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LIGHTING CONDITIONS FOR A LUNAR
LANDING MISSION

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Summary

For certain combinations of lighting and viewing conditions, the lunar landing site will be void of visible details because of the strong backscattering photometric properties of the lunar surface. This washout happens at zero phase angle (i.e., the angle between the source and the viewer). The effect has been observed from the earth and has been confirmed by Surveyor I pictures.

To demonstrate this effect, photographs of a scale model of a lunar surface dusted with copper oxide under various lighting and viewing angles were made. Copper oxide was chosen because its reflection properties are similar to those of a lunar surface. Each picture is identified on the CuO photometric function chart. Those pictures showing good terrain detail correspond to the high contrast region on the chart. It is shown that a substantial improvement of the astronaut's viewing conditions could be achieved with descent trajectories whose viewing angles are greater than the sun angles or trajectories in which the sun is off to one side.

The uncertainty of the lunar photometric function as compared to the photometric function of the model used for simulation is shown to be significant and the need for an accurate determination of a lunar photometric function is pointed out.

1. Introduction

The advent of the first lunar landing will bring new requirements on man's capabilities. He will operate in a unique visual environment where the intensity of visible radiation will change and contrast levels will be greatly altered because of the absence of a scattering medium. The nature of the lunar surface is currently being investigated by astrophysicists and geologists. The photometric properties of the lunar surface are one of the sources of the present knowledge of its microscopic structure and are characterized by several unusual features. B. Hapke summarized these features as follows:

"1. The albedo is uniformly low, varying from about 5% to 18%.

"2. The surface strongly backscatters light, so that the intensity of sunlight reflected toward the earth from nearly all areas on the moon reaches a sharp maximum at full moon.

"3. The maximum polarization is uniformly small, seldom exceeding 15%. Brighter formations on the moon generally polarize the light less strongly.

"4. The manner in which both polarization and brightness of a region vary during a lunation is almost exclusively a function of the lunar phase angle (i.e., of the angle between the source of illumination and the observer) and is very nearly independent of location on the lunar sphere or of the type of terrain.

"5. The moon is essentially colorless, and reflection from its surface only slightly affects the spectrum of sunlight. Except for albedo there is little difference in appearance or color between the various types of terrain."

These photometric properties are different from those one has been accustomed to here on earth. It is important, therefore, to define the new visual requirements which man must be able to meet effectively during his lunar landing descent. It is recognized that any manned lunar landing will involve many aspects of visibility and the psychophysical visual functions man has at his command. The visibility of the lunar surface is dependent on several factors, e.g., the scene contrast at the landing site, albedo variations in the lunar surface, surface detail indicated by the amount of shadowing present, the human visual system (search time, object off visual axis, etc.), and the intervening media (spacesuit faceplate, vehicle window, etc.). Because there are so many factors to be controlled, visual performance in laboratory simulations of practical operational conditions is very difficult; only part of the total task can be simulated. In order to reduce the visual task to a measurable, predictable phenomenon, it must be specified in terms of information content, e.g., awareness of the presence or absence of the target is considered to be one item of information. With this requirement in mind, a distinction can be generally made among three kinds of visibility tasks.

1. Visibility - the observer is required only to perceive some object against a uniform background, when the position is known.

2. Detectability - the observer is required to search for a target of unknown location but of known characteristics in a given search time.
3. Recognition - the observer is required to identify a target in addition to detecting its presence.

The above distinctions are useful measures of visibility tasks which can be determined in a laboratory test. However, in an operational situation it is difficult to separate the three factors and for that reason the so-called "field factors" have been developed by H. R. Blackwell to use in interpreting laboratory visibility data for practical visibility capability under operational conditions. The extent of understanding and knowledge of the proper values of such factors is still very limited in view of the complexity of operational considerations such as spacecraft vibration, window characteristics, spacesuit faceplate, etc.

