STAR-CALIBRATED LUNAR PHOTOGRAPHY*

M. MOUTSOULAS

Dept. of Astronomy, University of Manchester, England

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Abstract. Accuracy in the determination of the absolute coordinates of lunar features or the physical libration of the Moon can be greatly improved by a technique providing lunar photographs on star-calibrated plates. An outline of the photographic technique and the computer programme for the reduction of the plates is given. In the Appendix the technical details of the double slide plate carrier which, adjusted to the Data Corporation Camera, secures high quality stellar images, are presented.

From the early days of astronomical photography the important role that long-focus telescopes could play in stellar measurements has been realised. Nevertheless, the large potentialities of lunar photography have not yet been put to full use. Investigators of the rotation of the Moon, in particular, have been handicapped by the limited observational material at their disposal. Most of that material consists of measurements of the position angles and the distances of points of the lunar limb from a reference point (a crater) situated close to the centre of the lunar disc. Such measurements were made by means of heliometers, an instrument invented in 1748 by Bouguer, who thought that if an equatorial telescope has, instead of one objective, two similar objectives mounted side by side, they will produce two images for the same star at the focal plane. If one of the lenses is made to slide on its plane, the corresponding image of the star will slide on the focal plane as well; and it can be arranged that the image of another star will fall on the former's position. Thus, the measurement of angular distances in the sky is converted into the measurement of the motion of the sliding lens. A few years after Bouguer's invention, Dollond modified the technique by replacing the two complete lenses by the two halves of one bisected lens, so that when the two semi-lenses are placed one against the other, forming a circular lens, only one image of a star appears at the principal focus, since the images that the semi-lenses form are superimposed. If the one semi-lens slides upon the other in a direction parallel to the line of section, the image it produces at the focus follows its motion, so that the distance between the two images formed on the focus is equal to the distance between the centres of the two half-lenses.

High-accuracy measurements of angular distances could be obtained with this double-image micrometer; and since it was used also for measurements of the diameter of the Sun, it was called the 'heliometer'. Lalande used the heliometer at the end of the 18th century for measurements of the diameter of the Moon, while Bessel in 1839 introduced its use for measurements of distances between the centre and the limb of the lunar disc in order to detect the physical libration of the lunar globe. And, until the present day, the same technique has been the basis of almost all observational

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work for the investigation of the lunar libration, in spite of the fact that the heliometer proved to be incapable of providing the accuracy required in such measurements. The resolving power of the heliometers used so far does not exceed $\frac{1}{2}$ sec of arc; it is not surprising that nobody has taken the risk of cutting a larger lens into two pieces in order to obtain a more powerful heliometer.

However, investigators, even today, persist in using material of heliometric observations. That is due to the fact that the results obtained from reduction of photographs do not seem to indicate that a much better accuracy has been achieved. The main problem of the precise determination of the orientation and the scale of the lunar image has not yet been solved, and the techniques used so far do not deviate very much from that introduced by Puiseux at the beginning of this century – i.e., determination of the plate constants by comparison of the measured rectangular coordinates of lunar craters with the selenographic ones given in the catalogues. In this way, any systematic errors occurring in the determination of the coordinates, as well as the low degree of accuracy which can be achieved in the course of the measurement of the positions of lunar features, are transferred into the plate constants, thus affecting any further information. The results of this are the controversial contour-maps of the lunar surface which even today coexist and to a large extent an uncertainty as far as the shape and the rotation of the Moon are concerned, which uncertainty should not still exist at this stage of the lunar exploration.

It is obvious, therefore, that a new technique must be developed which should permit a more accurate and reliable determination of the plate constants. A photograph of the Moon on a stellar background would fulfil the requirements completely. The most successful technique developed so far to photograph the Moon against the stellar background was that of Markowitz (1960). In a Markowitz camera, a dark glass filter is used to reduce the intensity of the lunar light during an exposure of about 20 sec, which is long enough to record images of surrounding stars up to 9th magnitude. During the time of the exposure the filter is tilted gradually so that the relative motion of the lunar image with respect to the stars is eliminated by optical refraction. The Dual-Rate Moon Camera of Markowitz has been used in the last 20 years mainly for the determination of the position of the Moon with respect to the stars. However, there is not much that it can contribute to the solution of our problems of the precise measurement of lunar features, since the images of the Moon obtained by the Markowitz camera are very small and, therefore, the accuracy in the determination of positions of lunar landmarks is limited.

Another technique has been developed by Arthur (1966), with the use of star-trailed lunar photographs. According to this method, following a normal lunar exposure the drive is switched off, the telescope is moved in declination to intercept the transit of a star and a second exposure on the same plate is taken recording the trail of the star. In this way the plate orientation is defined; while if during the second exposure an oscillatory motion is given to the plate-holder, the trail will have the form of a sinusoidal curve which can also give the scale of the plate. That method, even if it is a real improvement in comparison with the simple lunar photography, was not expected to give much more accurate results, due mainly to the irregularities in the trail of the bright star.

A new technique which is now being developed in the Astronomy Department of the University of Manchester will be described briefly in the present paper.

