No. 114 THE INFRARED POLARIZATION OF THE MOON

by F. F. Forbes and P. A. Welch

November 9, 1967

ABSTRACT

Infrared polarization measurements of the lunar surface have been obtained at 1.25 and 2.2 μ for the lunar phase $-80^\circ.9$. The infrared polarization of the entire Moon was found to be 3.24 and 2.90 percent at 1.25 and 2.2 μ, respectively. The new infrared polarization results were compared to the visible and ultraviolet polarization obtained by Gehrels, *et al.* (1964), Coyne (1967), and Lyot (1929). As with other wavelengths, the infrared polarization is greater in the maria than in the highlands. In addition to the polarization scans and the determination of the polarization of the entire Moon at $-80^\circ.9$ phase, the geometric albedo was computed from photometric scans of the Moon at $3^\circ.48$ and $-80^\circ.9$ phases and found to be 0.211, 0.259, and 0.321 at 1.25, 1.62, and 2.24 μ, respectively. The ground-based geometric albedo values agree well with those obtained from Project Lamplighter of May 1966 on the Gemini 7 Mission.

1. Apparatus

The polarization and albedo observations were made in November 1965 and March 1966 with the Catalina Observatory 28-in. infrared telescope. The photopolarimeter consisted of a dry-ice-cooled lead sulfide photometer (Johnson and Mitchell 1962), with a rotating infrared polarization analyzer mounted between photometer and the 28-in. telescope. A Polaroid-Corporation-type HR-sheet polarizer (Shurcliff 1962) was rotated at 16 rps in the infrared polarization sandwich, thereby allowing rapid scan polarimetry to be done at the same time that photometric scans were made across the lunar surface. A calibrated micrometer-adjusted 6-in. offset finder was used to change the scan position in uniform increments of declination relative to a prominent central lunar feature recentered on the finder cross-hairs before each scan. The telescope was driven westward in right ascension beyond the lunar limb and then stopped; data were taken as the Moon drifted back through the field. The instantaneous field of view of the photopolarimeter was 29.35 arc sec in diameter. Three times during the mapping process the offset accuracy was determined by repeating the zero offset scans at 1.25 and 2.24 μ.

The polarization and infrared intensity signal and polarization analyzer phase angle were recorded on magnetic tape in the manner described by Forbes (1967). The data tapes were played back in the laboratory with a frequency-to-voltage converter and a true RMS voltmeter, the respective outputs of which gave the infrared intensity (DC component) and polarization (AC component). Ratios of the AC to DC components were then obtained to determine the precent polarization. The polarization phase was determined using the photographic technique described by Forbes (1967).

2. Calibration

The polarization analyzer efficiency and position angle were determined by using the technique described by Gehrels and Teska (1960). The instrumental polarization was found by measuring the polarization of four standard stars whose polarization in the visual and infrared wavelengths was known to be less than 0.5 percent. The probable error on the infrared polarization of the standard stars was found to be $\pm$ 0.2 percent.

For the determination of the geometric albedo two calibrations were required. The instrument was calibrated photometrically with measurements of four standard stars preceding and following the lunar scans. The colors of the Moon at 1.25, 1.62, and 2.24 μ were determined using Johnson's data (1965) and Johnson and Mitchell's technique (1962). The precision of reduction to the JKL photometric system is about $\pm$ 0.1 mag. The relative photometric response as a function of position in the diaphragm was measured by making repeated drift scans across a star image for various segments of the diaphragm. From integration of these scans the effective photometric diaphragm size was computed to be 29.35 $\pm$ .05 sec of arc in diameter.

3. *Results*

Figures 1 and 2 are maps of the lunar infrared polarization at 1.25 and 2.24 μ, respectively, at a phase of $-80^\circ.9$. The 1.25 and 2.24 μ polarization scans were positioned on a lunar scan by means of a computer program using equations (Arthur 1965) for transforming topocentric to selenographic coordinates for the particular phase of $-80^\circ.9$ on March 1, 1966. For clarity, only major lunar features are shown in Figures 1 and 2.

One of the scans is shown in detail in Figure 3 which compares polarization to intensity; this scan was repeated three times in each color to investigate the repeatability. The error bars represent the mean standard deviation of individual sample points based on residuals between the three scans normalized to their mean intensity to remove time-dependent effects, which have little bearing on the polarization errors. The polarization and intensity are related by the fact that the fractional standard deviation of a percent polarization measurement is equal to the fractional standard deviation of the intensity measures on which it is based. However, the errors so derived are strictly internal, and include the results of inexact reproduction of scan position.

