FINAL REPORT

A Photoelectric Study of the Nightglow

National Aeronautics and Space Administration
Research Grant ~~NsG-676~~ NGR-12-001-004
to the University of Hawaii

1 June 1964 - 31 October 1968

by

J. L. Weinberg*
Principal Investigator

November 1968

*Current Address:

Dudley Observatory
100 Fuller Road
Albany, New York 12205

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Background Information and Program Objectives

In 1959 the High Altitude Observatory initiated a program of zodiacal light studies with the cooperation of the Boulder Laboratories, NBS, and with the financial support of NASA (NsG-15-59). The objectives of the original study were to measure the Stokes parameters (less ellipticity) of the nightglow and, from these, to determine the characteristics of the zodiacal light. To accomplish these objectives we made use of a modified NBS airglow telescope followed by a synchronous detection system.

Field-testing of this one-color (5300A) photoelectric polarimeter was carried out at the NBS Fritz Peak Observatory. Observations there clearly showed the site to be unsuitable for zodiacal light studies because of its high latitude and the intense (and polarized) scattered light from nearby urban areas, including Denver, Colorado. Therefore, with the support of NASA (NsG-135-61) and with the collaboration of the NBS and the University of Hawaii, the program was moved to the favorable, low latitude (20.71°N) site of Mt. Haleakala, Maui, Hawaii (elevation 10,012 ft above sea level) as part of the newly-established observatory of the University's Hawaii Institute of Geophysics.

The one-color photometric system utilized a coupled rotating polaroid-synchronous detector to measure with Fabry optics the brightness of the total and of the polarized component of the nightglow and the orientation of the plane of polarization. Mounted in tandem with this photometer on an alt-azimuth mounting was a photometer[i] which recorded the intensities of the principal airglow line emissions (5577, 5890-5896, 6300A) and a photometer[ii] which recorded the brightness of the nightglow, again at 5300A. The airglow instruments and the facility as a whole were operated by H. M. Mann. The airglow data, generously made available by Dr. F. E. Roach of the NBS, was used in the analysis to assist in separating the components of the nightglow.

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i. Roach, F. E., L. R. Megill, M. H. Rees, and E. Marovich, 1958, *J. Atmospheric and Terrest. Phys.*, *12*, 171.

ii. Smith, L. L., F. E. Roach, and R. W. Owen, 1965, *Planet. Space Sci.*, *13*, 207-217.

J. L. Weinberg operated the polarimeter at Haleakala for seven months until May 1962. H. M. Mann returned to the NBS in July 1962. The polarimeter was operated irregularly by Haleakala staff until September 1963, when Weinberg returned to accept a position with the University of Hawaii.

In an effort to sort out the vagaries of the nightglow and of those techniques required for accurate and precise determination of its characteristics, we planned a versatile photometric facility that would be operated on a regular basis. This was prompted by a lack of information on the airglow continuum, the integrated starlight, the diffuse galactic light, and the Gegenschein and by the wide divergence or lack of results on the fundamental characteristics of the zodiacal light:

- Spatial extent;
- Position of the photometric axis, in total and in polarized light;
- Short- and long-term fluctuations;
- Asymmetry and/or spatial irregularities in the radiation field;
- Brightness[1] and polarization as a function of wavelength.

With a properly designed system and a good observing site, we felt that it should be possible to examine each of these within the framework of a long-term study of the complex interaction of zodiacal light, airglow (line and continuum emission), and starlight. At the same time, this would provide a library of observations that could serve as a backup for present and future balloon, rocket, and satellite experiments. The subject program received NASA support on 1 June 1964.

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1. In this report we use the term brightness in place of radiance.

Facilities and Instrumentation

The observing facility, shown in Plate 1, consists of a steel observation tower or silo and an attached building. The 20 ft high, 10 ft diameter tower, which was designed and built on Maui, rests on a 4 ft high concrete pad. The location and height of the tower were chosen so as to minimize radio frequency interference from nearby TV repeaters and radio communications facilities and to provide, as nearly as possible, an unobstructed horizon. Every effort was made to insure compatibility with other installations in the immediate area.

The tower consists of two parts: an upper, observing area and a lower storage area. A circular staircase and trap door connect the two areas. The upper area contains a platform which can be driven electrically up through a sliding hatch in the top of the tower. The platform supports a photoelectric polarimeter on an alt-azimuth mounting which can be programmed to scan over all or part of the sky. Tests, calibrations, and maintenance can be performed inside the tower under simulated nighttime conditions during the day or during bad weather. The observing area is lined with foam rubber and the exterior of the tower is painted titanium white to minimize diurnal temperature changes.

The tower was completed and the mounting and polarimeter were installed on the platform in February 1965. The control equipment was housed in the base of the tower until August 1965 when we added a semi-circular, attached building. Entry to the tower is through the inside of the building. The facility was built with the support of NSF grant GP-4518 (Atmospheric Sciences Facilities). In December 1966 we added, with University funds, approximately 350 ft^2 to the facility. The entire building has a poured-concrete roof, and the addition is that part of the building shown supporting a 6-foot diameter dome. With the addition we were able to provide adequate space for storage and for the observing equipment (Plate 2) and a small working electronics area for maintenance and construction (Plate 3). Eating, sleeping, and machine shop facilities are located in the nearby Mees Solar Laboratory of the University of Hawaii.

University buildings at the 3,000 ft level on Haleakala, convenient to residential areas and within twenty minutes' drive of the airport and local sources of supply, provided the necessary offices and other facilities for support of the program. One of these buildings, used solely for data handling, contained a Gerber Analog Data Reduction System (GADRS-4), two printing key punches, and storage cabinets for punched cards. A fireproof record vault was located adjacent to this building, and it contained the 4-channel strip-chart recordings and other records of the subject program.

The instrumentation can best be described by looking at individual parts of the system.

1. The Telescope and Associated Electronics.

The basic instrument used throughout this investigation is a photoelectric polarimeter - a modified version of the instrument used by the principal investigator in 1961-62[1]. A 5.75-inch achromatic doublet is followed by a Ross zero-corrector which reduces convergence of the beam to a value close to that of the light incident on the objective. We are able to use interference filters and polarization analyzers in this partially-collimated beam between the equal-curvature negative and positive lenses of the zero-corrector. The variable field of view is determined by an iris diaphragm located in the focal plane. A field lens system focuses an image of the objective on the cathode of the photomultiplier, so as to reduce the dependence of the response on position in the field of view.

The telescope is shown in Plate 4 in a calibration configuration; i.e., with the standard source and polarization calibrator covering the objective. The telescope consists of three principal parts:

a. The front end, containing the objective and four concentric diaphragms which prevent off-axis light from reaching the detector;

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1. Weinberg, J. L., 1964, Ann. d'Astrophys., 27, 718-738.

b. The center section, containing the polarization analyzer, the 8-color filter wheel, the shutter and iris diaphragm, and the zero-corrector and field lens. The telescope is designed to provide access to each of these components or to allow them to be removed. This section also contains refrigeration equipment.
c. The rear end, containing the photomultiplier and its adjustable mounting and a solid state signal preamplifier.

This Fabry photometer utilizes a coupled rotating polaroid-half wave synchronous (phase sensitive) detector to measure the radiance of the total and polarized components of the nightglow and the orientation of the plane of polarization. With increased AC and DC signal-to-noise ratio, interchangeable polarization analyzers, a variable field of view, and a removable 8-color filter wheel, the new photometer has considerably more efficiency and versatility than its predecessor.

2. Photodetectors.

Observations with this system began in March 1965. Various S-11 and S-20 cathode surface, end-on photomultipliers were used during the early months. In late 1965 we acquired a selected, high quantum yield, very red-sensitive S-20 Ascop photomultiplier. This tube has been used for most of the observations obtained during the past three years.

Approximately 2½ years ago we began long-term stability tests of the system. These monitoring tests were performed with controlled filter and photomultiplier temperatures and with no change of instrument settings. Voltage stability and drift were also monitored. Various filter combinations were used, and the shutter open/closed time was either 20/10 or 40/20 seconds, although other combinations were occasionally used. Some of the tests lasted minutes; some continued for several days. These tests consumed several thousand hours. An incandescent source and a blended-phosphor standard light source were used for these tests. Although the temperature of the phosphor source could not be controlled, it was continuously monitored since the intensity of the source increases as the temperature decreases.

From these system tests we found that the red-sensitive S-20 photomultiplier exhibits a peculiar, long-term (10 to 100 minutes) time rate of change of gain. This effect, which appears as an increase of gain with time and with other factors, is nowhere described in the literature and cannot be explained by the manufacturer. The high quantum yield and red sensitivity of this tube led us to use it regularly anyway and to commence detailed studies of its characteristics in order that proper allowance for the effect could subsequently be made in the analysis of the data.

As part of our plan to develop instrumentation capable of measuring the nightglow at all wavelengths visible from the ground by photoelectric techniques, we acquired two additional Ascop photomultipliers: an S-1 surface and an S-20 surface with a sapphire window. The properties of these photomultipliers are listed below:

	I	II	III
Model No.	541E-05M-14	541E-01-14	543C-01-14
Cathode Type	S-20	S-20	S-1
Voltage for 10^6 Amplification	2515	2600	2660
Corresponding Dark Current at 20°C, amps	2.9×10^{-10}	1.6×10^{-9}	8.0×10^{-7}
Cathode Luminous Sensitivity, μ amps/lumen	226.6	237	47.9
Per Cent Quantum Efficiency			
1470A	24.7		
2537	30.1		
3125	27.0		
3650	27.2		
4100		27.1	
4200	32.3		
4600		21.6	
5600		11.9	
6300	7.4	7.3	
8000	.33	1.7	.70
10000			.16
Test Dates	Aug/Oct/Nov 67	Oct 66	Oct 67
Window Material	sapphire	glass	glass

Additional calibrations have been made on dates other than those given above.

There has been a loss of gain in Tube II, as a result of being subjected to a high anode current by a former observer, but this was compensated for by using a somewhat higher voltage, with no appreciable increase in dark current. With this tube we have experienced no difficulty in obtaining observations out to 8700A.

A freon system is used to refrigerate the photomultiplier by using a set of cooling coils which encircle the tube envelope. The temperature at the sensor, which was located between the coils and the envelope, was generally held between -15 and -20 °C. The temperature variation of the photocathode was probably between ± 1 and ± 2 °C. Dry nitrogen is used to prevent fogging of the tube window or of the adjacent field lens surface.

From other tests at Haleakala, we have experienced considerable difficulty with Tube I as a result of high-energy radiation-induced fluorescence of the sapphire window[i]. This problem can be solved by using another window material such as magnesium fluoride. This tube also exhibits a peculiar, long-term (of the order of 1 minute) time-constant-like effect, unlike that of any other tube we have tested. This effect appears as a slowly increasing level of signal plus dark current after opening the shutter and an analogous decrease after the shutter is closed. It is thought that the effect is related to secondary emission characteristics of the dynodes. As a result, this tube is not suited for use in these studies. We hope to make further tests on similar tubes provided by the manufacturer (Electro-Mechanical Research, Inc.).

Tube II was used regularly for nightglow observations with the existing polarimeter. Tubes I (or a replacement) and III were to be used with a near ultraviolet/near infrared instrument which is described in a subsequent section.

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i. See, also:
Dressler, K., and L. Spitzer, Jr., 1967, Rev. Scient. Instr., 38, 436-438.

3. Optical Interference Filters.

The photoelectric polarimeter used in this study provides wavelength discrimination by sequential observation with narrow-band interference filters designed to be used at 35°F. Since we did not, at the beginning, have a refrigeration system for the telescope, the filters were designed for use at what was thought to be a representative temperature at night: 35 to 40 degrees F. It appears that 40 to 45 degrees is now more typical of year-round nighttime temperatures at Haleakala.

The filters are temperature-controlled by a combined compressed-air/freon refrigeration system designed by H. M. Mann. The use of this system to also cool the photomultiplier has been described in the previous section. Large volumes of air, which is cooled by the freon system, are passed around and through the center section of the telescope. Fine control of filter temperature is achieved by using dry compressed air with a vortex tube (Coriolis effect).

The filters were all obtained from Thin Film Products (now a division of Infrared Industries) of Cambridge, Mass. Measurements at the center of these 2.83-inch diameter filters give the following:

Central Wavelength, A	Half-Transmission Bandwidth, A
4000	7.2
4355	12.4
4760	10.4
5080	30.0
5300	30.0
5450	19.0
5577	23, 17.5, 14.2, 12.2, 10.8, 9.6, 7.1, 5.7
5752	23.6
6080	19.8
6300	31.7, 22.9, 18.6, 12.8, 10.0, 9.2, 6.9, 4.6

Central Wavelength, A	Half-Transmission Bandwidth, A
6437	13.2
6745	22.7
7100	23.4
8200	46.1
8700	49.5

These filters (except those at 5577 and 6300A) were chosen to avoid airglow line and band emission and, when possible, to sample the nightglow continuum at approximately equal intervals throughout the visible spectrum. Most of the filters are centered in "windows" at least 40A wide. These filters all have off-band transmissions less than 0.005 %. Additional filters (at 9250, 9550, 10650A) were obtained for use with the polarimeter described in a subsequent section and with the S-1 photomultiplier.

4. The Control and Digital Systems.

The programmable control system and magnetic tape digital data recording system are contained in the three central racks of equipment shown in Plate 2. The control system was installed in February 1965, and the digital system was installed in December 1965. Both systems were developed in cooperation with and were built by the Digital Instrumentation Group of the NBS in Boulder, Colorado.

The programmer is equipped with plug-boards which permit the use of any number of automatic or manual observing routines. Simultaneously, the programmer provides output information (time, coordinates, dark current and sky signals) to a 4-channel Sanborn recorder, to an indicator-studded panel, and to the digital system. Position is indicated only to 0.1 degree, although the platform and mounting positions are maintained to within 3 minutes of arc. The mounting can be programmed to scan in any alt-azimuth configuration and at any speed from 0.1 to 5.0 deg/sec.

The digital system was designed to complement this programmer, to use analog-to-digital conversion, and, by previous agreement, to be compatible with the CDC 3200 computer of the University of Michigan's Haleakala Observatory (Project AMOS). Soon after the digital system was installed and check-out tests became necessary, the Michigan project was classified, and we no longer had access to the computer or to the building. Although Michigan personnel were very cooperative, even to the extent of agreeing to run our tapes for us, their increased use of the computer for their own functions soon resulted in our jobs laying untouched for several weeks at a time. This delayed the required testing of the system and it has never been integrated into the program as planned.

Except for occasional use for calibrations and for studies of system stability, the digital system without modification cannot now be properly used. This means that the major portion of the data is in analog (strip-chart) form which must be reduced either by hand or by the use of a semi-automatic analog-to-digital chart reader.

4. Design and Testing of New Instrumentation.

Single-color observations of the zodiacal light can only provide coarse families of solutions for the size and spatial distributions and the number and mass densities of the zodiacal dust. Multi-color observations, aimed at eventually providing the wavelength dependence of brightness and polarization, can strongly limit the number of models which are applicable. Such observations may also yield information on the refractive indices and shapes of the particles which produce the observed zodiacal light. Multi-color observations can provide similarly-unique information on the diffuse galactic light and on the airglow continuum.

The existing polarimeter covers the spectral region from approximately 3600A to nearly 9000A. On the basis of a design and feasibility study conducted under the subject grant, construction was begun on a photoelectric polarimeter to cover the spectral region from 7500A to 1.1 or 1.2 microns. It became clear during the development of this instrument that it would be possible to extend the spectral range into the near ultraviolet using the same optical system and an interchangeable, dual photomultiplier assembly. Together with the existing polarimeter we would thereby cover the entire spectrum visible from the ground by photoelectric techniques. There are no polarimetric observations of the nightglow line or continuum emission in the near ultraviolet or in the near infrared.

A full wave synchronous detector-signal averager is under consideration for use in the new polarimeter. Recorder preamplifiers (for a 4-channel Sanborn recorder) and other aspects of the electronics have been completed. Wavelength discrimination will be provided by sequential observation with 14 narrow- and moderate-band interference filters mounted in two 8-color filter wheels in series, each having a blank section. Both the filters and the wheels will be interchangeable with those used in the existing instrument. We have not yet decided on the types of polarization analyzer to be used.

The optical system has not yet been designed, but it is anticipated that it will be a broad-band-transmitting, scaled-up version of the present telescope; probably with a primary objective of approximately 10 to 12 inches diameter. Since it will be a Fabry photometer that will be used only for extended sources, some of the usual difficulties associated with moderate-sized refracting systems can be avoided or ignored.

As noted earlier, S-1 and S-20 surface photomultipliers will be used for the near infrared and near ultraviolet spectral regions. We anticipate using compressed air cooling for the S-1 photomultiplier. The UV-transmitting S-20 photomultiplier will be used with thermoelectric temperature control.

If the cathode of the S-1 photomultiplier is found, by mapping, to have a region of uniformly high sensitivity, the optical system, including prismatic light injection, will be designed to illuminate that region. Magnetic defocussing may also be used, to prevent dark current photoelectrons from the unilluminated portions of the cathode from reaching the first dynode.

Some aspects of the electronics were tested with the present telescope using HR polaroid and the S-1 photomultiplier without proper cooling and without prismatic light injection. Even with this rather crude system we were able to get a measurable signal from the zodiacal light at 9250, 9550, and 10650A (half-transmission bandwidths of approximately 58, 80, 100A). The results of these tests insure that we shall be able to obtain usable observations in the near infrared out to at least 1.1 microns. Extension of the spectral range into the near ultraviolet is assured.

The lightweight, portable, 6-foot diameter fiberglass dome shown on the roof of the building (Plate 1) was acquired for use in testing a preliminary version of the near ultraviolet/near infrared polarimeter. A stripped-down, modified base and yoke of a government-surplus searchlight is located inside the dome. The dome and mounting will be used with a small telescope which is being modified for additional, preliminary sky tests of the electronics associated with the system. These tests will determine the final optical configuration and the refinements needed in the electronics.

Programs and Procedures

To perform a multi-purpose observational study of the nightglow, it is necessary to achieve a balance between special purpose programs that are used infrequently or irregularly and those that are routine or monitoring in nature. Equally important, it is necessary to make full use of all available observing time. As a general rule we observed, weather permitting, from the end of evening astronomical twilight until the beginning of morning astronomical twilight, less the time of the moon above the horizon[1].

A multi-purpose, ground-based study of the nightglow must also include some provision for study of airglow line and continuum emission. A program of monitoring airglow studies (5577, 5890-5896, 6300) has been continued virtually uninterrupted at the Haleakala Observatory since 1961. Neither the data nor the type of observing program fulfill our requirements, however, and the aforementioned polarimeter was adapted for use in measuring airglow line emission.

The programmable control system allows us to use various automatic, manual, or mixed programs. In this section we will describe the particular kinds of observing programs used in this study. Additional details and results of these programs are given in a later section.

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i. Exceptions: Extinction measurements were sometimes made when the moon was above the horizon, and occasional special programs were performed on the full moonlit sky and on the twilight sky.

The programs:

1. Celestial pole. Since its horizon, equatorial, ecliptic, and galactic coordinates are constant, the celestial pole is ideally suited for studies of covariance groups and short- and long-term variations in the nightglow. At the celestial pole the starlight is constant and on a given night the zodiacal light can only change via short-term variation (ecliptic latitude is a constant 66.6 deg and elongation varies annually from 66.6 to 113.4 deg - summer and winter solstices).

Measurements were generally made at six continuum wavelengths plus 5577 and 6300A. In this program (and in others) it is possible to use any combination or all of the 8 filters in the wheel and to program different DC gains for the different wavelengths. Repetitive observations with all the 5577 and, on other nights, the 6300 filters, have been made on several nights at the celestial pole. These observations, in conjunction with the detailed filter characteristics, will enable us to determine what filter characteristics are required to neglect the continuum in the presence of the line. Measurements at the celestial pole have been made on a total of 105 nights.

