No. 107 AN AUTOMATIC POLARIMETER FOR SPACE APPLICATIONS*

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ABSTRACT

Under a NASA contract, a compact automatic polarimeter was developed as a pilot model for lunar and planetary missions by spacecraft. The polarimeter simultaneously analyzes linearly polarized light into four intensities from which the Stokes parameters I, Q, and U can be determined. The measurements are made automatically by an electronic observation sequencer and an automatic gain selector. Five wavelength bands between 1900 Å and 6000 Å can be used, and each measurement is calibrated automatically. The successful operation during three high altitude balloon flights indicates that the design is sound, and that with modifications for rocket vibration it can be used in space missions. The feature of making simultaneous measurements makes it particularly useful on planetary scans with fly-by probes. Preliminary results on the wavelength dependence of the polarization of the whole lunar disk, obtained ground-based, between 2850 Å and 5100 Å are presented.

1. Introduction

Under a contract for the "Development and Testing of a Photopolarimeter for Space Vehicles", an automatic instrument was designed and constructed as a pilot model for scans of planetary disks on fly-by missions such as Mariner and Voyager. It would also be useful for lunar surface studies by Apollo.

The need for a small portable polarimeter for unmanned and manned space missions has been discussed.[1] The advantages of being able to do polarimetry from space vehicles are that a large range of phase angles is possible, and that individual areas of a planetary surface can be investigated.

As a means of testing the design in severe and changing environments, the polarimeter has been operated in several environmental chambers. It has also made three high altitude (35-km) nighttime and daytime balloon flights. Telemetry records show that the instrument performed nearly flawlessly on all three flights. Tests during the development and actual flights were important in testing components for the Polariscope balloon program.[1]

Between balloon flights, the instrument is used in a program in which the polarization–phase curve of the whole moon is observed during a complete lunation over a range of wavelengths 3200–6000 Å.

2. Design Specifications

The design specifications for space flight hardware are closely approximated by those for balloon-borne equipment. The obvious difference is that space flight equipment must be able to withstand severe vibration and shock and high vacuum. The polarimeter does withstand the parachute opening and landing shocks (~7 G) without damage. The limitations on weight, size, severe temperature profile, low ambient pressure, minimum number of ground commands, and low power consumption were observed as much as possible in this pilot model. Advantages of speed, simultaneity of measurements, and the redundancy available are discussed in Secs. III and VI.

The chassis was constructed mostly of magnesium, and the present model weighs a total of 17 kg. Existing electronic components were used, thus enabling the design-to-hardware-stage time to be short. In a space flight version the electronic module cans will be replaced by integrated circuit logic, thus reducing the weight and size of the instrument. The size is now 57 cm × 32 cm × 17 cm with 15-cm long telescope tubes. It is estimated that the volume could be reduced to one-third with microminiature electronics.

The temperature range over which the instrument is tested is from +40°C to −70°C. The altitude range is from sea level to 40 km. No difficulties in the performance of the polarimeter are encountered between these environmental extremes. The ceiling pressure is not too important for problems such as outgassing and vacuum welding, which are of concern in the high vacuum of space; but it is critical for the possibility of coronal discharge from voltages greater than 200 V. In fact, many of the eight or so environmental tests during the developmental stages showed corona problems from either the high voltage supplies or the photomultiplier tubes.