From the reference intensity plot in Figure 3, it is evident that in the infrared the maria are considerably more polarized than the highlands. This result is entirely in agreement with the results obtained by other observers in the visible wavelengths (Lyot 1929; Dollfus 1955; and Gehrels, *et al.* 1964). In addition, for regions of similar color on the Moon, no systematic variation in polarization was detected between the bright limb and the terminator.

In Figure 4, the infrared polarization data derived from two regions on the Moon (Nicolai and Mare Crisium) are compared to visible polarization results obtained for the same locations on the Moon by Gehrels, *et al.* (1964) for the phase of $-80^\circ.9$, although the fields of view are different.

The behavior of the infrared polarization for the entire Moon at $-80^\circ.9$ phase is plotted in Figure 5 together with the results obtained in the visible by Lyot (1929) and in the ultraviolet by Coyne (1967). The 1.62 μ in Figure 5 was computed from one scan at 1.62 μ compared to repeated scans, at the same declination, for the points at 1.25 and 2.24 μ.

The lunar geometric albedo was photometrically determined at 1.25, 1.62, and 2.24 μ from measurements at the phases of $3^\circ.48$ and $-80^\circ.9$ and found to be 0.211, 0.259, and 0.321, respectively. The albedo computations were done as described by Russel (1916) and Harris (1961). Rougier's phase function (Minnaert 1961) was used, although it was determined for .54 μ so that a direct comparison to the Gemini 7 (AFCRL-Project Lamplighter, 1966) could be made. These results are plotted in Figure 6 together with ultraviolet results and infrared spectral-photometry results of Gemini 7 and the visual measures of Harris (1961). Although the techniques used on Gemini 7 and those we used were quite different, both results show excellent agreement. The photometric tie-in to standard stars assured the photometric accuracy of our measurements and reassured us of the validity of the data taken by Gemini 7.

Higher spectral and spatial resolution are needed to extend the polarization measurements to specific regions of interest, such as hotspots (Middlehurst and Moore 1966) and color discontinuities (Whitaker, referenced by Gehrels, *et al.* 1964). Photopolarimetry of the entire Moon in the visible wavelengths, with an extention to the far-infrared, is also necessary to complete the lunar polarization picture. Furthermore, measurements should be made to determine the infrared phase function for all phases, with particular attention given to the near zero phase.

Acknowledgments The authors wish to thank Mr. R. Modica who prepared the lunar polarization maps and Mr. D. Steinmetz for assisting in the data reduction. In addition to many valuable discussions, Dr. H. L. Johnson made available the Catalina Observatory's 28-inch telescope and the lead sulfide photometer. This work was supported by the National Aeronautics and Space Administration, Contract No. NSR 03-002-048, and the National Science Foundation, Grant No. GP-4999.

