truths and be hypocritical. There is always the inherent danger in any revolutionary new approach that too much begins to be ascribed to it or expected from it. Or there is the danger that it becomes an end in itself rather than a tool of research—to the point where subjectivity becomes taboo, and one cannot even render an honest, personal opinion without numerical substantiation verifiable at the 1% level! Let us use it—let it not use us.

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*Significant Measurement in the Lunar Photograph**†

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ABSTRACT: *In obtaining source data for incorporation into a lunar chart, the principal input at present is from photographs taken with astronomical telescopes. These photographs are considerably different from the material normally used in photogrammetric studies; i.e., wide-angle aerial photographs, and the problems encountered in their interpretation require correspondingly different solutions. Various methods of analysis are presented, with relative effectiveness and limits of application given for each. The concept of smallest significant image areas is introduced, with a consideration of the errors inherent in photographs among the lunar plate collections of several observatories.*

INTRODUCTION

DURING the history of astronomy, the Moon has occupied a somewhat secondary position as a subject for extensive study. The principal area of investigation has been the descriptive analysis of lunar features; and this has been left largely to the domain of the amateur astronomers. They as a group have done much work over the years, but are generally limited by inadequate instrumentation. Groups of lunar photographs have been made at various observatories during the past 70 years; but many of these lacked any systematic program in their acquisition, with the result that the coverage is sparse.

The rapid development in rocket technology over the past few years has made us suddenly aware that lunar exploration missions are not just a part of Jules Verne's writings or

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"Flash Gordon" comics, but will soon be a reality in our own lives. With this stimulus, a great deal of activity has been generated to increase our knowledge about the Moon. The greatest part of this activity has been carried out in the analysis of photographs taken at telescopes; and in some cases, the methods of attack to the problems have been selected without a complete knowledge of the nature of the photographic material. At the U. S. Air Force Aeronautical Chart and Information Center, considerable effort has been made in evaluating inputs of lunar data and in concentrating programs of investigation upon the sources which seem most likely to give valid answers to lunar problems.

In order to evaluate these problems, this paper will summarize some of the difficulties which are encountered in acquiring lunar photography, discuss groups of lunar photographs now in existence, then consider the potential of several mensuration procedures for extracting data from these photographs.

THE LUNAR PHOTOGRAPH

In lunar photography, one of the first problems to consider is the extreme distance of the lunar surface from the observer and his telescope "camera." Although the distance varies somewhat due to orbital eccentricity, the mean Earth-Moon separation is about 239,000 miles. At this range, an object one kilometer in diameter would subtend an angle of 0.54 seconds of arc. (This would correspond to the size of a dime viewed from a distance of about 4.2 miles.) In considering the resolution of small objects on the lunar surface, one would be required to use apertures large enough to resolve fractions of a second of arc. If one goes to larger aperture telescopes in an effort to increase resolution, the expected gains are not achieved, as another factor becomes more critical than the optical diffraction limit. This limitation is atmospheric instability or "bad seeing."

The effect in the focal-plane is that of nearly constant image-motion, both along and perpendicular to the optical axis. The motion is not uniform but occurs differentially throughout the image, with the size of the image element which acts as an independent unit being a function of the instability. The resultant effect on a photographic exposure is a general loss of resolution (motion and defocussing) and an inherent lack of total geometry.

The variation of light intensity across the disk of the Moon creates a problem in the selection of the best emulsion for high resolution. From a sub-solar point to a shadowed area near the terminator, there may be a brightness ratio of several thousand to one. This dynamic range may be within the capability of a few emulsions; but when this requirement is coupled with a need for fine grain and high speed, the combination is almost impossible of achievement. As a result, most lunar photographs are exposed for an area of given brightness; and multiple shots of different exposure length are made for more complete photometric coverage.


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The telescopes which are practical for use in lunar photography have focal-lengths ranging from about 30 to 300 feet. A focal-length of 60 feet produces a plate scale of 11.3 seconds of arc per millimeter, which produces an image having a representative fraction 1/21,000,000 for mean lunar distance.

At a scale of several million to one, the stability of an emulsion and its backing is of tremendous importance. While many lunar photographs were made on glass plates, the shift of the emulsion with respect to the glass during processing, drying and storage can be considerable. Statistical studies of star plates made under similar conditions show random shifts and stretching of the order of 5 to 10 microns, while there are cases of emulsion "creeping" in segments over larger distances (100 to 200 microns).

One of the deficiencies in lunar photographs is the lack of instrument calibration. Thus, there is an area of indeterminacy as to the amount of scattered light in the system, the photometric variation as one works off-axis, or perhaps the focal-length and collimation of the optics (particularly in the case of multi-element reflectors whose mirrors are changed frequently for varied application).