This paper is concerned exclusively with the scene contrast at the landing site and its variation as the viewing conditions change. In Section II, the effect of the peculiar photometric properties of the lunar surface is demonstrated by a series of pictures taken of a lunar surface model dusted with copper oxide under various lighting and viewing conditions. The selection of these conditions includes the so-called "washout" (zero phase angle), "dog-leg" (sun off to one side), and "buttonhook" descent (landing towards the sun). In Section III, selected pictures of a lunar surface obtained from Surveyor I and Lunar Orbiter II are compared with the laboratory pictures of a scaled model dusted with copper oxide. In Section IV, the lunar photometric function is presented and compared with the photometric function of the model dusted with copper oxide. In Section V, the discussion is focused on the presentation of a descent trajectory on the lunar photometric chart and the lighting conditions for a given descent trajectory are predicted.

II. Interpretation of Pictures of a Scaled Lunar Model Dusted with Copper Oxide

Recent studies show that the landing site will be void of visible shadows for certain lighting conditions because of the strong retroreflective photometric properties of the lunar surface and thus its relief will produce very little contrast with respect to the background.

To demonstrate this effect, pictures of a scaled model of a lunar surface were made under various lighting and viewing angles. The selection of these conditions is shown in Table I. The pictures were arranged into Figures 2-4 and the viewing and lighting angles are specified by the viewing angle (VA), sun angle (SA), and azimuth (AZ), which are defined in Figure 1. Looking at the pictures in Figures 2-4 through the eyes of an astronaut descending to the surface, it is apparent that visibility of the landing site would be extremely poor if the viewing and lighting conditions were such as in Figure 2.1. This condition corresponds to the washout which is characterized by a small phase angle (the angle between the sunlight and the observer line-of-sight). For this case, the sun is directly behind the astronaut's head. His visibility of a landing site could be improved by allowing him to approach the landing site in such a way that his viewing angle would be always greater than the sun angle as shown in Figure 2.4.

Now suppose that the astronaut looks to one side of his intended landing site, or that he makes a turn and lands to one side of the straight-ahead landing point. This is called the dog-leg maneuver. The azimuth angle between the sun and his eye becomes different from zero (see Figure 1). The result is a substantial increase in contrast (compared to Figure 2.1) as depicted in Figures 2.2 and 2.3 for a 30° and 60° azimuth, respectively. In comparison with Figure 2.4, the azimuth turn of 30° or 60° (Figures 2.5 and 2.6) does not show any great change in contrast for the case of the viewing angle greater than the sun angle. It will be shown quantitatively in Section IV that for this case the contrast actually slightly decreases below that obtained with zero azimuth angle.

Another way to improve the contrast is to look toward the sun or to perform the buttonhook maneuver in which the astronaut, after passing over the landing site, makes a 180° turn in azimuth or in the vertical plane and doubles back. The surface view will be similar to Figure 2.7, with considerably improved contrast over that in Figure 2.1. The two difficulties here are glare and low surface brightness.

The effect of glare can be seen by comparing Figure 4.7 with 4.7A and Figure 4.14 with 4.14A. Figures 4.7 and 4.14 were taken with a collimated light source, which eliminates glare; Figures 4.7A and 4.14A have not had the glare removed. Imperfect shielding of the eyes or internal reflections in the spacecraft window may increase the glare.

All of the pictures in Figure 2 have been taken with a sun elevation angle of 15° (the landing sites are 15° from the terminator). Since the surface contrast varies with the sun angle, the geometric conditions of Figure 2 have been repeated in Figure 3, but with a sun angle of 55°. The significant differences are mainly in the reduction of the geometric shadowing and the improvement in contrast by increase of the phase angle as indicated by a comparison of Figures 3.8 and 2.1. This condition will be discussed quantitatively later in Section IV. Furthermore, even for this relatively high sun angle, the azimuth turn (dog-leg maneuver) prevents the washout which occurs for zero phase angle, as shown in Figures 3.12 and 3.13.

