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WADC TECHNICAL REPORT 52-93

ON THE POSSIBILITY OF OBTAINING GEODETIC CONNECTIONS BETWEEN TWO DISTANT POINTS ON THE EARTH'S SURFACE BY LUNAR PHOTOGRAPHY

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The Ohio State University Research Foundation

January 1952

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Wright Air Development Center
Air Research and Development Command
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FOREWORD

This report was prepared by the Mapping and Charting Research Laboratory of the Ohio State University Research Foundation, under, USAF Contract No. AF 18 (600)-90. The contract was administered under the direction of the Mapping and Charting Branch, Photographic Reconnaissance Laboratory, Wright Air Development Center, with Mr. J.J. Deeg, Chief of the Mapping and Charting Branch, as Project Engineer.

Research and Development Order Nos. R-683-44, "Charting, Aeronautical, Photogrammetry and Geodesy," and R-683-58, "Aeronautical Charting Systems," are applicable to this report.

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ABSTRACT

The use of lunar photography to obtain geodetic connections on the earth's surface has great advantages over the occultation and solar eclipse methods. The success of this method depends upon the accuracy with which a point on the moon's surface can be measured relative to the background of stars. The observational problem is a difficult one, but experiments now being carried out at the U. S. Naval Observatory should indicate whether the method of lunar photography is feasible for geodetic purposes.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

Richard W. Philbrick
fr GORDON A. BLAKE
Brigadier General, USAF
Chief, Weapons Components Division

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ON THE POSSIBILITY OF OBTAINING GEODETIC CONNECTIONS BETWEEN TWO DISTANT POINTS ON THE EARTH'S SURFACE BY LUNAR PHOTOGRAPHY

I. Introduction

The astronomical methods of measuring long distances on the earth's surface are all based on the fact that a near-by celestial object viewed from two different points on the earth's surface will have a different apparent position on the celestial sphere as seen from those two points, and that the change in its apparent position is related to the distance between the points. The celestial object used in these methods is the moon, since this is the only body close enough to the earth to yield accurate geodetic results.

Of the astronomical methods, those of most recent interest employ solar eclipses and occultations of stars by the moon. [1] Here, the light of the sun or star falling on the moon causes the latter to cast a shadow on the earth. This shadow will sweep across the earth in an easterly direction with a known velocity; the accurate timing of the passage of the shadow between two stations will then yield the distance between the stations. Although not as direct a method as simply measuring the angular displacement of the moon as seen from two different stations, the observational requirements of solar eclipses and occultations are less stringent: the time of the sun-moon or star-moon contact can be very accurately obtained by the use of cinematography or photoelectric equipment. On the other hand, the usefulness of the method is impaired by the limited frequency of the phenomena. Since the lunar shadow must

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[1] For a review and bibliography on the subject, see Eclipses and Occultations for Geodetic Purposes, Technical Paper No. 108, Mapping and Charting Research Laboratory, The Ohio State University Research Foundation, 1950.

sweep over areas which are judged to be of geodetic importance, it is necessary to select particular eclipses and occultations which will be suitable. This requirement is particularly severe for solar eclipses, the use of which may entail waiting a number of years between suitable eclipses. We fare considerably better with occultations, since the moon occults many stars every night. Restricting ourselves to bright stars and discarding all occultations near grazing incidence, however, the number of occultations observable from two selected areas on the earth's surface is reduced to the order of a dozen per year.

It would, therefore, be of the greatest importance if the apparent shift of the lunar disk with respect to the background of stars could be directly measured at two stations with an accuracy which would permit the geodetic connection of these stations. The observations could be made at any points on the earth's surface from which the moon is simultaneously visible. This would increase the probability of success by making available many more observing nights than could be obtained by solar eclipses and occultations. Coupled with this is the added advantage that the observations could be made at existing observatories, thus eliminating the need for portable instruments and expeditions.

The method of obtaining position on the earth's surface by simultaneous measurements of the moon's position with respect to the background of stars from two stations is not a new idea. In its oldest form it was known as the method of lunar distances [2]/ and was useful as a means of determining longitude at sea. Here, one of the stations was

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[2]/ For a complete description of the method of lunar distances, see William Chauvenet, A Manual of Spherical and Practical Astronomy (Philadelphia, 1863), I, pp. 393-420.

the ship and the other the center of the earth. Ephemerides were available, giving the angular distance, as seen from the center of the earth, from the center of the moon to the sun, to the brightest planets, and to nine bright fixed stars. The observer measured the apparent angular distance from the moon's center to one of the aforementioned objects with a sextant. The two values differed in consequence of the lunar parallax (and the refraction, which was taken into account). By reducing the observations to the center of the earth and comparing them with the ephemeris, the observer determined the Greenwich mean time. Knowing the local mean time, he derived his longitude. Longitudes obtained in this way were uncertain by five or ten minutes of arc.

