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RESEARCH ON LUNAR PHOTOMETRIC AND
TOPOGRAPHIC ANALYSIS

by

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TECHNICAL (FINAL) REPORT

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The research reported in this document has been sponsored by the Air Force Cambridge Research Center of the Air Research and Development Command, United States Air Force, through its European Office.

The aim of the present report will be to summarize the methods and results of the work in the domain of lunar topography, performed under Contract AF 61(052)-168 in the period of 18 months between November 1958 through April of 1960. The progress made in the course of this work was previously reported in a series of 6 quarterly Technical Status Reports under this contract; and following its expiration, further work towards its ultimate objectives is being supported by the new Contract AF 61(052)-380. The termination of the former contract affords, however, a convenient opportunity for summarizing herewith the principal achievements attained under its sponsorship, with particular emphasis on such results and experiences as may be pertinent to its continuation and planning for the future.

PERSONNEL.

The programme sponsored by the present contract was supervised throughout the entire period covered by this report by Professor Zdenek Kopal, head of the Department of Astronomy in the University of Manchester, in collaboration with Dr. James Ring, Senior Lecturer in the same University; and with the help of the following research assistants:

Mr. David B. Clarke (between November 1958 and September 1959; part time),

Dr. Gilbert Fielder (between January 1959 and April 1960; full time),

Mr. Thomas W. Rackham (from February 1959; full time),

Mr. Geoffrey Turner (between January 1959 and March 1960; full time).

The foregoing Mancunians were joined from February 1960 by M. R. LePouriel on Pic-du-Midi, who in the past three months of the period covered by this report joined our staff as a full-time photographer on the Pic, working under direct supervision of Dr. Jean Röscher, Director of the Observatory.

In addition to the foregoing technical staff, the principal secretarial assistance to the project throughout the entire period of 18 months was given by Miss Ellen B. Finlay, secretary of the Department of Astronomy, who served also as editor of all publications and reports issued under

the contract; while in January 1959 Miss Jennifer Bristow joined the project in the dual capacity of computer and assistant secretary.

RESEARCH.

The principal research task undertaken under the present contract was the development of the methods for lunar cine-photography, which should record the growth and diminution of the shadows cast by the lunar mountains and other formations on the surrounding landscape during sunrise or sunset on the Moon, the measurements of which (by suitable micro-photometric methods) could then lead to a determination of the heights of the shadow-casting obstacles, essentially by the process of triangulation.

In order to approach this task and to secure the necessary basic photographic material, the Observatoire du Pic-du-Midi (located at $\lambda = 0^{\text{h}}0^{\text{m}}34.3^{\text{s}}$ E, $\beta = 42^{\circ}56'12''$ N), accessible to us through the courtesy and cooperation of its director, Dr. Jean Röscher, has been selected as the best site for such work, largely because of the renowned steadiness of seeing. This observatory is situated at an altitude of 2862 metres - 14 metres below the actual summit of Pic-du-Midi on the northern border of the Pyrenees - well above the level of atmospheric dust and sufficiently far from disturbing city lights, and yet easily accessible to any equipment, and provided with excellent facilities (power, living conditions, etc.) for sustained long-range work. Whatever we have been able to accomplish on the Pic in the past 18 months is, to a large measure, due to the splendid cooperation which we have been fortunate enough to enjoy on the part of Dr. Röscher and all his staff on the spot.

In order to secure the actual photographs, a 35-mm film camera was attached to the Observatory's 24-inch refractor of 18 metres focal length, giving a linear scale of $11\frac{1}{4}$ mm; and as, at the mean distance of the Moon, 1" corresponds to 1864 m, it follows that one millimetre in the focal plane of our telescope corresponds to 21.3 km on the surface of the Moon. The actual resolving power will, of course, be limited by the size $1.22 (\lambda/D)$ of the Airy diffraction disk of our objective, which for $D = 60$ cm and $\lambda = 5600 \text{ \AA}$ (i.e., yellow light) becomes equal to $0''.23$ and corresponds to 20 microns in the focal plane (or some 430 metres on the Moon). Although, in practice, this definition gets further impaired by seeing, we have reasons to conclude (on the basis of all available material) that an accuracy of this order of magnitude is indeed attainable from Pic-du-Midi on approximately 10% of our films.

