THE LUNAR CRESCENT AND EARTHSHINE OBSERVED
AT 2° SOLAR ELONGATION*

by

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ABSTRACT

From the earth's surface the lunar crescent and earthshine are difficult to see at small solar elongations, because of the brightness of the twilight sky. At elongations less than 7° the crescent disappears completely (Danjon, 1933), and the earthshine is masked by the sky. Photographs made from an Aerobee-150 rocket with an externally occulted Lyot coronagraph show the earthlit moon at an elongation of only 2°. A vestige of the lunar crescent is visible. The coronagraph was launched at 1638 UT from the White Sands Missile Range on 12 November 1966, the day of the total solar eclipse in South America. The photographs closely resemble those of the full moon in their rendering of relative brightnesses of surface features. From this one concludes that there is a negligible amount of light-scattering material between the moon and earth. If there were such material its strong forward scattering would have produced some additional

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brightness; the coronagraph would then have recorded the earthlit moon with an anomalous brightness distribution because its surface would have been viewed through the overlying light from this material. Since the forward scattering at 2° is approximately 10^5 to 10^7 stronger than that at 90° for particles in the 10 to 100 μ diameter range, the brightness amonaly should be a sensitive indicator of cis-lunar dust. Limitations of the method will be discussed.

The trace of the new moon crescent was present as an irregular glint near Mare Marginis. If this was indeed a diffuse surface reflection the glancing angle of incidence over the illuminated area seen from the earth ranged from 0° to 2°. Therefore surface tilts greater than 2° would have prevented the reflection. The conclusion is that Mare Marginis, if this is indeed the source of the glint, has large regions with surface tilts no greater than 2° in the line of sight.

Some thirty years ago Danjon (1936) made an exhaustive study of the moon's crescent and the earthshine. He was able to see the crescent to 8° elongation, where it was reduced to an arc of 66° measured from the moon's center. At $\leq 7^\circ$ elongation the crescent vanished. The earthshine was invisible at less than 16.2° elongation. Obviously, several factors cause a rapid loss of visibility as the elongation is decreased: the increasing brightness of the sky associated with reduced solar depression angles; the increasing atmospheric attenuation as the horizon is approached; and for the crescent the decreased brightness associated with the diminishing angles of incidence of sunlight, coupled with the rough character of the moon's surface.

The NRL rocket-coronagraph (Tousey, 1965) offered the possibility of photographing the moon at less than 7° elongation, because the high altitude eliminates the Rayleigh sky and leaves only the solar corona. The requirement was that the moon be not more than 8 $R_\odot$ from the sun, the outer limit of the coronagraph field, nor closer than 3 $R_\odot$, the inner limit of the field. It was also necessary that the sun at the launch site of White Sands, New Mexico, be at an elevation angle between 20° and 50° where the biaxial solar pointing control would function reliably.

The first objective was to look for the new moon's crescent. This is of interest in connection with the character of the moon's surface. The geometry provides also an extremely sensitive method of detecting a transient cloud of dust in the lunar atmosphere because the Mie scattering coefficient is very large at these small scattering angles, for particles ≈ 10 to $\geq 100\mu$ diameter.

The second objective, discussed in detail by Tousey, Koomen, McCullough, and Seal (1965) concerned the possibility of detecting dust between the moon and the earth, that might contribute to the brightness of the F-corona. Dust in the space extending from the moon several tenths of the distance to the earth might be revealed by a shadow cast by the moon, and also by changes in the contrast of the moon's disk features from the edge near the sun to the edge opposite, compared to the normal contrasts present in the earthshine. An overall reduction in lunar contrasts, relative to those in the full moon, would be expected from dust near the earth, not shadowed by the moon.

From earlier flights of the coronagraph there was evidence that cis-lunar material was present in quantity sufficient to increase the brightness of the corona by a factor of 2 or more. On June 28, 1963, the increase was 2 to 3 (Tousey, 1965) and on April 28, 1966, the factor was 3 to 4 (R. Tousey and M. J. Koomen, 1967).

The instrumentation is shown in Figure (1), mounted in a test fixture rather than a rocket. Two Lyot coronagraphs were situated side by side on one side of the instrument box. The objective lenses were of 30 cm focal length and 25 mm diameter. External occulters were used to place a solar umbra on each objective lens when the instruments were pointed at the sun. Each occulter was constructed of three smooth-edged discs (Newkirk and Bohlen, 1963, 1964), designed so that the second obstructed the light diffracted from the edge of the first, and the third, that from the second. This system has proved to be more satisfactory than the saw-toothed occulter (Purcell and Koomen) which suffers a greater loss in efficiency when small foreign particles adhere to the edge.

The use of two coronagraphs was advantageous because the arms supporting the external occulters lay opposite one another; therefore the region shadowed in the one instrument was recorded in the other.

The corona was photographed on Eastman Kodak Spectroscopic 1-D film with exposures between one and 8 seconds.

The instrument was flown on two occasions when the moon was in the field of view. A flight on 9 May 1967 took place at 1618 U.T. with the moon at 5 R_s (1.°2) from the sun (center to center). A pair of 4 sec exposures, at an altitude of 110 Km, is shown in Figure (2). The K-corona is prominent especially above solar regions of low latitude; many streamers are present. The remaining background is the F-corona, i.e. zodiacal light.