Helmert [3] considered the determination of the geocentric coordinates of a point on the surface of the earth by means of observations of the lunar parallax. The method consists of measuring the azimuth and zenith distance of the moon and comparing it with the azimuth and zenith distance as seen by an observer at the center of the earth. The latter is obtained from the lunar tables. Helmert came to the conclusion that this method would not be accurate enough for geodetic purposes because of uncertainties in the lunar tables.

Berroth [4] recently suggested a return to Helmert's method, in view of astronomical progress in the last few years. In particular, he points out that the absolute corrections to the moon's motion for one

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[3] F. R. Helmert, Die Mathematischen und Physikalischen Theorieen der Höheren Geodäsie (Leipsig, 1884) II, pp. 451-460.

[4] A. Berroth, "Uber die Fixierung von Europa und Amerika in ihrer Absoluten und relativen Lage auf dem Globus," Geofis. Pura Appl., 1949, XV, pp. 20-26.

night do not enter into the determination. Only the relative corrections for the evening of observation will be important, and these can be evaluated by means of a numerical procedure by Sundmann.5/ To carry this one step further, it might be pointed out that if the observations from the various stations could be carried out simultaneously, or nearly simultaneously, no corrections for the lunar motion would be necessary at all. This would not be difficult, since the time could be accurately determined with the aid of the signals from WWV.

II. Theory of the Method

The following derivation is due to Chauvenet. 6/

Let a point on the moon (hereafter simply referred to as the moon) be referred by rectangular coordinates to three orthogonal planes passing through the center of the earth: the first, the plane of the equator; the second, the plane containing the equinoctial points; the third, the plane containing the solstitial points. Let the axis of x be the straight line drawn through the equinoctial points, positive towards the vernal equinox; the axis of y, the intersection of the plane containing the solstitial points with the plane of the equator, positive towards that point of the equator whose right ascension is 90°; the axis of z, the axis of the heavens, positive towards the north.

5/ K. F. Sundmann, "The Motions of the Sun and Moon at the Solar Eclipse of 1945, July 9," L'activité de la Commission Géodesique Baltique Pendant les Années 1944-47, Helsinki, 1948, pp. 63-94.

6/ William Chauvenet, A Manual of Spherical and Practical Astronomy (Philadelphia, 1863) I, pp. 119-24.

Let

α = the moon's geocentric right ascension,

δ = the moon's geocentric declination,

Δ = the moon's geocentric distance.

The rectangular coordinates of the moon are then

$$x = \Delta \cos \delta \cos \alpha,$$

$$y = \Delta \cos \delta \sin \alpha,$$

$$z = \Delta \sin \delta .$$

Now let the moon be referred to another system of planes parallel to the first, the origin being the observer. The vanishing circles of these planes in the celestial sphere are still the equator, the circle containing the equinoctial points, and the circle containing the solstitial points.

Let

α' = the moon's observed right ascension,

δ' = the moon's observed declination,

Δ' = the moon's distance from the observer,

where by observed right ascension and declination we now mean the values which differ from the geocentric values by the parallax, depending on the position of the observer on the surface of the earth. The rectangular coordinates of the moon in this system will be

$$x' = \Delta' \cos \delta' \cos \alpha',$$

$$y' = \Delta' \cos \delta' \sin \alpha',$$

$$z' = \Delta' \sin \delta'.$$

Now, if

θ = the sidereal time = the right ascension of the observer's meridian at the instant of observation,

Φ' = the geocentric latitude of the place of observation,

ρ = distance from the center of the earth to the observer,

then θ, Φ', and ρ are the polar coordinates of the observer, entirely analagous to α, δ, and Δ of the moon, so that the rectangular coordinates of the observer, taken in the first system, are

$$a = \rho \cos \Phi' \cos \theta,$$

$$b = \rho \cos \Phi' \sin \theta,$$

$$c = \rho \sin \Phi'.$$

To transform from one system to the other we have

$$x' = x-a,$$

$$y' = y-b,$$

$$z' = z-c.$$

Thus, we obtain

$$\Delta' \cos \delta' \cos \alpha' = \Delta \cos \delta \cos \alpha - \rho \cos \Phi' \cos \theta,$$

$$\Delta' \cos \delta' \sin \alpha' = \Delta \cos \delta \sin \alpha - \rho \cos \Phi' \sin \theta,$$

$$\Delta' \sin \delta' = \Delta \sin \delta - \rho \sin \Phi'.$$

By suitable transformation of the latter equations, it can be shown that

$$\sin (\alpha-\alpha') = \frac{\rho \sin \pi \cos \Phi' \sin t'}{\cos \delta},$$

$$\sin (\delta-\delta') = \frac{\rho \sin \pi \sin \Phi' \sin (\gamma-\delta')}{\sin \gamma},$$

where

$$\tan \gamma = \frac{\tan \Phi' \cos 1/2\,(\alpha-\alpha')}{\cos [t'-1/2\,(\alpha-\alpha')]},$$

$t' = \theta-\alpha'$ = apparent or observed hour angle,

$\sin \pi = \frac{1}{\Delta}$ = sine of the lunar horizontal parallax.