Since all lunar hypsometric work must be based essentially on photographs of the terminator regions of the Moon - where the shadows are long but contrasts relatively low - we found it necessary to use photographic emulsions characterized by high contrast, but a grain size smaller than the effects of diffraction or of atmospheric disturbances in the focal plane. Extensive tests have revealed that the actual resolution on our films is, in fact, limited by these two factors rather than the grain size. Of eight photographic emulsions tested in combination with five different colour filters, four different developers, and different times of development at constant temperature, the most promising turned out to be the British film Ilford Pan F, calling for exposures of the order of 0.5 sec. Extensive tests were also carried out with Ilford 5G91, with 0.75 sec exposures; but the larger grain size of this emulsion proved to be a disadvantage. These films were employed in combination with orange or yellow glass filters (such as Chance OY2) and developed mostly in Microphen at 20°C.

OBSERVATIONS.

The following list contains the survey of all photographic data secured at the Pic, under our programme, between January 1959 and April 1960:

<u>Date</u>	<u>Lunar Region</u>	<u>Number of Exposures</u>
1959 Jan 28	Roemer, Fracastorius	330
29	Theophilus, Cyrillus	450
31	Aristillus, Autolycus and M.Imbrium	461
Feb 1	Tycho	407
12	Atlas and Hercules	25
13	Cyrillus	224
14	Maurolycus	514
18	Philolaus	436
20	Billy and Hansteen	568
21	Pythagoras	294
Mar 1	Abulfeda	72
22	Hevelius	604
25	West of North Pole	510
26	Cleomedes	215
29	Fracastorius	98
Apr 13	Theophilus	240
Nov 23	Plato - Mare Imbrium	176
23	Archimedes - Mare Imbrium	176
23	Straight Wall, Thebit, Alpetragius	178

<u>Date</u>	<u>Lunar Region</u>	<u>Number of Exposures</u>
1959 Nov 24	Barry, Bonpland, Mare Nubium	183
24	Copernicus	184
24	Cichus, Capuanus, Bullialdus, Hesiodus	176
25	Vitello, Doppelmayer, Mare Humorum	178
25	Kepler, Encke, Oceanus Procellarum	181
25	Heraclides, Delisle, Diophantus	159
25	Sinus Iridum, Harpalus, Sinus Roris	68
1960 Jan 4	Theophilus	180
5	Albategnius region	216
7	Timocharis region	186
7	Eratosthenes region	180
7	Gambart region	180
9	Gassendi	183
9	Kepler	180
9	Gassendi (2nd series)	180
Feb 8	Copernicus	180
Mar 4	Mare Serenitatis	360

The gaps in these series of observations were partly caused by weather, but mainly by the unavailability of the Manchester observers on the Pic in certain parts of the year. In order to avoid gaps arising from this latter cause, arrangements have been made in March 1960 with Dr. Rösch for the services of one French observer, who should be always on the spot and could take advantage of any spell of good weather; and such arrangements will be developed further in the future.

MEASUREMENTS AND REDUCTIONS.

All measurements and reductions as performed up to the end of the period covered by this report were carried out in the department of astronomy at the University of Manchester, by methods developed for this purpose in the course of our work.

Since the finite angular diameter of the Sun is bound to endow all lunar shadows with a penumbra whose width can (for low obstacles) be quite considerable, any settings on their characteristics under a microscope would, at best, be of very limited accuracy and hardly reproducible. We have, therefore, resorted to microphotometric tracing of the profiles of lunar shadows, by means of a Mark II recording microdensitometer purchased from Joyce, Loebel and Co., of Newcastle-upon-Tyne early in 1959.

In performing the actual measurements, the width of the scanning slit has been adjusted so as to intercept, on the negative, a strip equal in width to the diameter of the Airy's disk of the 24-inch objective (i. e., 0.02 mm) in the direction of scanning; to make it narrower would merely have resulted in exaggerated effects of plate grain; while to open it more widely might have resulted in a significant loss of information. It was, moreover, found that, in any but the most rugged regions of the surface of the Moon, the effects of plate grain on our tracings could be diminished with impunity by increasing the length of the slit to 3-4 times its width and admitting proportionally more light to the scanning beam. The output of the micro-densitometer was then automatically recorded on calibrated sheets, and smooth curves drawn by free hand through such records. The data necessary for evaluation of the heights of lunar mountains were then read off and put through the mill of the appropriate reduction procedure.