In order to avoid confusing the above comparisons of contrast, Figures 2-4 through 4.16, 4.17A, and 4.14A have been printed to approximately the same density without destroying the relative contrast. This conceals the considerable average brightness decrease
in Figures 4.7, 4.7A, 4.14, and 4.14A and consequently another set of three pictures has been prepared, taken at identical exposures and processed identically. These are labeled 4.1E, 4.8E, and 4.7E, respectively, and illustrate the brightness range.

No attempt has been made to control the actual contrast in the pictures as printed here; however, printing to the same density ensures maintaining the proper relationships between individual photos.

III. Comparison of Surveyor I and Lunar Orbiter II Pictures with the Laboratory Pictures of a Scaled Model

In the last section, pictures taken of a scaled lunar model dusted with copper oxide revealed some peculiar photometric properties. In particular the washout was demonstrated for zero phase angle. Furthermore, it was shown how to prevent this washout by an azimuth turn.

In this section, selected pictures obtained from the NASA unmanned lunar programs, Surveyor and Lunar Orbiter, were chosen for comparison with the laboratory pictures. Figure 5 shows a spherical mosaic of narrow-angle photographs of the lunar scene at low sun angle (~10°) transmitted by the Surveyor I spacecraft. Craters and fine detail of the surface are quite evident. A portion of this lunar scene is now shown in Figure 6 under different lighting conditions, namely, at zero phase angle (in Figure 6 the spacecraft takes a picture of its own shadow). The resemblance to Figure 2.1 is remarkable for the region of zero phase angle - the washout condition. Moreover, the detailed texture of the lunar surface at the bottom of Figure 6 corresponds to the lighting conditions of Figure 2.4 where the camera viewing angle is greater than the sun angle. Another interesting observation of Figure 6, which has a 25° field of view, reveals that the azimuth turn must be more than 15° or the viewing angle must be 5° - 10° greater than the sun angle in order to prevent this washout condition. This observation will be substantiated analytically in the next section where the lunar photometric function is discussed.

Figure 7 shows the first close-up of the lunar crater Copernicus, taken with Lunar Orbiter II's telephoto lens on November 23, 1966. This picture is very interesting to geologists who are trying to understand the crater formation as well as to people working in the area of lunar lighting. The lighting conditions were reported by NASA as follows: the viewing angle 10° - 20°, the sun angle about 28°, and the azimuth angle about 90°. The similarity of scene contrast in Figures 2.3 and 7 is quite apparent.

Many more examples could be cited for comparison between the pictures obtained from the NASA unmanned lunar programs and the laboratory pictures of a scaled lunar model dusted with copper oxide. For the purposes of this paper, however, the demonstration of the washout for the condition of zero phase angle, the increase in scene contrast by viewing angle being larger than sun angle (for zero azimuth angle), and the increase in scene contrast and the avoidance of washout by the dog-leg maneuver (for large azimuth turn) are of primary interest. In the next section some of the analytical explanations for this peculiar behavior are given by introduction of the lunar photometric function.

IV. Discussion of the Lunar Photometric Function

The function that relates the normalized reflectance of the moon to viewing angle and solar incidence angle is called the photometric function which for any area of the lunar surface is primarily a function of the two angles α and τ. The angle α is the phase angle, measured between the direction of emittance (viewing) and direction of incidence (sun) and τ is the angle of emittance projected on to the plane phase (see Figure 1). The justification for this simplified dependence of the photometric function is due to observational evidence that all objects which have the same photometric longitude have the same brightness after albedo differences of individual objects have been taken into account. Thus the photometric function, φ(α, τ), is independent of luminance latitude and can be represented as shown in Figure 8, where φ is normalized so that at zero phase angle φ(0, τ) = 1.0. The angle τ is plotted on the abscissa and by definition is positive if it lies between the solar vector and the projected surface normal (see Figure 1). Otherwise, it is negative. The parameter is the phase angle α.

