of the tilts are shown in Figures 23 and 24.
FIGURE 21 LIGHTING CONDITIONS

VIEWED FROM NORTH ECLIPTIC
WITH \( t = 0 \), AT START OF 2nd QUARTER.
ORBITER CROSSING EQUATOR.
FIGURE 22  AREA OF MOON WITH GOOD LIGHTING CONDITIONS
DRAWN FOR POSIGRADE ORBIT - ASCENDING NODE.
SOLAR AND J₂ PRECESSION EFFECTS

(a) Ascending Node

(b) Descending Node

CALCULATION OF SLOPE OF BAND

TO MOVE FROM CENTER TO EDGE REQUIRE LOSS OF 12.5°. RATE OF LOSS = (1 + .6)°/day

# OF DAYS = \frac{12.5}{(1 + .6)} = 7.8 \text{ days}

FOR CONVENIENCE OF PLOTTING COMPUTE S-N MOVEMENT FOR 5 DAYS (= 5 × 13.2° = 66°)

IN 5 DAYS (66°) LOSES \frac{3.1}{2} \times \frac{5}{7} = 1.2°

FIGURE 23
SOLAR AND $J_2$ PRECESSION EFFECTS

RETROGRADE

(a) Ascending Node

(b) Descending Node

CALCULATION OF SLOPE OF BAND

TO MOVE FROM CENTER TO EDGE REQUIRES LOSS OF 12.5° RATE OF LOSS

$= (1 - .60)/day$

$\# \ OF\ DAYS = \frac{12.5}{1 - .60} = 30\ days$

FOR CONVENIENCE OF PLOTTING COMPUTE S-N MOVEMENT FOR 5 DAYS ($=5 \times 13.2° = 66°$)

IN 5 DAYS LOSES $\frac{3.1}{2} \times \frac{5}{30} = .3°$

FIGURE 24
REFERENCES


12. Boeing Documents D2-100100 series on 939 Lunar Orbiter contract #NAS 1-3800 including D2-100103.

13. Requirements for Data in Support of Project Apollo, Issue III, February 25, 1964 (Confidential)


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