The observing procedure would now be as follows. We first assume that the lunar parallax is known with high accuracy, and that the values of ρ for the various stations are also known.7/ At all stations, therefore, ρ and $\sin \pi$ are known. Let us consider station A as the base station: Its position (Φ'_A, λ_A) is assumed known, and the positions of all other stations will be referred to it. At station A the moon is photographed against the background of stars and the observed coordinates of a point on the moon (α'_A, δ'_A) are measured on the plate. By means of the above equations, the geocentric coordinates of the observed point on the moon (α, δ) are computed. Now at any other station B of unknown coordinates (Φ'_B, λ_B) the moon is simultaneously photographed against the background of stars. The observed coordinates of the same lunar point which was measured at station A are measured on the plate as seen from station B; these are (α'_B, δ'_B), and they differ from (α'_A, δ'_A) in virtue of the lunar parallax. Now ρ_B and $\sin \pi$ are known, and (α, δ) have been determined from the observations at station A, the observations being simultaneous; it is then possible to solve the above equations for (Φ'_B, t'), or equivalently (Φ'_B, λ_B), the position of station B with respect to the position assumed for station A.

7/ The quantity ρ at each station is the algebraic sum of three quantities: the geocentric radius of the adopted geodetic ellipsoid for the latitude of the station, the geoidal height at the station with respect to the ellipsoid, and the elevation of the station with respect to the geoid as determined by spirit leveling. For details concerning the determination of these quantities see W. Heiskanen, The Geodetic Significance of World-Wide Gravity Studies, Technical Paper No. 124, Mapping and Charting Research Laboratory, The Ohio State University Research Foundation, 1950.

III. Accuracy of the Method

Let us assume that the precision required in our determination of position on the earth's surface is ± 200 feet. This requires that the mean parallax of the moon be known with an accuracy of ± 0.04 second of arc.[8] It also requires that the observed position of a point on the moon with respect to the background of stars be measurable on the photographic plate with an accuracy of ± 0.04 second of arc.

The observational problem is that of obtaining images of comparable density on the photographic plate of celestial objects which differ by a factor of 1000 or more in brightness. Clearly, the light of the moon must be cut down in some fashion. This can be done by placing an optical filter or a rotating sector in the optical system such that the lunar intensity is cut down by the necessary amount. If the telescope is following the stars, a blurred lunar image will result because the moon moves eastward with respect to the stars at the rapid rate of one second of arc every two seconds of time. There would be no hope of measuring lunar features with an accuracy of ± 0.04 second of arc on a blurred lunar image. Guiding on the moon and letting the stars trail might be another alternative. Again, it seems doubtful to the writer that measurements of the star trails could yield the aforementioned accuracy, but experimental work would be desirable. Diaphragming the moon out for most of the exposure, while the telescope follows and records the stellar images, is another means of obtaining equivalent images of moon and stars. At some accurately determined time during the exposure,

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[8] For a discussion of the observational accuracy of the lunar parallax, see Eclipses and Occultations for Geodetic Purposes, reference 1.

the diaphragm is removed for the brief interval of time in which a correctly exposed lunar image can be given. With a telescope of even moderate size this time interval can be made sufficiently short to "stop" the moon's motion with respect to the stars and give a sharp lunar image. This method of determining the moon's position photographically is due to H. N. Russell and his collaborators.[9] An occulting disk was placed at some distance in front of the telescope to cut off the light of the moon before it reached the telescope objective; thus the moonlight diffusely reflected from the glass could not reach the photographic plate. Russell used a telescope of 16-inch aperture diaphragmed to 3.5 inches. The focal length was 87 inches, giving a scale on the photograph of 93 seconds of arc per millimeter. A pole projecting 108 inches in front of the objective carried an occulting disk 5 inches in diameter. Under these conditions, the average exposure on the stars was 10 minutes, while the lunar exposures varied from 0.2 to 0.4 seconds. An electric contact was connected with the occulting disk in circuit with the chronograph to determine very accurately the exact time of the exposure on the moon.