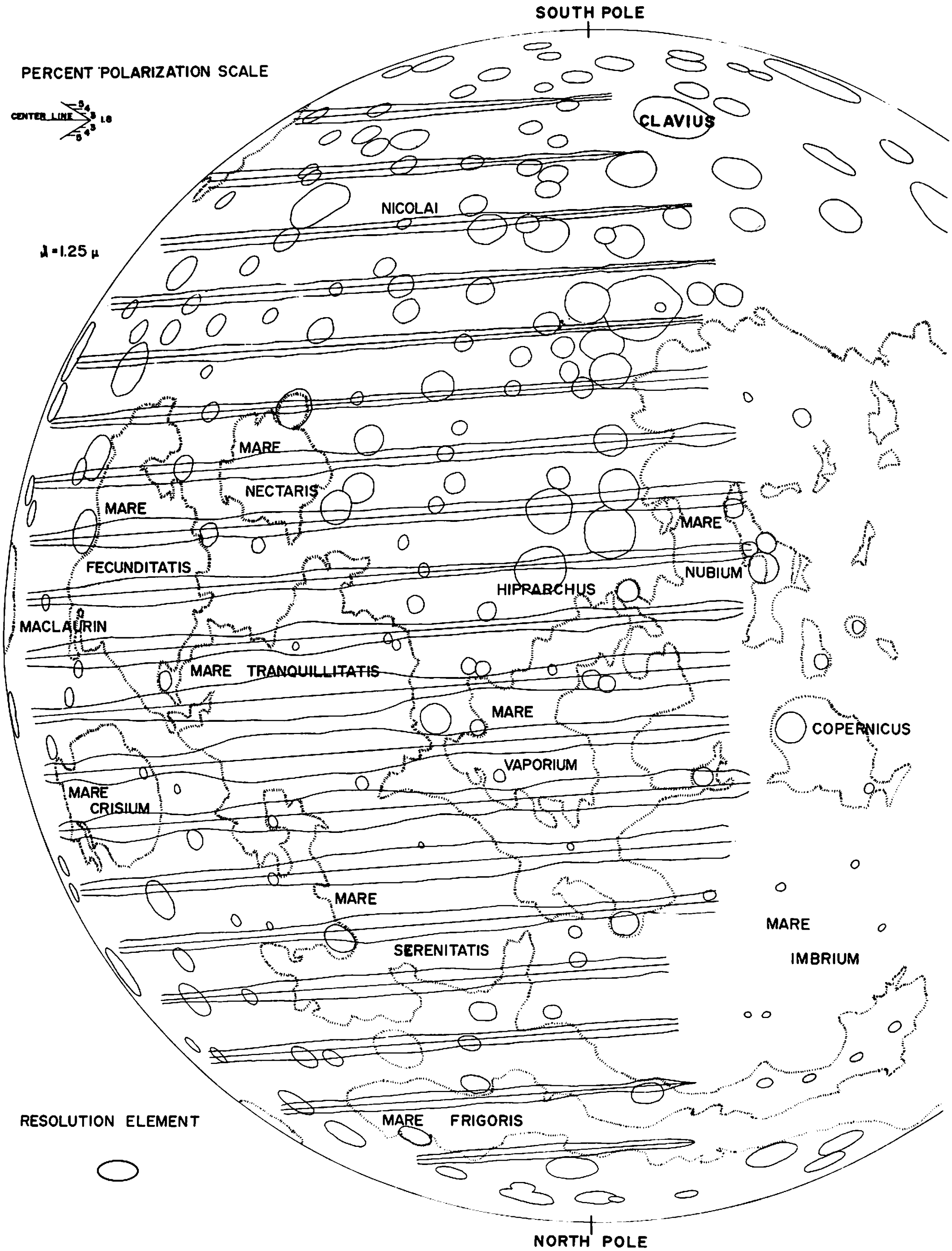


Fig. 1 Lunar Polarization Map at 1.25 μ. The center line represents the center of the diaphragm for each scan and has a value of 1.8 on the percent polarization scale. The spacial resolution is approximately 60 by 35 arc sec.