According to this technique, a stellar field having the same declination and hour angle which the Moon will attain 1–2 hours later is photographed, and the drive is switched off until the time when the Moon comes into the centre of the field. A slightly underexposed photograph of the Moon is then taken on the same plate. By an ap-

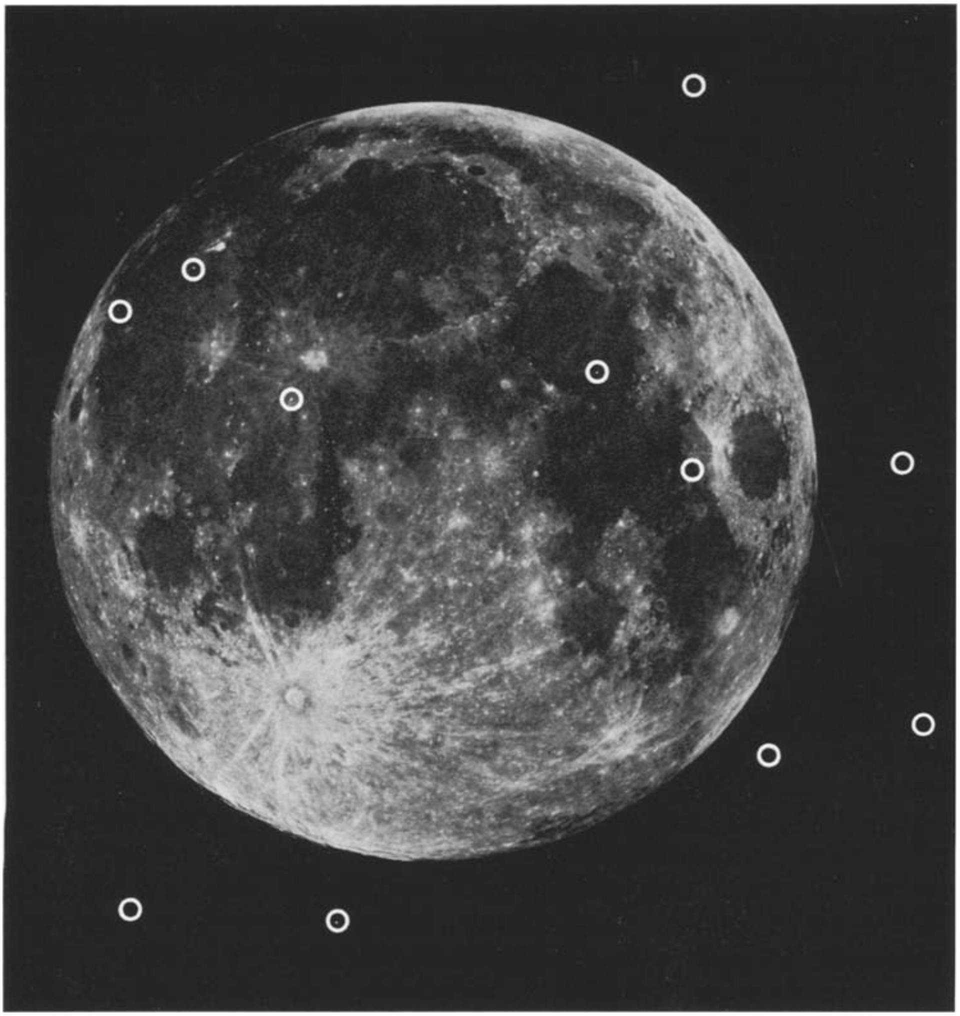

Fig. 1. The Moon photographed on a star-calibrated plate. This picture, the first to be taken from the Pic-du-Midi Observatory with the use of the new plate-carrier described in the Appendix, indicates the potentialities of the new method. Images of stars (encircled in the picture) as faint as 14th magnitude have been recorded on Eastman Kodak 103aE emulsion after an exposure of 6 min. The length of exposure for the Moon was 0.2 sec.

propriate choice of the stellar field enough stars can be recorded on the photographic plate to define its orientation and scale. If no considerable temperature changes occur during the interval between the two exposures while the telescope remained stationary, these constants can be used for the reduction of the measures.

The 24-inch refractor of the Pic-du-Midi Observatory has been used for the development of this method and a double slide plate-holder specially designed to be attached to the Data Camera mounted on the telescope has been constructed, so that very accurate guiding during the stellar exposure is secured. The technical details of the modified camera are described in the Appendix. The usual length of exposure on plates of Eastman Kodak 103aE is about 5 min. That time is sufficient to record stellar images as faint as of 14th apparent magnitude, while during longer exposures the plate is darkened by the scattered lunar light. The quality of the images is improved with the use of an OY2 filter. Obviously the precise length of exposure is estimated by the observer, depending on the transparency of the atmosphere and the angular distance of the Moon from the photographed stellar field. For the Moon, exposures of about 0.2 sec seem appropriate, as they are long enough to record small craters and other lunar landmarks used as control points for the lunar measures, while at the same time are short enough to permit stellar images previously recorded on the plate to be visible. A review of the lunar control points used so far has been proved necessary. Craters large in size and irregular in shape chosen by previous investigators and repeatedly used by their successors have to be rejected as misleading. A typical example is the crater Manilius, the position of which under the best seeing conditions cannot be defined with an accuracy better than 3–4 km, and which has been used several times in the past for the measurement of the lunar physical libration, a phenomenon that does not exceed 2 km in amplitude.

For the improvement of the lunar images, intensified contact copies of the original plates can be produced. It has been proved that this technique is better than 'fluorododging', since the second, even if it makes the identification of small features easier, by increasing their size, it increases at the same time the errors in their measurement. Comparative measurements of copies of the same plate treated with either of the two techniques led to the conclusion that after 'fluorododging' we should expect an increase of 20% in the errors of the measurements.

For the measurement of the plates the Zeiss 3030 measuring engine has been used with an attained accuracy in the position of stellar features of $\pm 5\,\mu$, and $\pm 10\,\mu$ in the position of lunar images.