The mathematical elements of this procedure were worked out by the writer of this report early in the period covered by this contract; and the necessary computations - originally performed with desk-type computing machines, were later programmed (by Mr. R. James) for use on the University's "Mercury" electronic computer. This effort met with full success, and enabled us eventually to reduce our measurements in as many minutes as it took days to secure them at the micro-densitometer. The micro-densitometric measurements proved to be the real bottleneck of the entire programme; and the ways for their adequate mechanization have not yet been discovered.

As long as this situation continues to prevail, new film records can be secured and reduced much faster than they can be measured. In order to process these films through all stages as rapidly as they can be secured at the telescope, a much larger staff would be required than one which can be conveniently managed by a University department. At a conference held between December 14th to 16th 1959 at the Geophysics Research Directorate of the Cambridge Air Force Research Center in New Bedford, Mass., between Drs. Kopal and Ring and the representatives of GRD as well as ACIC from St. Louis, it was agreed that, in the future, the bulk of the films from the Pic should be shipped to ACIC (via the USAF base at Dreux, France) for development and reductions; and by the end of the period covered by the present report this procedure was put into effect - thus absolving the Manchester end of the joint collaborative effort from responsibility for routine cartographic measurements, and enabling us to concentrate on the observations.

With regard to the ultimate accuracy attainable in lunar mapping by the means at our disposal, our experience (as summarized in the series of papers and reports quoted below) has established that our

shadow technique permits us to ascertain the relative altitudes of lunar mountains within the errors of less than 10 metres at the centre of the apparent lunar disk, growing proportionally towards the limb. The selenographic positions can be measured on our negatives with a precision of the order of 1' in either selenographic coordinate; and the errors inherent in such positions constitute, in fact, also the principal source of errors affecting the computed heights. It is confidently expected that both these sources of error will be appreciably reduced in further development of our work.

From the topographic point of view, the principal new feature which has emerged from our work was the realization that there appear to be no steep slopes on the Moon, of sizes larger than a few kms, which would be inclined to the horizontal direction by more than 10° .

PUBLICATIONS AND CONFERENCES.

In the course of the operation of the present contract, the following Technical Scientific Notes were issued under it, summarizing different contributions by our staff to the subject of lunar topography:

- No. 1: Z. Kopal and G. Fielder, "Studies in Lunar Topography, I. Determination of the Heights of Mountains on the Moon."
- No. 2: D. Clarke, "Studies in Lunar Topography, II. Techniques of Photographic Determination of Lunar Mountains, with application to the Region of Theophilus,"
- No. 3: G. Turner, "Studies in Lunar Topography, III. Errors Involved in the Photographic Determination of Heights and a Preliminary Study of the Region of Ptolemaeus and Alphonsus."
- No. 4: G. Fielder, "Studies in Lunar Topography, IV. Measured Profiles of the Moon's Surface, and the Estimates of Magnitudes of the Errors in Relative Altitudes."
- No. 5: T. W. Rackham, "Studies in Lunar Topography, V. A Systematic Micro-densitometric Technique and its application to Formations in the Mare Imbrium."

- No. 6: G. Turner, "Studies in Lunar Topography, VI. Measured Heights of Mountains in the South-Eastern Part of Mare Tranquilitatis."
- No. 7: G. Turner, "Studies in Lunar Topography, VII. Measurement of the Height and Depth of the Walls of the Crater Archimedes."
- No. 8: G. Turner, "Studies in Lunar Topography, VIII. A Catalogue of Measured Heights in the Regiomontanus and Hell Plain Regions of the Moon."

Between January 9th and 16th of 1960, Professor Kopal and Dr. Ring took part in the first International Space Science Symposium held by COSPAR at Nice; and the former presented a paper on the topographic programme sponsored by the present contract, which has since appeared in print (cf., Space Research, ed. H. K. Kallmann, Nth. Holland Pub. Co., 1960).

Towards the end of the period covered by the present contract Professor Kopal and Dr. Röscher arranged for an international conference of a selected working group of experts on the current problems of the lunar coordinate systems. By invitation of Dr. Röscher, this conference met between April 19th through 23rd of 1960 at Bagnères de Bigorre, bringing together the following participants:

H. Camichel,	Z. Kopal,
C. Campen,	K. Koziel,
R. Carder,	T. W. Rackham,
A. Dollfus,	J. Ring,
M. Hunt,	G. Schrutka-Rechtenstamm,
A. G. Kearns,	T. Weimer,

from five different countries. The proceedings of this USAF-sponsored conference are being edited by Professor Kopal and Miss Finlay, and should be published in report form in the near future.