2. Pole/scan. This program was used to obtain information on the brightness variations, with wavelength and time, of Polaris, which subscribed an arc of a circle about the center of the field of view. The technique involves observing at the celestial pole through 4 sequences of filters[1] and then scanning back and forth, first in azimuth then in altitude, across Polaris. This provides information on both

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1. We generally used shutter open/closed times of 40/20 or 20/10 sec at each wavelength.

the background and Polaris and permits the removal of the small, added effect of Polaris in large-field celestial pole observations. This program was used on 10 nights.

3. Zenith. Negligible polarization of the atmospheric radiations in the zenith and the reduced extinction and scattering permit special study of several phenomena: the Gegenschein, the polarized component of zodiacal light far from the sun, integrated starlight and diffuse galactic light.

Observation of the low (and sometimes zero) light levels in polarized light require added smoothing and fields of view larger than 3 degrees. The polarimeter is equipped with variable time-constant. Various short time-constants are used with scanning programs and long time-constants are used with fixed-position programs.

As at the celestial pole, measurements were generally made at six continuum wavelengths plus 5577 and 6300A. Measurements at the zenith have been made on 104 nights.

4. Zenith/pole. This program was designed to search for simultaneous, short-term variations in airglow line and continuum emission at the zenith and celestial pole. To provide sufficient coverage in time, measurements were generally made at only 4 wavelengths: 2 continuum plus 5577 and 6300A. After making one observation in each color at the celestial pole, the instrument is moved to the zenith for a similar sequence. This routine is continued throughout the program. This program was used on 7 nights for a total of 46 hours.

5. Extinction. Atmospheric extinction measurements were made with the polarimeter as a regular part of the observing program. Most of the measurements were

made by observing a single bright star[1], rising or setting, over a period of minutes to hours. At Haleakala we are able to make extinction measurements through large air masses within 0.1 deg of the horizon, with no apparent effects except those associated with rapidly increasing or decreasing air mass. This procedure results in an extinction coefficient which is representative of a large area of the sky and, therefore, more meaningful for use in studies of the nightglow.

In an effort to provide information on wavelength effects, observations were generally made at 4 widely-separated wavelengths from the blue to the red. The method is illustrated in Figure 1 for observations of Vega on 14/15 April 1966. Measurements are shown at 4 different times and positions. θ, Z, m_H are sidereal time, zenith distance, and Haleakala air mass, respectively. The instrument is prepositioned, and the shutter is opened when the star is in the center of the field of view. After 30 seconds, the instrument scans back and forth in azimuth across the star to provide the necessary background. When the star is at large air masses, measurements are made continuously at the maximum rate of one/min (15 measurements per color per hour). Extinction measurements have been made on 163 nights.

6. Miscellaneous. A number of other automatic or manual programs were performed. Among these were programs designed to provide information on selected regions in the ecliptic and in the Milky Way, on regions of unusual airglow structure, on diffuse-source extinction, and on the Stokes parameters of the twilight and full moonlit sky. These programs

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1. The principal stars used were Vega, Capella, Arcturus, and Altair.

often involved measurement at a single position or at a sequence of fixed positions. For example, we would scan along the meridian and then return by making a number of fixed position measurements of the same region. In this way we were able to determine the influence of statistical fluctuation noise, which results from scanning through a region of low polarization.

These miscellaneous, special programs were performed on 17 nights. To this we should add those numerous programs having to do with tests of the instrument: the effects of time-constant, measurement of field of view and field uniformity, etc.

Most of the aforementioned programs have involved measurements at fixed positions. To complement these programs and to provide extensive spatial coverage, most of our measurements have been made in almucantar, vertical circle, or mixed scanning configurations. It is possible to scan in either continuous or stepped modes. Step-scanning has the advantage that the data can be smoothed and digitized; it has the greater disadvantage that it takes too long and it gives the observer a distorted analog "picture" of the sky. Among the scanning programs are:

7. Airglow scan. This program was devised to provide a means of monitoring the airglow line emissions; usually with the narrowest of the 5577 and 6300A filters (page 8). The procedure involves making 360-degree scans in azimuth at speeds of 2 or 2.5 deg/sec and elevations of 5, 7.5, and 10 deg or 5, 10, and 15 deg. These low elevation regions are especially sensitive to changes or enhancements, usually toward the south, in the 6300A emission. This program was used as frequently as once or twice nightly, when it would not conflict with other programs. Other programs were used to delineate spatial structure when these emissions were unusually enhanced, and all-sky observations were occasionally made.

8. Meridian airglow. This program was used to provide information that would permit a comparison of the observed and predicted distributions of intensity with elevation (optical depth). It was also used as an alternate means of measuring the amount and direction of polarization of the airglow line emissions. Vertical circle scans were used in the N-S and E-W meridians and in regions of enhanced line emission.

9. Mixed airglow. This program was designed to alternately scan in azimuth and elevation through regions of detailed structure and to periodically measure the intensity in the zenith.

236 separate airglow programs (7,8,9), generally involving 5577 and 6300A, were carried out on 185 nights since March 1965.

10. L-program. L refers to the L_4 and L_5 libration areas in the earth-moon system. Measurements were made in these areas on 18 nights. On several nights the regions were scanned at 5577A as well as at continuum wavelengths (5080, 5300, 6080A).

Two methods were used in the search for enhanced nightglow emission in these areas. In one of these, fixed-elevation, azimuth scans were made of the sky before, during, and after the time that the libration point was in the area. The other method involved mapping the region containing the libration point; on a single night or, under optimum conditions, a series of three nights (see page 50).

Observations have also been made of libration regions in the earth-sun system.

11. Axis scan. This program was designed to provide information on the position of the photometric axis of the zodiacal light. The position of the peak zodiacal light is not sharply defined, and measurements of this kind are useful only at elongations less than 60 degrees from the sun and when the ecliptic is

approximately vertical.

A wide range of scanning rates and fields of view were used in this program. Measurements were made at small, stepped intervals of elevation over a small range of azimuth centered on the ecliptic. 37 different sets of measurements at various wavelengths were made for the specific purpose of determining the position or positions of the axis of zodiacal light. This program was also used for extensive measurements on Comet Ikeya-Seki (1965 VIII) and on unusually detailed structure in the 6300A airglow emission.

12. Fixed-elevation scan. In this program repetitive azimuth scans are made at a fixed elevation. This program has the advantage that the astronomical components of the nightglow move through a fixed window of altitude and azimuth such that short-term changes in airglow continuum and in atmospheric extinction and scattering are minimized.

This program was used for a wide range of topics including airglow continuum, lunar libration clouds, Comet Ikeya-Seki (1965 VIII), and, especially, for investigation of small-scale structure and asymmetries in the zodiacal light and in the Milky Way. Observations of these same regions on successive nights provide information on structure and night-to-night variations in the airglow continuum. Also, since continuum polarization of atmospheric origin remains essentially constant, measured changes in polarization can be attributed to the different regions of the ecliptic and galactic systems that move through this "window".

13. Vertical circle. This program involves scanning in elevation at a fixed azimuth. Vertical circle programs are inefficient for many purposes since they over-observe regions of the sky near the zenith. These programs provide unusually advantageous geometries at certain times, however.

At selected times near the equinoxes, vertical circle measurements were made in the ecliptic. These measurements have provided us with observations of the principal Stokes parameters in the ecliptic at every continuum wavelength for which we have filters. Various azimuth-scanning programs were also used, when the ecliptic was vertical, to obtain information on the zodiacal light in directions normal to the ecliptic.

At sidereal time 270 degrees the ecliptic is at its greatest inclination (44.1 deg from the zenith) and the north ecliptic pole is on the prime meridian. A vertical circle at this time can provide observations from south of the ecliptic through both the ecliptic and the north ecliptic pole. The south ecliptic pole is never above 2.7 deg elevation and therefore cannot be observed from Haleakala. 28 separate vertical circle programs were carried out during this study.

14. All-sky almucantar. In this program, measurements are made through 360 deg in azimuth at a large number of elevations. A typical sequence of elevations is 10(05)45 deg and zenith, after which the sequence is repeated. These observations are used for mapping lines of zero polarization, for investigating the all-sky distribution of airglow line emission, and for general-purpose all-sky data on the nightglow.

15. Milky Way. This multi-purpose program has been used more extensively than any other scanning program. This program was designed to make measurements at 20 or more elevations (generally 5(01)24 deg) over a range of 160 deg of azimuth centered on the ecliptic and including the Milky Way. These 1-, 2-, or 4-color programs were run in the evening (MW west) and in the morning (MW east) on 357 separate occasions.

The single-color (generally 5300 or 5080A) MW west (east) programs were used for measurement of the bright regions of zodiacal light just after (before) astronomical twilight. The 2- and 4-color[1] programs similarly included the bright regions of zodiacal light, but they were started approximately 4 min earlier on successive nights. As an example, the 2-color (MW east) program was used on 13 out of a possible 14 nights in October 1967. The only change in scattering geometry among the 13 nights is the daily motion of the sun.

The MW programs contain a considerable amount of information on zodiacal light in the ecliptic and at high ecliptic latitudes, on short-term fluctuations in zodiacal light and airglow continuum, on the separation of components, and on nearly every fundamental aspect of the nightglow continuum in general and the zodiacal light in particular.

Miscellaneous other programs:

In a continuing study of the competing influences of line and continuum emission, continuum filters were used in scans across regions of unusually enhanced airglow line emission, and line filters of various widths were used in scans across bright regions of the zodiacal light.

Visible and near infrared measurements were made of the time rate of change of brightness and polarization immediately before morning twilight in October 1968. These measurements were made for comparison with anomalous near infrared results obtained by broad-band photometry[ii].

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i. These were generally 5080/5577 and 5080/5300/5450/5577A.

ii. Wolstencroft, R. D., J. C. Brandt, and L. J. Rose, 1966, Planet. Space Sci., 14, 445-447.

Comments concerning miscellaneous other procedures:

Measurements have frequently been made at elevations closer than 10 degrees to the horizon, although we are not yet able to make proper allowance for atmospheric scattering in these regions.

The circular field of view can be varied from approximately 0.7 to 5.0 degrees (diameter). Small fields are generally used in bright regions containing small scale structure and for extinction measurements. Field uniformity allows us to delineate detail which is smaller than the field of view. The Fabry field is wavelength-dependent, and its size and shape are determined from drift crossings of bright stars.

We have had considerable difficulty in maintaining reproducibility in the position of the platform which moves the mounting and polarimeter into position for observing. These difficulties have required that the position of the system platform-mounting-polarimeter be checked before each night's observations[i]. The difficulties attendant with the moving platform are far outweighed by the advantages of being able to perform all operational procedures either inside or outside the observing tower.

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i. Position is indicated to 0.1 deg in azimuth and elevation. System position is maintained to 3 min of arc.

Observing Conditions

Although nighttime observing conditions were irregularly recorded between 1962 and 1965, some general impressions can be given concerning conditions prior to March 1965:

Skies were unusually transparent during 1961-62 and the atmospheric extinction during this period was relatively stable.
During 1961-62 there was considerably less high overcast and cirrus, a somewhat higher percentage of usable observing time at night, and little or no solar aureole.
Subsequent to the explosive Bali eruption in the spring of 1963, the extinction coefficient increased by as much as 50% and it experienced large variations. More pleasantly, sunsets in Hawaii were quite spectacular for some months.

Extensive measurements were made by Bullrich, et al.[1] of solar radiation extinction, skylight, and the atmospheric aerosol during April 1964 and August-September 1965.

During the period March 1965 through October 1968, detailed records were kept of sky conditions. In summary:

	Total Hours Possible to Observe	Total Hours Observed	Percentage Possible to Observe	Number of Nights Observed
1965[ii]	1289.4	439.7	39.5 %	105
1966	1624.9	609.1	43.3	136
1967	1655.1	417.5	26.8	105
1968[iii]	1341.5	422.9	34.0	99

ii. Commencing on 23/24 March 1965.
iii. January through October 1968.

In Appendix II we tabulate the data upon which these figures are based and indicate how they were obtained.

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1. Bullrich, K., R. Eiden, R. Jaenicke, and W. Nowak, 1968, Pure and Applied Geophysics, 69, 280-319.

Additional measurements were made of outside air temperature and relative humidity. These were recorded continuously together with filter and photomultiplier temperature.

Observations were not made when clouds, including thin cirrus, were present or when the relative humidity exceeded 80 %. The Observatory is situated near the rim of the large, dormant Haleakala volcano, and high humidity and often low-level ground fog occur after clouds have entered the crater through its two channels or gaps to the sea. The infrequent winds from the north or northwest are generally accompanied by very low humidity (RH $<$10 %) and highly transparent skies.

The winter months in Hawaii are generally the rainy months, and observing conditions are degraded at that time by the lack of strong trade winds (from the east and northeast) and their associated temperature inversion. During the past two years the weather has been highly irregular and these conditions have occurred frequently during the year. In addition, increased nighttime tourist traffic to the adjacent Haleakala National Park, the increasing number of installations at or near the summit, and the lack of cooperation among scientific groups using the summit area-in our attempts to restrict traffic and lights-have further served to degrade Haleakala's status as a dark site capable of high percentage use for nightglow studies.

Data Reduction and Calibration

The plane-polarized nightglow radiation is completely specified for a given wavelength by the orientation of the plane of polarization, χ, the total degree of polarization, p_{tot}, the total brightness, B_{obs}, and the brightness of the polarized component, B_{pol}. These quantities are related by

$$p_{tot} = \frac{\sum_j B_{pol,j}}{\sum_j B_{obs,j}} \neq \sum_j p_j , \qquad (1)$$

or

$$p_{tot} = \frac{(I_\perp - I_\parallel)_{ZL} + \sum_i (I_\perp - I_\parallel)_i}{(I_\perp + I_\parallel)_{ZL} + \sum_i (I_\perp + I_\parallel)_i} , \qquad (2)$$

where $I_\perp$ and $I_\parallel$ are orthogonal components of brightness having their electric vectors perpendicular and parallel, respectively, to the plane through the source, the earth, and the observed point. ZL and i refer to the zodiacal light and other brightness components, respectively, and $j = ZL + i$.

As noted earlier, we measure χ, B_{obs}, and B_{pol}. These parameters are related through the total degree of polarization, p_{tot}, by a calibration using a pile-of-plates polarizer[1] and a diffuse, unpolarized standard source. This polarizer also permits a calibration of the direction of polarization, χ.

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1. Weinberg, J. L., 1964, Applied Optics, 3, 1057-1061.

The brightness standard is a C-14-activated, blended phosphor source obtained from the U. S. Radium Corporation. This source has a 7-inch luminous diameter, and it is placed directly over the objective for brightness calibrations. For polarization calibration the pile-of-plates polarizer is placed between the source and the objective.

The standard source has been calibrated periodically by Dr. M. Gadsden in the calibration laboratory of the NBS Fritz Peak Observatory. Comparison tests and calibrations have been performed with other similar sources. These results will be compared with our measurements[i] of bright standard stars whose spectral energy distributions have been independently determined. Additional details of the calibrations, including this comparison, will be given in the first paper of a series now in preparation: Studies of the Zodiacal Light. We estimate that we can achieve an accuracy of between 5 and 10 per cent in our determination of brightness.

In addition to the occasional detailed calibrations and system monitors (page 5), brightness calibrations were made at the beginning and end of each night's observation. Polarization calibration is required less frequently.

Our use of synchronous detection has been described previously[ii]. In brief, there are three pairs of detectors, each of which is alternately on and off for

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i. Using the zero air mass results of our extinction programs.

ii. Weinberg, J. L., 1963, Photoelectric Polarimetry of the Zodiacal Light at λ 5300, Ph.D. Dissertation, University of Colorado.
Weinberg, J. L., 1964, Ann. d'Astrophys., 27, 718-738.

90 degrees rotation of the polaroid. A 3-phase permanent-magnet generator drives the detector switch drivers which turn the detectors on and off in the proper sequence. Each detector pair is 120 deg (electrically) or 60 deg (optically) out of phase with the other pairs. Overlap in detector "on" time is used to obtain the orientation of the plane of polarization with respect to a pre-determined reference direction in the instrument.

The difference in output of the two detectors of each pair is presented on one channel of a 4-channel Sanborn recorder. The remaining detector pairs are similarly recorded. The fourth channel records the total brightness (DC). Although only two channels are required to obtain the polarization parameters χ and B_{pol}, we make use of the extra channel to reduce the uncertainty resulting from sky or instrument noise-in-signal. This results in a better solution to the equations which represent the instrument function.

Since March 1965 we have conducted various routine and special observing programs on approximately 450 nights. The major portion of this data, and all single-color (5300A) observations dating back to 1961, is in analog (strip-chart) form which is reduced either by hand or by the use of a semi-automatic analog-to-digital chart reader.

With funds from the NSF we acquired, in early 1967, a Gerber Analog Data Reduction System (GADRS-4). This analog-to-digital chart reader was chosen over other systems on the basis of its suitability for use with our 4-channel strip-chart recordings. Additions and alterations were made to the system logic and to various electro-mechanical elements for the purpose of reading the strip-chart recordings of our particular observing programs. This chart reader has proven to be a versatile and essential tool in the reduction of our large library of observations.

All of the early observations were hand-reduced by the author. The number and diversity of observing programs very quickly made necessary an extensive and more efficient methodology for handling and reducing the observations. One MW program, for example, contains 25,600 separate bits of signal information, when the records are scaled every 0.5 deg of azimuth. Seven pieces of information are required for every observation:

sidereal time and/or local time
zenith distance
azimuth
4 galvanometer deflections.

One such MW program is usually contained on 6,400 punched cards.

The precision (reproducibility) and flexibility of the Gerber chart reader provided a means of reducing the observations more rapidly. Furthermore, with proper care and training, it was possible to obtain agreement to within 0.2 units (100 units = full-scale deflection = 5 cm) among different users of the system and between results obtained by hand reduction and with the chart reader. The chart reader was used six days per week, and on four of these days for ten hours, for a total of 56 hours per week.

All of the brightness and some of the polarization information has been reduced for all nights on which we obtained fixed-position observations (celestial pole, zenith, etc.). Some of the scanning programs have been similarly reduced.

There are two procedures performed after scaling the strip-chart recordings:

1. Coordinate transformations are performed to give the position of each observation in each

of the equatorial, ecliptic (including elongation[i]), and galactic (I and II) systems. The predicted integrated starlight is determined for each observed position by a cubic interpolation in the tables based on star counts[ii].

2. The principal Stokes parameters are determined for the observed radiation.

Three of the observed or derived parameters are shown in Figure 2 for a MW east program from 29/30 October 1965. Note the appearance of Comet Ikeya-Seki (1965 VIII) south of the main cone of the zodiacal light (at A $\simeq$ 110 deg). Note, also, the regular change in the orientation of the plane of polarization in the vicinity of the main cone. This characteristic will be used to provide information on the position, in polarized light, of the axis of zodiacal light.

After converting the raw observations to Stokes parameters as seen at the base of the atmosphere, it is necessary to apply extinction and scattering corrections and to separate the individual components. These procedures have been discussed elsewhere[iii], and related topics are discussed in the subsequent section.

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i. Angular distance from the sun.

ii. Roach, F. E., and L. R. Megill, 1961, Astrophys. J., 133, 228-242.

iii. Weinberg, J. L., 1964, Ann. d'Astrophys., 27, 718-738.

Results of the Observing and Interpretive Programs

Among the topics that have been studied under the subject grant are:

1. Tropospheric scattering.

K. L. Coulson and the principal investigator are continuing studies of the redistribution of the total and polarized components of the nightglow by tropospheric scattering. The polarization of the scattered light is being investigated for various models of azimuth-dependent incident radiation fields.