It is seen from Figure 1 that for a given viewing angle, sun angle, and azimuth angle, the phase angle, α, and the luminance longitude, τ, can be calculated:

\[ α = \cos^{-1} \left( \cos(VA) \cos(SA) \cos(AZ) + \sin(VA) \sin(SA) \right) \]  

and from spherical trigonometry

\[ τ = \sin^{-1} \left( \frac{\tan(α) \cot(τ)}{\cos(α)} \right) \]

where

\[ δ = \sin^{-1} \left( \frac{\cos(VA) \sin(δ)}{\sin(VA)} \right) \]

and

\[ ω = \cos^{-1} \left( \frac{\sin(δ) - \cos(δ) \sin(VA)}{\sin(VA)} \right) \]

Thus for a given VA, SA, and AZ, a position on the photometric chart is uniquely specified, as shown in Figure 8. The number of the pictures in Table I corresponds to the number located on the photometric chart.

Assuming that the contribution of albedo variations to scene contrast will be small for observations close to the lunar surface, contrast can be defined as the brightness difference caused by a slope change divided by the brightness:

\[ * \text{A comprehensive review study on photometry and polarimetry of the moon and their relationship to physical properties of the lunar surface was reported by Pearse. An exhaustive list of references on this subject is included in the report.} \]
For a fixed phase angle \( \alpha \), a change in surface tilt produces a change in \( \tau \) as given in equation (2). Thus, the photometric function can be used to determine the change in reflected light as a surface is tilted relative to the background. It is then the component of the surface slope in the plane phase. The locus of constant contrast on the photometric chart, as defined by Eq. (3) for \( \Delta \tau = 10^\circ \), is shown by the dotted lines in Figure 8. It can be seen that the relative quality of the pictures in terms of visible detail resulting from different viewing and lighting conditions, corresponds to relative values of contrast.

From the definition of contrast (Eq. 3) it is seen that for a specified \( \Delta \tau \) there are two areas in the photometric chart (Figure 8) with high contrast, where the slope \( \Delta \tau / \Delta \phi \) is large and where \( \phi \) is small. The slope is large for positive \( \tau \) (the viewing angle is larger than the sun angle, e.g., Figures 2.4, 2.5, 2.6). However, even for the case of positive \( \tau \), the phase angle, \( \alpha \), must be greater than 5°. Low values of \( \phi \) correspond to large values of phase angle. From Figure 1 it is seen that the phase angle can be made large by looking towards the sun. This explains the contrast improvements in Figures 3.8, 3.14, and 2.7 as compared to Figure 2.1.

The phase angle can also be increased by an azimuth turn. In Figure 9 the phase angle is plotted versus the difference of sun and viewing angle (SA - VA). The parameter is the azimuth angle for three different viewing angles. It is seen that the phase angle increases with increasing azimuth angle for a given VA. The importance of the azimuth turn is noticed near (SA - VA) of zero - the washout condition for \( AZ = 0^\circ \). The negative of the (SA - VA) difference is not shown because this condition changes the sign of the luminance longitude \( \tau \) to positive and thus the contrast is good because of the increase in slope of the photometric function.

It has been recognized in Section I that any manned landing will involve many aspects of visibility. However, it is generally agreed that the visual evaluation of a landing site of the lunar surface will be enhanced with increasing contrast. In a purely suggestive manner with no other justification than the author's subjective assignment of a relative measure of quality to the laboratory pictures shown in Figures 2-4 the photometric chart (Figure 8) was divided into three regions defined by lines of constant contrast:

\[
\begin{align*}
\text{poor} & \leq \frac{\Delta \phi}{\phi} < 0.025 \quad \text{fair} \leq \frac{\Delta \phi}{\phi} < 0.10 \quad \text{good}
\end{align*}
\]

So far the discussion has been based on the lunar photometric function adopted by JPL in 1962 and is generally called the Fedorets function (based on data collected by Fedorets (1952)). However, there exists a second function reported by JPL in "EM-54 Lunar Scientific Model (1966)," which is called the Lunar Reflectivity Model (LRM) and is shown in Figure 10 (based on data collected by N. N. Sytinskaya and V. V. Sharanov (1952)). Further uncertainty arises from the difference between the lunar photometric function (Fedorets or LRM) as compared to the photometric function of the model dusted with copper oxide. Figure 11 was obtained from reference 8 and shows the photometric function chart for copper oxide dust (again, numbered data points correspond to the numbered pictures in Table I). It should be noted that nearly all the plotted points remain in their original contrast regions. However, the significance of the discrepancy between the lunar photometric function and the one for copper oxide is still open to question.