As a result of the various problems in acquiring lunar photographs, the wide range of instruments that have been used, and the different approach and purposes of the individuals working in this field, the groups of Moon plates of various observatories and periods of time are considerably different. Some of these groups might be characterized as follows, beginning with the earlier plates and extending to the present:

1. THE PARIS OBSERVATORY PLATES OF THE 1890's

An amazing series for the period in which they were taken, the Paris plates have a pleasing visual effect in spite of their graininess. The maximum resolution is several kilometers on the Moon's surface, and the photometry is undetermined due to the photographic plates used.

2. MOUNT WILSON OBSERVATORY

The plates taken at the Cassegrain focus of the 100-inch telescope present some of the best resolution ever attained in photographs of the Moon. The scale of 5 sec/mm gives a lunar image of $14\frac{1}{2}$ inches across, so only a portion can be recorded on an $8'' \times 10''$ plate.

3. LICK OBSERVATORY

Many excellent plates have been obtained with the 36-inch refractor at Lick; however, many of the plates were processed, reduced, and reprocessed to enhance contrast; and the photometric fidelity is almost nonexistent. Some plates have fairly good resolution, but considerable grain. Current work at Lick with the 120-inch reflector has produced a few plates having resolution at least as good as the Mount Wilson series.

4. YERKES OBSERVATORY

An early series of plates was produced at Yerkes by Ritchey, who showed his versatility as a photographer, as well as an optician. However, the most significant lunar work at Yerkes has been the series produced over the last few years under the direction of Kuiper. These plates contain an entire lunar image of about 7 inches in diameter. Out of the series, these are several hundred photographs having good resolution, the best few having resolution of the order of one to two kilometers. The grain is reasonably fine; but the contrast is high, and most of the plates were exposed heavily for terminator coverage. One group of full Moon plates is lightly exposed and has a star trail superimposed for orientation.

5. MCDONALD OBSERVATORY

A recent collection has been made at the McDonald Observatory by Kuiper. Most of these are on $5'' \times 7''$ plates; and since they were taken at the Cassegrain focus of the 82-inch reflector, the coverage of any single plate is only partial. Some of this series have excellent resolution; but, like the Mount Wilson plates, the lack of geometric calibration makes them more suitable for descriptive work than a detailed measurement program.

6. PIC DU MIDI OBSERVATORY

Although several excellent photographs have been made in the past from the Pic du Midi Observatory in the Pyrennes, a new series is being generated which attacks the photographic problem through volume coverage at every opportunity. Libration and terminator coverage are fairly complete, with good photometric calibration, fairly fine grain, and exposure variation for terminator emphasis.

In developing analytical programs, the efforts at ACIC have been built around a utilization of the best photographs from all available sources.

MEASUREMENT OF THE MOON

What are the procedures by which data are extracted from lunar photographs? There are two basic types of information desired, and it develops that there is an interplay between them.

One requirement is to determine positional information of lunar features with respect to a selenographic coordinate system, and programs to fill this requirement are built around the detection and measurement of linear distances between images in the lunar photograph. The other requirement is the description and portrayal of lunar features, and programs in this area consist of form analysis through pattern recognition, shadow studies and measures of relative light intensities reflected by different areas of the Moon's surface.

The relation between the two types of measurement is easily derived. In order to locate a point on a photograph, the investigator must know something of the shape and dimensions of the feature concerned. This is necessary in order to apply a "best fit" to the density pattern in the image. Small changes in the angle of illumination can produce a considerable difference in the appearance of an object; and low, rounded objects will undergo an apparent displacement as the angle and direction of sunlight change.

In a similar form of dependence, adequate description of features must be tied to positional information. A larrge part of the programs in form analysis rely upon accurate sun angles being known. This requires a previous determination of the selenographic latitude and longitude of the object. Also, since most of the features on the earthward hemisphere of the moon are viewed with some degree of foreshortening, positional data are required for restoration of image geometry.

CONTROL

How is control work carried out for the Moon?

As a first approximation, one considers the Moon to be a spherical body, and a photograph taken from the Earth's distance as approaching an orthographic projection. Then, in the light of this approximation, displacements in the projected disk are used as a measure of distance on a sphere. Relative distances derived in this manner are fairly good near the center of the lunar disk; but are considerably degraded as one approaches the limb, where projections of vertical deviations are greatest.

For a more sophisticated control solution, one must use photographs taken under different angles of libration, corresponding to slightly different aspects of the lunar surface. Relative positions of images in plates of opposite libration are compared, and the angles of parallax are used to derive deviations from a sphere. The librations are mainly due to the eccentricity and inclination of the lunar orbit and have maxima of about $6\frac{1}{2}°$ in latitude and $7\frac{1}{2}°$ in longitude. Therefore, it must be realized that the separation of angles of aspect will be 20° or less, and that very few photographic pairs are in existence which record this extreme an angular difference.