A technique has been developed that will allow us to derive, from the observed radiation field, the Stokes parameters of the scattered light for the case of a plane-parallel Rayleigh atmosphere. This technique will later be extended to a spherical atmosphere with Rayleigh and non-Rayleigh components. In the first of a series of papers on tropospheric scattering, we develop the mathematical formulation and compare the observed polarization for the 5577A airglow emission line with that expected from Rayleigh scattering. We have found that the degree of polarization of the 5577 emission is small and probably explained by tropospheric scattering of an unpolarized radiation incident on the scattering atmosphere from the F and/or E regions (Coulson and Weinberg, in preparation).

2. Atmospheric extinction.

Reduction has been completed of more than 150 nights' measurements of atmospheric extinction at various wavelengths. These measurements indicate that the extinction from atmospheric dust is not wavelength-dependent; i.e., the particles are large. We have also detected local and global changes in the extinction associated with the Bali and other volcanic eruptions.

Since the visual polarimeter has been used for these measurements, both extinction and calibration data can be derived therefrom. With this narrow-band system we have been able to measure stars through as many as eight to ten air masses without significant departure from linearity in the plot of log deflection versus air mass. An example is shown in Figure 3 for observations of Vega on 29/30 March 1966 at 5750A. The solid line is the least-squares fit to all the data. Note the effect on the slope (extinction coefficient) of the reddening from those relatively few measurements at large ($>$ 10) air masses.

For a comparison of broad- and narrow-band extinction measurements, an extinction photometer used in the University's site survey studies was mounted in tandem with the polarimeter in November 1966. Observations of Vega on 9/10 November 1966 are compared in Figures 4 and 5 . The broad-band measurements, denoted as green and blue in Figure 5, are typical of the standard UBV-type measurements so frequently used. Note, in particular, the greater curvature in the blue and green measurements and the subsequent need to make such extinction determinations only by using one or two air masses.

To determine the influence of such effects, we use what is called extinction shuffle. In this "shuffle" we examine statistically the parameters (extinction, correlation coefficient, intercept, and appropriate probable errors) for all the data, all the data minus one observation, etc. This is done from both large and small air mass directions and is denoted by beginning minus and end minus in the extinction (tau) examples shown in Figures 6 and 7. This procedure will allow us to determine where the observations depart from linearity and, thereby, to derive an effective extinction coefficient and associated parameters most representative of the atmosphere in the region observed. The results will be made available in the form of an Observatory report.

3. Observations of the 5577A and 6300A airglow line emissions.

When the airglow radiations were enhanced, special programs were used to observe the spatial and temporal structure and to assess the relationship of 6300 to 5577. An example of this structure is shown in Figure 8 where copies of the original record are used to make a map of the intensities of 6300 and 5577 in the same part of the sky (to the south). The observations cover 60 degrees in azimuth and scans at 1-degree intervals of elevation. Simultaneous polarization data will be examined for possible changes related to the geomagnetic field threading the observed regions. The nature and frequency of occurrence of such activity combined with our practice of having made periodic (once or twice nightly) scans of the sky in these emissions, has insured that, weather and lunar phase permitting, few major events have gone undetected.

As noted earlier, the degree of polarization of the 5577 emission is small (approximately .01 at 20 degrees elevation, for example) and probably explained by tropospheric scattering. The polarization at 6300 is quite different in character, however. It changes direction and magnitude over the sky, in contrast to the relatively-featureless polarization associated with the 5577 emission.

We now have an extensive library of polarimetric observations of the principal airglow line emissions. These results will be made available in the form of an atlas of those observations obtained from the 236 sky-scanning programs carried out during 185 nights since early 1965. We believe this to be a new and essential key to our understanding of these often-observed and poorly-understood emissions.

4. Covariance groups in the nightglow and separation of components.

Observations of the continuum have been compared with observations of the 5577A and 6300A airglow line emissions at the celestial pole on 103 nights since March 1965. Figure 9 shows the brightness observed through eight filters at the celestial pole on 16/17 December 1966. The small variation seen through the continuum filters is typical even when the line emission varies by a factor of two or greater.

To investigate covariance groups, we make a statistical study of line versus line (5577 vs 6300) and line (5577) versus continuum, coupled with an examination of the time variation of the line and continuum emissions. Our preliminary results indicate that the 5577 line covaries with the continuum on occasion, but we do not confirm the degree or frequency of occurrence found by other investigators[1]. The 5577 line emission has its principal maximum at 90 km and a secondary maximum in the F-region which coincides with the maximum of the 6300 line emission. Under "normal" conditions the 5577 and 6300 line emissions do not covary. When the 6300 line emission is enhanced, and factor-of-ten enhancements are not uncommon at Haleakala, it covaries with the F-region portion of the 5577 emission. This further complicates the study of line and continuum covariance.

The airglow line radiations are not enhanced in the zodiacal light; i.e., we observe no enhancement when we scan across the bright regions of zodiacal light with narrow airglow filters. Similarly, we observe no appreciable enhancement through suitably-blocked continuum filters when we scan across regions of enhanced airglow line emission. Further studies are required of the effect of line and continuum filter characteristics on the inferred degree of covariance.

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i. See, for example:
Barbier, D., 1956, in The Airglow and the Aurorae (E. B. Armstrong and A. Dalgarno, eds.), 38-59, Pergamon Press, London.

The principal difficulty in making an accurate separation of nightglow components is the airglow continuum. We know neither its nature nor its origin, and it is quite possible that it is not there (at some wavelengths). Pending the results of additional studies of nightglow covariance groups and of a new technique which utilizes both the predicted and observed directions of polarization, we find that the most successful means of separating components involves subtraction of the starlight by some technique and an examination of the remainder (zodiacal light plus airglow continuum) with time and over the sky.

5. Narrow- versus broad-band measurements of nightglow polarization.

As shown earlier, the total degree of polarization, Ptot, can be written as

$$P_{tot} = \frac{\sum_j B_{pol,j}}{\sum_j B_{obs,j}} \neq \sum_j P_j \, , \qquad (1)$$

or

$$P_{tot} = \frac{(I_\perp - I_\parallel)_{ZL} + \sum_i (I_\perp - I_\parallel)_i}{(I_\perp + I_\parallel)_{ZL} + \sum_i (I_\perp + I_\parallel)_i} \qquad (2)$$

It is generally assumed that all or most of the nightglow polarization arises from the zodiacal light, i.e.: $\sum_i (I_\perp - I_\parallel)_i = 0$, whereby the problem is reduced to separating the components in the denominator of equation (2)[1]. The sum of the component degrees of polarization is not equal to the total polarization (equation (1)). Therefore, while the degree of polarization of one or more of the components may be small compared to that of the zodiacal

1. Weinberg, J. L., 1963, Nature, 198, 842-844.

light, the brightnesses of the polarized components are not. The effect of a bandpass which includes both line and continuum emission is illustrated in the sample of observations taken from data on 5/6 July 1967[1]:

Table 1. Comparison of the brightnesses and polarizations of the nightglow at 5080A and 5577A at the celestial pole on 5/6 July 1967

		5080A	5577A
Local standard time		2324	2323
Orientation of the plane of polarization, χ		105°.2	0°.5
Total degree of polarization, p_{tot}		0.046	0.0116
Total brightness, B_{obs}	i.	4.68×10^{-7}	8.72×10^{-6}
	ii.	358	6844
	iii.		198
Brightness of the polarized component, B_{pol}	i.	2.15×10^{-8}	1.01×10^{-7}
	ii.	16.5	79.4
	iii.		2.3

i. ergs/cm^2 sec ster A
ii. S_{10}(vis)
iii. rayleighs

Note that the "bright" airglow line with its small degree of polarization has a brightness in polarized light, B_{pol}, that is considerably higher than that of the "faint" zodiacal light with its higher degree of polarization. Broad-band detection does not, therefore, permit the

1. Weinberg, J. L., H. M. Mann, and P. B. Hutchison, 1968, Planet. Space Sci., 16, 1291-1296.

assumption that $\sum_i (I_\perp - I_\parallel)_i = 0$ in equation (2). This difficulty is more pronounced for observations at high ecliptic latitudes and it may account, in part, for the large polarization (degree) attributed by some observers to zodiacal light near the poles. Also, the frequent use of broad-band systems may account for the wide discordance in polarization results in the ecliptic.

6. The polarized component of zodiacal light at large distances from the sun.

The existence of negative polarization[i] far from the sun has proven to be a powerful discriminant in models of the interplanetary matter. Negative polarization has previously been found between neutral points (zero polarization) at 165 and 180 degrees elongation in the ecliptic[ii].

In a recent result[iii] we found that the position of the neutral point is wavelength dependent: it moves closer

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i. The degree of polarization can be written as

$$p = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel},$$

where $I_\perp$, $I_\parallel$ refer to orthogonal components of brightness having their electric vectors perpendicular and parallel, respectively, to the scattering plane. Negative polarization refers to the case when the electric vector is parallel to the scattering plane; i.e., $I_\parallel > I_\perp$.

ii. Weinberg, J. L., 1964, Ann. d'Astrophys., 27, 718-738. Wolstencroft, R. D., and L. J. Rose, 1967, Astrophys. J., 147, 271-292.

iii. Weinberg, J. L., and H. M. Mann, 1968, Astrophys. J., 152, 665-666.

to the sun with increasing wavelength. The observed wavelengths and the approximate positions of the neutral points in the ecliptic are given in Table 2.

Table 2. Neutral point positions in the ecliptic

wavelength, A	elongation of neutral point, deg
5080	165-175
6080	138-154
7100	133-144
8200	102-122

The polarization is small in regions around the neutral point, and it is not possible to delineate position except by a range of elongation. There is less polarization at the longer wavelengths, and it is possible that the indicated neutral point positions for 7100 and 8200 <u>may</u> just be where the polarization tends to zero; i.e., there may not be negative polarization at the longer wavelengths. This work will be extended to other wavelengths as part of a program of mapping lines of zero polarization over the sky.

Small, dielectric particles are required to produce this negative polarization, and such particles also produce enhanced brightness in the backscattering (Gegenschein) domain. It is interesting to note that in a recent study of the color and polarization of light from reflection nebulae[1] it was found that dielectric spheres predict a shift of the neutral point with wavelength in the same sense as that which we observe in the zodiacal light.

1. Greenberg, J. M., and M. S. Hanner, 1968, Astrophys. J., in press.

7. Polarization measurements at high ecliptic latitudes and the size distribution of zodiacal dust.

Contrary to the results of most Russian observers, there is now considerable evidence for an appreciable polarization in regions far from the ecliptic. Broad-band studies of the zodiacal light at high ecliptic latitudes by Beggs, et al.[i] are in agreement with our results on the measured polarization in these regions but in disagreement with the inferred polarization of the zodiacal light.

We have shown[ii] that at least part of the polarization observed at high ecliptic latitudes is associated with the zodiacal light. This is not at all an obvious conclusion, since we have found nonzodiacal light sources of polarization in the nightglow. This is further[iii] illustrated in Figure 10, where the brightness and polarization parameters at 5080A are shown for observations at the north celestial pole on 5/6 July 1967. The diurnal variation of the direction of polarization, χ, is primarily associated with the zodiacal light and with the changing position of the sun with respect to the observer and the celestial pole. This variation clearly exists only for ground-based observations, but it gives further evidence for the extension of zodiacal light to high ecliptic latitudes[iv].

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i. Beggs, D. W., D. E. Blackwell, D. W. Dewhirst, and R. D. Wolstencroft, 1964, Mon. Not. Roy. Astron. Soc., 128, 419-430.

ii. Weinberg, J. L., 1965, Planet. Space Sci., 13, 1311-1312.

iii. Weinberg, J. L., H. M. Mann, and P. B. Hutchison, 1968, Planet. Space Sci., 16, 1291-1296.

iv. The ecliptic latitude at the north celestial pole is 66.6 degrees.

It has been proposed[i] that the zodiacal light at high ecliptic latitudes may owe its origin, in part, to interstellar grains which arrive in such a way as to have orbits of random inclination. If the interstellar grains are, as expected, considerably smaller than the interplanetary grains, we would expect a change in the wavelength dependence of polarization in a direction normal to the ecliptic.

Vertical circle observations were made at sidereal time 270 degrees, when the ecliptic is at its greatest inclination and the north ecliptic pole is on the prime meridian. This provides information in a direction normal to the ecliptic, including regions of high (north and south) ecliptic latitude. These observations will be used to compare neutral point positions at high ecliptic latitudes with their corresponding positions in the ecliptic. These observations, and observations at other times, will be examined for differences in the wavelength dependence of the polarized component in and normal to the ecliptic.

8. Fluctuations in the position and brightness of the zodiacal light.

In October 1967 we obtained observations of the same bright regions of the morning zodiacal light on thirteen out of a possible fourteen nights. A similar sequence was obtained in February 1968 of the evening zodiacal light. This particular program of observations should enable us to confirm or deny the existence of short-term fluctuations in the zodiacal light. N. B. Divari states[ii], for example, that both the position and brightness of the zodiacal light undergo changes associated

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i. Greenberg, J. M., presented at 1968 meeting of COSPAR, Tokyo; to be published in Space Research IX.

ii. Divari, N. B., 1964, Soviet Astron.-AJ, 7, 547-548.
Divari, N. B., and N. I. Komarnitskaya, 1966, Soviet Astron.-AJ, 9, 632-636.
Divari, N. B., N. I. Komarnitskaya, and S. N. Krylova, 1968, Astron. Vestnik, 11, 102-107, and ST-AA-ID-10731.

with lunar phase.

In the aforementioned observations the total brightness varies from night to night, but we have not yet determined the amount, pattern, or origin of these changes. In these same observations and in other special programs, the position of the photometric axis[i] is being analyzed. Similar observations will be used to examine the question of short- and long-term solar-associated fluctuations. Worthy of mention is the fact that the zodiacal light and Gegenschein were unusually bright during May 1968.

The characteristic dimensions and scattering geometry associated with a plasma cloud are such that it would be difficult to detect scattered light from the cloud, since small-scale fluctuations are effectively masked by uncertainties associated with the airglow continuum. Preliminary calculations[ii] suggest that the solar wind may produce some degree of particle alignment. Effects of this kind are more amenable to observation.

From an analysis of a great number of observations by different observers, some investigators[iii] have concluded that the zodiacal light has both annual and solar cycle variations. We now have sufficient data to begin a search for such variations within the framework of a single, consistent body of observations from one location.

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i. The photometric axis is defined as the locus of points of maximum brightness.

ii. Greenberg, J. M., 1967, in Proceedings, Symposium on the Zodiacal Light and the Interplanetary Medium, Honolulu, NASA SP-150, 215-223.

iii. See, for example:
Thom, A., 1939, Journ. Brit. Astron. Assoc., 49, 103-112.
Weill, G., 1966, Compt. Rend., 263, 943-946.
Asaad, A., 1967, Observatory, 87, 83-87.
________, 1967, Nature, 214, 259-261.

9. All-sky determination of the wavelength dependence of the polarization of zodiacal light.

The brightness and polarization as a function of wavelength are perhaps the most fundamental observational parameters of the zodiacal light. These parameters for the nightglow as a whole are given by

$$p_{tot} = \frac{B_{pol}}{B_{obs}} \quad .$$

Each of these quantities, previously defined, refers to the uncorrected radiation as observed at the instrument. If zodiacal light were the only source of polarization, measurement of B_{obs} and p_{tot} would give the brightness of the polarized component of zodiacal light directly - at any wavelength and over the sky. This situation does prevail under certain circumstances.

Extinction and scattering are greatly reduced in the zenith and the polarization at continuum wavelengths is due only to zodiacal light and, perhaps, to diffuse galactic light when low galactic latitude regions are in the zenith. We thus have a direct means of obtaining B_{pol} of the zodiacal light as a function of wavelength for those regions which can be seen in the zenith. The range of ecliptic latitude in the zenith at Haleakala is -2.7 to 44.1 degrees.

Multi-color observations in the zenith have been obtained on 104 nights during the past five years. All of the brightness and some of the polarization data have been reduced.

If the Milky Way and regions closer than ten degrees to the horizon are avoided, this technique can also be used to derive the zodiacal light polarization from our all-sky scanning observations.

The brightness of the polarized component and the measured orientation of the plane of polarization give us two of the three parameters required to completely specify the zodiacal light radiation field. Knowledge of these two parameters will assist in deriving the third (total brightness).

10. The distribution of starlight at low galactic latitudes.

Starlight is defined as the sum total of brightness from integrated starlight, diffuse galactic light, and other sources not having their origin in the atmosphere or in interplanetary space. An empirical technique for deriving the starlight is illustrated in Figure 11 where we have plotted the observed brightness at 5300A for part of an almucantar including the peak zodiacal light and regions of both high and low (denoted as I and II, respectively) galactic latitude. These regions are bounded by points a, b, c, and d, whose galactic coordinates (b^I, l^I) are shown at the top of Figure 11. The smooth curve drawn in region I is used as a background for region II above which the differential starlight (the cross-hatched area) is measured. This differential starlight is corrected for atmospheric extinction and scattering and is then added to the integrated starlight corresponding to the b^I, l^I of the background or mirror points via a cubic interpolation in tables[1] based on star counts in the Selected Areas. This sum is termed "starlight".

For best results the almucantar scan should be approximately centered on the peak zodiacal light. The central value of azimuth, from which the mirror regions are reckoned, is chosen to approximately the brightness distribution near its peak value. The choice of boundaries is governed by the range of azimuth over which the total brightness is measured, by the position of the plane of the galaxy with respect to the peak zodiacal light, and by how close the mirror points are in ecliptic latitude and elongation. To satisfy these requirements and to assure that differential atmospheric scattering will be minimized, the ecliptic must be within $\pm$ 5 degrees of the vertical. The aforementioned Milky Way programs are used for this purpose.

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1. Roach, F. E. and L. R. Megill, 1961, Astrophys. J., 133, 228-242.

Inherent in the technique are the assumptions that (1) the zodiacal light is approximately symmetric about its axis, (2) the airglow continuum is constant over the range of azimuth included in the measurement, and (3) the starlight is constant. The reproducibility of results obtained on different nights indicates that these assumptions are valid. This technique applied to satellite observations made perpendicular to the ecliptic appears to be especially well suited for giving the nonzodiacal light component over a range of perhaps ± 40 degrees of galactic latitude.

Observations taken in October 1965 and January 1966 at 5300A have been reduced and are being analyzed in a program to prepare a table/map of the starlight in selected regions of the Milky Way. Similar tables will be constructed from observations at other wavelengths and at other times. These results can then be compared with the integrated starlight derived from high resolution star count studies and photometry of the Selected Areas[i], and they can be used to facilitate the subtraction of starlight from nightglow observations.

We observe a considerable amount of small-scale structure which is not found in the smoothed star-count results (Figure 12), and although our results are generally above those predicted by the star counts, in some regions the calculated integrated starlight exceeds the total observed brightness. Although the existing star-count results cannot be used as a base for separating components of the nightglow at low galactic latitudes, the use of the tabular values does not introduce a significant error at high latitudes where the starlight is relatively faint.

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i. See, for example, the reports of the Committee of 'Selected Areas' of Commission 33 of the International Astronomical Union.

11. The diffuse galactic light.

Although the diffuse galactic light cannot be separately observed, there is widespread belief that it does exist in significant amounts at low galactic latitudes[1]. The gross differences in structure and amount between the observed radiation and that predicted from the analysis of early work on star counts precludes the use of such a comparison to establish either the existence or the characteristics of the diffuse galactic light.

The subject star counts cover a relatively small number of regions of the sky such that there is, necessarily, very limited spatial resolution. At the Tokyo Astronomical Observatory a technique has been developed and is being used by Dr. H. Tanabe to systematically measure numbers, magnitudes, and colors of stars over extensive regions in the Palomar Sky Atlas. One result of this important study will be the ability to prepare detailed, high resolution tables of the integrated starlight. These can then be compared with our starlight results and with other photometric studies at low galactic latitudes to provide detailed information on the diffuse galactic light.