The large black disc is the moon. At this position it should have cast an appreciable shadow into the corona if a significant contribution to the F-corona is indeed made by cis-lunar material. Our pictures show that on May 9, 1967 there was no detectible shadow. We could have detected a shadow magnitude approximately 5% of the coronal brightness. Therefore we can place an upper limit on the amount of cis-lunar scattered light from the shadowed region, $R = 6\ R_\odot$ to the edge of the field, $R = 9_\odot$. The limits were 2.5×10^{-11} at 6 $R_\odot$ and 10^{-11} at 9 $R_\odot$, where the umbra extended respectively 1/3 and 1/6 of the distance to the launch site. Since the scattering angle was 1.5° to 2.25°, scattering was well within the forward scattering lobe of the

Mie-function, where the scattered intensity is 10^4 - 10^6 greater than at 20°, for particles in the tens of microns range. Therefore the shadow technique is a sensitive test for particulate matter of this size.

The same experiment was flown from White Sands Missile Range on November 12, 1966, the day of the solar eclipse that crossed South America. The time was chosen so that the moon lay at 9 $R_\odot$ elongation. A figure of the companion paper in this meeting (Purcell, Tousey and Koomen, 1967) is a reproduction of one of the photographs. There the earthshine shows very well, whereas at 5 $R_\odot$ it was so faint that it could not be reproduced from the original negative along with the corona.

Figure (3) shows three photographs of the moon, made on three different occasions with the rocket coronagraph. At the center is the ordinary full moon. To the left is the earth-lit moon at 2° elongation on 12 November 1966 and to the right is a similar image at 1.2° on 9 May 1967; these two photos show the moon closer to the sun than it has ever been recorded.

First, compare the center and the right images. The full moon is seen against a dark sky, and with dark maria. The earthlit moon is superimposed on a bright background, the sun's corona. It looks about the same at the full moon, but not exactly, because there is some image smearing, caused by motion at right angles to the sun's direction, during the 2 sec. exposure. There is some suggestion that the contrast between light and dark regions on the sunward side is less than the contrast on the far side, as compared to the full moon. If there is cis-lunar scattered light, the diagram of Figure (4) shows that on the sunward edge we would be looking through all of it, hence the contrasts would be reduced. On the opposite edge a column extending 1/3 of the way to the earth would be shadowed, hence the contrast reduction would be less. Photometric reduction of the images is required to establish a possible anomalous contrast, and is in progress.

The left-hand image is still different. Its left edge blends perfectly into the corona, but its lower right edge is much brighter than the corona. This is because the corona was darker on the right, while on the left it was brightened by the presence of a K-coronal streamer.

In this image at 2° elongation the contrast of lunar features may be a little greater than for the full moon, a result not understood. Cis-lunar dust would reduce the contrast, hence this result indicates no such dust. The bluish color of the light reflected from the earth was considered as a possible explanation; full moon exposures made through a blue filter showed no significant difference in contrast. However, the precise photometric study of these images has not yet been attempted.

Since the moon experiments showed little suggestion of cis-lunar dust, the question arises whether the high values of coronal brightness relative to total solar eclipse data as observed on June 23, 1963 and April 28, 1966, can be explained by an increase in dust. Stray light in the instruments has been evaluated with care, and does not seem to account for the high brightnesses observed. As it happens, the coronal brightnesses on November 12, 1961 and May 9, 1967 were not significantly enhanced; they agreed with eclipse results, to within experimental error. Additional experiments are required to prove that cis-lunar material is never present in quantity sufficient to increase the observed coronal brightnesses.

In Figure (3), at the edge of the moon toward the sun, for 2° elongation, there is a conspicuous glint; this lies about 20° away in latitude from the point nearest the sun. It may be thought of as a small bit of the new moon, which would indeed form a complete crescent if the moon were a perfect diffusing sphere with no irregularities.

What caused this glint? It is located close to Mare Marginis, 10° North-Latitude. The geometry of the situation is shown in Figure (5). For the moon at 8 $R_{\odot}$ the edge closest to the sun is at 7 $R_{\odot}$, hence the rays from the center of the sun are deviated through 1.75° and those from either edge are deviated through 1.5° or 2.0°. This means that the angle of incidence in the usual sense is not greater than 1°. Is it possible that there could be a surface properly tilted to be a specular reflector?

Figure (6) illustrates the geometry. The glint lies from 14° to 23° away from the point where a specular reflection from a horizontal surface would take place, that is, the position nearest the sun. The dotted line shows the locus of a cylindrical surface, centered about the line of sight to the sun, which reflects specularly. At the position of the glint the surface would have to be tilted by at least 30° from the moon's horizontal if it were to reflect like a plane mirror, a most unlikely possibility.

Referring to Figure (5), it is obvious that a repeated series of surfaces tilted 2° or greater from the moon's horizontal, the sun-moon-earth plane, will prevent the reflection of sunlight, acting like grooves cut on the inside of a camera lens mounting. Here the width of the segment of the moon's surface that is both illuminated by the sun and observable from the earth is 60 Km. At the center of this strip, repeated tilts greater than $\pm 1^\circ$ destroy the reflection.