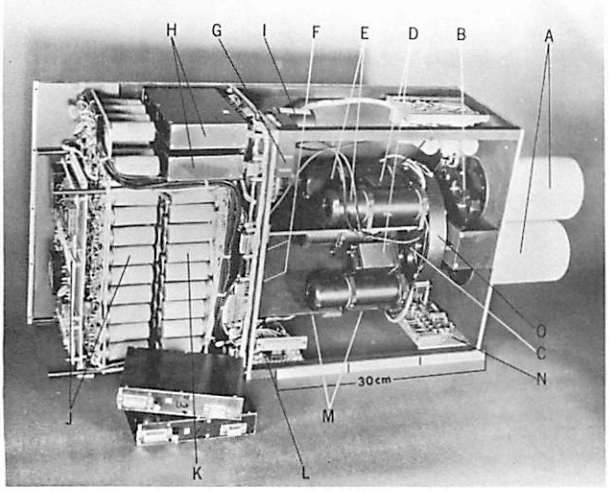

Fig. 1. Polarimeter with sides removed. A: telescopes, B: depolarizer arm, C: filter wheel, D: Wollaston prisms, E: photomultipliers (caps on PM tubes hold nickel sulfate hexahydrate crystals used for filtering), F: Fabry mirrors (not visible), G: integrator power supply, H: integrators, I: 1-/oscillator, J: gain select logic, K: sequencing logic, L: high voltage selector relays, M: high voltage power supplies (not visible), N: voltage reference supply, O: mounting for filter position indication.

To increase the versatility of the present prototype on balloon flights, it was not made completely automatic. The high voltage selection, integration time selection, and a *start* after each filter cycle are required commands from the ground.

The electronics are completely solid state; therefore, there is essentially no warm-up time, and measurements can begin as soon as the PM tubes have recovered from the initial high voltage application. The power consumption is presently 25 W, but with microminiature electronics this can be reduced to about 6 W. The battery voltages (+12 V and −12 V) can vary by ±12% without affecting the operation of the instrument. Typical precision on bright objects is better than ±0.04 in percentage polarization.

3. Optics Section

Figure 1 shows the polarimeter, with one side removed and two integrators unplugged. The instrument is divided into the optics and the electronics sections by the vertical partition. The front face, including telescopes and filter wheel mounting, can be separated from the main body which holds the PM tubes and electronics plugs. The logic-module decks can also be separated from the main body.

The optical configuration is shown diagrammatically in Fig. 2. There are two such optical trains mounted at 45° to each other, and otherwise optically completely independent of each other. By comparing Figs. 1 and 2, the path that the light takes can be traced.

Light is collected by two $f/8$ Cassegrain-type telescopes (7.5-cm-diam primary). The mirrors are aluminized in such a way that their polarizing properties are negligible, and overcoated with a $\lambda/2$ (at 2250 Å) coating of magnesium fluoride to protect the aluminum from the atmosphere. The glow discharge and aluminization are done normal and symmetrical to the mirror surface.

The beams pass first through the Lyot depolarizers which are used to calibrate each observation. They are constructed of two disks of birefringent magnesium fluoride crystal, cut parallel to the optical axis, the first disk having twice the retardation of the second. The two disks are aligned with the axes precisely at 45° to each other. The effect on a wide band of light is that different wavelengths in the band emerge with different polarization forms, i.e, linear, elliptical, circular, at many azimuth angles. As a result of the blending of these many polarization forms, polarized light cannot be distinguished from unpolarized light. Magnesium fluoride is used because it has higher transmission below 2500 Å than quartz. The depolarizers are automatically put into and out of the beams in a systematic sequence (Sec. IV) for each measurement. This nearly simultaneous calibration allows for possible drifts in the photometers between pairs of integrations. The intensities are kept nearly equal (except for polarization) by the use of amorphous silica equalizer disks in the beams when the depolarizer is out. This minimizes the light hysteresis which is present in some tubes (notably ASCOP 541F-08 and 05 and RCA 7102). This effect is that an appreciable time (up to 30 sec) is required for the signal to decay if light is removed from the tube, and conversely, to reach a final value if light is put onto a tube that has been dark.

Following the depolarizer, light passes through one of the five filters in the filter wheel. The filters are mounted in five pairs, each pair being identical and opposite on the filter wheel, so that the same wavelength band is observed by both telescopes simultaneously. At the end of a cycle of five filters the filter wheel signals the logical sequencer to *hold* (Sec. IV). Readout of positions is accomplished by the closing of glass magnetic-reed switches by magnets mounted on the moving depolarizer arm and filter wheel. The filter wheel and depolarizer arm are moved by pulsed stepping motors.