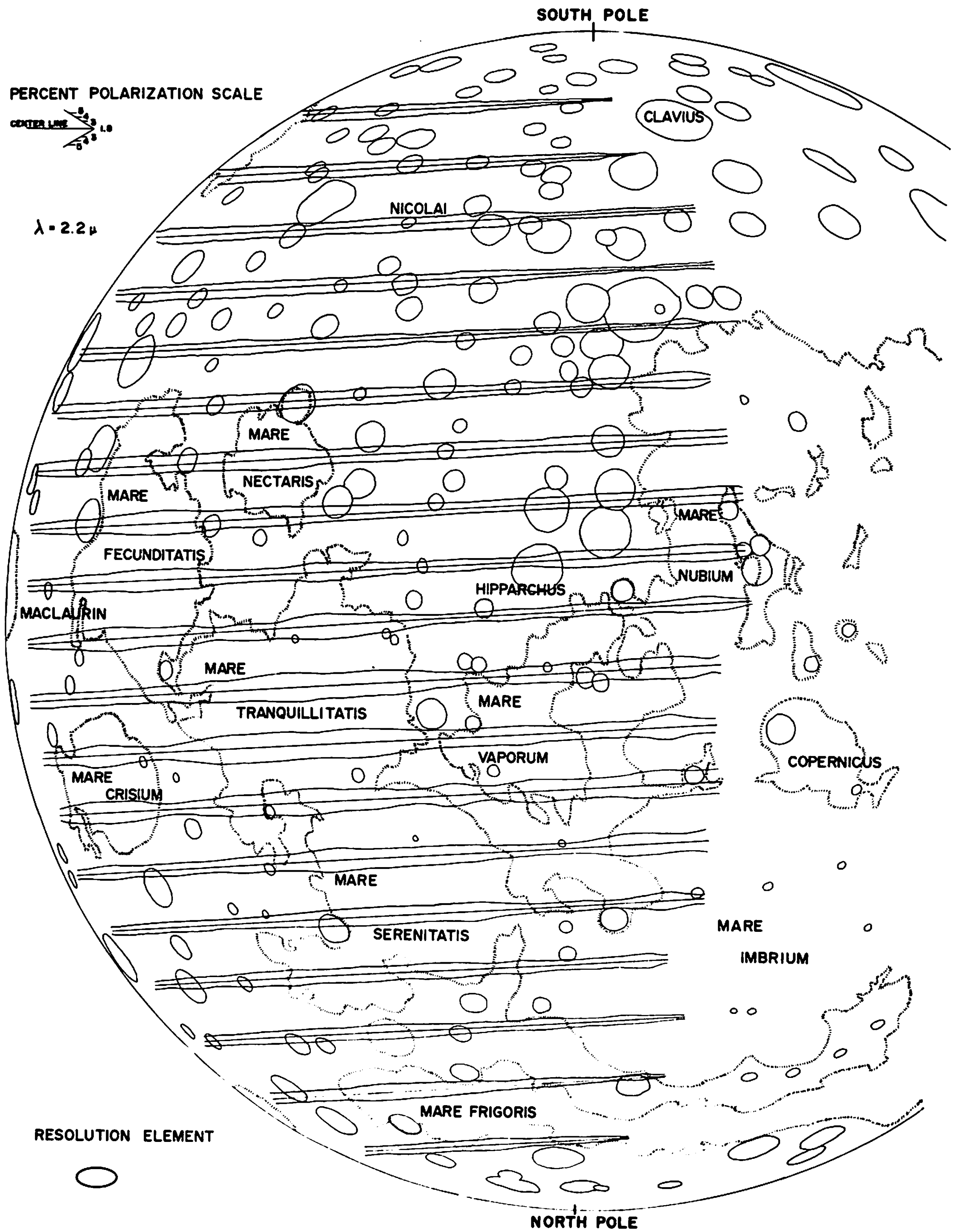


Fig. 2 Lunar Polarization Map at 2.24 μ. The center line represents the center of the diaphragm for each scan and has a value of 1.8 on the percent polarization scale. The spacial resolution scale is approximately 60 by 35 arc sec.

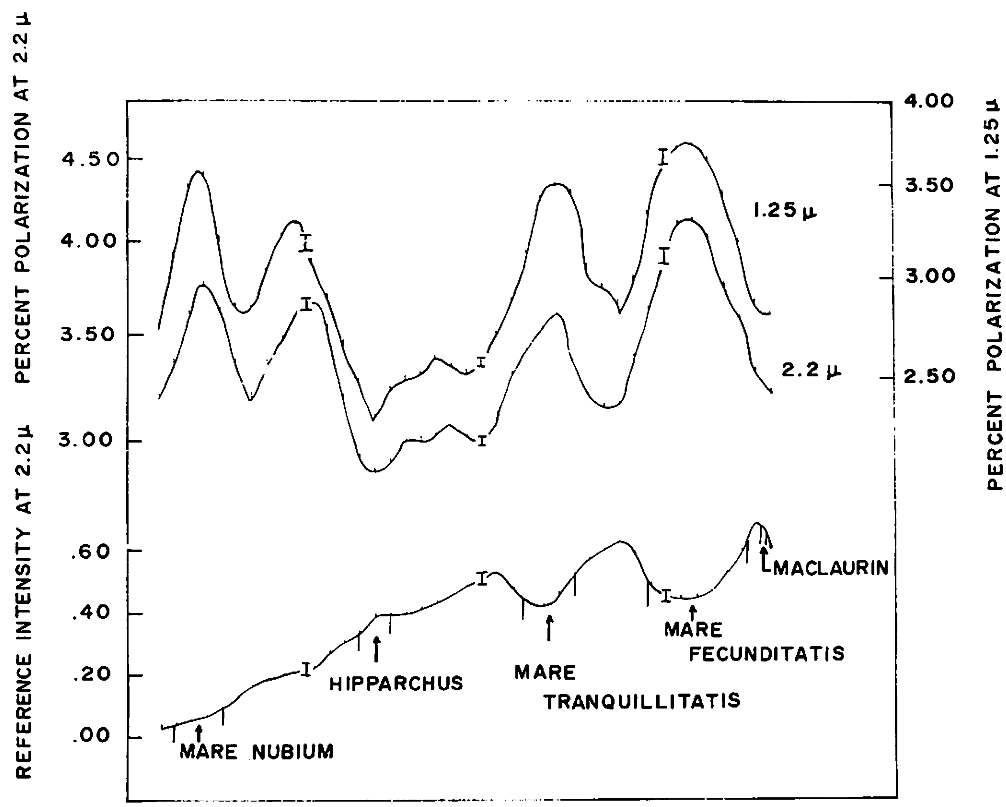
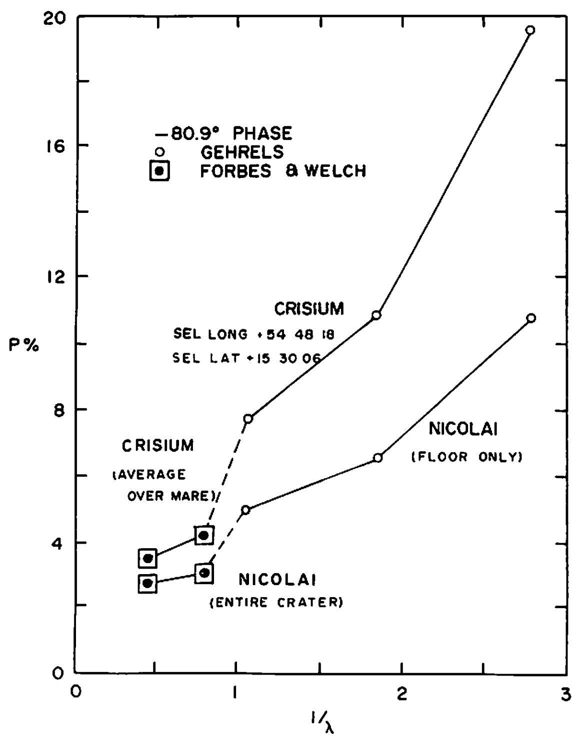