The four pairs of photographs that show this glint best are reproduced in Figure (7), a negative print. There seems to be a fading and diffusion, that progresses from exposure to exposure. This, of course, would be expected if the glint happened to be produced by a transient cloud of dust. However, this may have been caused by motion of the image, produced by rocket precession or hunting of the pointing control. Further study is required.

The glint is by no means uniform and has a bright central core; also, there is a trace of another glint somewhat nearer the point closest to the sun. Photographs of this region obtained by Lunar Orbiter IV, show that Mare Marginis is quite smooth but with many small craters (Liddel, 1967). Our conclusion as of the present time is that the reflection is probably produced by the floor of Mare Marginis which must be free of tilts greater than 2°. There are craters, but between the craters there must be many smooth flat, horizontal surfaces which scatter diffusely. The craters must be almost rimless, otherwise the rims would present the tilted surfaces that would eliminate the reflection.

We have studied the moon's image obtained at 5 R_s on May 9th; without finding a glint. The libration angle is the same within one degree. The smaller elongation places a more severe requirement on surface tilts and the sun's corona, against which a glint must be seen, is four times brighter at 4 R than at 7 R. Therefore it is not surprising that no glint is visible.

FIGURE CAPTIONS

Figure (1) Rocket experiment package showing spar and solar occulting disks in the deployed position for two side-by-side coronagraphs. Objective apertures are covered to preserve cleanliness. The large apertures on the left are for ultraviolet spectroheliographs which record the solar disk.

Figure (2) Simultaneous 4 sec. exposures of the outer solar corona and the moon obtained with the double coronagraph of Fig. (1), on May 9, 1967. The central image in each photograph is an extreme ultraviolet image of the solar disk taken with the ultraviolet instrumentation.

Figure (3) Photographs of the earthlit moon at small elongation, and the full moon (center) taken with the coronagraph of Figure (1).

Figure (4) Diagram showing how shadowing of cis-lunar material produces anomalies of brightness and contrast across the face of the earthlit moon observed from the earth.

Figure (5) Reflection of sunlight from the moon's limb when observed at an elongation 8 $R_\odot$ (2° center to center).

Figure (6) Observed position of glint on limb from Figure 5. Time was 1642.5 UT, 12 November 1966, at White Sands Missile Range, New Mexico.

Figure (7) Enlargements from pairs of simultaneous photographs showing glint on moon's limb, at position indicated in Figure (6). Exposure time on each was 2 sec. but image motion was slightly greater on the latter three exposures.