The preliminary computer programme constructed for the study of the star calibrated lunar photographs is mainly based on the algebra described in the books of spherical astronomy and astrometry (Chauvenet, 1891; Smart, 1962; Podobed, 1965; van de Kamp, 1967), as well as in books dealing particularly with the Moon (Kopal, 1962; Middlehurst and Kuiper, 1963; Kopal, 1966). If there seem to be some differences between the symbols used in the present text and the previous works on which it has been based, this is due to the fact that one purpose of this text is to be used as a guide to those wishing to use the same computer programme and therefore symbols appear as in the computer programme which cannot accept Greek letters or the representation of different quantities by the same symbol. The programme has been written in the 'Atlas Autocode' language, which is very efficient for use with the University of Manchester Atlas Computer and contains a considerable number of

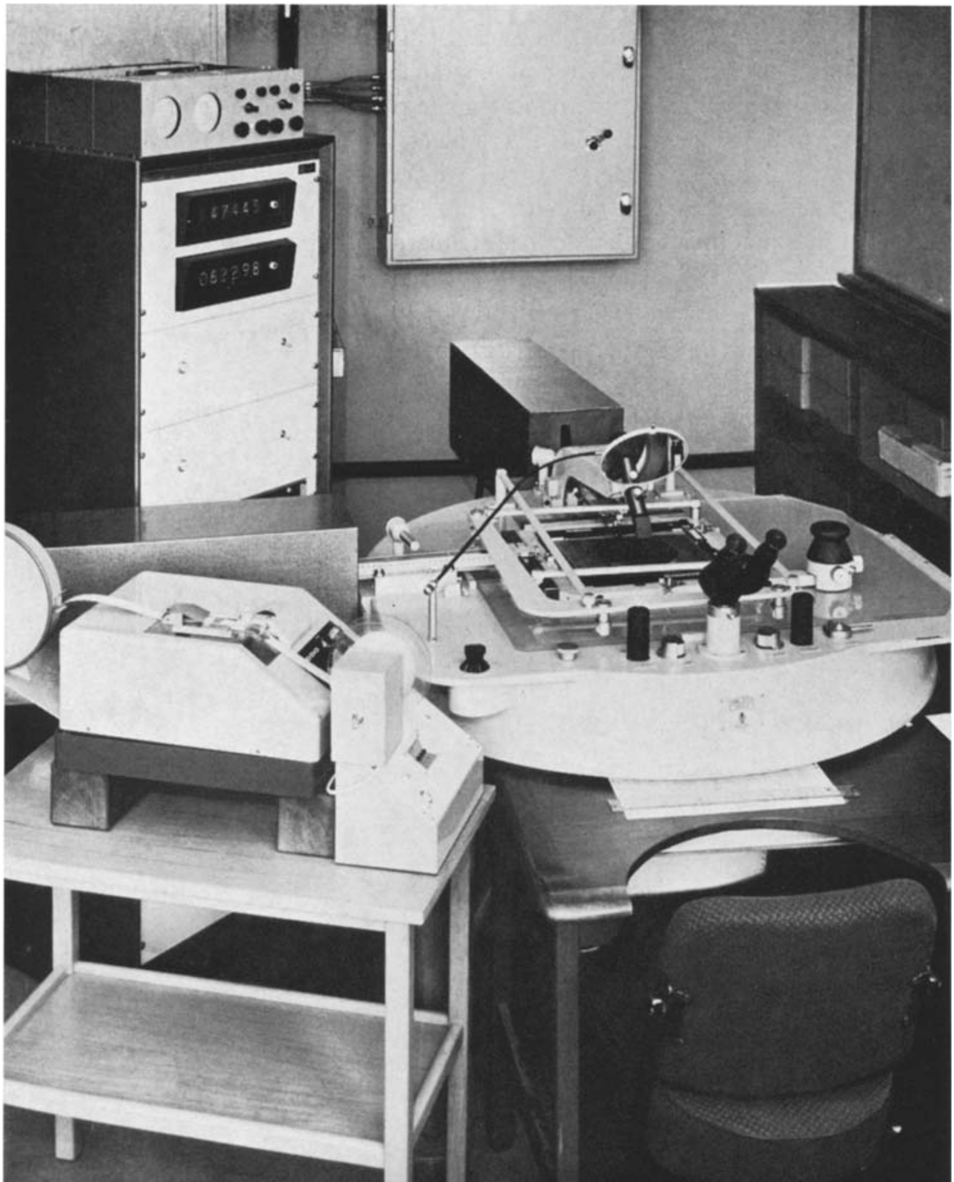

Fig. 2. The Zeiss 3030 measuring engine with the Ferranti digitized output unit, used at the University of Manchester for positional measurements of lunar negatives.

mathematical sub-routines. Moreover, some additional routines have been constructed which appeared necessary for most convenient manipulation of this programme, such as the routines converting data given in degrees, minutes and seconds into radians, or vice versa, the interpolation routine which performs a sixth order Bessel interpolation, etc. The computer capacity and capability permitted reductions to be made without simplifications of the formulae and truncation of terms (phenomena which were quite usual in earlier astronomical calculations).

The equatorial coordinates of the photographed stars are read first and next the measured stellar positions on the photographic plate. Since each star is measured 4 times, the average is adopted, while the residuals are examined. From 4 measures of the edge of the plate, the readings *cx*, *cy* for its centre are determined and the corresponding stellar coordinates *p*, *q* of the centre of the photographed stellar field are calculated in a first approximation. The standard coordinates *xs*, *ys* are determined by the formulae,

$$xs = \frac{\cos(ita)\cdot\sin(xi - p)}{\sin(ita)\cdot\sin(q) + \cos(ita)\cdot\cos(q)\cdot\cos(xi - p)}$$

and

$$ys = \frac{\sin(ita)\cdot\cos(q) - \cos(ita)\cdot\sin(q)\cdot\cos(xi - p)}{\sin(ita)\cdot\sin(q) + \cos(ita)\cdot\cos(q)\cdot\cos(xi - p)},$$

where *xi* and *ita* represent the hour angle and the declination of the stars respectively. These are multiplied by the focal length of the telescope expressed in the unit used in the measures (microns).