A more immediate means of establishing the nature of a component of diffuse galactic light involves polarization. One of the nonzodiacal light sources of polarization we have detected in the nightglow appears at low galactic latitudes as a change in direction of polarization as we scan through these regions[11]. The detection,

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1. See, for example:
   Elvey, C. T. and F. E. Roach, 1937, Astrophys. J., 85, 213-241.
   Henyey, L. G. and J. L. Greenstein, Ann. d'Astrophys., 3, 117.
   Roach, F. E., 1967, in Modern Astrophysics, Paris, 49.

11. In a private communication (1965), R. D. Wolstencroft reported that he had obtained similar results.

quantitatively, of such a polarized component would verify the existence of the diffuse galactic light and it would provide an independent source of information on the nature of the interstellar grains.

As noted in section 9, zenith observations are capable of providing, directly, the brightness of the polarized component of zodiacal light and, perhaps, the diffuse galactic light. In the zenith, declination equals geographic latitude and right ascension equals sidereal time. The annual course of ecliptic and galactic latitude in the zenith is shown in Figure 13 for geographic latitude 21 degrees. There is generally a sidereal time at which the ecliptic (galactic) plane moves through the zenith at high galactic (ecliptic) latitudes. An increase in the brightness of the polarized component, B_{pol}, as low galactic latitude regions move through the zenith is a direct measure of the polarization of the diffuse galactic light.

Although the range of ecliptic and galactic latitude in the zenith is generally limited at a single observing site (Table 3), the zenith at Haleakala is able to provide detailed information on the diffuse galactic light in some regions of the galaxy. If the diffuse galactic light has a polarization sufficiently large that it can be measured, we should be able to derive its wavelength dependence from our zenith and all-sky observations.

Table 3. Ecliptic and galactic latitude in the zenith at various geographic latitudes.

geographic latitude	range of ecliptic latitude		range of galactic latitude	
66°.6[i]	43°.2	to 90°.0	4°.3	to 51°.1
60	36.6	83.4	-2.3	57.7
50	26.6	73.4	-12.3	67.7
40	16.6	63.4	-22.3	77.7
30	6.6	53.4	-32.3	87.7
20.7[ii]	-2.7	44.1	-41.6	83.0
10	-13.4	33.4	-52.3	72.3
0	-23.4	23.4	-62.3	62.3
-10	-33.4	13.4	-72.3	52.3
-20	-43.4	3.4	-82.3	42.3
-30	-53.4	-6.6	-87.7	32.3
-40	-63.4	-16.6	-77.7	22.3
-50	-73.4	-26.6	-67.7	12.3
-60	-83.4	-36.6	-57.7	2.3
-66.6[iii]	-90.0	-43.2	-51.1	-4.3

i. The ecliptic pole is in the zenith at this latitude at sidereal time 270 degrees.

ii. Haleakala Observatory.

iii. The ecliptic pole is in the zenith at this latitude at sidereal time 90 degrees.

12. Comet 1965 VIII and the zodiacal cloud.

Multi-color polarimetric observations of the tail of Comet Ikeya-Seki (1965 VIII) were obtained on 4 nights[i] following perihelion on 21 October 1965. Since we had not yet acquired a red-sensitive photomultiplier, these observations were made with a Dumont 6291 tube with an S-11 surface. This tube, selected for high AC signal-to-noise ratio, was used for nearly all observations made with the polarimeter from its installation at Haleakala in October 1961 until January 1966. With this tube we made observations of Comet 1965 VIII at six continuum wavelengths[ii] and, with two different filters centered on the same line, at the 5577A emission of [OI].

One set of observations at 5300A on 28/29 October 1965 has been reduced. The measurements were made by scanning at 0.5 deg/sec over a 9 x 20 deg section of the sky containing the Comet: in azimuth, from 105 to 114 deg (90 = east), and in elevation, from 0 (horizon)[iii] to 20 deg in steps of 1.0 deg. This method of scanning results in considerably more information normal to the axis of the tail of the Comet. At other times, different scanning programs were used that provided more detailed coverage along the axis. The observations, which were hand-reduced by the author, are shown in Figures 14 through 18 .

Figure 14 shows the total brightness of background plus Comet for elevations (altitude) 2 to 20 deg, as seen at the base of the atmosphere. This particular set of observations began at 1432 and ended at 1441 UT on 29 October 1965. The Comet nucleus was 5.3 deg below the horizon at the start of the 2 deg elevation scan.

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i. October 27/28 and 28/29; November 1/2 and 3/4, 1965.

ii. 4355, 4760, 5080, 5300, 5450, 5752A.

iii. The Observatory has a depressed horizon of approximately 1.7 deg.

To illustrate the relative positions of the Comet and of our observations, we acquired a photograph of the Comet taken from Haleakala on the morning before our measurements. The position of the Comet in this photograph (Figure 15), which was made available by the SAO, was modified by a translation and a rotation. The Comet aspect is shown for 1435 UT, which corresponds to its position at the end of the 6 deg elevation scan. The Comet, horizon (solid line), and scans (even-numbered elevations from 2 through 10) are correct as shown; star positions are not. The width of the Comet tail, as seen by the polarimeter, is a direct result of our use of a 3-degree Fabry field of view.

Figures 16 and 17 show the brightness of the polarized component and the total degree of polarization, respectively. Of particular interest is the change in polarization between 6 and 7 deg elevation (approximately 11 deg from the nucleus). Since the background (primarily zodiacal light) and Comet radiations are independent, their Stokes parameters are additive. The polarization of zodiacal light in this area is positive; i.e., the electric vector is perpendicular to the scattering plane. Only negative polarization at distances greater than 11 degrees from the nucleus can produce the observed net decrease in total polarization in the direction of the Comet tail.

This is further illustrated by the total orientation of the plane of polarization (Figure 18), χ. The fluctuations in χ between 7 and 15 deg elevation are a result of the combination of components polarized in nearly orthogonal directions and, between 9 and 11 deg elevation, of the nearly zero total polarization. The negative polarization continues from the neutral point (zero polarization) at 11 degrees from the nucleus throughout the remainder of the tail.

The Comet is ideally positioned with respect to the main cone of the zodiacal light (Figure 2), and the separation of the Comet from the uniformly-varying total brightness is easily accomplished. The irregular variation of the background polarization makes separation of this component somewhat more difficult. The method being used to derive the Comet radiation field is illustrated by the solid lines shown in Figure 14 (2 deg) and Figure 16 (3 deg).

Negative polarization, as in the case of zodiacal light, requires the presence of dielectric particles. The use of additional observations at several wavelengths at different times suggests that it may be possible to delineate a rather small family of allowable solutions for the size distribution and chemical composition of the particles in the tail of the Comet.

Numerous observations before and after perihelion make it possible to search for effects resulting from the newly injected cometary material. We have found no large-scale changes in the zodiacal light in a two-week period including perihelion.

13. Lunar libration clouds.

The Maui tracking station of the SAO has photographed, with a Baker-Nunn camera, regions in and near the positions of L_4 and L_5 while we simultaneously carried out visual and photoelectric observations of the same regions. On the possibility that either the existence or extent of these clouds may be time-dependent, we have obtained observations of these regions on 18 nights between March 1966 and July 1968. These nights were chosen on the basis of ephemerides carefully prepared to avoid the disturbing effects of the Milky Way, the Gegenschein, and regions near the horizon.

No visual enhancement that could be associated with libration clouds was observed in or near the predicted regions at any time. The atmospheric transparency was high on many of these nights, and some observers were able to distinguish stars to magnitude 7.4.

We have developed what may be described as a photoelectric blink-method. This involves observing an area of the sky on three successive nights such that the libration point in question traverses the diagonal of a 3 x 3 observing window matrix. Copies of the strip-chart recordings are used to make an alt-azimuth "map" of the observations. This map is then photographed and the negatives of the maps for each night are examined in various overlay configurations. With this technique we are able to distinguish any differential enhancement that is approximately 0.3 % above the background.

An example of such a map is shown in Figure for three successive nights beginning with 29/30 January 1968. These observations, at 5080A with a 3-degree field of view, were obtained by scanning at 2 deg/sec over a range of azimuth from 251 to 295 deg (270 = west) and from 20 deg to 41 deg elevation in steps of 0.1 deg. The map in Figure 19 was prepared from data every 0.2 deg in elevation. A similar set of data is available for alternate elevations and the opposite scanning direction. The program was performed, on the first night, between 2049 and 2255 HST. The program was started approximately 4 minutes earlier on each of the subsequent nights. The only change in scattering geometry among the 3 nights is the movement of the libration point and the daily motion of the sun, which will affect the background level but not the detailed structure.

In this data, and in data on several other nights, we are unable to detect the presence of a photometric enhancement that could be attributed to lunar libration clouds. The remaining photoelectric data, including polarization, is being similarly evaluated.

A casual examination of the photographic observations also fails to produce any positive results. Isodensitometry will be performed on selected Baker-Nunn negatives of the subject regions.

If the remaining observations similarly produce negative results, we shall establish an upper limit to the brightness associated with these "clouds".

Miscellaneous other topics for which we have applicable observations:

1. The Gegenschein.
2. Atmospheric components of zodiacal light (false zodiacal light and zodiacal twilight).
3. Meteoric material in the plane of cometary orbits.
4. Near-Earth versus interplanetary dust.

Results communicated during the grant period:

Summary Report on Zodiacal Light, July 1964, Hawaii Institute of Geophysics report HIG-64-11, 18 pp., 1964.

The Current Status of Zodiacal Light Research, paper presented at 12th General Assembly, IAU, Hamburg, August, 1964; comments and bibliography in *Trans. IAU*, *XIIA*, *B* (1964), Academic Press, 1966.

Zodiacal Light at the Celestial Pole, *Planet. Space Sci.*, *13*, 1311-1312, 1965.

Photoelectric Polarimetry of Comet 1965f, paper presented at 122nd meeting, AAS, Cornell, July 1966; abstract in *Astron. J.*, *71*, 875, 1966.

Zodiacal Light as an Indicator of the Nature of the Interplanetary Matter - Past, Present, and Prospective Results, *Smith. Contr. Astrophys.*, *11*, 203-212, 1967.

Summary Report II on Zodiacal Light, July 1967, Hawaii Institute of Geophysics report HIG-67-13, 26 pp., 1967.

A Program of Ground-Based Studies of the Zodiacal Light, in Proceedings, *Symposium on the Zodiacal Light and the Interplanetary Medium*, NASA SP-150, 3-8, 1967 (with H. M. Mann).

Proceedings, *Symposium on the Zodiacal Light and the Interplanetary Medium*, Honolulu, 1967, 430 pp., NASA SP-150 (J. L. Weinberg, editor).

Negative Polarization in the Zodiacal Light, *Astrophys. J.*, *152*, 665-666, 1968 (with H. M. Mann).

Polarization of the Nightglow: Line versus Continuum, *Planet. Space Sci.*, *16*, 1291-1296, 1968 (with H. M. Mann and P. B. Hutchison).

Additional results of the observations and other studies performed under the subject grant will be given in two series of papers: Polarization of the Nightglow, now appearing in Planetary and Space Science, and Studies of the Zodiacal Light, to appear in the Astronomical Journal.

Personnel and Collaborative Projects

The size and diversity of this program have involved a large number of personnel and have made extensive collaborative projects both possible and desirable. In summary:

1. Principal Investigator. The program has been directed during its entirety by Dr. J. L. Weinberg. Dr. Weinberg took up residence near the Observatory in January 1965 and devoted full time to this program.

2. Other.

H. M. Mann, Research Associate. Mr. Mann has worked on studies of the nightglow for over a decade, and he has worked closely with the principal investigator on all aspects of the program.
H. D. Hultquist, Electronics Technician, July 1966 - Oct 1968.
R. W. Owen, Data Analyst, May 1966 - June 1967.
D. E. Beeson, Research Assistant, Aug 1967 - Aug 1968.
P. B. Hutchison, Research Assistant, Dec 1966 - Oct 1968.
J. G. Carlson, Instrument Machinist, July 1966 - May 1967.
K. A. C. Bruns, Research Assistant, Feb 1967 - Aug 1968.
C. A. K. Dilley, Observer, July 1965 - Feb 1968.

Mrs. C. Hensley, Assistant, Fall 1965 - Sept 1968.
Mrs. M. Perry, Assistant, Data Handling, Oct 1966 - July 1967.
Mrs. B. Walker, part-time assistant, clerical and data handling, 1966 and 1967.
Mrs. J. Enterline, Assistant, Data Handling, Mar 1967 - spring 1968.
Mrs. E. Larsen, Assistant, Data Handling, Aug 1967 - Oct 1967.
Mrs. K. Kimbrough, Assistant, Data Handling; spring, summer 1968.
Mrs. S. Bialecki, Assistant, Data Handling; spring, summer 1968.

E. V. Ashburn, Physicist, Lockheed; summer 1964.
K. L. Coulson, Professor of Meteorology, University of California, Davis; December 1966.
J. M. Greenberg, Professor of Physics and Astronomy, RPI; summer, 1968.

Mrs. M. Weinberg, Mathematician-Programmer; as needed.
Mrs. P. Kahanamoku, Clerical; as needed.

3. Students.

Miss Sharon Miki, summer 1964.
Donald Hughes, summer 1966 and 1967.
Jerry Cole, summer 1967.
Josh Greenberg, summer 1968.
Mrs. M. Hanner, graduate student, RPI; summer 1968.

4. Collaborative Projects.

i. University of California, Davis. K. L. Coulson and the principal investigator have continued studies of tropospheric scattering of the nightglow. Dr. Coulson worked at the Observatory in December 1966, and the principal investigator spent several days in Davis in August 1967 and June 1968.

ii. ESSA/ITSA, Boulder, Colorado.

(1) T. E. van Zandt, V. L. Peterson, and L. L. Smith have been provided data on the 5577 and 6300 airglow line emissions on several occasions when these radiations were unusually active.

(2) We have operated an earth current recording system for W. H. Campbell, who is following local magnetic disturbance variations in the 1 hour to 1 second period range and comparing signal spectra and wave front arrival times between College, Alaska and Hawaii. We are examining the possibility that these variations may be advance indicators of activity in the airglow emission lines.

iii. Rensselaer Polytechnic Institute. The theoretical group under J. M. Greenberg has worked closely with the principal investigator on several problems associated with the interplanetary/interstellar spaces. Dr. Greenberg and one of his students, Mrs. M. Hanner, spent part of the summer, 1968, at the Observatory.

iv. Smithsonian Astrophysical Observatory.

(1) Meteoric material in the plane of cometary orbits. At the request of F. L. Whipple, and based on ephemerides provided by B. G. Marsden, a joint program with the SAO Baker-Nunn camera was planned to search for "patchyness" in the

nightglow along the directions of the tangents to the orbits of major periodic comets. Bad weather precluded our making observations at the required times. Existing records dating back to 1961 will be searched for this effect.

(2) Lunar libration clouds. The SAO Baker-Nunn camera has photographed regions in and near the positions of L_4 and L_5 while we were making visual and photoelectric observations of the same regions. As noted earlier, a preliminary analysis has not confirmed the existence of these clouds. There is added interest by the Dudley Observatory (C. L. Hemenway) and by NASA (M. Dubin) in the possibility of particle collection in the subject areas.

v. The University of Manchester. J. F. James of the Physical Laboratories has developed a multiplex spectrometer of high light gathering power and high resolution, and arrangements have been made for Mr. James to bring the instrument to Haleakala in late December 1968 or early January 1969. His study will be aimed at a detailed comparison of a Fraunhofer line in the direct (solar) and scattered (zodiacal light) radiation for estimating electron densities and for information on particle dynamics in the interplanetary space. The instrument will be housed on a pad adjacent to the night-sky facility and the electronics will be located in the main building.

Conference ZLIM

The International Symposium on the Zodiacal Light and the Interplanetary Medium (ZLIM) was organized[1] by Drs. Roach and Weinberg and hosted by the University of Hawaii. The Symposium, the first international meeting on the subject of zodiacal light, opened on Monday morning, 30 January 1967 at the East West Center on the campus of the University of Hawaii. During the four days of the Symposium, consisting of sessions in the morning (invited papers) and afternoon (contributed papers), 55 papers were presented by a group of 75 participants coming from Canada, Europe, Israel, Japan, and the United States.

On Friday, 3 February 1967, approximately seventy participants and guests toured the University's Zodiacal Light Observatory. A tour was also conducted of other University of Hawaii facilities, of the Smithsonian Observatory, and of the University of Michigan Observatory. The dozen people who stayed at the Observatory in the evening were rewarded by perfect weather and an unusually transparent sky. The zodiacal band could easily be followed across the sky to the Gegenschein, which most people saw for the first time. As a further bonus, observations with the zodiacal light polarimeter indicated unusual structure in the 5577A airglow line emission on this night.

The Symposium Proceedings was published as a NASA Special Publication: The Zodiacal Light and the Interplanetary Medium, NASA SP-150, 430 pp., 1967.

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1. Under the auspices of Commission 21 of the IAU, and with the financial support of NASA (NGR 12-001-031), the AIAA, and the University of Hawaii.

The Editor, J. L. Weinberg, was assisted by M. Dubin, G. A. Newkirk, and F. E. Roach. Appendix III contains a cover page and list of contents. Perhaps most worthy of mention is not individual results, of which many merit attention, but the somewhat interdisciplinary nature of the Symposium. The meeting afforded an opportunity to bring together groups working on many diverse aspects of the problems pertaining to zodiacal light and the interplanetary medium.

The Next Five Years

The principal investigator and H. M. Mann assumed positions with the Dudley Observatory on 1 November 1968. Future studies are being planned in two broad areas:

1. Reduction and analysis of existing data.

The existing instrument has been utilized to its full capability for polarimetric observations of the nightglow, and we have one of the most extensive libraries of such observations ever obtained. It is our intent to conduct an intensive analysis of nearly seven years of observations in the academic environment provided by the State University of New York at Albany, the Dudley Observatory, and the Rensselaer Polytechnic Institute.

There are two series of laboratory measurements which must be performed before the existing observations can be properly analyzed in their entirety: completion of tests involving the red-sensitive photomultiplier designated as Tube II (page 6), and additional polarization calibrations. As noted earlier, several thousand hours of monitoring tests have already been made of the polarimeter and associated electronics, including several photomultipliers. Additional tests are required of Tube II to determine the relationship of the time rate of change of gain to the amount and area of cathode illumination.

To properly assess the spectral purity[i] needed to be able to neglect the continuum in the presence of line

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i. Spectral purity relates the positions of the central wavelength and emission wavelength, the bandwidth, the off-band rejection, the area under the curve of transmission versus wavelength, and a shape factor.

emission, we have made repetitive observations of airglow line emission at the celestial pole with all of the filters previously described. Complementary measurements are required of the detailed optical characteristics of these filters. In practice, the characteristics of such filters vary with temperature and over the filter surface, and it is necessary to measure their characteristics in an optical configuration similar to that in which the filters are used. We hope to acquire a Czerny-Turner monochromator with which we will be able to properly measure and monitor such characteristics as bandwidth, band position, off-band rejection, temperature and pressure effects, and uniformity. We have shown[11] that both the bandwidth and band position are critical factors in evaluating polarization measurements of the nightglow.

If the Gerber data reduction system is not available for use in the continuing reduction of these observations, it will be necessary to build another similar system. This is complicated by the fact that the subject system is no longer produced by the manufacturer. We may be able to acquire a used Gerber reading head and interface it to the small computer of the Dudley Observatory.

From the beginning of this program, it has been our intent to provide a large, versatile library of nightglow observations. It is now appropriate to make the results of this study available in the shortest possible time. Active graduate student and post-doctoral participation will be sought in both the reduction and analysis of these observations.

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1. Weinberg, J. L., 1963, Nature, 198, 842-844.
   Weinberg, J. L., H. M. Mann, and P. B. Hutchison, 1968, Planet. Space Sci., 16, 1291-1296.