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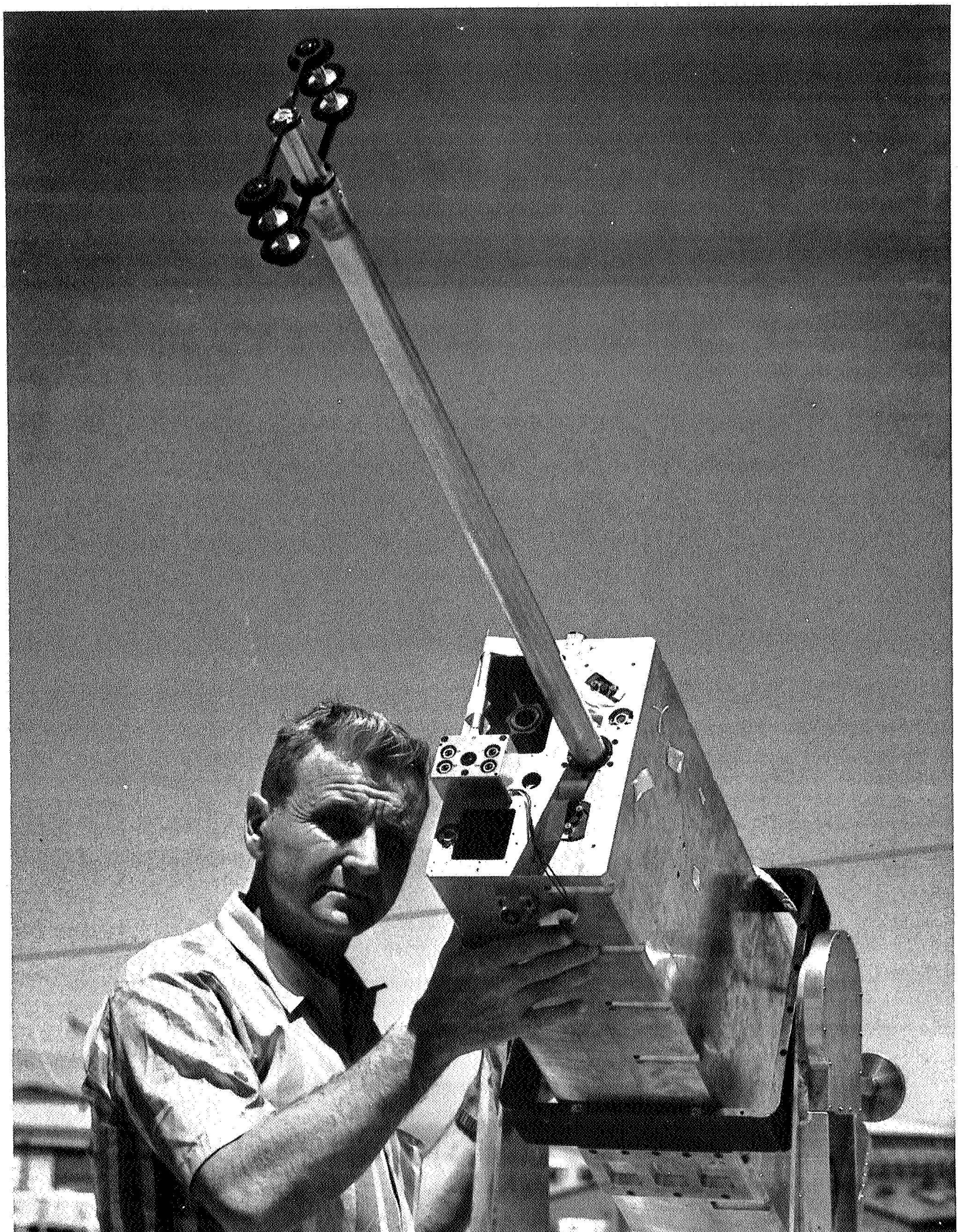
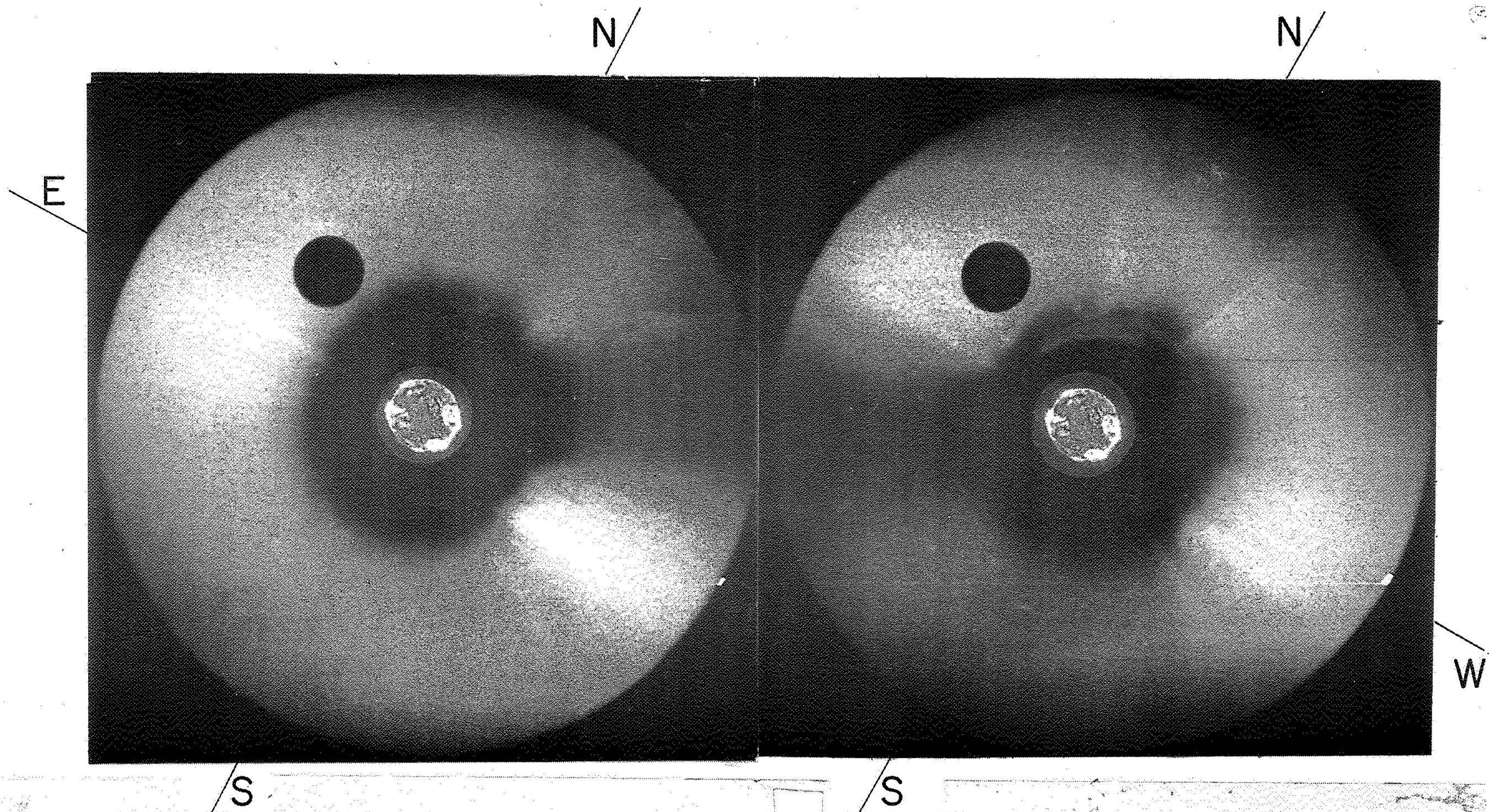