Thus we get the set of normalised Turner's equations,

$$\begin{aligned} xs_{(i)} - x_{(i)} = {} & a_{(i,1)}\cdot x_{(i)} + a_{(i,2)}\cdot y_{(i)} + a_{(i,3)} + a_{(i,4)}\cdot x^2_{(i)} \\ & + a_{(i,5)}\, y^2_{(i)} + a_{(i,6)} x_{(i)}\cdot y_{(i)} \end{aligned}$$

and

$$\begin{aligned} ys_{(i)} - x_{(i)} = {} & d_{(i,1)}\cdot x_{(i)} + d_{(i,2)}\cdot y_{(i)} + d_{(i,3)} + d_{(i,4)}\cdot x^2_{(i)} \\ & + d_{(i,5)} y^2_{(i)} + d_{(i,6)} x_{(i)}\cdot y_{(i)}, \end{aligned}$$

where *i* stands for the order of each star. From these equations the plate constants $a_1, a_2, \ldots, d_1, d_2, \ldots$ are determined with the use of a least-squares solution routine available in the computer library. In case there are less than 6 measurable stars in the field, the quadratic terms can be truncated since they are extremely small, but that happens rarely. In general there is a sufficient number of stars in the field to enable both linear and second order coefficients to be determined and studied.

Subsequently the lunar reductions are performed and since the Moon is close to the Earth, the time and place of observation play a considerable role in the relative figure which appears on the photographic plate. Therefore the set of data consists of the geographic coordinates of the observatory (*lp*: longitude, *f*: latitude), as well as its altitude (*al*), the universal time at the time of the lunar exposure (*ut*) and the sidereal time at Greenwich at 00h UT on the day of the observation. Six subsequent values for the right ascension, declination, semi-diameter, horizontal parallax, optical libration in longitude, optical libration in latitude and position angle of the axis of the Moon are read from the Astronomical Ephemeris, three at either side of the time of the lunar exposure, and the interpolation routine is called, which carries out a 6th order Bessel interpolation between the above elements in order to give their value for the time of the observation. In the first column d1, i ($i=1, 2, \ldots, 6$) of a 6×6 two-dimensional array, the six figures between which interpolation is required are stored. Their differences of various orders are constructed by the 'cycle' $d_{j,k}=d_{j-1,k-1}-d_{j-1,k}$, where $j=2, 3, \ldots, 6$ and $k=1, 2, \ldots, 5$. The value xx of the quantity required is given by the formula

$$xx = d_{1,3} + A \cdot a' + B \cdot b' + C \cdot c' + D \cdot d' + E \cdot e' ,$$

where

$$A = n , \quad B = \frac{A \cdot (n-1)}{2} , \quad C = \frac{B \cdot (n - \frac{1}{2})}{3} , \quad D = \frac{B \cdot (n+1)(n-2)}{12} ,$$

$$E = \frac{D \cdot (n - \frac{1}{2})}{5}$$

$$a' = d_{2,3} , \quad b' = \frac{d_{3,2} + d_{3,3}}{2} , \quad c' = d_{4,2} , \quad d' = \frac{d_{5,1} + d_{5,2}}{2} , \quad e' = d_{6,1} ,$$

and n represents the time which has elapsed at the time of the lunar exposure, expressed as a fraction of the time interval between the two central readings of the tabulated data. In the case of the horizontal parallax, for example, where the time step is 12 hours, n gets the value $n=(ut)/(12 \times 3600)$, as the universal time has been, for convenience, converted into seconds, while provision has been made in the programme so that in the case of evening exposures ($ut > 12 \times 3600$), 12 hours are subtracted from the value of ut, and n takes the value $n=(ut-12 \times 3600)/(12 \times 3600)$.

The geocentric hour angle (ho) of the Moon is determined by converting the universal time (ut) into interval of sidereal time between 00h UT and the time of the exposure, adding that to the sidereal time at Greenwich at 00h UT and subtracting the longitude of the observatory and the right ascension of the Moon from the result.

In order to calculate parallax corrections for the data, the geocentric values for which are given, from the geographic latitude f of the observatory, its geocentric latitude f' and geocentric distance are computed.

The local radius fr of the Earth at latitude f is computed from the formula,

$$fr = \sqrt{\frac{(fs)^2 + (fc)^2}{2} + \frac{(fc)^2 - (fs)^2}{2} \cdot \cos(2 \cdot f)} ,$$

where

$$fc = (\cos^2(f) + (1 - fl)^2 \cdot \sin^2(f))^{-\frac{1}{2}}$$

$$fs = (1 - fl)^2 \cdot (fc) ,$$

and fl stands for the flattening of the Earth's ellipsoid defined as the difference of its largest and smallest semi-axis divided by the semi-major axis. Attention should be paid to the fact that of the 9 decimal figures accuracy presented in the corresponding formulae of various textbooks, or the 8 figures accuracy given in the final formula of the Explanatory Supplement to the Astronomical Ephemeris, which is usually copied by investigators, only the first 5 figures are correct, since their values are based on the value $fl = \frac{1}{297}$ for the flattening of the Earth given by Hayford in 1909. However, the value adopted today is $fl = \frac{1}{298.25}$ (NASA, 1968). (In *Astrophysical Quantities* the figure $fl = \frac{1}{298.26}$ is quoted (Allen, 1963).) Adding to fr the quantity $1568 \cdot (al) \cdot 10^{-10}$ we get the distance r of the observatory from the centre of the Earth, expressed in terms of the Earth's equatorial radius, i.e.,

$$r = fr + 1568 \cdot (al) \cdot 10^{-10}.$$

The geocentric latitude f' of the observatory is given by the formula

$$f' = \arcsin\left(\frac{1}{r} \cdot (fs + 1568 \cdot (al) \cdot 10^{-10} \cdot \sin(f))\right).$$