To satisfy the lack of acceptable filters for the 2000–3000 Å region, a set of narrow band filters was developed. The filters are described elsewhere[2], and meet the requirements of good rejection outside the passband, stability to low temperatures, low pressure, and uv radiation, and high transmission with bandwidths of 225–250 Å. After passing through identical filters, each light beam comes to a focus at its respective focal plane diaphragm, which is also the entrance end of the prism cells (see Fig. 2). The field of each telescope can be made as large as 1°.3 diam in order to include the lunar disk and allowing for errors in guiding.

The entrance window of each Wollaston prism is a plano-convex fused silica lens which has the function of making the primary mirror appear to be infinitely distant. Through the use of this lens the large angles that rays from the edge of the primary mirror have (up to 5°) are accommodated. This allows the use of a smaller prism and a small prism interface angle without excessive reflection loss and without approaching inter-

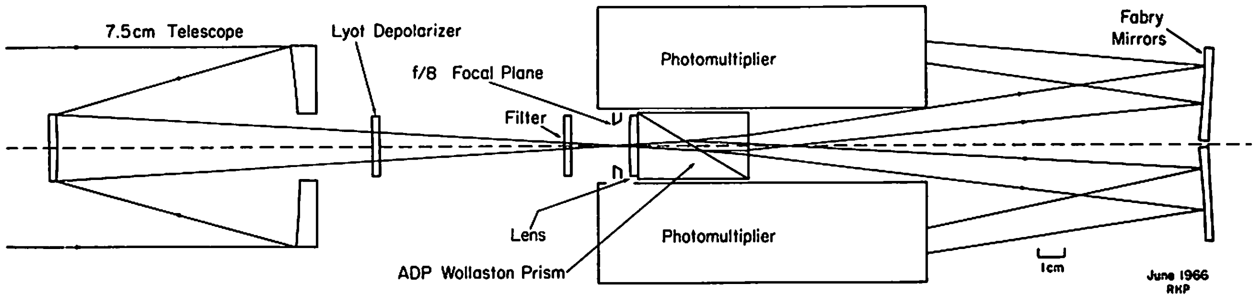

Fig. 2. Optical train of polarimeter.

nal reflection. This lens, and a plano exit window of fused silica, protect the prism from the atmosphere.

The Wollaston prism is constructed of crystalline ammonium dihydrogen phosphate (ADP). ADP is used because it has high transmission in the uv (40% at 2000 Å for 43 mm thickness[3]), but especially because of its high birefringence (0.054 at 2537 Å).[4] The crystal is water soluble and soft, and a technique of polishing surfaces flat was, therefore, developed by E. J. Plamondon and R. L. Waland of the Lunar and Planetary Laboratory Optical Shop. Preliminary polishing is done on paper toweling with a 50% mixture of Cr_2O_3 and cornstarch using Dow Corning 200 Silicone Fluid with a 5-cS viscosity as the lubricant. Paper has less drag than the usual honeycomb foundation, so it has a smaller tendency to pull out chips of ADP. Final polishing is done with a honeycomb foundation on the normal pitch lap. The above polishing materials are used with a circular stroke. The flatness normally obtainable is 1 λ over a surface, but with longer polishing times ¼ λ flatness can be obtained.

ADP is susceptible to fracture from thermal shocks. However, after more than a dozen environmental tests and four actual flights, there has been no fracture of such a prism due to careful mounting. Our prisms are mounted in aluminum cells with the entrance face mechanically held perpendicular to the incident beam and the exit face located and held in contact with the ADP by four springs on the back end of the cell. The prism halves are mounted in the cell in a semikinematic manner, and are held against small pads of silicone rubber by pressure from the springs. For optical coupling we use a thin film of Dow Corning 200 Silicone Fluid which has high transmission[3] and the proper refractive index[5] for our optical materials.