Figure 1



WHITE-LIGHT CORONA, XUV SUN (171-370Å) AND MOON AT $5R_\odot$ ELONGATION
WSMR 9 MAY 1967 16:18 UT

Figure 2

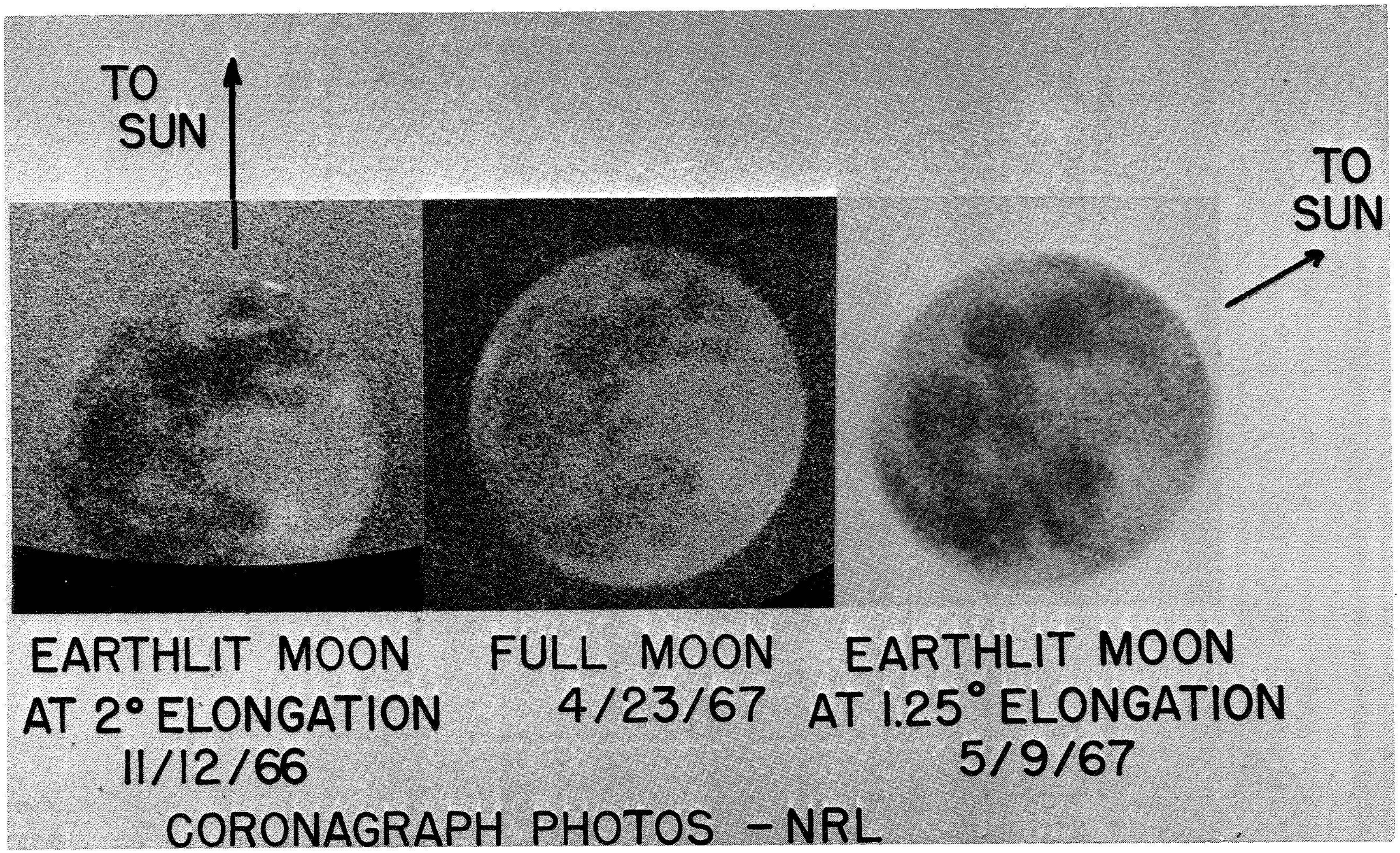

TO SUN
TO SUN
EARTHLIT MOON
AT 2° ELONGATION
11/12/66
FULL MOON
4/23/67
EARTHLIT MOON
AT 1.25° ELONGATION
5/9/67
CORONAGRAPH PHOTOS - NRL