Fig. 3 Percent polarization and corresponding intensity scan for the ninth trace from the top in Figs. 1 and 2.



← *Fig. 4* Comparison of visual and infrared polarization percents for Nicolai and Mare Crisium at —80°.9 phase. The field of view used by Gehrels was about 5 arc sec, compared to approximately 30 arc sec for the infrared. The values given by Gehrels have been interpolated to —80°.9 phase.

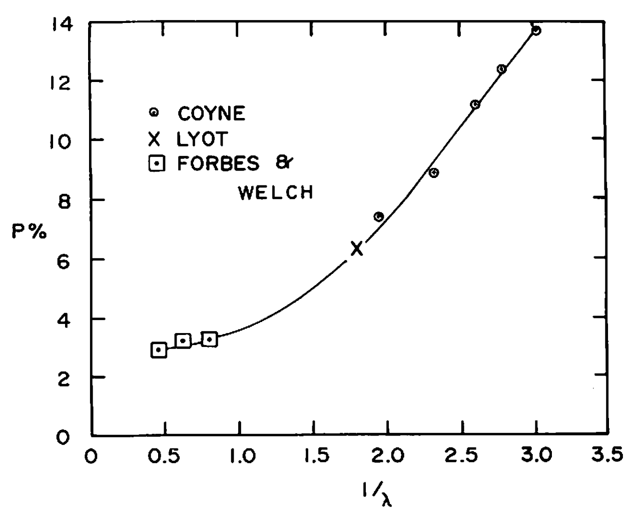


Fig. 5 Polarization of the entire Moon at —80°.9 phase for infrared, visual, and ultraviolet wavelengths. The values for Lyot and Coyne have been interpolated to —80°.9 phase.