The Wollaston prism analyzes the incoming light into two orthogonally and completely linearly polarized beams, and deviates them so they strike the Fabry mirrors. The purpose of the Fabry mirrors is to image the primary mirror on the cathode of the associated photomultiplier and thus eliminate the motion of the image on the cathode as the guiding in the diaphragm varies. Investigations made in the laboratory showed that the sensitivity of the cathodes of some types of tubes can vary as much as 20% from one area to the next.

The photomultipliers originally used for the balloon flights had CsTe cathodes (solar blind) with response from 2900 Å to below 2000 A. At first EMR-541F were flown, and later the less expensive RCA C-31005. Recently, CsSb (S-13) cathodes (EMI 9526B) were substituted in order to extend the wavelength region to 6000 Å to 1900 Å total. The tubes have 17% quantum efficiency (cf. 9% for the CsTe), but they have appreciable dark current for faint objects unless cooled.

The Silastic potting of the cathode electrode on the first tubes failed, causing corona in an environmental test. This was repaired with silicone rubber. Considerable experience has been gained in potting the RCA and EMI photomultipliers for the balloon environment while at the same time not adding appreciable leakage current between the high voltage and the signal electrodes. High voltage corona problems are more critical for balloon altitudes (pressure ~4 mb) than for the space environment.

Because individual tubes of a specific type can vary greatly in cathode sensitivity and multiplier gain unless specially selected, the four tubes are matched to each other in total response to unpolarized light of a chosen wavelength by adjusting their multiplier gains. This is done to make the tubes give comparable output levels except, of course, for appreciably polarized light.

The optical configuration for each telescope is identical as mentioned previously, but one prism is at 45° to the other. The reason for this is to provide *simultaneous* observations of the components of the Stokes parameters for linearly polarized light. This allows a solution for the magnitude and azimuth of the polarization vector at a given wavelength with one observation. This feature fills the need for fast measurements such as would be necessary on a planetary scan with a fly-by probe. Another advantage is that the need to rotate large assemblies (the Wollaston and all of the optical train following it) is avoided; thus, the questionable reliability of precisely moving such an assembly in the space environment is eliminated. In addition, simultaneous photometry at the given wavelength can be obtained.

4. Electronics Section

The polarimeter electronic system consists of four photomultiplier tubes, four current integrators, two programmable high voltage power supplies, an automatic sequencer, and an automatic gain selector (plus