2. Observations and instrumentation.

It is anticipated that construction and testing of the preliminary version of the near UV/near IR photoelectric polarimeter (page 10) could be completed by early 1970. At that time the final optical configuration could be designed. Subject to the availability of funds and to the usual delays attendant with acquisition of even small optical systems, the near UV/ near IR polarimeter could be completed in early 1971. It is appropriate to consider locating this instrument at the site to be chosen by the New York Astronomical Corporation for its observing facility.

In the design of this new instrument, we have been guided by the importance of extending the present studies to wavelengths not previously observed, while providing overlap with wavelength regions and studies previously obtained. For example, it is clear that additional studies are indicated for the polarization of airglow emission in the visible[1] and in other spectral regions.

Another aspect of this new instrument has more far-reaching implications. This new instrument is also being designed as a prototype for tests of a multi-purpose, state-of-the-art facility designed specifically for photometric studies of extended sources: ranging from reflection nebulae, diffuse galactic light, cosmic light, and zodiacal light in the astronomical sense to airglow, twilight, and day-sky studies in the atmospheric sense. There does not exist a facility, for graduate student instruction or research, that is suitable for the multi-disciplinary studies associated with the photometry of extended sources.

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1. For example, the lines of the OI $_{21}$ red doublet should have an intensity ratio 6300/6364 of 3 to 1, and the direction and magnitude of polarization of the two lines should be different (J. W. Chamberlain, private communication).

Support is currently being sought in three principal areas:

1. Continued analysis of the observations and performance of those laboratory tests required for this analysis;

2. Modification of the polarimeter for use in special observing programs from an airborne platform;

3. Continued construction and testing of the near UV/ near IR photoelectric polarimeter.

Acknowledgements

A great many people have contributed to this program. In addition to those personnel listed earlier in this report, I wish to acknowledge the assistance of R. H. Lee of the High Altitude Observatory, A. Gray of ESSA/ITSA, Dr. F. E. Roach, and the Office of Research Administration and the Computing Center of the University of Hawaii. The program was developed in and supported by the University's Hawaii Institute of Geophysics, under Dr. G. P. Woollard, between June 1964 and July 1967. After 1 July 1967 the program was under the auspices of the University's Institute for Astronomy, under Dr. J. T. Jefferies. The National Science Foundation provided funds for the facility, for equipment used in the data analysis, and for a substantial number of salaries. Special thanks go to H. Mack Mann; without his tireless devotion to the program, it could not have been performed in so short a time.

Appendix I. Inventory of major items of equipment (costs in excess of $1000) obtained with funds from NASA grant NsG-676 or from its predecessors (NsG-135-61, NsG-15-59)*.

Item and Description

1. Tektronix oscilloscope, portable, model 422, approx cost $1400.

2. Parabam Astrodome, fiberglass, model 3339C, approx cost $1300.

3. U. S. Radium Corporation C-14-activated, blended phosphor standard source, approx cost $1400.

4. Ascop photomultipliers (Electro-Mechanical Research):

   541E-01-14 (D936), S-20 surface, approx cost $2100.
   541E-05M (7905), S-20 surface, approx cost $2100.
   543C-01 (D7857), S-1 surface, approx cost $2100.

   D936 is a red-sensitive photomultiplier; 7905 is a blue-sensitive photomultiplier with a sapphire window.

5. One photoelectric polarimeter, visual spectral region. This instrument consists of a small telescope (5.5-inch diameter objective), a controllable, recording refrigeration system, an alt-azimuth mounting, interference filters designed specifically for use with this telescope, a 4-channel recording system, amplifiers, power supplies, a synchronous detector, and other electronic and optical components.

6. One solid-state programmable control system. This system controls the polarimeter and its mounting for the specific observing programs to be performed. It was built by the Digital Instrumentation Group of the NBS at an approximate cost of $20K.

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*The telescope and some of the electronics in item no. 5 were developed under NsG-15-59 (High Altitude Observatory) and under NsG-135-61 (High Altitude Observatory and University of Hawaii).

Appendix I - continued.

7. One digital system designed and built specifically for use with the aforementioned polarimeter and control system and with CDC computing equipment. This system was also built by the NBS - at an approximate cost of $25K.

8. One photoelectric polarimeter, near ultraviolet and near infrared spectral regions; under construction. Some of the items which are part of this partially-completed instrument are:

   1 Fluke 408B high voltage supply
   1 Sanborn 7700 four-channel recorder and power supply
   6 Philbrick HFPMP operational amplifiers
   1 Sanborn 7714A-04A driver amplifier
   2 Data Device operational amplifiers
   1 Philbrick SPR-30 power supply.

Appendix II. Observing conditions - March 1965 through October 1968.

	Total Hours Possible to Observe[i]	Total Hours Observed	Percentage Possible to Observe[ii]	Number of Nights Observed
1965				
Mar	68.5[iii]	13.2	19.3 %	5
Apr	134.1	33.4	25.8	7
May	127.4	38.4	30.1	8
June	113.3	61.5	54.3	16
July	117.9	47.5	40.5	10
Aug	127.8	76.8	61.6	16
Sept	133.8	59.1	54.7	15
Oct	150.2	70.7	65.4	16
Nov	153.1	11.8	11.7	4
Dec	163.3	27.3	31.4	8
Totals	1289.4[iii]	439.7	39.5 %	105
1966				
Jan	163.1	69.6	55.9	18
Feb	150.9	25.9	21.4	8
Mar	150.8	81.0	61.3	17
Apr	134.1	71.1	59.5	13
May	124.6	33.4	27.9	9
June	116.8	42.7	46.0	11
July	115.6	14.4	12.5[iv]	5
Aug	120.3	31.7	56.1[iv]	10
Sept	127.0	85.9	68.3	15
Oct	130.7	11.2	8.6[iv]	4
Nov	140.1	48.8	39.3	10
Dec	150.9	93.4	62.8	16
Totals	1624.9	609.1	43.3 %[iv]	136

i. Based on end of evening twilight to beginning of morning twilight, less time of moon above horizon.

ii. 100 % - perfect weather whenever it was possible to observe.

iii. Commencing on 23/24 March 1965.

iv. Times of maintenance and modification: July 15-August 7 and October 1-10, 1966. Since weather records were not kept at these times, the percentage possible to observe figures are slightly low and are based only on times when the instrument could be used.

Appendix II - continued.

	Total Hours Possible to Observe[i]	Total Hours Observed	Percentage Possible to Observe[ii]	Number of Nights Observed
1967				
Jan	158.5	65.5	41.6 %	14
Feb	142.9	35.7	25.0	9
Mar	152.1	8.7	5.7	3
Apr	138.5	6.2	17.5[iii]	2
May	131.9	19.2	17.0	6
June	115.7	25.6	22.1	8
July	118.0	46.6	40.1	13
Aug	124.8	28.5	25.6[iii]	7
Sept	127.9	37.2	29.1	13
Oct	145.8	76.6	52.7	14
Nov	142.4	37.0	26.0	9
Dec	156.6	30.7	20.2	7
Totals	1655.1	417.5	26.8 %[iii]	105
1968				
Jan	149.4	45.7	33.2	12
Feb	139.5	66.9	48.0	10
Mar	151.7	25.0	20.0	6
Apr	134.4	19.6	15.7	6
May	128.8	85.0	67.0	16
June	118.0	38.3	33.0	10
July	125.1	19.5	15.7	5
Aug	130.6	47.3	43.4	13
Sept	129.1	26.3	23.1	9
Oct	134.9	49.3	40.6	12
Totals	1341.5	422.9	34.0 %	99

i. Based on end of evening twilight to beginning of morning twilight, less time of moon above horizon.

ii. 100% would indicate perfect weather whenever it was possible to observe.

iii. Times of maintenance and modification: April 14-27 and August 17-29. Weather conditions were not kept at these times, but, since both periods included full moon, the percentage possible to observe figures would be only slightly affected.

NASA SP-150

Appendix III.

The Zodiacal Light and the Interplanetary Medium

Edited by

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University of Hawaii

Scientific and Technical Information Division
OFFICE OF TECHNOLOGY UTILIZATION 1967
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D C

Contents

I

PHOTOMETRIC OBSERVATIONS

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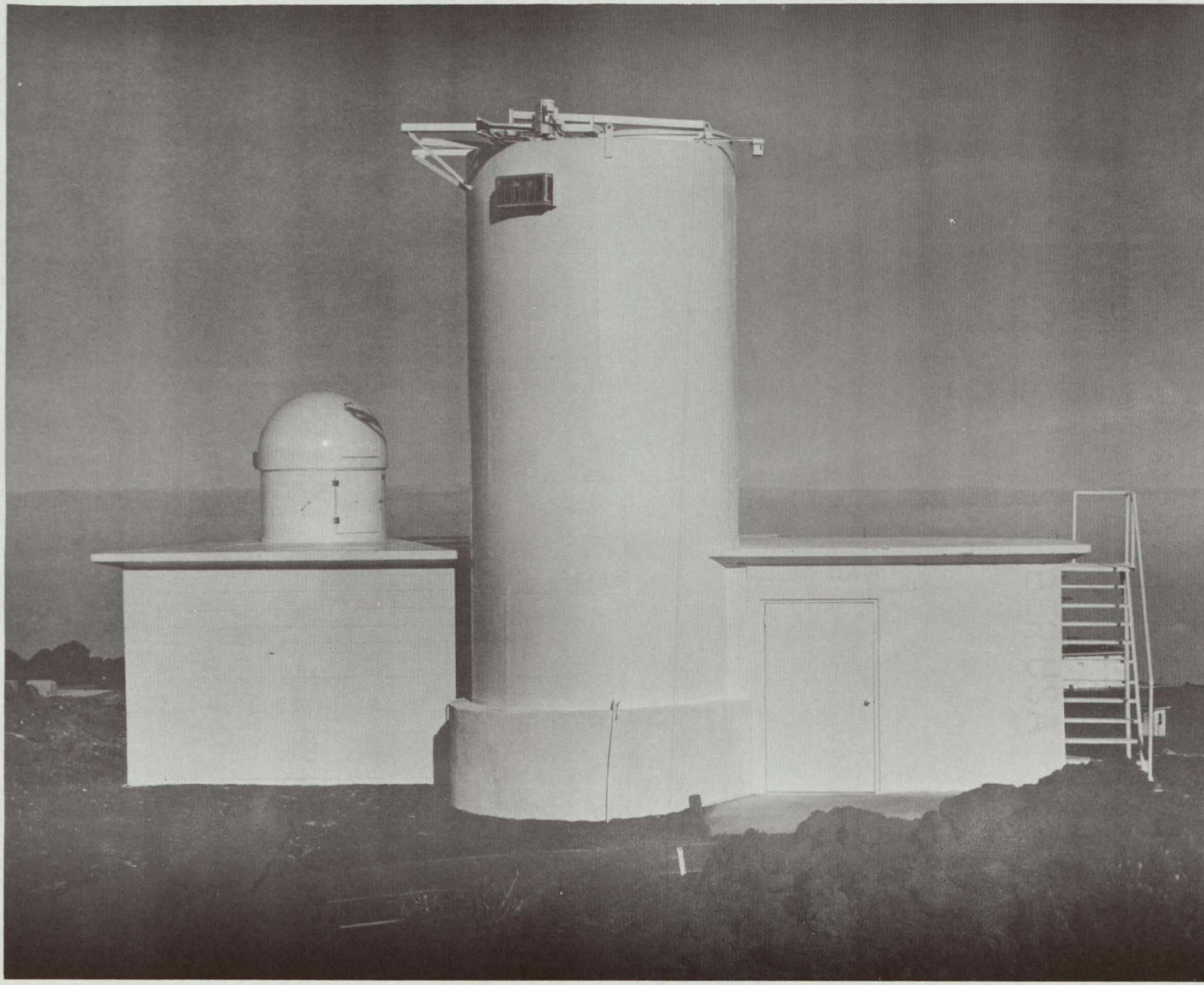


PLATE I

PLATE 2

PLATE 3

PLATE 4

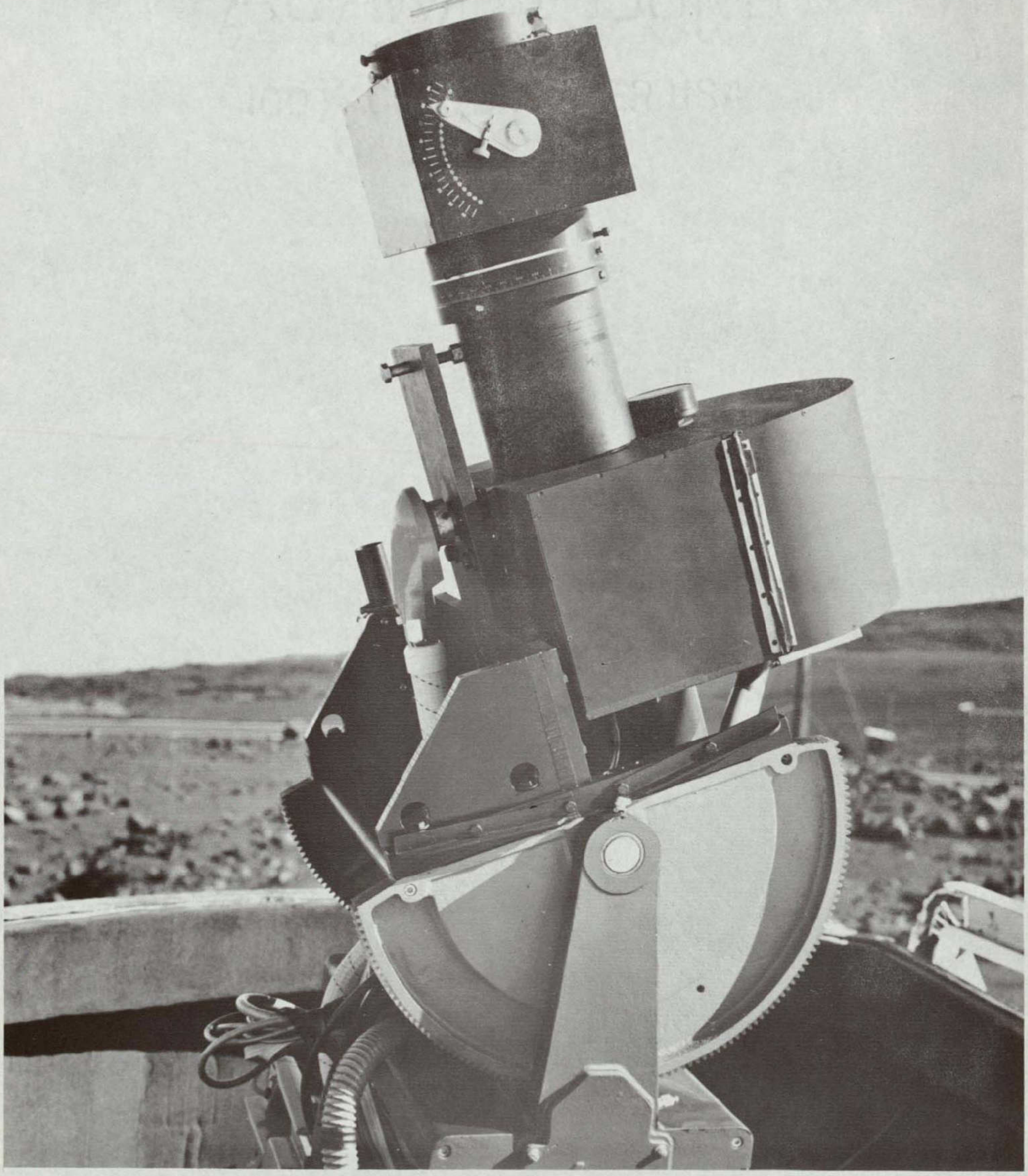
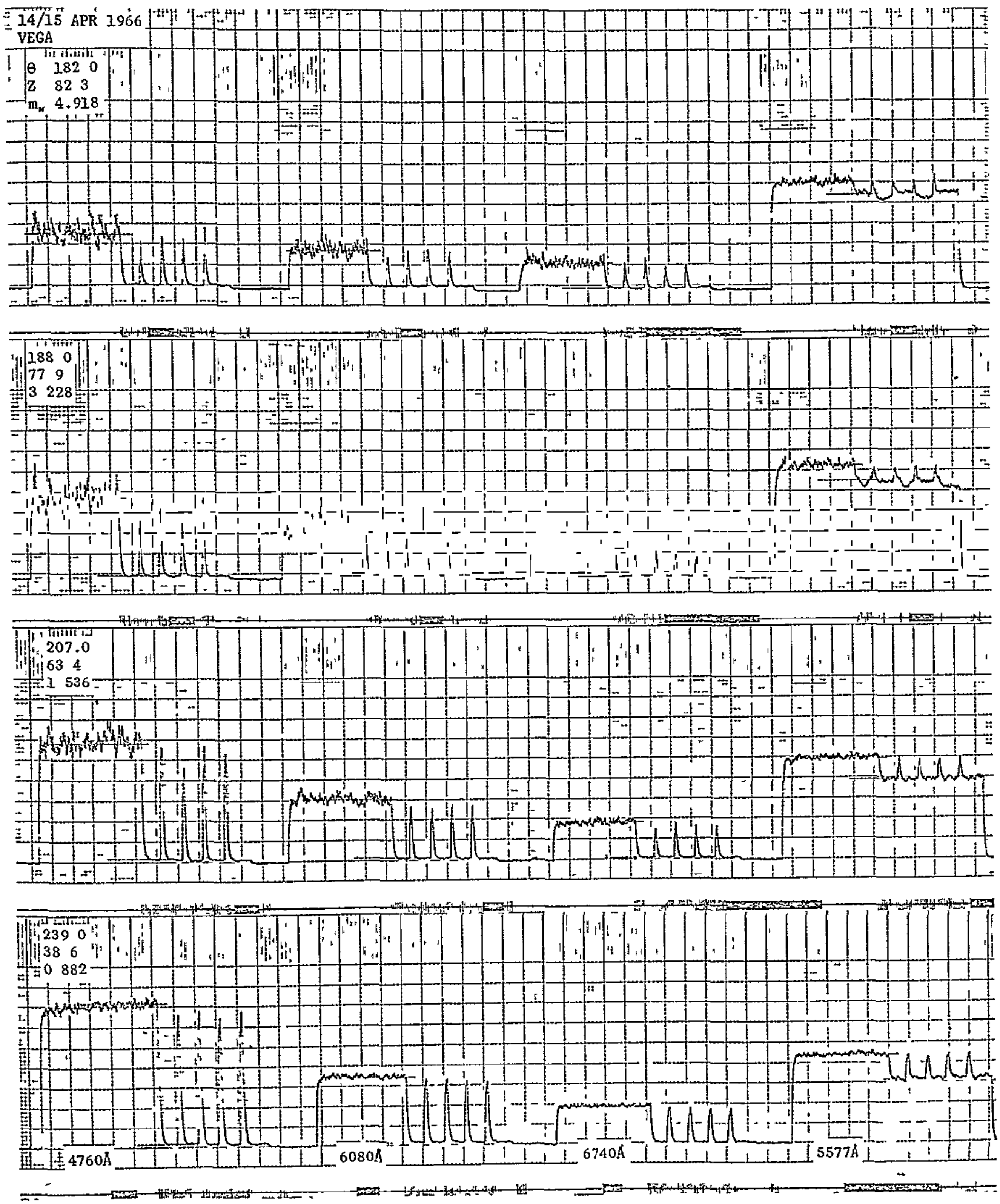


FIG 1


14/15 APR 1966
VEGA
θ 182 0
Z 82 3
m_w 4.918
188 0
77 9
3 228
207.0
63 4
1 536
239 0
38 6
0 882
4760Å
6080Å
6740Å
5577Å