In order to develop a solution from the plate displacements occurring with libration, several programs of measurement have been tried, with varying degrees of success. First, when visual stereographic equipment is used, two plates of opposite libration are used to synthesize different camera points; the operator establishes a model for the pair and attempts to derive relief and control from the visual parallaxes. However, when the material itself is examined more critically with respect to the technique, it becomes apparent that the solution will not be of sufficient accuracy to be definitive. The angle of separation of the points of aspect is too narrow for a good visual effect; and the area contained between the "sub-camera" points is only a small region near the center of the disk. So most areas are not viewed from two directions, but from two narrowly separated angles in the same direction.

Since the moon subtends only about one-half a degree from the earth, lunar photographs are far from the "wide-angle" shots desired for steep intersecting rays. There are also visual difficulties incurred since there is no natural background in the photograph to permit the operator "seeing" the ground, recognizing only the grain pattern of the plate. Also, the fact that relief is seen in terms of the shadows cast forces a selection of a pair which has identical illumination as well as opposite libration. This condition in itself is almost sufficient to eliminate most of the high-resolution plates from consideration.

In addition to these objections to a visual approach, there is the stark reality that a single pair of plates is just not adequate to provide a solution—the positional errors introduced by seeing effects, emulsion instability, illumination effects, and lack of resolution are of the same order or greater than the quantities one wishes to measure.

Another approach is similar to a visual stereo method in its solution, but overcomes some of the problems of operator recognition of parallax. This method involves the measurement of plate coordinates of points in the image with a precision linear comparator. The scale and libration are determined from the time at which the photographs were taken, and a rotation matrix is used to transform one set of measures into the other. Relative displacements from an arbitrary plate control are interpreted as measures of parallax. This method has some advantages over a visual solution since the measuring precision of such instruments is of the order of 2 to 5 microns. Also the setting accuracy is only a function of the observer's ability to recognize features in the image plane rather than in the somewhat indeterminate stereo model. Many of the same problems are felt, however, since the image displacements are slight and the errors inherent in the single pair of photographs will have a considerable effect on the solution.

As an improved approach to this analytical method, groups of photographs taken at similar libration are separately measured, and a statistical reduction of the measures is made to determine a set of relative feature coordinates for a given plane of projection. Thus the measuring error, random emulsion shifts, and image displacements due to seeing effects can be greatly reduced. Several of these plane reductions may be combined in separate or collective rotation matrices to give a solution for the parallax displacements.

In all of these cases, measurement is dependent on the ability of the operator to recognize control points, which for the Moon are usually craters, within the photographic image. In one respect, the analytical methods lend themselves to this, since the operator may use a curve-fitting technique to obtain a crater position by making several independent measures of positions along the crater rim, as well as a bisection of the crater with the comparator hairline.

DESCRIPTIVE ANALYSIS AND RELATIVE CONTROL

Descriptive lunar work is primarily concerned with feature form analysis for the purpose of portrayal in shaded relief drawings or in relief models. A great deal of descriptive work depends upon an observer's ability to recognize forms under variable illumination. Accordingly the principal requirements are having high resolution images suitable for visual presentation and having an observer experienced in visualizing topography from such conditions. It seems probable that current techniques being developed in the field of optical and electronic image enhancement will lead the way toward a more satisfactory visual image through the combination of several photographs for eliminating random geometrical variation and photographic system "noise."

More quantitative studies are made possible through the analysis of areas under near-tangential lighting conditions. Since objects are detected principally by shadows, the emphasis of vertical dimensions is most pronounced when the terminator is crossing. The position of the Sun with respect to the Moon is well determined for any given time; therefore, if the length of a shadow is measured and the lunar coordinates of the point are known, there is only a simple trigonometric problem to determine the relative height of the point casting the shadow above the point where the shadow ends. If a sequence of photographs is available in which the shadow progresses with changing solar elevation, then the spot elevations can be combined to give a profile of the section across which the shadow moves.

In flat regions such as the lunar maria, where there is very little relief to cast shadows, another effect of low illumination can be used for a determination of relative slope. As one approaches the terminator, there is a drop in brightness due to diminishing illumination which is proportional to the cosine of the angle between the surface normal and the direction of illumination. If the local variations in reflectance are known, then deviations in the photometric response from the cosine function can be interpreted as a slope with respect to a mean plane at that longitude.