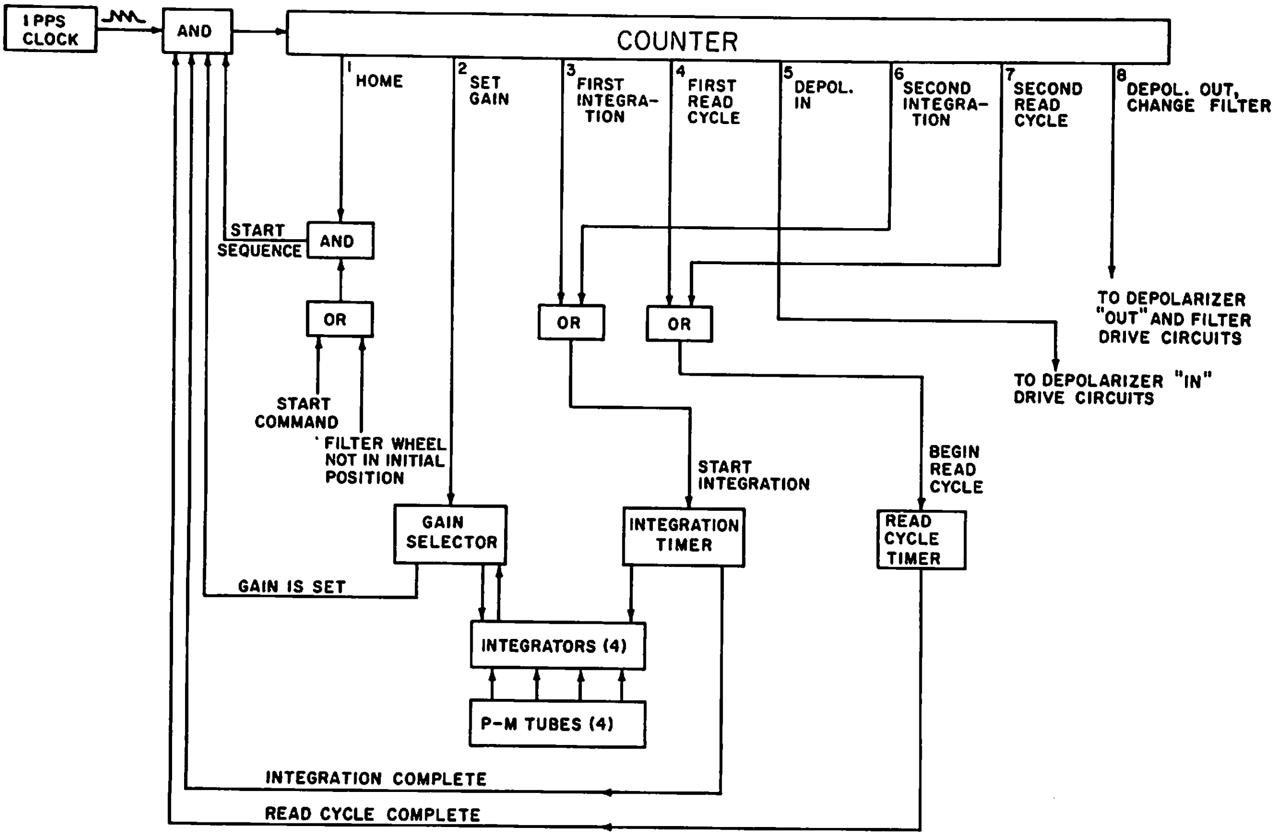

Fig. 3. Block diagram of electronic logic for automatic polarimeter.

batteries to power this equipment). Associated equipment used in balloon operations includes two electronic magnetometers, a moontracker/gondola stabilization system, a command receiver/decoder, and a data encoder/transmitter. The latter three pieces of equipment are provided for the balloon flights by the National Center for Atmospheric Research.

The outputs of the four PM tubes are fed to four current integrators. Power for the tubes is supplied by transistorized, regulated high voltage power supplies* whose output voltage is controllable from the ground between 600 V and 1400 V. For added reliability, one supply is used for each pair of tubes, so if one supply fails, photometry is still possible. Polarimetry is still possible if the position angle of the electric vector is known. The nine steps of integrator sensitivity (gain) together with fifteen steps of high voltage and three possible integration times give a total dynamic range (with transmission losses included) of about fifteen magnitudes (1 to 10^6 factor in intensity).

Initially, the integrators are placed in a logarithmic amplifier mode in order to facilitate aiming the instrument. The amplifier output is transmitted continuously to the ground and the observer scans in azimuth and elevation until a maximum output is obtained. The integrators are then returned to their normal mode by ground command, and the automatic observation sequence is begun.

The automatic gain selector and sequencer perform the assignments normally performed by an astronomer making polarization measurements with equipment at a telescope. The specific assignments of the automatic sequencer and gain selector are as follows. (1) Select one of nine integrator sensitivities (gains) so as to give data as close to full scale as possible, but never off scale. (2) Execute precisely timed integrations of 7 sec, 15 sec, or 31 sec, as selected by command from the ground. (3) Control the filter wheel, thereby selecting the wavelength to be observed. (4) Control the depolarizer. (5) Carry out the above functions in a sequence which will result in an efficient observation procedure, provide sufficient time for ground recording of the polarimetry data after each integration, and require as little active control by the observer as possible while maintaining a high degree of system flexibility.