Figure 3

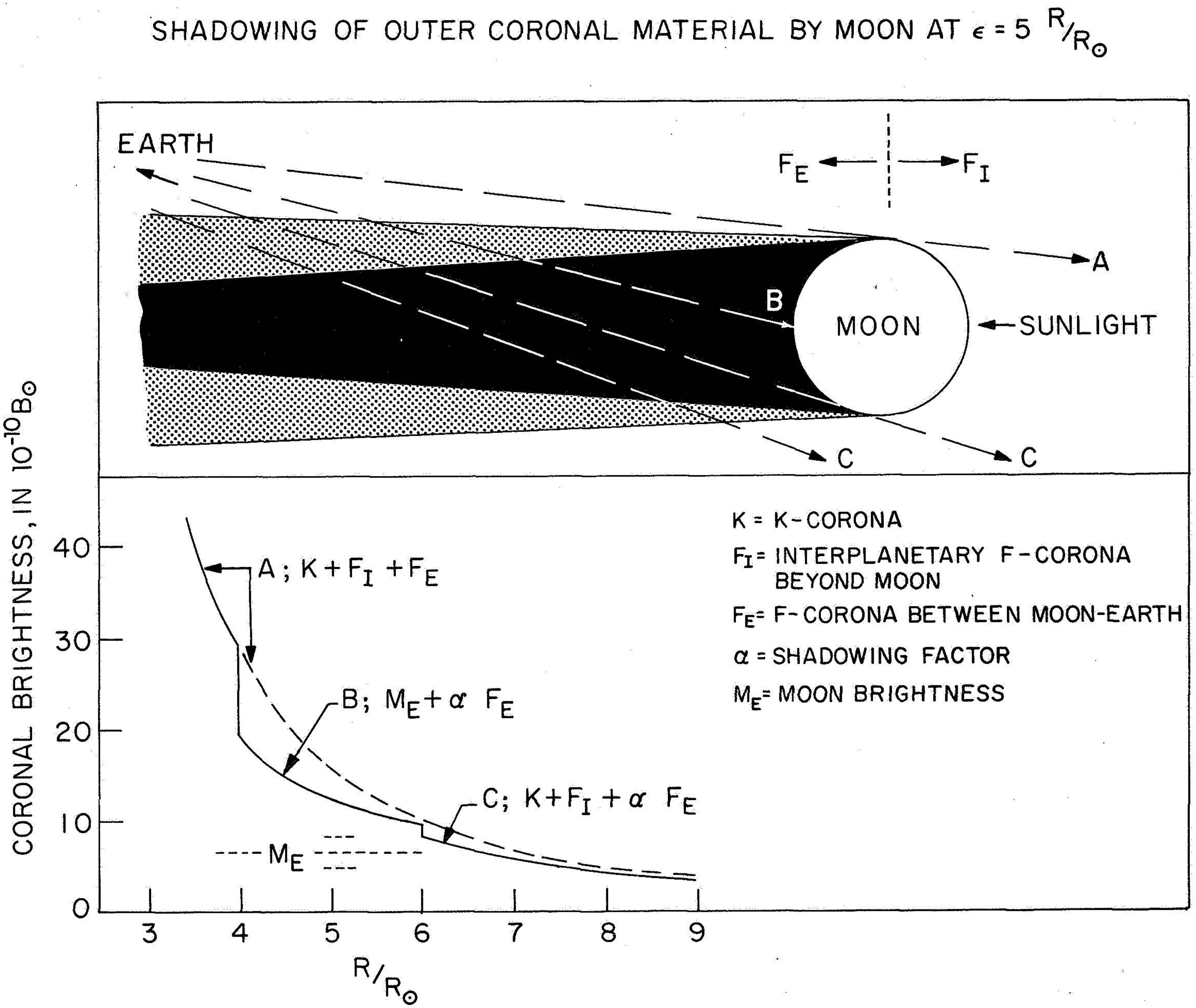

SHADOWING OF OUTER CORONAL MATERIAL BY MOON AT ε = 5 R/R⊙
EARTH
F_E
F_I
A
B
MOON
SUNLIGHT
C
C
A; K + F_I + F_E
B; M_E + α F_E
C; K + F_I + α F_E
M_E
K = K-CORONA
F_I = INTERPLANETARY F-CORONA BEYOND MOON
F_E = F-CORONA BETWEEN MOON-EARTH
α = SHADOWING FACTOR
M_E = MOON BRIGHTNESS
CORONAL BRIGHTNESS, IN 10^-10 B⊙
R/R⊙
0
10
20
30
40
3
4
5
6
7
8
9