From the Tiffany data, for high luminances such as one has on the lunar surface it is shown that the detection threshold follows

\[
C_1 A_1 = C_2 A_2
\]

where \( C_1 \) and \( C_2 \) are threshold contrasts for areas \( A_1 \) and \( A_2 \) respectively (areas \( A_1 \) and \( A_2 \) are measured in angles subtended and equation (4) holds for small angles).

Relating equation (4) to the detection range \( R \) one can write

\[
\frac{A_1}{A_2} = \left( \frac{d_2}{d_1} \right)^2 = \frac{C_2}{C_1}
\]

where \( d_1 \) and \( d_2 \) are the projected diameters of the viewing objects. For clarity of argument, the assumption is made that \( d_1 = d_2 \) (i.e., the same diameter objects), thus the equation (5) becomes

\[
R = \frac{C_2}{C_1}
\]

The contrasts \( C_1 \) and \( C_2 \) can now be related to the photometric function through equation (3).

To show the relative merit of the three photometric models, the detection range was set to unity for the conditions of \( SA = 10^\circ \), \( VA = 15^\circ \) and \( AZ = 0^\circ \). The contrasts for this condition derived from the three photometric models are approximately equal. One can now write an equation for the normalized detection range, \( R \), as

\[
\bar{R} = K \left( \frac{\Delta \phi}{\phi} \right)^{1/2}
\]

In fact there may be even more photometric functions for the whole moon because of the individual differences of the craters and their different statistical distribution functions assumed by many investigators.

17-4
where $K$ is the normalizing constant for the above conditions and $\alpha$ was chosen to be $10^6$.

The normalized detection range, $\bar{R}$, is plotted in Figure 12 as a function of sun angle for the three photometric function models. It is seen that there is about 20% difference in detection range between the photometric function model of JPL '66 (LM) and Fedorets. Furthermore, the copper oxide dust model predicts larger detection range values than the two lunar photometric models and the values are closer to the Fedorets model. In Figure 13 the normalized detection range $\bar{R}$, is shown for an azimuth turn, $AZ$ of 30°. Here again, the answer to the question of how much an azimuth turn affects the detection range is dependent on the photometric model used. It is seen that the azimuth turn improves the detection range considerably in the washout region, namely, when $SA = VA$, but it decreases the detection range for $VA > SA$, and, for instance, for $SA = 10^6$ the detection range decreases by 17% for the Fedorets model whereas for the JPL '66 model it decreases by 35%.

From these examples it would seem prudent to re-examine the lunar photometric model. Maybe a new statistical distribution function of the lunar albedo values over the complete lunar surface should be constructed and it is hoped that Surveyor I, whose photometric measurements were made at the scale of objects hazardous to any lunar landing vehicles, will help to provide the necessary data.

V. Discussion of a Descent Trajectory Presentation on the Lunar Photometric Chart

A portion of an illustrative landing trajectory is shown in Figure 14. Four discrete points were chosen to represent the trajectory, namely, $SA = 10^6$ and $SA = 66^6$ for $AZ > 90^6$ and $VA > SA$.

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These points are now plotted on the photometric chart in Figure 15 (arrows show the sequence of points from 1 to 4) as a function of $SA$ for $AZ = 0^6$. It is seen that for $SA = 10^6$ the visibility should be good, as shown by the high contrast. However, for $SA = 20^6$, a portion of the trajectory is in a region of very low contrast and thus very poor visibility, even though the contrast is increasing as the landing site is approached. A very interesting point is demonstrated by the $SA = 30^6$ curve for which an inversion occurs, namely, a portion of the trajectory has $VA < SA$ (luminance longitude = $-1$), whereas a later portion of the trajectory has $VA > SA$ ($+1$). This inversion might be a quite surprising experience for the astronaut. An inversion is seen as an abrupt change in the appearance of the viewing surface, i.e., craters appear as hills and vice versa. Of further significance in the plot in Figure 15 is the increasing contrast for large sun angles (the phase angle $\alpha$ increases and thus contrast is improving as pointed out in Section IV).