The system consists of 99 transistorized digital logic modules†, each of which has a specific logic function, i.e., *and* gate, *or* gate, etc. A block diagram of the system appears in Fig. 3. The sequencer is basically a digital counter which counts from zero to eight and then starts over; each of the eight states of the clock

* Grafix, Inc., Albuquerque, New Mexico, Model 148 C.

† Engineered Electronics Co., Santa Ana, California, T-Series Logic Modules.

corresponds to a function, e.g., *set gain*, *integrate*, *read*, etc. When the clock is triggered into a state by a pulse from a 1-c/s oscillator, the function corresponding to that state is initiated, and further pulses are prevented from triggering the clock until the function is completed. A pulse is then gated to the counter and it goes on to the next state, starting the next function.

The sequence begins in the *home* state of the counter with the depolarizer out of the beam and the filter wheel in its starting position. A start command from the ground gates a pulse to the counter, causing it to go to the *set gain* state. The gain selector makes a series of trial integrations, each 1 sec long, on the light signal entering the telescopes. The first trial integration is made with the integrator gain at its least sensitive value. The resulting integrator outputs are compared with a fixed reference; if they are less than this reference, the value of gain is too low to give an on-scale readout, and the integrators are set to the next, more sensitive, gain value and another trial integration is made. This process is repeated until one of the nine gain values yields an output voltage at least as large as the fixed reference, but not large enough to cause any of the integrator outputs to be off-scale. This value of gain is selected, and a *gain is set* signal is sent to the counter.

When the gain is set another pulse is gated to the counter, causing it to go to the third state. This causes the first integration to be carried out. A second counter, driven by the precise 1-c/s clock, times the integration—either 7 sec, 15 sec, or 31 sec as selected from the ground. For spacecraft use, command requirements could be simplified with a scheme of not using fixed integration times but integrating until one of the four integrators reaches full scale, and then terminates the integration.

When this operation is complete, another pulse is gated to the counter, and the *read cycle* begins. This is a 15-sec interval during which the data are held at the outputs of the integrators so they can be recorded on the ground three times (Sec. V).

After the read cycle, two pulses are gated to the counter. The first puts the counter in the *depolarizer in* state, causing the depolarizer to be put into the light path, and the next pulse—1 sec later—moves the counter to the second integration. This is carried out exactly like the first integration, and at the same gain, and a second read cycle follows it. The eighth and last counter state, following the second read cycle, causes the depolarizer to be put out of the beam and the filter wheel to be advanced. The complete set of two integrations at one filter occupies about 1 min of time for 7-sec integration times with the 15-sec readout times. The next pulse from the clock puts the counter back in the *home* state.

The counter will not stop in the home state until five complete cycles have been made, one on each filter position, and the filter wheel is back in its initial position. At this point the observer has the option of examining his data before proceeding, or signaling the sequencer to make another cycle through the filters. If repeated measurements are desired, the filter wheel can be held at any one filter on command from the ground.

Primary developmental problems were the previously mentioned corona discharge and noise triggering of monostable and bistable logic circuits. The noise problems arose chiefly from the operation of relays and stepping motors from the same power source as the logic circuitry, and from cross-coupling of low rise time pulses in long multiwire cables. These difficulties were eliminated by using two sets of batteries (one for relays and digimotors, the other for logic), and by adding signal conditioning circuits at various points in the system.

5. Data Recording

For the balloon flights, data are continuously telemetered, decoded, and recorded by the NCAR system. The data are printed out in thirty columns of three digits each by a Frieden Flexowriter. Important data are repeated three times in the thirty columns.

For use on the ground, a system was designed to record the important data automatically on signal from the polarimeter. Ten voltages are recorded in digital form: integrator gain, filter position, depolarizer state, four integrator outputs, two high voltage supply outputs, the reference voltage, and the time of the measurement.