Since the topocentric equatorial coordinates (hh, dd) are related to the geocentric ones (ho, de) by means of the equations,

$$\begin{aligned}
(FF) \cdot \cos(dd) \cdot \sin(hh) &= \cos(de) \cdot \sin(ho), \\
(FF) \cdot \cos(dd) \cdot \cos(hh) &= \cos(de) \cdot \cos(ho) - r \cdot \cos(f') \cdot \sin(pi), \\
(FF) \cdot \sin(dd) &= \sin(de) - r \cdot \sin(f') \cdot \sin(pi),
\end{aligned}$$

where (FF) is the ratio of the topocentric and geocentric distance of the centre of the Moon, the topocentric hour angle (hh) and declination (dd) of the Moon can be computed as,

$$hh = \arctan\left(\frac{AA}{BB}\right)$$

and

$$dd = \arcsin\left(\frac{CC}{FF}\right),$$

where

$$\begin{aligned}
AA &= \cos(de) \cdot \sin(ho), \\
BB &= \cos(de) \cdot \cos(ho) - r \cdot \cos(f') \cdot \sin(pi), \\
CC &= \sin(de) - r \cdot \sin(f') \cdot \sin(pi),
\end{aligned}$$

and

$$FF = \sqrt{(AA)^2 + (BB)^2 + (CC)^2}.$$

There are conditional instructions in the computer programme so that whenever the inverse of a trigonometric function is calculated the right value for the outcoming arc is chosen.

The values of the topocentric optical librations of the Moon and position angle of its axis l', b' and C' are determined from their geocentric values given in the

Ephemeris. From the spherical triangle defined by the North celestial pole, the geocentric position of the Moon on the sky and the zenith of the observer, we find the zenith distance z of the Moon,

$$z = \arccos(\sin(f)\cdot\sin(de) + \cos(f)\cdot\cos(de)\cdot\cos(ho)),$$

as well as the azimuth Q of the observer at the point when the Moon is at zenith,

$$Q = \arccos\left(\frac{\sin(f) - \cos(z)\cdot\sin(de)}{\sin(z)\cdot\cos(de)}\right).$$

The parallax of the Moon (sig) is given in terms of the horizontal parallax (pi) and the zenith distance (z) by the formula,

$$sig = \arctan\left(\frac{\sin(z)\cdot\sin(pi)}{1 - \sin(pi)\cdot\cos(z)}\right).$$

From the selenocentric spherical triangle defined by the centre of the lunar face as seen from the centre of the Earth, the actual centre of the face for the observer and the lunar north pole, the relations,

$$b' = \arcsin(\cos(sig)\cdot\sin(b) + \sin(sig)\cdot\cos(b)\cdot\cos(Q - Co)),$$

$$l' = l - \arcsin\left(\frac{\sin(sig)\cdot\sin(Q - Co)}{\cos(b')}\right)$$

and

$$C' = Co + \arctan\left(\frac{\sin(b)\cdot\sin(l' - l)}{\cos(b')}\right) - sig\cdot\sin(Q) \cdot\tan\left(de - \frac{sig\cdot\cos(Q)}{2}\right)$$

can be derived, which connect the topocentric optical librations and position angle of the axis of the Moon to the geocentric ones.

The topocentric value of the parallactic angle Q' is

$$Q' = \arccos\left(\frac{\sin(f) - \cos(z')\cdot\sin(dd)}{\sin(z')\cdot\cos(dd)}\right),$$

where in the calculation of the zenith distance z', the topocentric values dd and hh for the declination and the hour angle of the Moon have been considered.

After these preliminary calculations, the selenocentric longitude $XI_{(i,1)}$ and latitude $XI_{(i,2)}$ of the measured lunar points are read, as well as their measures $x_{(i)}$, $y_{(i)}$. If we consider the rectangular system of coordinates (X, Y, Z), where Y is the axis of rotation of the Moon, Z is the direction of the observer and X, being perpendicular to the two others, points eastward (towards Mare Crisium), the instantaneous direction cosines $X_{(i)}$, $Y_{(i)}$, $Z_{(i)}$ of landmarks on the lunar surface can be derived from their selenocentric coordinates by application of the transformations,

$$X_{(i)} = xi_{(i)} \cdot \cos(l') - zeta_{(i)} \cdot \sin(l'),$$
$$Y_{(i)} = -\, xi_{(i)} \cdot \sin(l') \cdot \sin(b') + ita_{(i)} \cdot \cos(b') - zeta_{(i)} \cdot \cos(l') \cdot \sin(b'),$$
$$Z_{(i)} = xi_{(i)} \cdot \sin(l') \cdot \cos(b') + ita_{(i)} \cdot \sin(b') + zeta_{(i)} \cdot \cos(l') \cdot \cos(b'),$$

where

$$xi_{(i)} = rr_{(i)} \cdot \cos(XI_{(i,2)}) \cdot \sin(XI_{(i,1)}),$$
$$ita_{(i)} = rr_{(i)} \cdot \sin(XI_{(i,2)}),$$
$$zeta_{(i)} = rr_{(i)} \cdot \cos(XI_{(i,2)}) \cdot \cos(XI_{(i,1)})$$

are the standard direction cosines, and $rr_{(i)}$ the radius of the Moon at the particular point. At a first approximation the lunar radius is taken as constant, while for a higher degree of approximation its appropriate values are put into the programme.