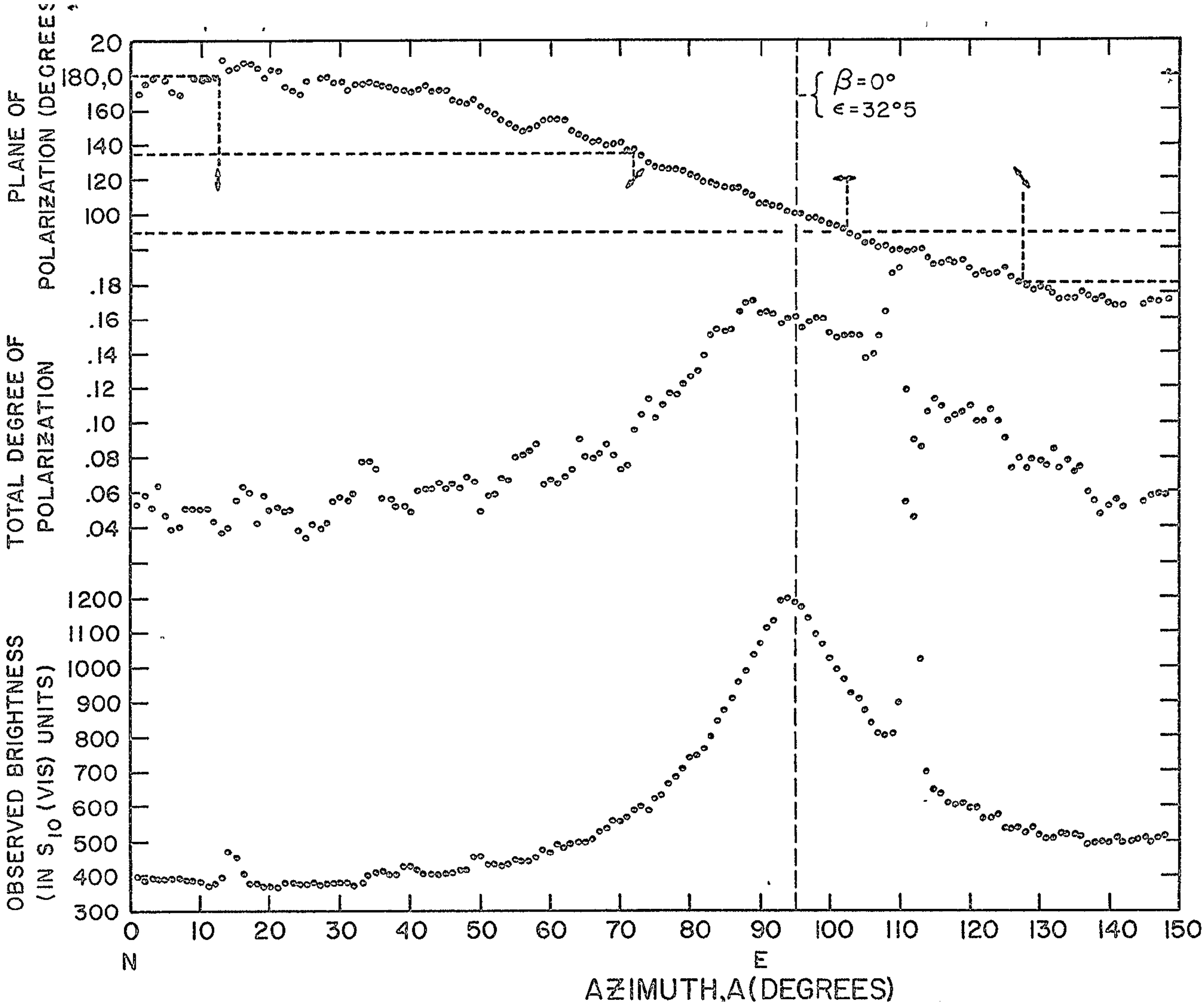
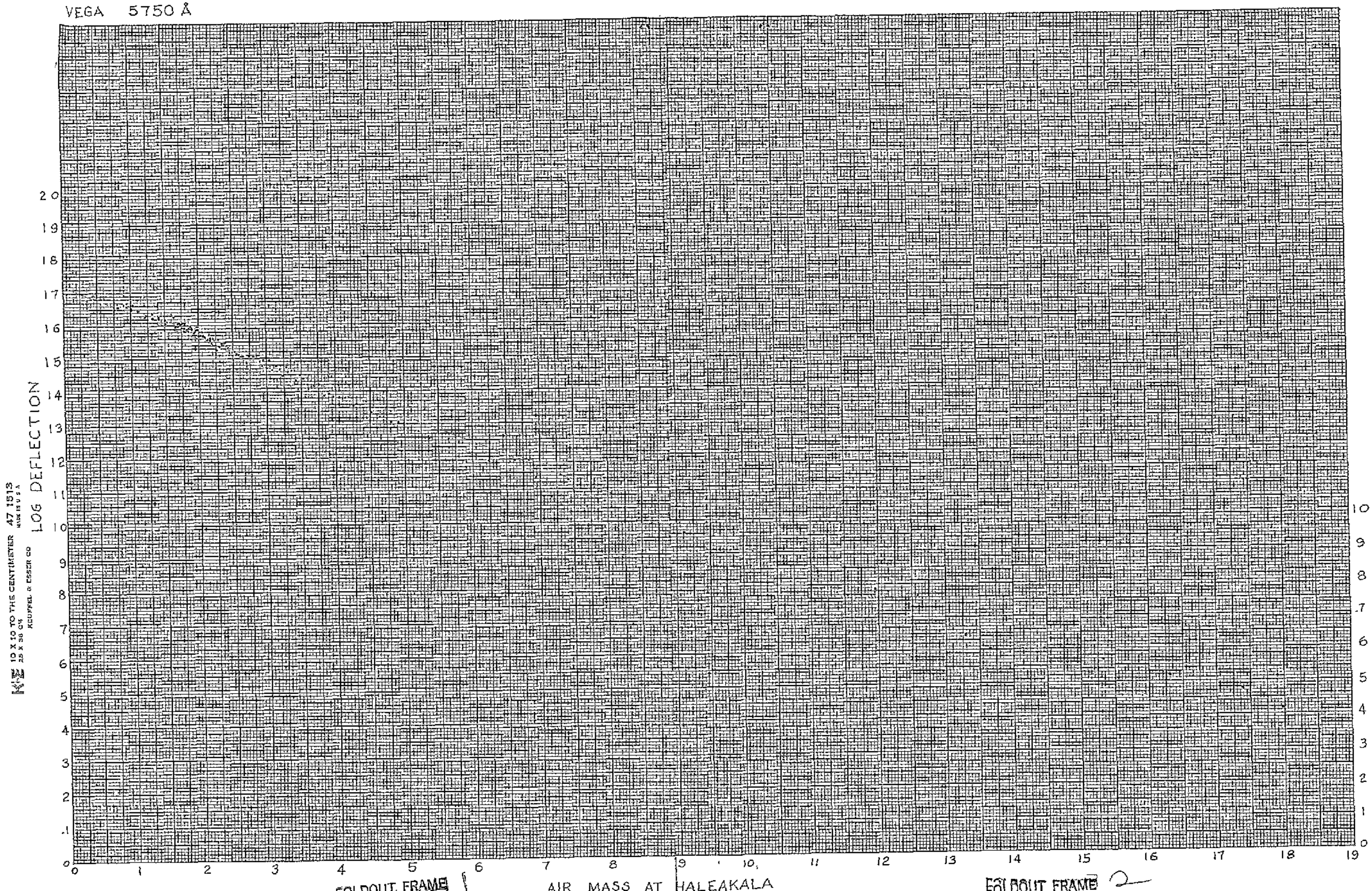

PLANE OF POLARIZATION (DEGREES)
TOTAL DEGREE OF POLARIZATION
OBSERVED BRIGHTNESS (IN S_{10} (VIS) UNITS)
$\beta = 0°$
$\epsilon = 32°5$
N
E
AZIMUTH, A (DEGREES)