The data recording system consists of a ten-channel data commutator, a digital voltmeter, a digital decoder, a digital clock, and a digital printer.

During the *read* time after each integration, a signal is sent by the polarimeter in order to cycle the data commutator. This connects sequentially each of the analog data voltages to the digital voltmeter, which converts them to a digitally coded number. Each of the digits in the number is represented by a four-bit digital word. The data appear in binary--coded—decimal (BCD) form at the voltmeter output.

The BCD output is converted to a ten-line code which is accepted by the digital printer. The conversion is done by a diode-transistor logic unit which consists of a diode decoding matrix and ten current amplifiers for each digit.

The digital clock consists of a torsional pendulum oscillator which drives a counter. It gives five BCD output digits of time in units from tenths of minutes to tens of hours in factors of ten.

In operation, the digital voltmeter gives a *print* command to the printer after sampling each input voltages. The voltage is recorded and the commutator advances. After recording the ten channels, the commutator returns to its initial position and waits for the next *record* signal from the polarimeter. Data outputs are on a scale of 0 V to 10 V. Four digits are recorded for ground based work with an accuracy of one in the fourth digit.

6. Calibrations and Data Reduction

During aluminization, efforts are made to minimize the amount of polarization by reflection from the

Table I. Wavelength Dependence of the Polarization of the Whole Moon[a]

$^1/_\lambda$	$P(\%) \pm$ p.e.[b] at 40°[c]	$P(\%) \pm$ p.e. at 63°8	$P(\%) \pm$ p.e. at 88°8
3.04	4.580 ± 0.013	11.203 ± 0.006	17.016 ± 0.025
2.79	4.112 ± 0.006	10.325 ± 0.002	15.176 ± 0.024
2.62	4.007 ± 0.030	9.599 ± 0.024	14.427 ± 0.015
2.33	3.087 ± 0.008	7.721 ± 0.040	11.272 ± 0.051
1.95	2.842 ± 0.004	6.701 ± 0.006	9.067 ± 0.021

[a] Preliminary values, September to October 1966. See Fig. 4.
[b] Probable error. See Sec. VII.
[c] Angle at center of moon subtended by sun and observer.

telescope mirrors (Sec. III). To determine how effective the efforts are, two tests of instrumental polarization are made. For visual wavelengths, stars of negligible polarization are observed. For uv wavelengths, measurements are made at normal incidence on an aluminum screen which has been blasted by fine sand dust and is illuminated by an arc source (having small, if any, polarization). The screen provides uniform illumination of the primaries, and depolarizes the light from the lamp. Any residual polarization of the combination is eliminated by making measurements at one orientation and then rotating the screen and lamp 90° for a second set of measurements. The residual polarization of the mirrors is on the order of 0.1%.

Measurements of a source of 100% linearly polarized light are made to determine how effective the depolarizers are as calibrators for each measurement. The residual polarization with the 9-mm thick magnesium fluoride depolarizers acting on 100% polarized light is 0.15%. These corrections are applied to the measurements.

The equations for the solution of linear polarization result from combinations of the four measured intensities in the Stokes parameters I, Q, and U which define polarization[6]

$$P_{0,90} = \frac{I_0 - (I_{0d}/I_{90d})\, I_{90}}{I_0 + (I_{0d}/I_{90d})\, I_{90}}$$

and

$$P_{45,135} = \frac{I_{45} - (I_{45d}/I_{135d})\, I_{135}}{I_{45} + (I_{45d}/I_{135d})\, I_{135}},$$

where the subscripts refer to the angles between the transmission axes of the Wollaston beams and the sides of the polarimeter (which are perpendicular to the equator when an equatorial mounting is used). The d indicates depolarized intensities. The multiplying ratios normalize for transmission differences between depolarizer in and out.