If the Earth was at infinite distance from the Moon, any point of the lunar surface would appear projected on the plane XY along lines parallel to the Z direction, and therefore perpendicular to that plane. In such a case, $X_{(i)}$ and $Y_{(i)}$ would represent exactly the apparent rectangular plane coordinates of the lunar points. Since, however, the observer is at a finite distance from the Moon, the direction of observation of various lunar points deviates from the perpendicular to the XY plane by an amount depending on the distance of the particular point from the centre of the lunar figure. The apparent coordinates $X'_{(i)}$, $Y'_{(i)}$ of the lunar points are related to the rectangular ones $X_{(i)}$, $Y_{(i)}$ by means of the equations,

$$X'_{(i)} = \frac{X_{(i)}}{1 - Z_{(i)} \cdot \sin(s')},$$
$$Y'_{(i)} = \frac{Y_{(i)}}{1 - Z_{(i)} \cdot \sin(s')},$$

where s' is the topocentric semidiameter of the Moon, which can be determined from the geocentric lunar semidiameter s by means of

$$s' = \text{arc}\sin\left(\frac{\sin(s)}{\sqrt{1 + r^2 \cdot \sin^2(pi) - 2 \cdot r \cdot \sin(pi) \cdot \cos(z)}}\right).$$

The coordinates $X'_{(i)}$ and $Y'_{(i)}$, which correspond to directions parallel to the first lunar meridian and the lunar equator, are transformed into horizontal and vertical coordinates of the photographic plate with the use of the rotation transformation,

$$xs_{(i)} = fO \cdot (X'_{(i)} \cdot \cos(C' - Q') - Y'_{(i)} \cdot \sin(C' - Q')).$$
$$ys_{(i)} = fO \cdot (X'_{(i)} \cdot \cos(C' - Q') + Y'_{(i)} \cdot \sin(C' - Q')).$$

The mean of four measurements is taken for each point, and the residuals of the measures are examined. After the measurements of the points have been checked, their measured coordinates, the origin of which is arbitrary on the plate, are transformed into coordinates having as origin the centre of the plate and the computer routine which performs the least-square solution of the system of equations is called.

The differences between the plate constants derived from the lunar measures and those derived from the stellar measures are studied in an attempt to obtain information about the general shape and the physical libration of the Moon. Also, the deviations of the actual measures of lunar points from the predicted values for them are examined in order to indicate local deviations of the shape of the Moon from the ellipsoid, as well as to increase the accuracy in the adopted values of coordinates of the lunar features.

Investigators working on the determination of absolute altitudes of lunar points from the study of the apparent changes of their position under different librations have so far limited themselves to copying the method described by Saunder (1905). However, the precision in the calibration of the photographic plates that we have attained permits a much more sophisticated treatment of the lunar measures. The general plan of a serious statistical manipulation of the lunar data has already been outlined by Eckhardt and Hunt (1962). Therefore, the next step in our programme consists of a close collaboration between our group and the U.S. Air Force Cambridge Research Laboratories towards the most efficient statistical treatment of the star-calibrated lunar plates which we have started to accumulate.

Appendix: the 8 × 8-inch Astrometric Camera

A. GENERAL REQUIREMENTS

It is common experience in astronomical photography that during a stellar exposure the recorded stellar images appear as large non-symmetrical spots rather than as small circular dots on the photographic emulsion. Large telescopes are, of course, equipped with 'driving' mechanisms enabling them to 'follow' the stars faithfully in their diurnal motion, and as a result to present a constant field of the sky in the field of view.

However, there are several factors causing the stellar images to move in the field and therefore to be projected at various points of the photographic plate during a long exposure. The outcome is that a bright star will give a quite distorted image, while a faint star will not appear at all, since the exposure time on any particular point of the emulsion on which the star has been projected has not been long enough for it to be recorded. The following can be considered as the five main reasons causing these discrepancies.

(1) Non-precise rate in the telescope driving mechanism.

(2) Errors in the telescope drive gearing.

(3) Flexure changes of the telescope at various orientations.

(4) Variation of atmospheric refraction with the zenith distance.

(5) Changes of atmospheric refraction caused by atmospheric currents of various temperatures.

Of these, the first can be decreased considerably with careful adjustment. The second and third are almost inevitable in the large long-focus refractors used in astrometric work. The fourth can be predicted, but in order that a correction can be made in advance, a quite complicated telescope-control device is required. Finally, the fifth is not predictable.

Apart from driving mechanisms, telescopes are provided with additional motion control devices so that at least four of these errors which appear as long-period effects can be corrected by appropriate displacement of the telescope. Nevertheless, not much is gained since the inertial effect of the telescope's mass causes a considerable vibration of the whole instrument with any change of its kinetic condition, and therefore brings about an oscillation of the stellar image on the plate. In order to avoid that effect the light photographic plate has to be moved rather than the heavy telescope.

That is how we have come to the point of constructing a special camera with a plateholder which can be moved so that the stellar field can be followed at any displacement it might show during a long exposure. The plateholder is guided by the observer who checks the position of a chosen star in the field to the crosswires of a camera-mounted optical system. Any correction in the position of the plate-holder is given by means of two lead screws, the one of which enables movement in the direction of the right ascension of the field, while the other, being orthogonal to the first, enables movement in declination. The screws are operated by electric motors controlled by the observer through a box of two pairs of button-switches, so that during the exposure the camera itself is not touched, as that could cause vibration of the whole telescope.

Since the high-accuracy photographs obtained with such a camera, which is used in conjunction with a long-focus telescope, are appropriate for astrometric work, the name 'astrometric camera' is given to it, in order to distinguish it from other cameras in the observatory.

B. DESCRIPTION OF THE CAMERA

1. *Electrical Supply and Control Lamps*

The mains supply socket and controls are at the back of the camera. The camera is supplied with 220 V A.C. and the current can be switched to 'on' and 'off' with a switch situated next to the input socket. When electrical supply is passing into the camera the red light is on, while if supply is coming through but the safety fuse has blown the red lamp flickers.