FIG 2

29/30 MAR 1966
VEGA 5750 Å

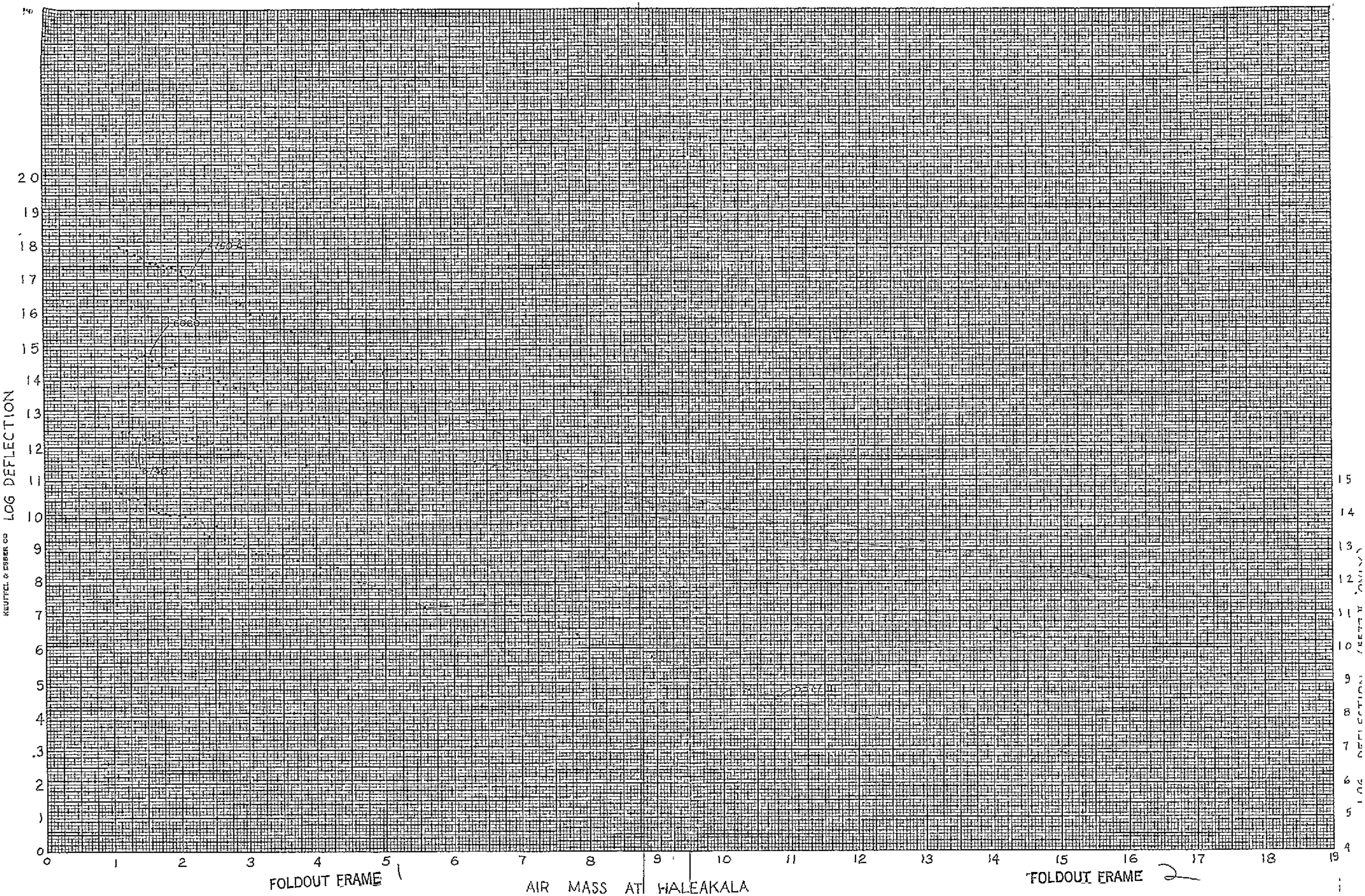


FOLDOUT FRAME 1

FOLDOUT FRAME 2

FIG 3

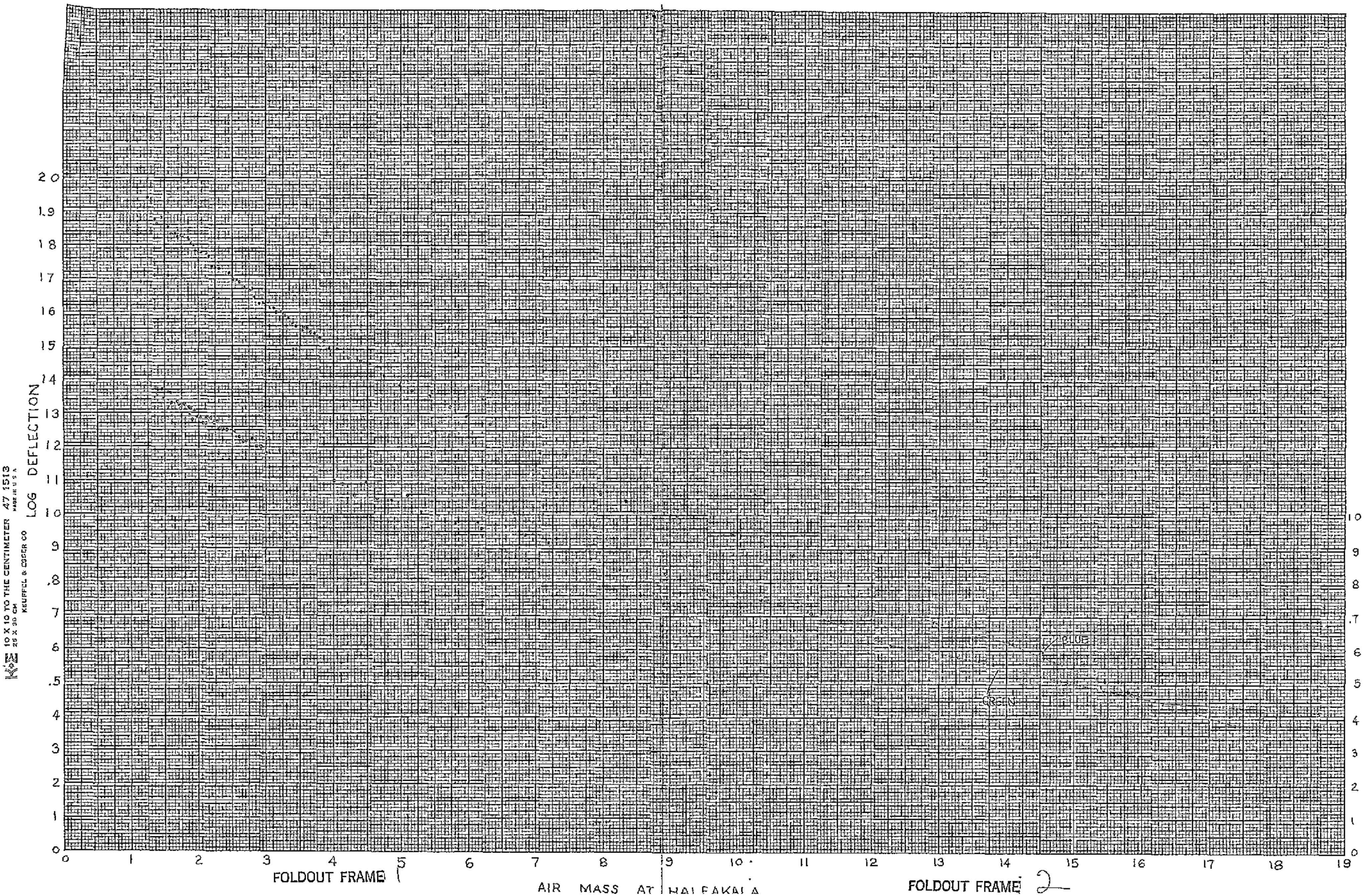
9/10 NOV 1966
VEGA



FOLDOUT FRAME 1

FOLDOUT FRAME 2

9/10 NOV 1966
VEGA



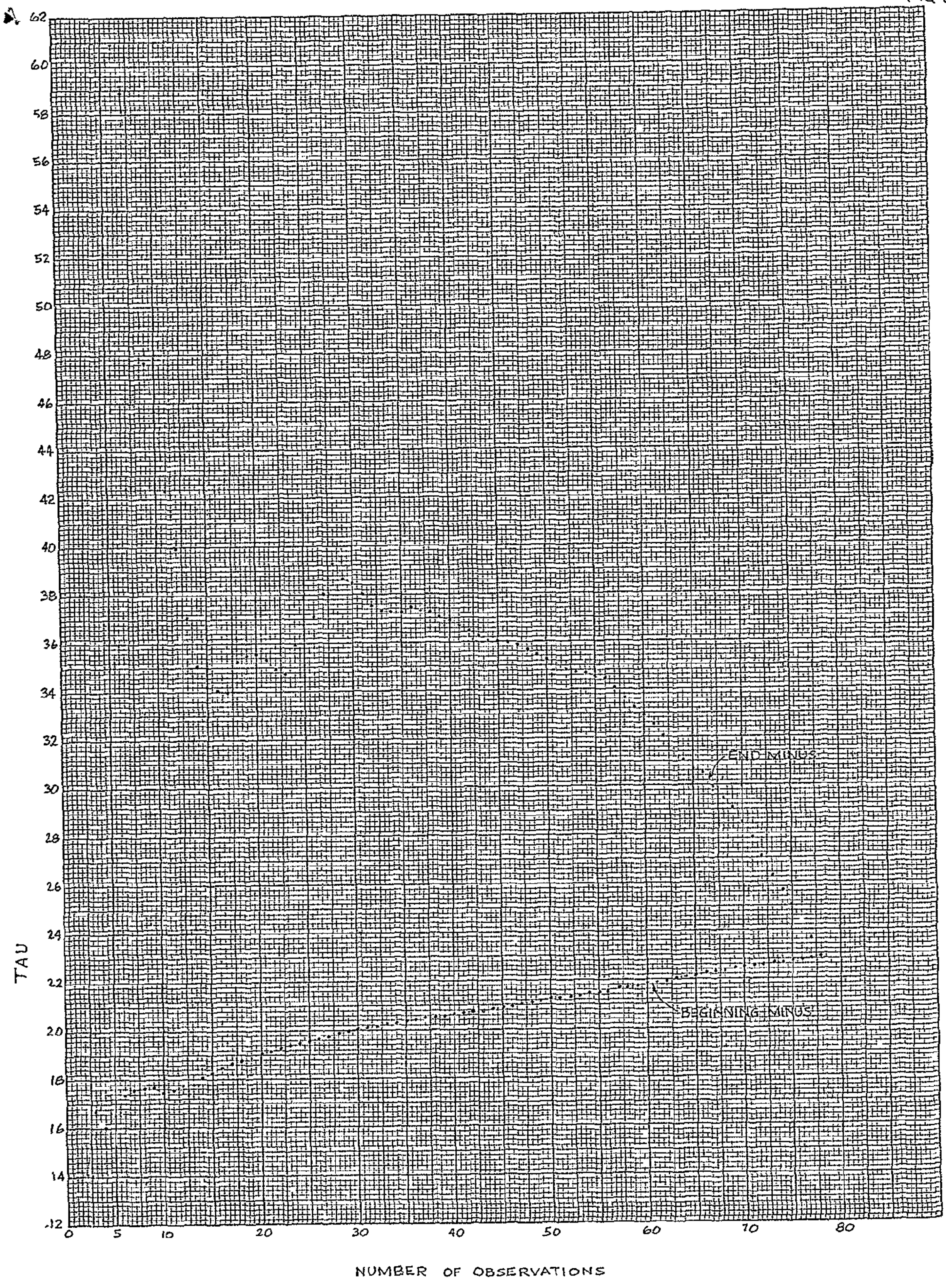
FOLDOUT FRAME 1

FOLDOUT FRAME 2

"EXTINCTION SHUFFLE - TAU vs NUMBER OF OBSERVATIONS

9/10 NOV 1966
VEGA - BLUE

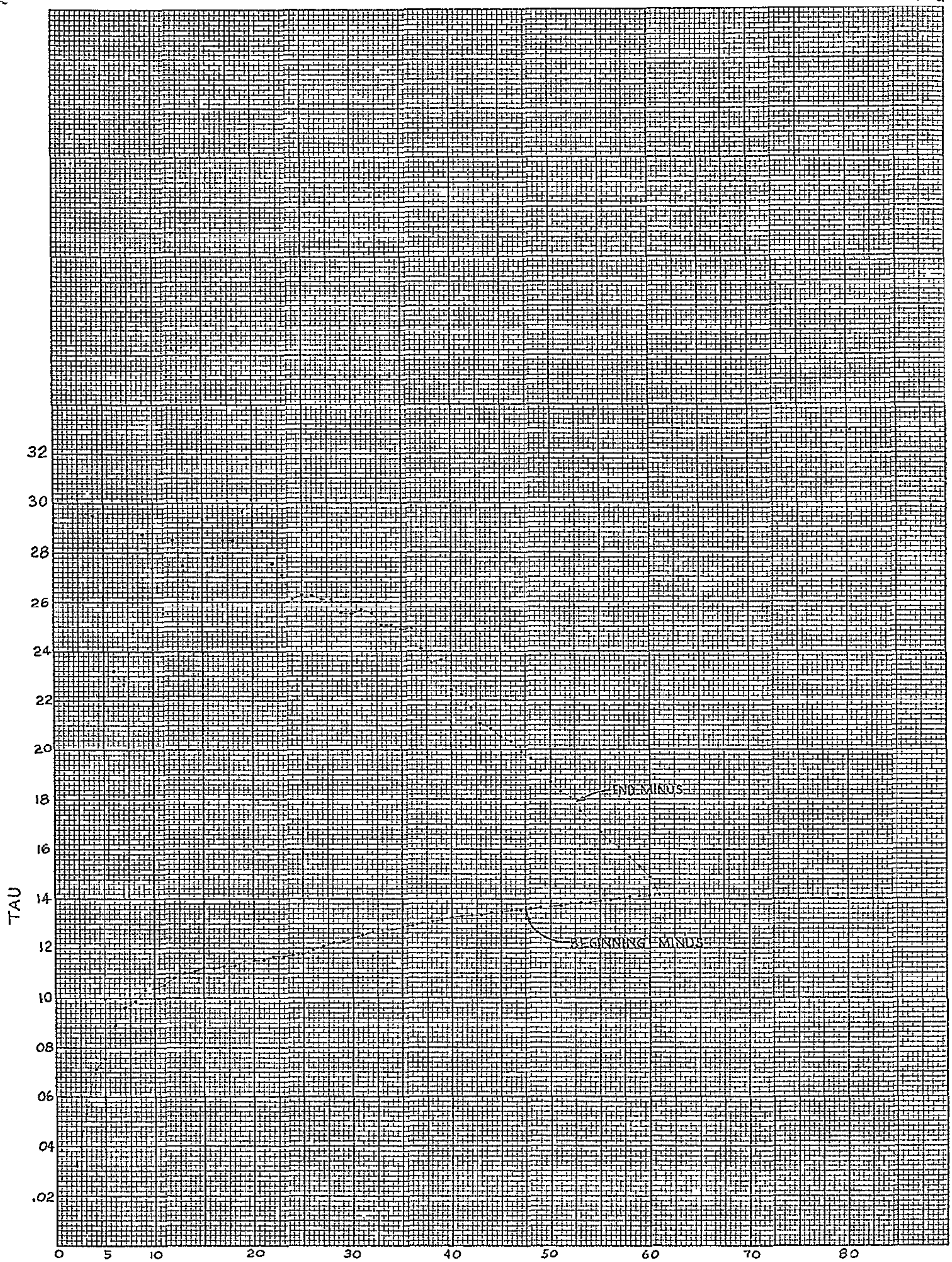
FIG 6



EXTINCTION SHUFFLE - TAU vs NUMBER OF OBSERVATIONS

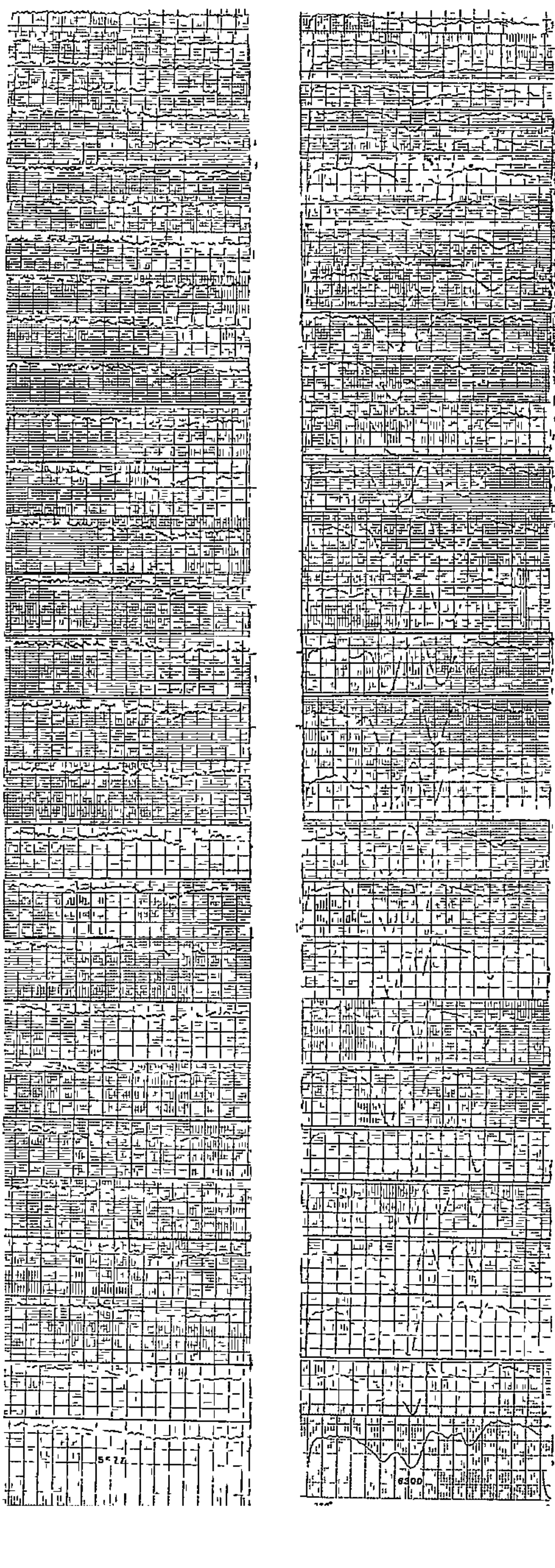
9/10 NOV 1966
VEGA - GREEN

FIG 7



NUMBER OF OBSERVATIONS

FIG 8.



Oct 7/8 1957

h=3°

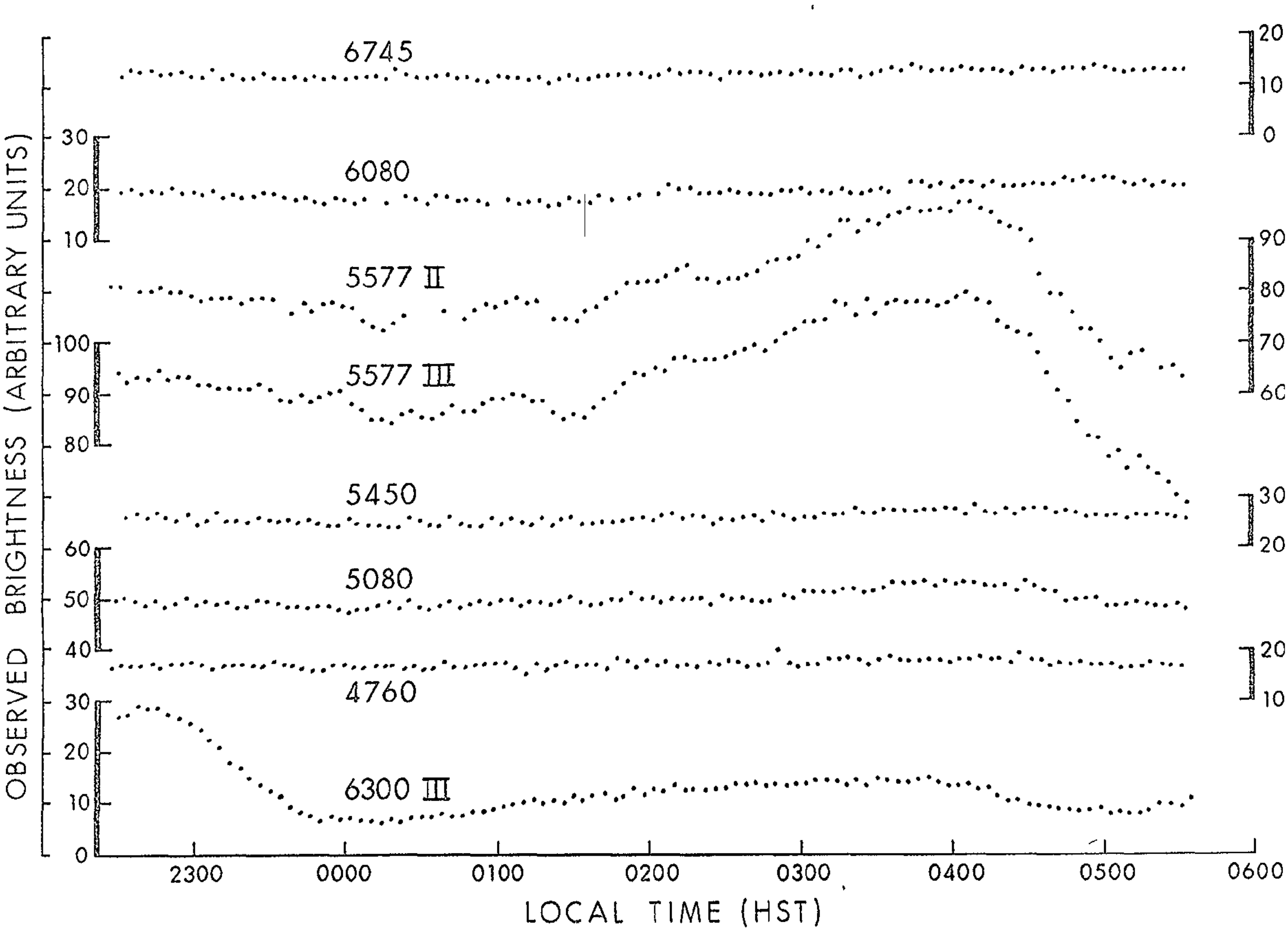

6745
6080
5577 II
5577 III
5450
5080
4760
6300 III
OBSERVED BRIGHTNESS (ARBITRARY UNITS)
LOCAL TIME (HST)
2300
0000
0100
0200
0300
0400
0500
0600
30
20
10
100
90
80
60
50
40
30
20
10
0
20
10
0
90
80
70
60
30
20
20
10

FIG 9

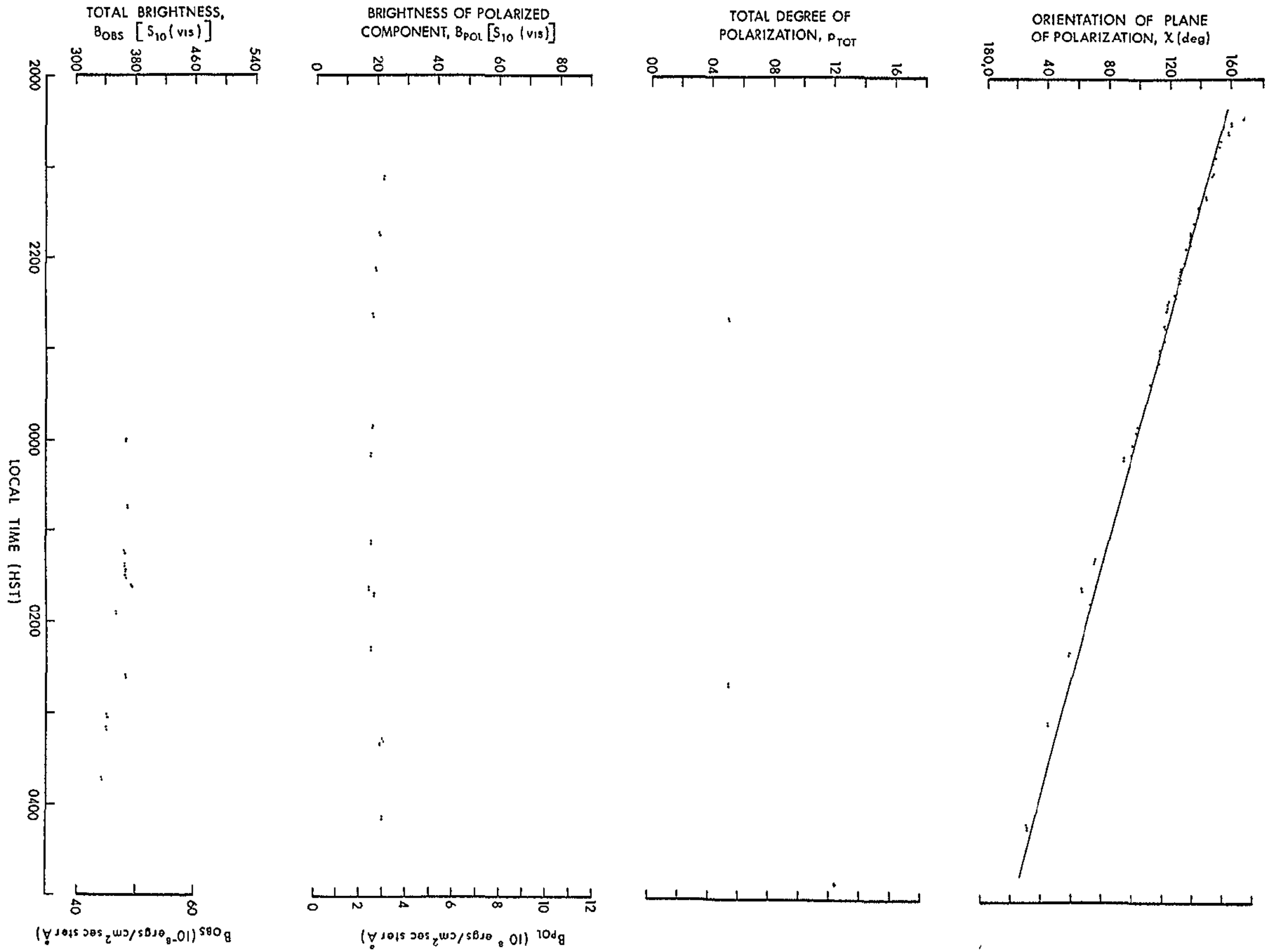
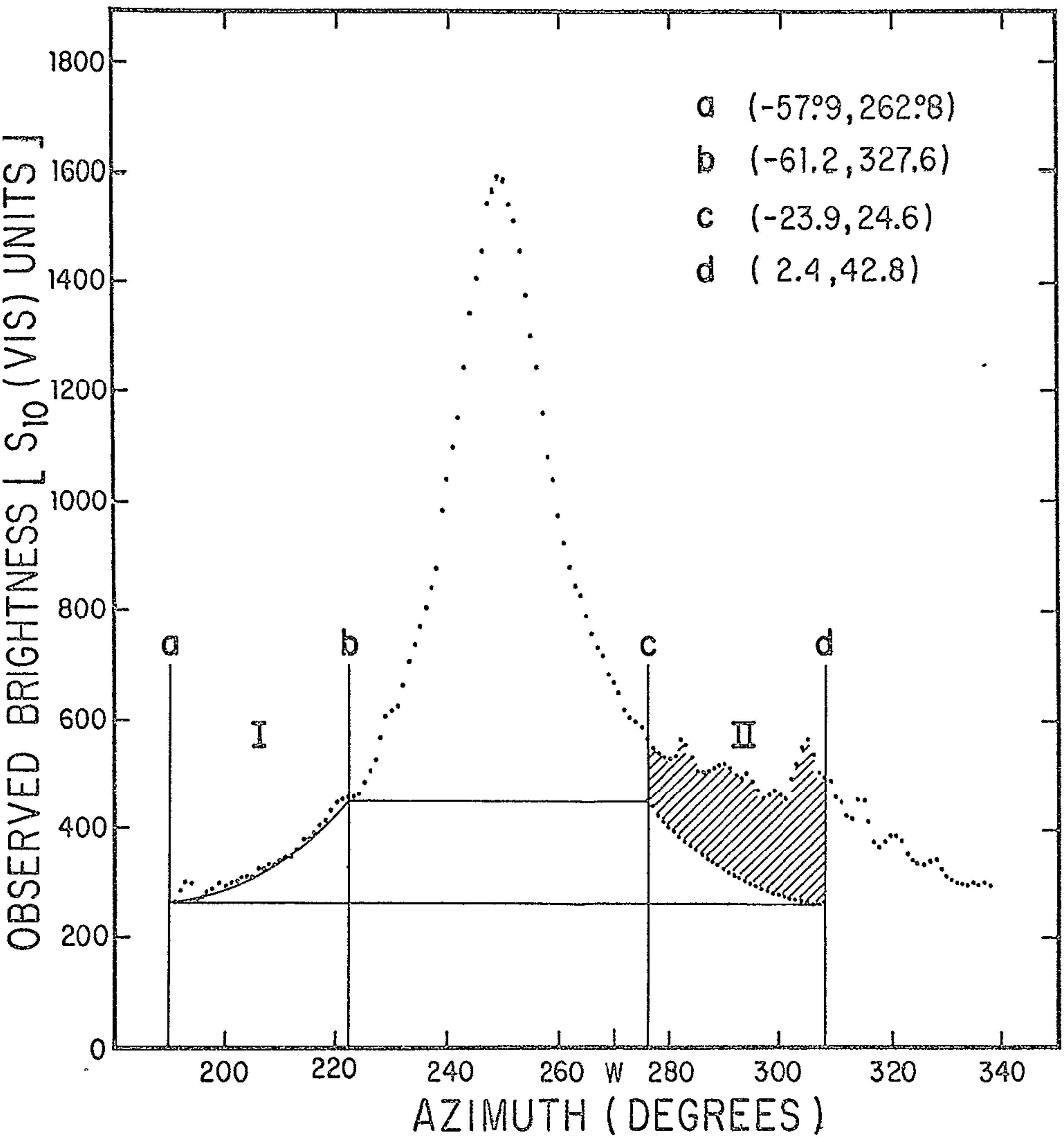

TOTAL BRIGHTNESS, B_{OBS} [S_{10}(vis)]
BRIGHTNESS OF POLARIZED COMPONENT, B_{POL} [S_{10} (vis)]
TOTAL DEGREE OF POLARIZATION, p_{TOT}
ORIENTATION OF PLANE OF POLARIZATION, χ (deg)
LOCAL TIME (HST)
2000
2200
0000
0200
0400
B_{OBS} (10^{-8} ergs/cm^2 sec ster Å)
B_{POL} (10^{-8} ergs/cm^2 sec ster Å)

FIG 10

FIG 11



a (-57°9, 262°8)
b (-61.2, 327.6)
c (-23.9, 24.6)
d (2.4, 42.8)
OBSERVED BRIGHTNESS [S_{10} (VIS) UNITS]
1800
1600
1400
1200
1000
800
600
400
200
0
a
b
c
d
I
II
200
220
240
260
W
280
300
320
340
AZIMUTH (DEGREES)