Figure 4

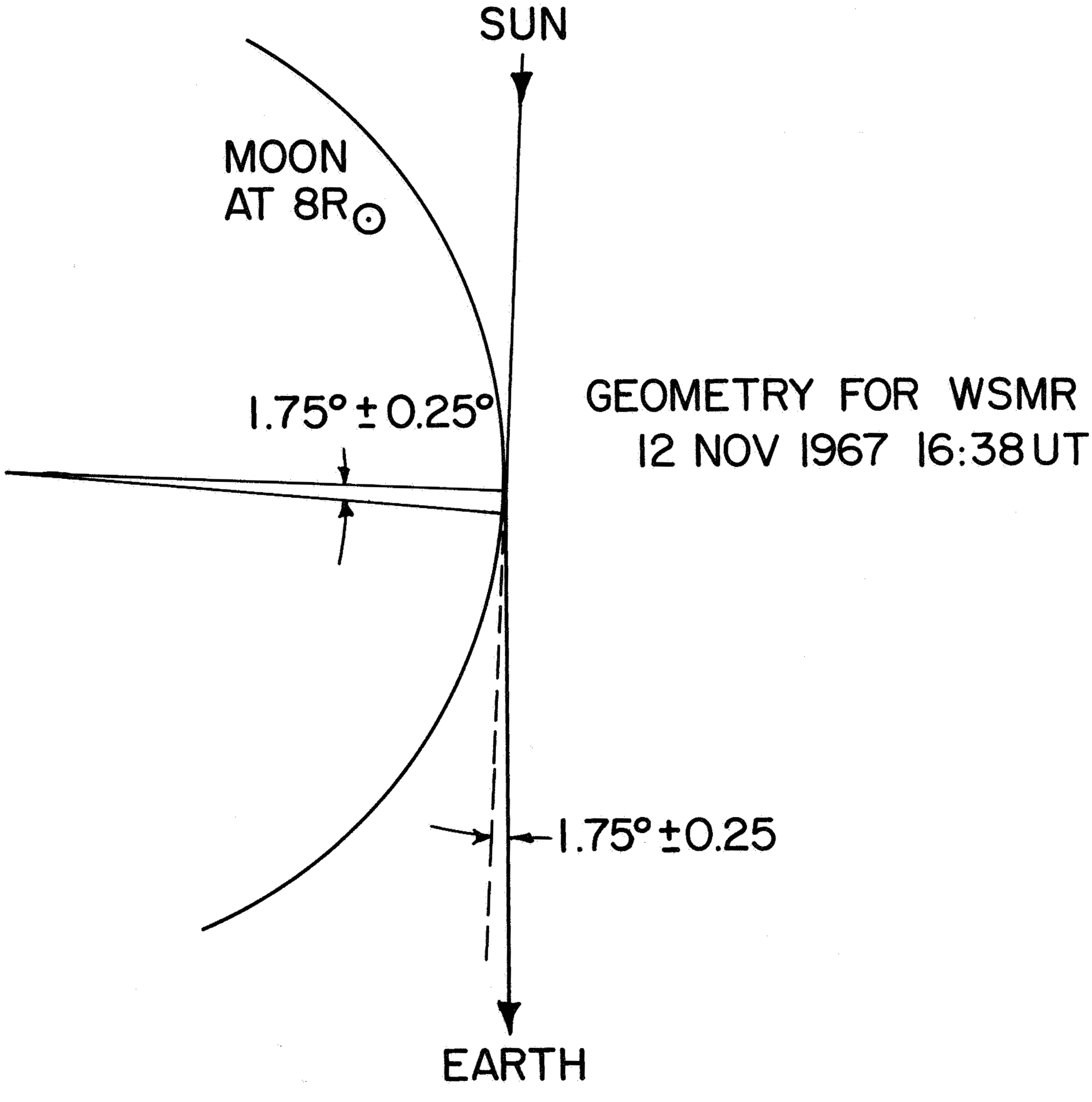

SUN
MOON
AT 8R$_\odot$
1.75° ± 0.25°
GEOMETRY FOR WSMR
12 NOV 1967 16:38 UT
1.75° ±0.25
EARTH

Figure 5

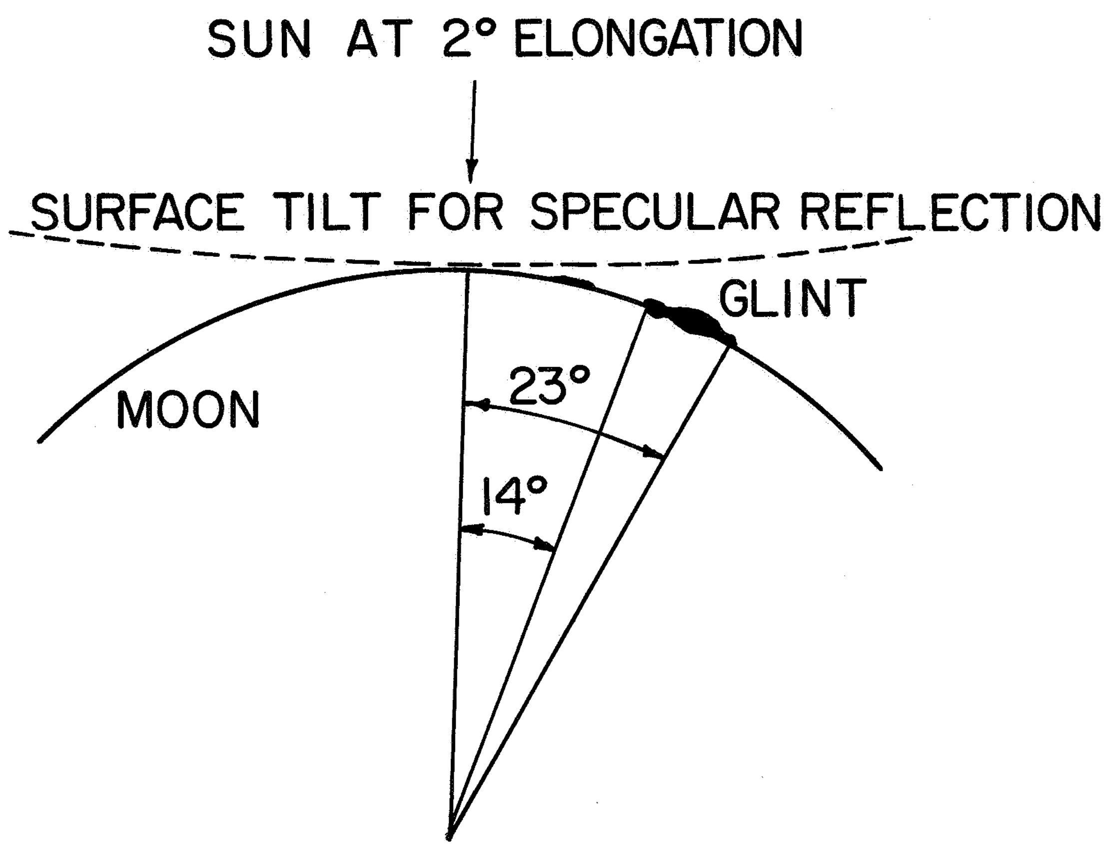

SUN AT 2° ELONGATION
SURFACE TILT FOR SPECULAR REFLECTION