The 24 V supply socket is at the left-hand side of the camera. On the same side is the socket for the connection of the camera with the exposure timing unit, and a red lamp indicating that the shutter is open and therefore exposure in progress.

2. *Guidance System*

The guidance system which is located in front of the shutter consists of an elliptical flat of one inch minor axis, aluminised and siliconised, which is set at an angle of 45° with respect to the optical axis and reflects the light of a chosen star in the field

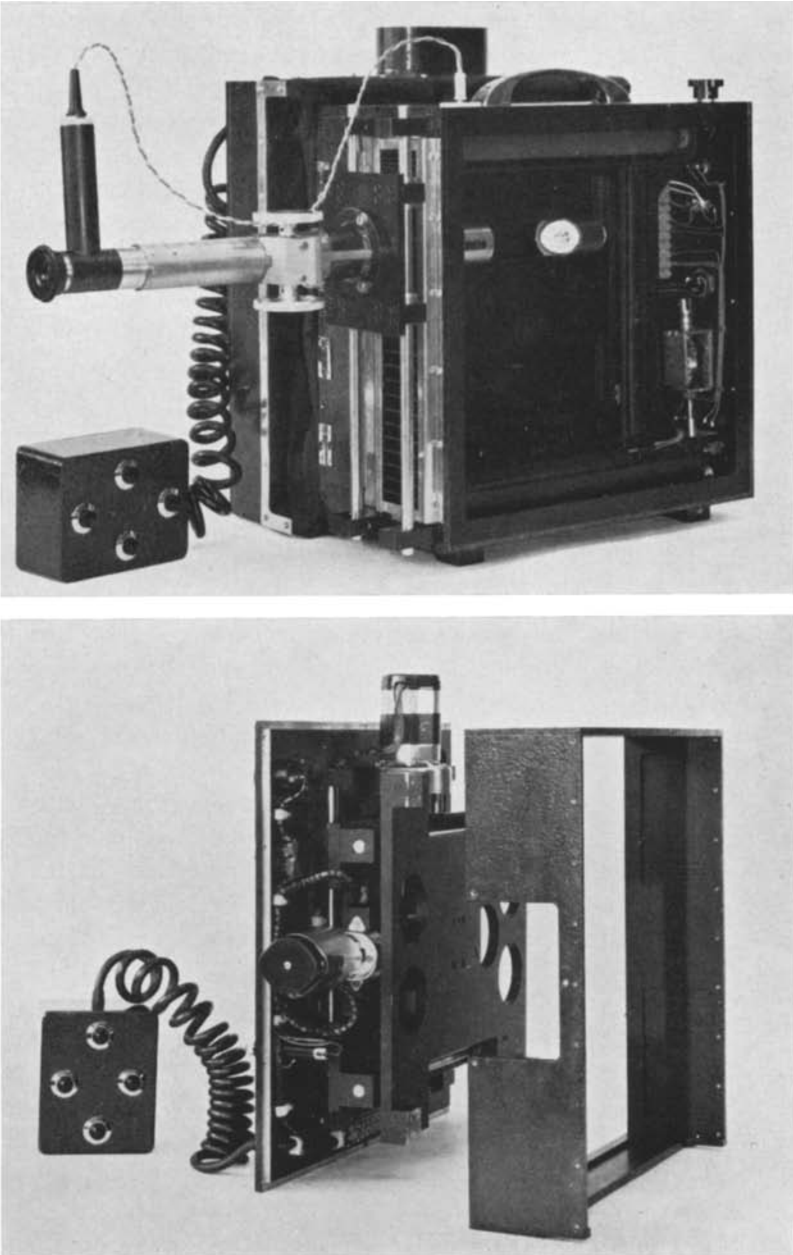

Fig. 3. General view (top) and the double slide system (bottom) of the camera modified for star-calibrated lunar photography.

of view towards the Ramsden eyepiece where the observer can see the stellar image against a graticule illuminated by a side light. The flat lies 3.343″ inside the focal plane. On its back there are three kinematically mounted adjustment screws. In order to align the flat we place a black disc of paper, 5 inches in diameter, on the objective end of the telescope. That will be seen as a small black disc when looking from the centre of the finder tube with the eyepiece removed, and by screwing and unscrewing the adjustment screws it can be centralised. The flat is then aligned.

The deflected cone of light is focused 0.25″ in front of the field lens. That is where the focusing attachment is fixed. On the front of the graticule tube is the pair of achromatic doublets which focus the star image on to the graticule. From the two Ramsden eyepieces which are provided, the one (of 1-inch focal length) is used during the normal guiding, while the other (of $\frac{1}{2}$-inch focal length) is only used for focusing the camera.

The guidance tube can be moved in right ascension by means of a pair of handles and the relative position of the flat in right ascension can be read on a scale on the side of the tube. The motion in declination takes place along a pair of linear shafts and the relative position in declination can be read on a scale at the side of the camera. In that way the flat's movement covers the whole format area so that any star in the field can be picked up and brought to the centre of the graticule for guidance. The tube can be locked in position with a knob.

The lamp illuminating the graticule is supplied with 24 V current taken from a socket at the top of the camera and the intensity of the illumination can be changed with a control knob.