MEASUREMENT ACCURACY AND SIGNIFICANCE IN INTERPRETATION

It would be impossible to make a statement about the absolute accuracy of a single measurement in a lunar photograph as it relates to the quantity being sought. However, for the purpose of assigning relative weights to various mensuration programs, and for establishing an order of accuracy which can be achieved, it is necessary to consider those factors which limit accuracy in any stage of the photographic and mensuration programs, and to assign a reliability function which is most probable for the output data.

In general, a plate may be found for most librations with a lunar surface resolution of the order of two to three kilometers. If one assumes a plate scale of about 20 million to one, then the plate diameter of resolved features will be about 100 microns at the center of the Moon's disk. With a reasonable degree of accuracy in identification, the position of a crater may be measured to a *plate* accuracy of 15 to 20 microns. The correspondence between measures on successive plates taken on the same evening at a telescope is variable with emulsion shift, seeing conditions, and to some extent with the contrast of the image being measured. The variation is generally random, however, and only increases the point measuring error to about 25 microns. As one selects plates made at different terminator positions and having different contrasts, grain pattern and resolution, the ability to reproduce measures to the same point is decreased. The errors are not entirely random and may easily be 50 or 60 microns, even when the best measurement techniques are used.

One of the greatest problems in lunar measurement is in the operator decision of *what* is the point being measured. If the center of a crater is the point being sought in the photographic image, then the location of that crater requires a visual bisection on the part of the operator. If a shadow edge is being measured, the operator must locate the "true" shadow boundary from an image edge of finite width and steps of grey.

In these types of measurement, the techniques of microdensitometry are extremely valuable for locating image points that enter into a solution for position. For an example, if a scan is made across a shadow edge, a preselected part of that image, such as the half-intensity point, may be located to a high degree of accuracy. Therefore, if one has positional precision coupled with the densitometer scan, individual measuring errors can be reduced considerably; and the only limitation on measuring accuracy will be in the interpretation of measurements and the correlation with the feature generating the image. One will still be left with the geometric uncertainties of the emulsion and the seeing conditions, but the measurement process itself will have very little error.

In considering this type of measuring process, an important factor is the size of the microdensitometer spot one might use. The largest possible spot should be used in order to reduce grain and emulsion "noise" in the signal measured. But the spot should be small enough to consider the area it covers as an image unit of a single grey value without a loss of resolution. For most lunar photographs, this spot, *the smallest significant image unit*, will be a rectangular area of about 2:1 side ratio, with the longer dimension about one-third the plate resolution limit, the rectangle being aligned parallel to the terminator. Thus, for the typical lunar photograph, the area might measure 15×30 microns in the image plane; however, this would vary considerably with scale and resolution. If a photograph is analyzed in this fashion, separate profiles of density may be made or a complete raster of measurements may be taken.

After considering optical resolution limits, emulsion speed and resolution, seeing variations, and the various mensuration limits, several operational accuracies can be given as an indication of what one may hope to achieve in a lunar mensuration and reduction program.

CONTROL

The best absolute horizontal positions are near the central portion of the lunar disk and have assigned probable errors of the order of 500 meters. There is a degradation of accuracy which is experienced as one goes out toward the limb, due to the interaction of vertical components with horizontal position and the increased amount of foreshortening.

Vertical deviations from a sphere are least measurable near the center of the disk, but as the projected length of verticals increases near the limb, the inadequate horizontal position prohibits an appreciable increase in accuracy of determination. Using a statistical reduction of many parallax measures, there are only a few points which have absolute vertical values with probable errors of less than 1000 meters.

RELATIVE HEIGHTS

Using microdensitometry, a shadow length can be determined to a standard deviation of about 15 microns on a photograph of good contrast. If a closely spaced group of exposures is available, combined measures can be used to determine a shadow length on the Moon within a probable error of 300 meters. For a point 5 degrees from the terminator, the uncertainty of the relative height would be 26 meters. Relative height profiling from terminator progression photographs would tend to be more accurate than single measures, since uncertainties in longitude would be removed as a systematic error.

SLOPES

The direct measurement of slopes from photometric variation is sensitive to slight changes in elevation, but the level of illumination is low, and systematic errors can be introduced if calibration is not adequate. Through studies currently being conducted by ACIC, it has been found that after albedo and the general photometric gradients have been removed, integrated slopes of small areas can be measured to less than 1° deviation.

CONCLUSION

Any program in the analysis and interpretation of lunar photographs will be only as good as the information recorded in the photographic image. Mensuration in these images must be in keeping with the type of data recorded, and the limitations imposed by the nature of the material should be recognized. Any attempt to override these limitations with programs of high precision but false accuracy will lead to a state of self-deception. The desire for accuracy should be tempered with an awareness of reality, such that our lunar data will not need to be tagged, "*Caveat Emptor*," "Let the Buyer Beware."