The above quantities are substituted into equations of the form $P = P_{0,90} \cos 2\alpha$ and $P = P_{45,135} \cos 2(\alpha + 45)$, where α is the uncalibrated position angle of the electric vector. The resultant P_R is determined by a least squares solution of $P_R = (P^2_{0,90} + P^2_{45,135})^{1/2}$.

The Stokes parameter S_V which is used to analyze elliptically polarized light is not measured. It could be determined by inserting a quarter-wave retarder into the beam from the $P_{45,135}$ telescope and measuring $I_{45,\pi/2}$ and $I_{135,\pi/2}$ in addition to the above intensities.

An advantage of the design of the polarimeter is that if any one of the four PM tubes or integrators would become defective, the other three would still give information suitable for solving for the polarization. This redundancy lends reliability to the instrument and increases the chance for success on a space mission. Equations for the solution using only three components of the incident intensity are easily derived.

7. Preliminary Results and Future Plans

Table I lists preliminary results on the moon obtained at three phase angles. (Phase angle is the angle at the center of the moon subtended by the sun and the observer.) These data are part of a large set made over a range of phase angles[7] (extending from first to last quarter). Positive phase angles occur from full through last quarter. Probable errors are from the main residual of the least squares solution assuming a normal distribution of the residuals. In Fig. 4, the wavelength dependence of the polarization of the whole lunar disk between 2860 Å and 5100 Å is presented. The point at 2860 Å is uncertain because the gondola stabilization failed. Points at these phase angles obtained by Lyot[8] are plotted for comparison.

More extensive work is in progress, and the results will be reported elsewhere.[7] Future plans include the use of narrower filters to investigate some of the detail shown in Fig. 4, extension of the wavelength range of the instrument to the ir, and some observations of terrestrial features from aircraft.

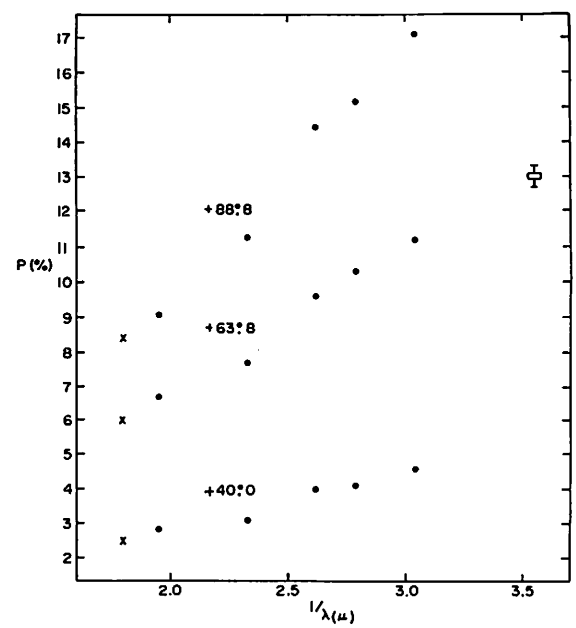

Fig. 4. Preliminary data obtained with the automatic polarimeter on the ground and from a high altitude balloon. Filled circles: ground based data at phase angles indicated. Rectangle: balloon point at −56°8 phase angle. Crosses: points obtained by Lyot (1929) at the above phase angles.

We are indebted to T. Gehrels for his encouragement and guidance. The close assistance of T. M. Teska on many matters was indispensable; he is responsible for the design of the integrators. L. C. Hess did most of the wiring; D. E. Hall and S. Sutton provided technical assistance. E. E. Harber set up a program of rigid environmental testing, and helped prepare the system for the first two flights. D. L. Brumbaugh (who designed the digital clock) and G. V. Coyne assisted with the third flight. E. H. Roland devised the mounting technique for the prisms. And lastly, we acknowledge the assistance and patience of Ruth and Judy during some long days and nights. The project is supported by the National Aeronautics and Space Administration (NASr-138).

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