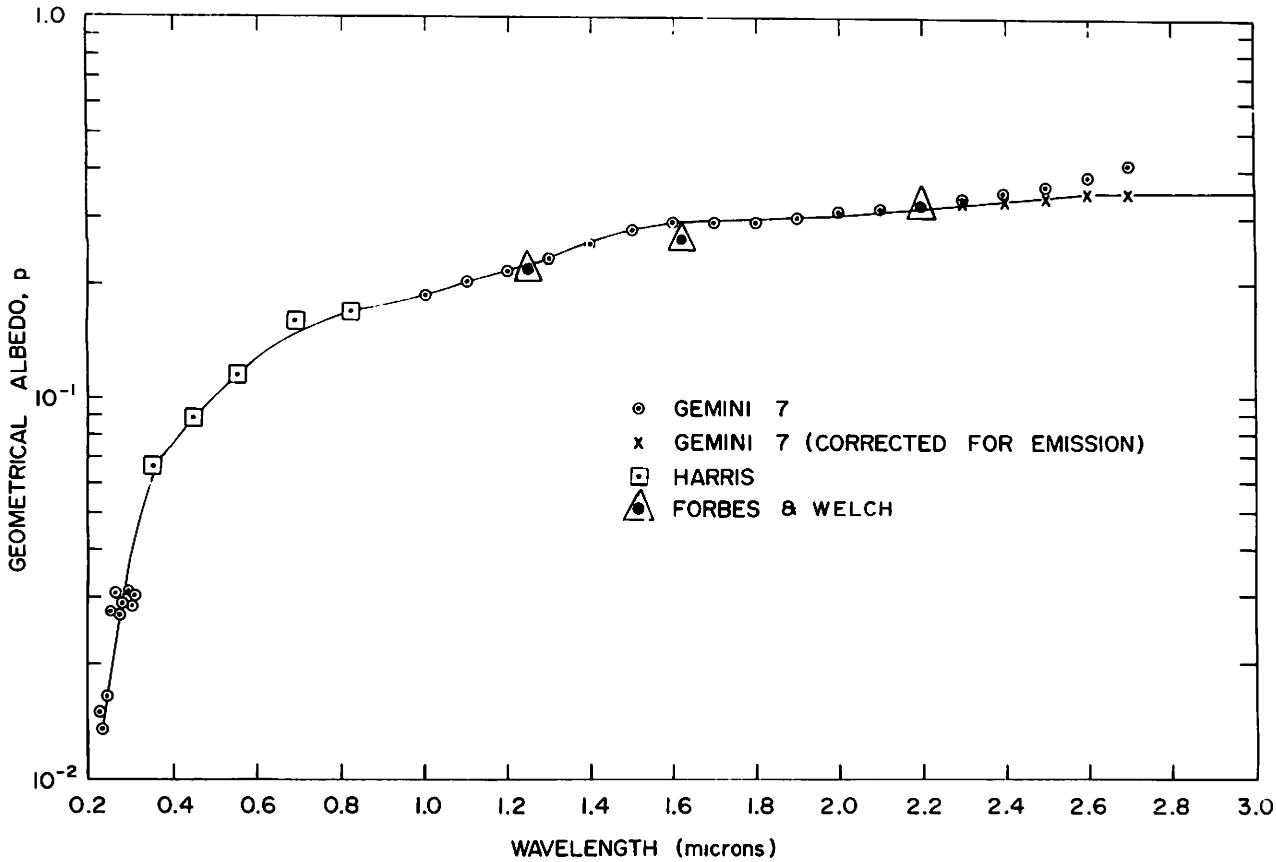


Fig. 6 Geometric albedo for the entire Moon in ultraviolet, visual, and infrared wavelengths.

REFERENCES

AFCRL — Project Lamplighter 1966, *Gemini Optical Measurements Series,* Report No. 8.

Arthur, D. W. G., 1965, *Comm. LPL,* 4 (62), 89.

Coyne, G. V. 1967, Private Communication.

Dollfus, A. 1955, *Tech Transl. F-188* (NASA, Washington, D.C. 1964).

Forbes, F. F. 1967, *Ap.J.,* **147**, 1226.

Gehrels, T., Coffeen, D., Owens, D. 1964, *Ap. J.,* **69**, 826.

Gehrels, T., and Teska, T. 1960, *Pub. ASP,* **72**, 115.

Harris, D. L. 1961, *Planets and Satellites, The Solar System,* eds. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press), 3, 272.

Johnson, H. L. 1965, *Comm. LPL,* 3, (53), 73.

Johnson, H. L., and Mitchell, R. I. 1962, *Comm. LPL,* 1, (14), 73.

Lyot, B. 1929, *Tech. Transl. F-187* (NASA, Washington, D.C., 1964).

Middlehurst, B. M., and Moore, P. A. 1966, *Science,* **155**, 449.

Minnaert, M. 1961, *Planets and Satellites, The Solar System,* eds. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press), 3, 213.

Russel, H. N. 1916 *Ap. J.,* **43**, 173.

Shurcliff, W. A. 1962, *Polarized Light* (Cambridge, Mass.: Harvard University Press), p. 62.

SUPPLEMENTARY REFERENCES

Arthur, D. W. G., and Huzzen, 1962, *Comm. LPL,* 1, (10), 45.

Johnson, H. L., Mitchell, R. I., Iriarte, B., and Wiśniewski, W. Z. 1966, *Comm. LPL,* 4, (63), 99.

Treanor, P. J. 1962, *Astronomical Techniques, Stars and Stellar Systems,* ed. W. A. Hiltner (Chicago: University of Chicago Press), 2, 247.