Russell measured the positions of a number of stars on the plate and from 10 to 13 points on the illuminated semi-circumference of the lunar disc, all corrected for differential refraction. A circle passing as closely as possible to the latter was determined by the method of least squares, and the center of this circle was taken as that of the moon. The probable error of the measured position of a star image was found to be ± 0.25 second of arc, a very high precision in view of the

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9/ "Position of the Moon Determined Photographically," Harvard Annals, 1913, LXXII, No. 1; 1916, LXXVI, No. 7; 1917, LXXX, No. 11; 1923, LXXXI, No. 5; 1930, LXXXV, No. 9.

scale employed. In order to improve appreciably on this accuracy, a telescope of much longer focal length and consequent greater scale would be necessary. The average distance of one of the measured points on the lunar limb from the circle passed through the points corresponded to a probable error of ± 0.47 second of arc. This was nearly double the error of measurement, showing that the greater part of the discrepancies were due to real irregularities of the lunar limb. Since these are not of a random nature, [10] they must be taken into account in order to obtain the accuracy required for geodetic purposes. The existing charts of the lunar limb do not seem to be accurate enough for these purposes, but forthcoming charts by Mr. C. B. Watts of the U. S. Naval Observatory will probably give the requisite accuracy. [11] It should be pointed out that since we are concerned with the simultaneous observation of the moon from a number of stations, the lunar limb need not be measured at all. The tips of the shadows of several mountain peaks might be selected and measured at all stations to give the desired geodetic connection. Once again, however, the scale of the telescope must be of sufficient size to enable the measurement of the lunar feature to a fraction of a second of arc. This would probably require a telescope with a focal length of 20 feet or more.

The possibility of large errors exists in this method if the driving mechanism of the telescope is imperfect. Such errors will

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[10] See C. B. Watts, "Systematic Effects of Limb Irregularities in the Results of Occultations," Astronomical Journal, 1940, XLVIII, p. 170.

[11] For a discussion of the accuracy of existing and forthcoming charts of the lunar limb, see "Eclipses and Occultations for Geodetic Purposes," reference 1.

appear if the instrument is not directed toward the same point in the celestial sphere during the short exposure on the moon. To detect such errors and determine their magnitude, Russell took special plates, using bright stars in place of the moon.

Perhaps the most serious objection to the method just outlined arises from the difficulty in obtaining comparable images of the moon and stars. The use of an occulting disk results in images which are comparable in density on the photographic plate, but these are obtained with very different exposure times. The stellar images result from an exposure which is of the order of a minute or more; they represent, therefore, the sum of the meanderings of the star due to fluctuations in the earth's atmosphere and will (if the telescope is optically perfect) be circular in shape and vary in size by an amount depending upon the state of the earth's atmosphere. The lunar image results from an exposure which is a fraction of a second in duration: it does not represent the sum of the moon's meandering, but instead an instantaneous snapshot of the moon as distorted by the earth's atmosphere at a particular moment. Unfortunately, the effect of unequal exposure times is not a small one, in terms of the accuracies which are required for the geodetic application of this method: errors up to 0.5 second of arc in the position of a lunar point can occur. [12] The refraction anomalies in the earth's atmosphere which cause these errors are fairly localized, however; they do not result in a bodily displacement of the lunar disk, but rather in a displacement of one portion of the disk

[12] This information was contained in a private communication from Dr. George Van Biesbroeck, Yerkes Observatory, Williams Bay, Wisconsin.

relative to another. Anyone who has observed the "shimmering" of the lunar disk through a small telescope can verify this. And since the displacements are probably random, the measurement of a large number of points distributed across the lunar disk will give more accurate geodetic results. Lunar photography for geodetic purposes should, of course, be undertaken only when the earth's atmosphere is relatively steady in order to ensure the most accurate results. Mr. G. M. Clemence, of the U. S. Naval Observatory has suggested a method of obtaining somewhat longer exposure times for the moon, thus reducing the above effect. A plane-parallel glass filter placed in the optical system at an angle to the photographic plate will cut down the light of the moon and displace the image on the plate. By rotating the filter, the lunar image could be made to follow the stars for a short period of time, thus permitting a somewhat longer exposure time without blurring the image.

The problem of obtaining geodetic connections by means of simultaneous lunar photography from a number of stations is clearly a very difficult one. Whether an accuracy of ± 200 feet on the earth's surface is possible cannot be said at this time. The observational difficulties have been pointed out and shown to be formidable - only experimentation can decide whether or not they are insurmountable. Such experimentation is now being inaugurated at the U. S. Naval Observatory by Mr. G. M. Clemence and his co-workers. They are attempting to obtain the precise position of the moon through lunar photography with the object of using the moon as a fundamental timekeeper. The observational problem, however, is identical to that which confronts the geodesist - if the work done at the U. S. Naval Observatory portends obtaining the lunar position with the accuracy required for geodetic connections, the method of lunar photography should be very seriously considered.

I am grateful to the following for valuable discussions of the subject matter considered in this paper: Dr. George Van Biesbroeck, Yerkes Observatory; Dr. D. L. Harris and Dr. J. J. Nassau, Warner and Swasey Observatory; Mr. C. B. Watts and Mr. G. M. Clemence, U. S. Naval Observatory; and Father Francis J. Hayden, Georgetown College Observatory.

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