Sun angles greater than 90° are not shown even though they would still enhance the contrast. However, the problem of a sun glare becomes important at sun angles greater than 90°.

It was shown in Sections II and IV that the contrast could be increased by performing the dog-leg maneuver ($AZ > 0^6$). The same trajectory as discussed above for the $AZ = 0^6$ is now plotted on the photometric chart for $AZ$ angles of 45° and 90° in Figure 16. Three apparent trends can be observed:

1. The contrast increases with increasing azimuth angle
2. The increase in contrast is greater for $VA < SA$
3. For $AZ > 45^6$ the dependence on $SA$ is less significant.

VI. Conclusions

The visibility during a lunar landing approach, defined as a function of viewing geometry alone, does not guarantee the astronaut a good view of the landing site. Because of the peculiar structure of the lunar surface, demonstrated by a series of pictures of a lunar surface model dusted with copper oxide, the visibility of the landing site is also dependent on the lighting constraints. In particular, the pictures of the landing site taken at approximately zero phase angle are void of details. The conditions which degrade visibility of the landing site can be avoided by restricting the sun elevation at landing and designing the descent trajectory so that the astronaut's viewing angle is always greater than the sun angle, or by performing a dog-leg maneuver for avoidance of the washout region, or by performing the lunar landing against the sun - the buttonhook descent. However, the last scheme suffers from the sun's glare and from decreased brightness. Comparison between the pictures of a lunar surface model and the available pictures from Surveyor I and Lunar Orbiter II showed good agreement.

The uncertainty of the lunar photometric function as compared to the photometric function of the model used for simulation is significant and an accurate determination of the lunar photometric function is needed.
Acknowledgments

The author wishes to acknowledge his indebtedness to H. W. Radin who collaborated on pictures shown in Figures 2-4 and who also was a co-author on the subject presented in Section II which was reported earlier in a Bellcomm Technical Memorandum. This work was suggested and consistently encouraged by D. B. James. Discussions and numerous suggestions from C. J. Byrne and others from Bellcomm Technical Staff helped to shape the present concepts of the paper.

References


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Figure 1. Sketches Defining Angles VA, SA, AZ, τ, and α. Angle τ is considered to have positive values when the viewing line lies between the source line and the normal to the reflecting plane under observation.
Figure 2. Photographs taken of a scaled lunar model dusted with copper oxide.
Figure 3. Photographs taken of a scaled lunar model dusted with copper oxide.
Figure 4. Photographs taken of a scaled lunar model dusted with copper oxide.
Figure 5. Photograph from NASA's Surveyor I spacecraft. Spherical mosaic of narrow-angle photographs of the lunar scene at low sun illumination (SA $\sim 10^\circ$).
Figure 6. Photograph from NASA's Surveyor I spacecraft. Surveyor I's survey television camera photographs its own shadow on the lunar surface (25° field of view).
Figure 7. Photograph from NASA's Lunar Orbiter II spacecraft. The first close-up of lunar crater Copernicus taken with Lunar Orbiter II's telephoto lens on November 23, 1966.
Figure 9. The dependence of phase angle, $\alpha$, on the difference of sun and viewing angle, (SA-VA), for three different viewing angles. The parameter is the azimuth angle, AZ.
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Figure 12. Normalized detection range, $\overline{R}$, as function of the sun angle for the three different photometric models ($AZ = 0^\circ$).
Figure 13. Normalized detection range, $R$, as function of the sun angle for the three different photometric models ($\text{AZ} = 30^\circ$).
Figure 14. Trajectory characteristics for landing phase.
AZ = 0°

Figure 15. Trajectory presentation on lunar photometric chart (AZ = 0°).
Figure 16b. Trajectory presentation on lunar photometric chart (AZ = $90^\circ$).