In order to focus the camera, the guidance tube is moved to the top right-hand corner to facilitate the positioning and fixing of the focusing attachment. The $\frac{1}{2}$-inch eyepiece is focused on to the graticule and the graticule tube is moved until the cross-wires on the focusing screen are in focus. The focusing screen is then removed and the guidance tube repositioned so that the flat comes at the centre of the telescope aperture (8 cm on the tube scale and 14 cm on the side scale). With the help of the telescope finder a suitable celestial body is positioned at the centre of the field and

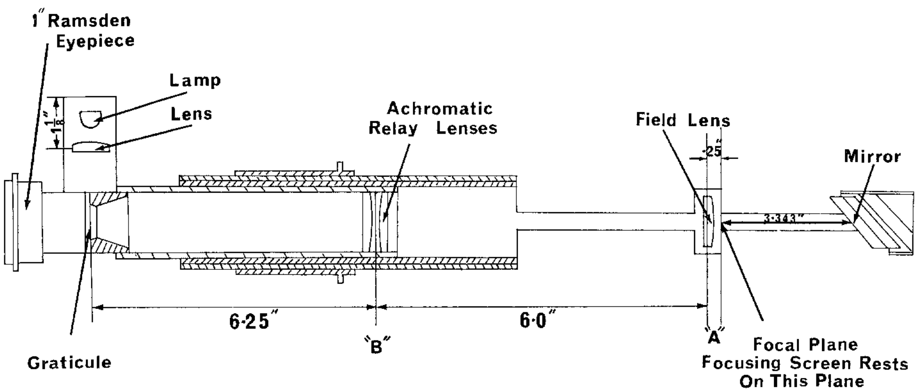

Fig. 4. Guidance system optical design.

by means of the telescope focusing adjustment the camera is focused. On completion of focusing the ½-inch eyepiece is replaced with the 1-inch, and guiding can be started.

3. *Guiding Operation*

Once a star has been brought to the centre of the graticule and the shutter is opened in order to start the exposure, any displacement of the star can be corrected with the use of four buttons with which the plate-holder and the attached guidance system can be moved towards the left or the right as well as downwards or upwards. The relative position of the plate-holder, of which the range of motion in both directions is 2 inches, is shown on two scales, the one at the back of the camera indicating displacement in right ascension, while the scale on the left-hand side indicates displacement in declination.

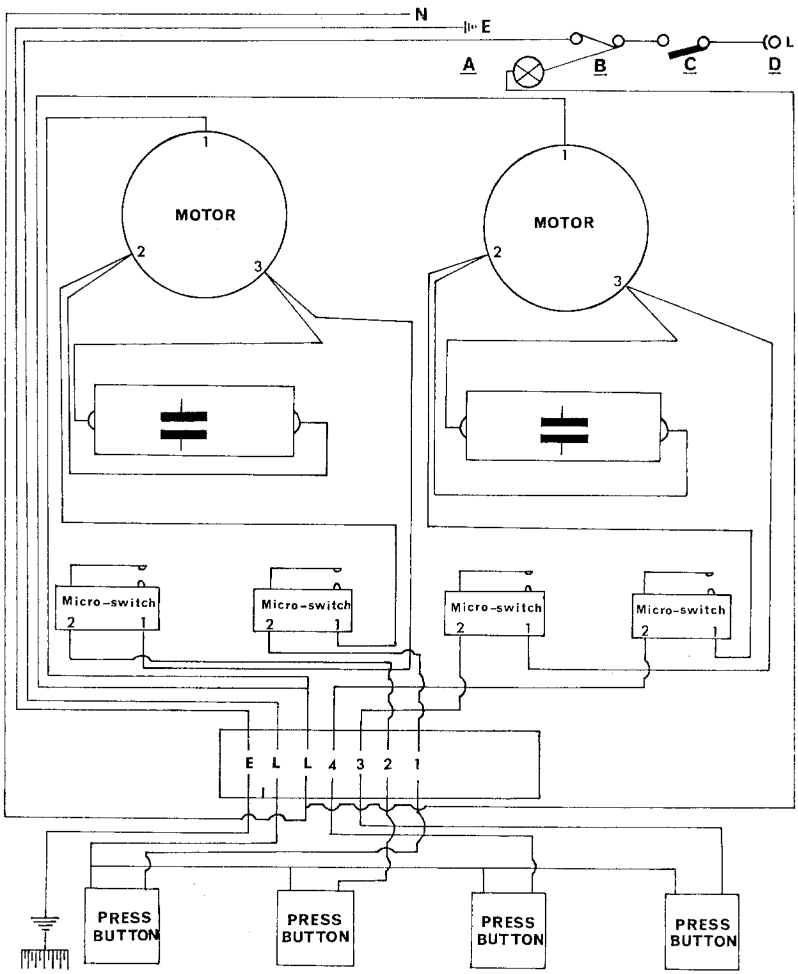

Fig. 5. Electrical circuit for the controlled motion of the plateholder, A = lamp. B = Fuse. C = Switch. D = Plug.

4. *Plate-holder Motion Assembly*

The plate-holder can be inserted into position through a hinged door at the right-hand side of the camera.

The guidance linear bearing shafts can be removed by unscrewing the screws at the side of their upper housings. The plate separating the front from the rear part of the camera can be removed by unscrewing the four pairs of screws at its corners, and removing the cloth protection cover joining the movable plate with the rear part of the outer casing. This plate houses the filter holder and the plate-holder. By removing it the rear part of the camera becomes accessible. That consists of the motion units. The first plate is movable in declination and bears the four blocks which connect the rear and the front of the camera. Under the top and side cover are the two motors supplied with 220 V A.C. and the gearboxes which reduce the motor's motion to 4 revolutions per minute. By removing the side of the case the electric connections of the sockets and lamps become easily accessible, as well as the connection of the camera with the guiding handset and the electrical circuit distribution block.

The motion is transferred from the motor through the gearbox and the coupling to the lead screw of 0.5″ diameter, 26 threads per inch, running in a threaded bush of PTFE material. There are eight Ransome and Marles linear ball bearings (one at each corner of the two moving plates) and through them hardened and ground steel shafts (two to each plate) giving a frictionless movement, as well as four overriding micro-switches.

Figure 4 represents the guidance system optical design and Figure 5 the electrical circuit for the controlled motion of the plateholder.

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