GLINT
MOON
23°
14°

Figure 6

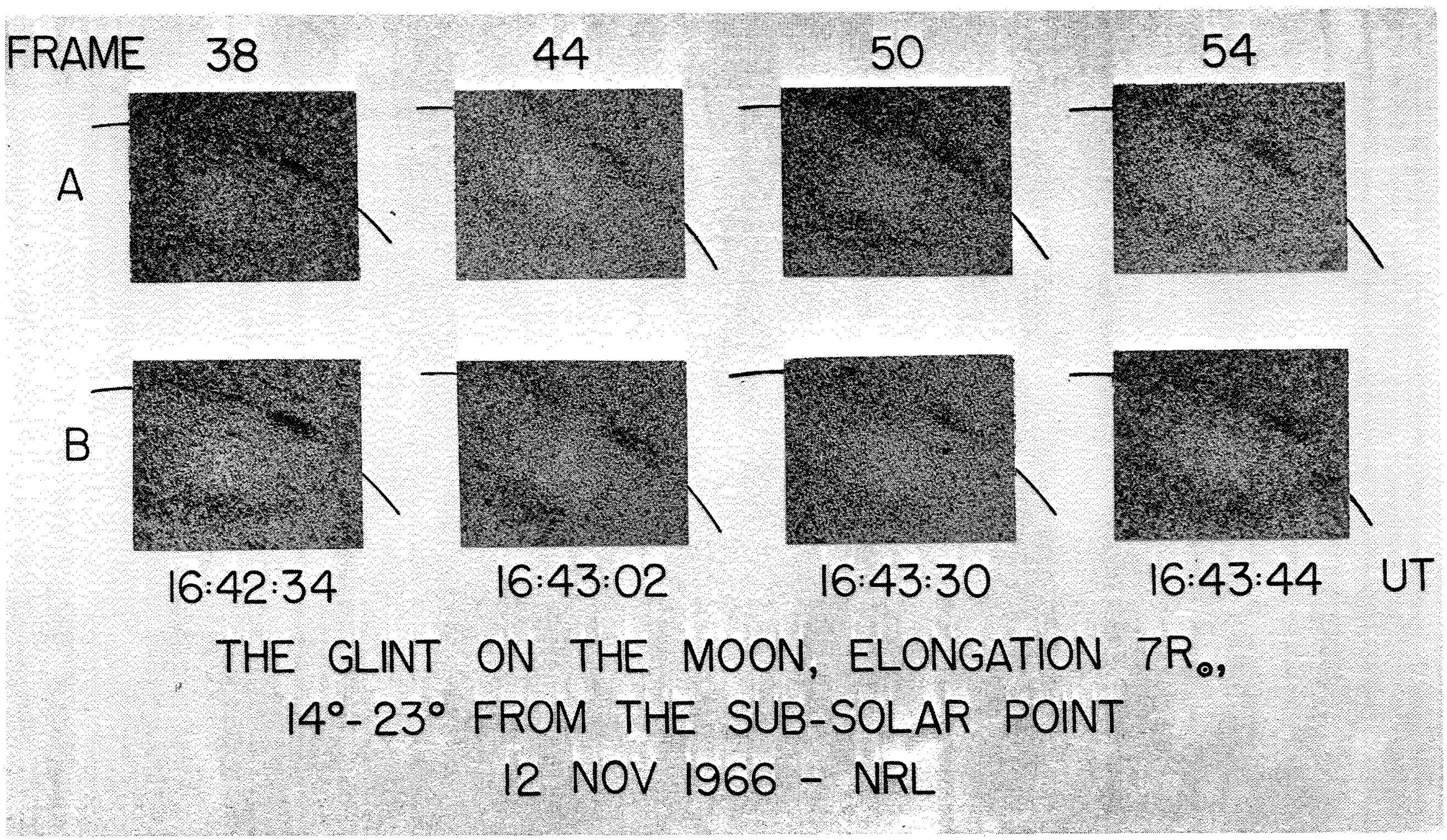

FRAME 38
44
50
54
A
B
16:42:34
16:43:02
16:43:30
16:43:44 UT
THE GLINT ON THE MOON, ELONGATION 7R☉,
14°-23° FROM THE SUB-SOLAR POINT
12 NOV 1966 - NRL

Figure 7