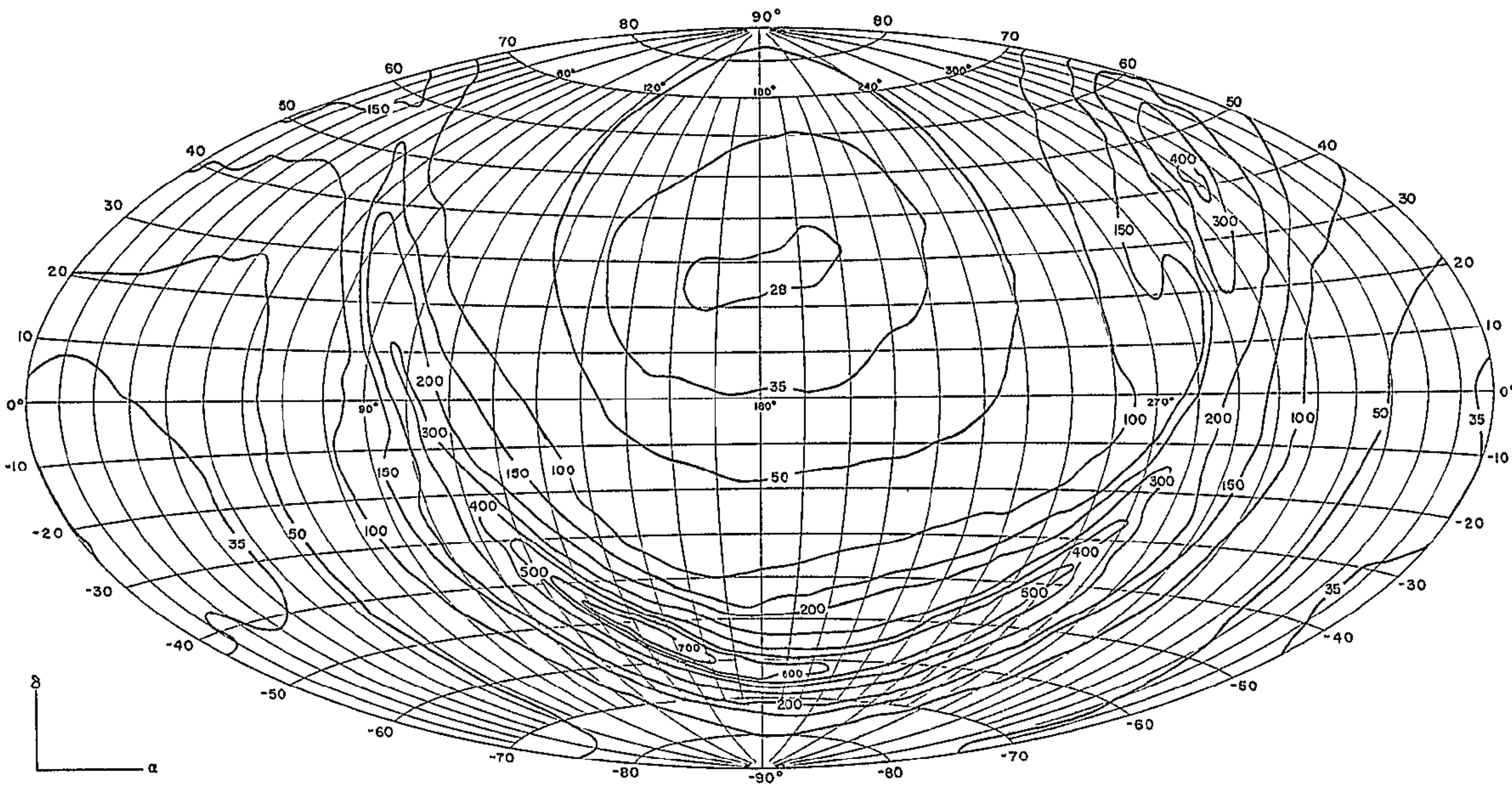

90°
80
70
60
50
40
30
20
10
0°
-10
-20
-30
-40
-50
-60
-70
-80
-90°
60°
120°
180°
240°
300°
90°
270°
28
35
50
100
150
200
300
400
500
600
700
δ
α

FIG 12

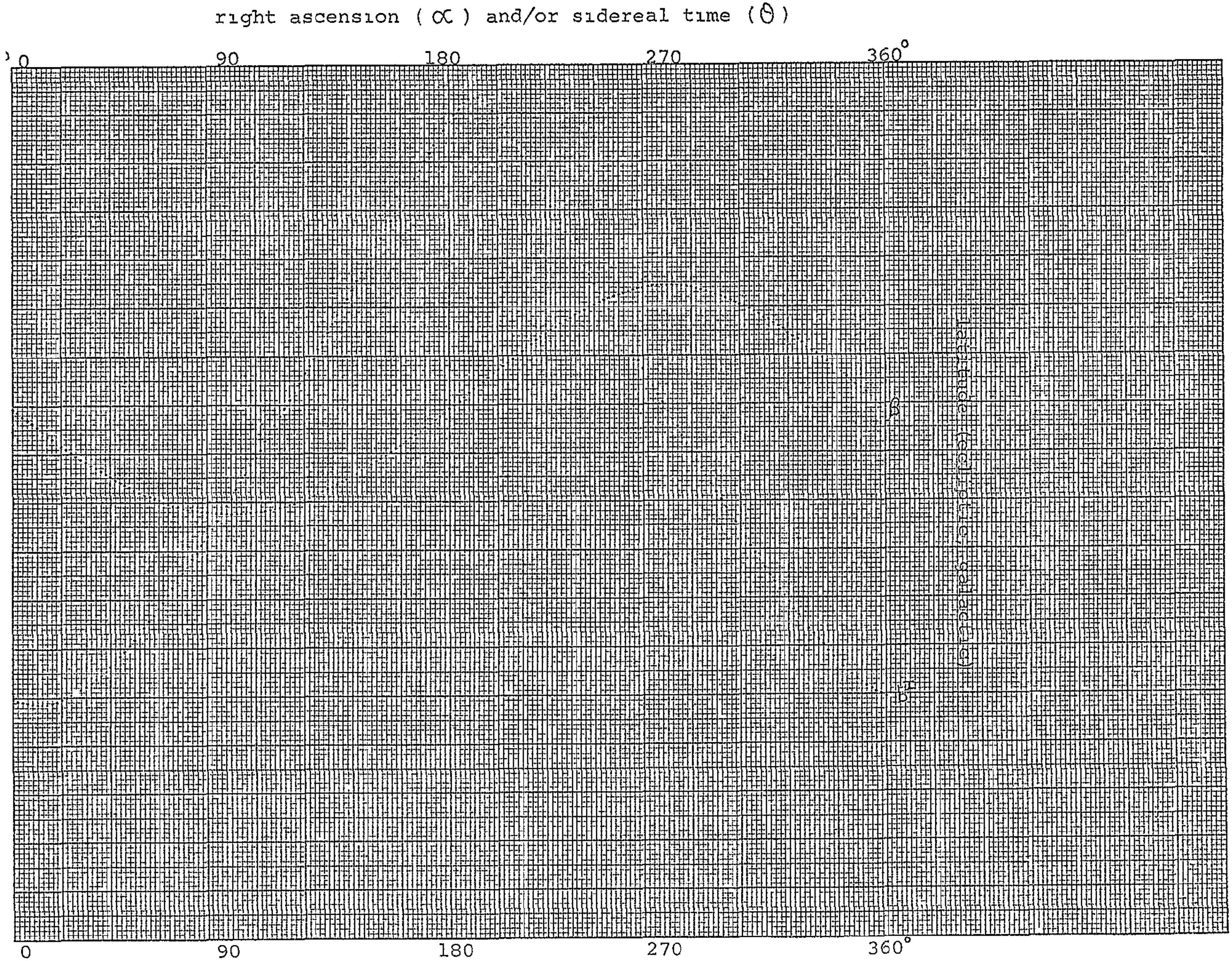
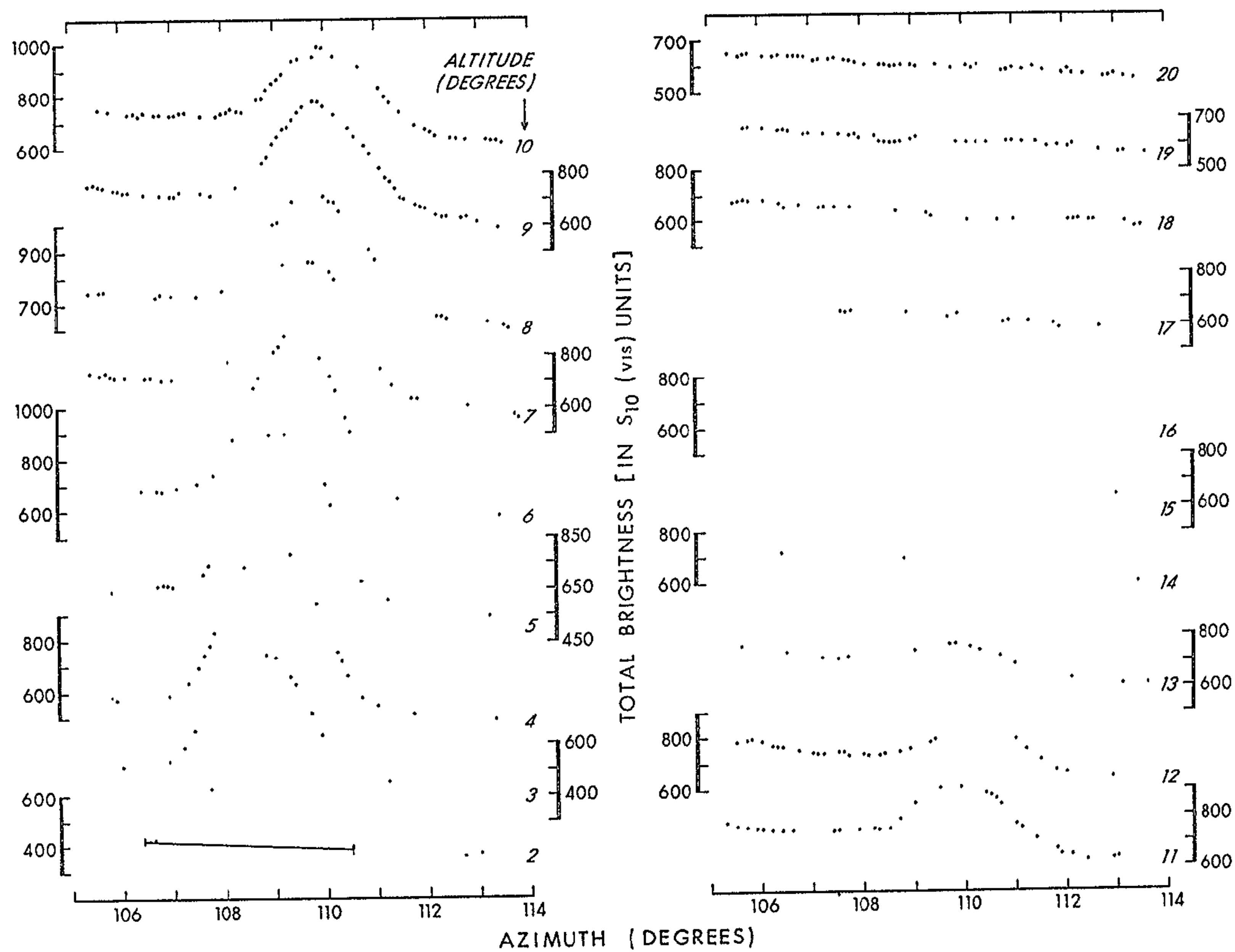

right ascension (α) and/or sidereal time (θ)
0
90
180
270
360°
latitude (ecliptic, galactic)
β
0
90
180
270
360°

FIG 13



ALTITUDE (DEGREES)
TOTAL BRIGHTNESS [IN S10 (vis) UNITS]
AZIMUTH (DEGREES)
106
108
110
112
114
10
9
8
7
6
5
4
3
2
20
19
18
17
16
15
14
13
12
11

FIG 14.

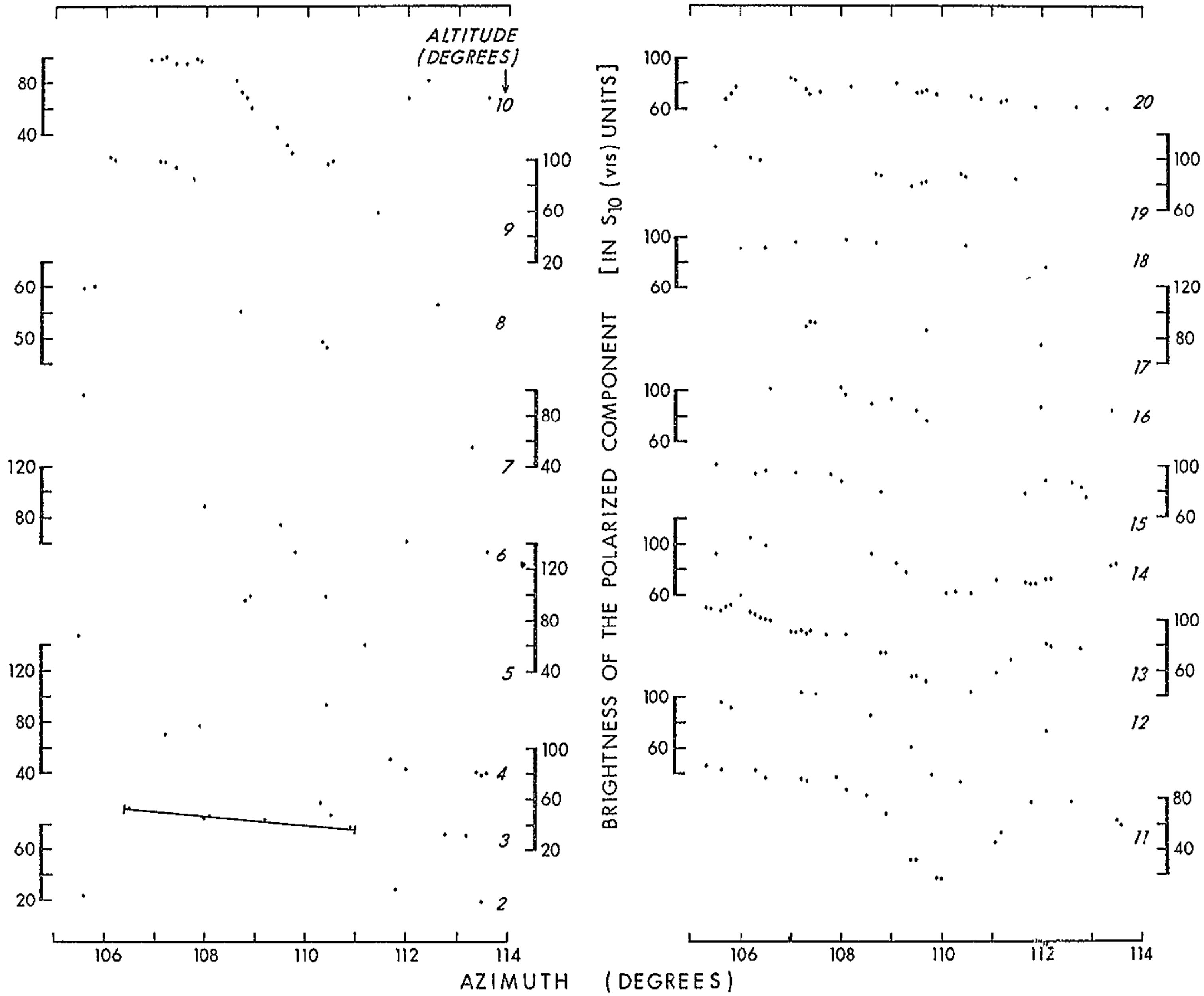

ALTITUDE (DEGREES)
BRIGHTNESS OF THE POLARIZED COMPONENT [IN S_{10} (vis) UNITS]
AZIMUTH (DEGREES)
106
108
110
112
114
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

FIG 16

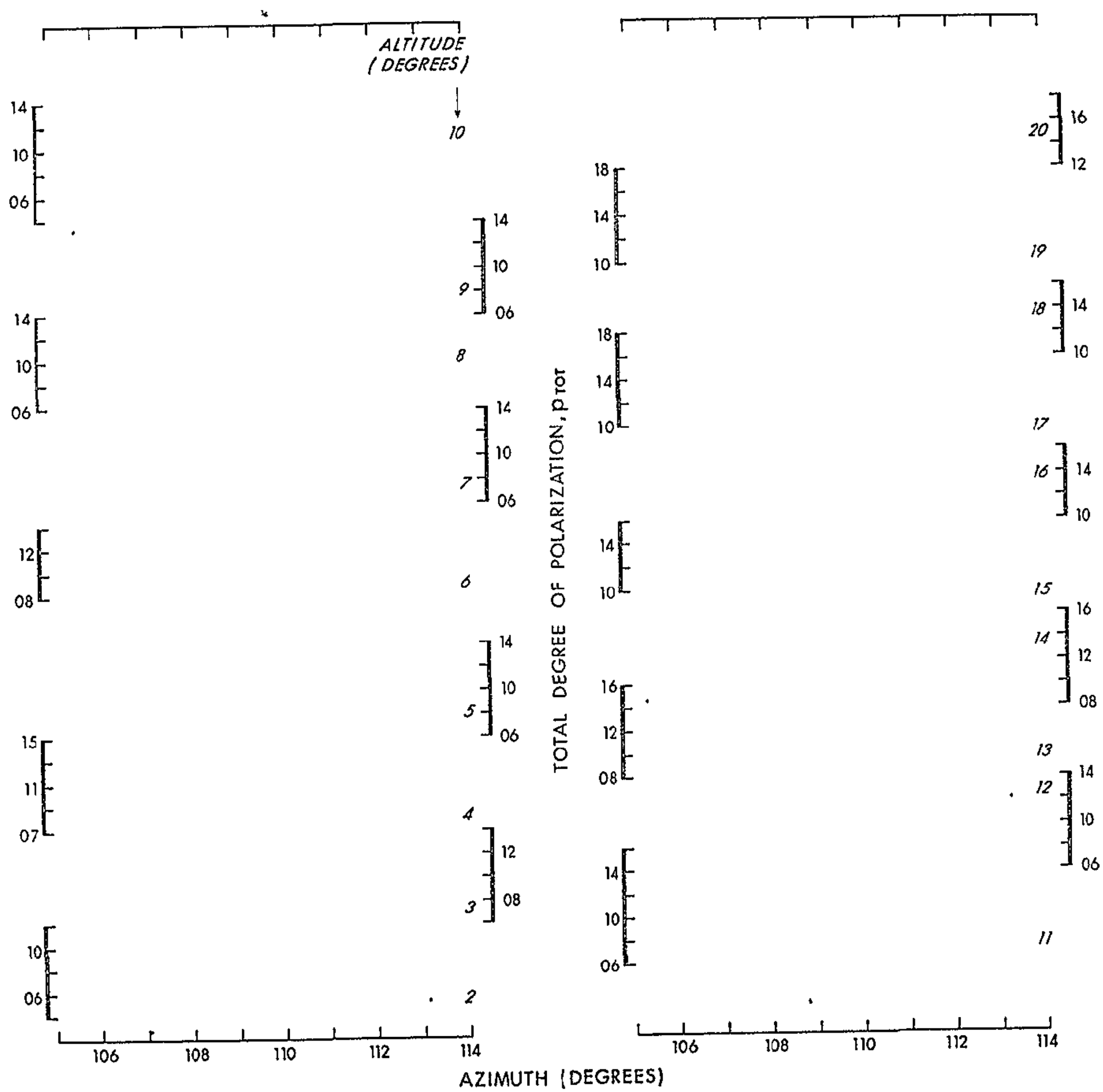

ALTITUDE (DEGREES)
TOTAL DEGREE OF POLARIZATION, p_{TOT}
AZIMUTH (DEGREES)
106
108
110
112
114
10
9
8
7
6
5
4
3
2
20
19
18
17
16
15
14
13
12
11

FIG 17

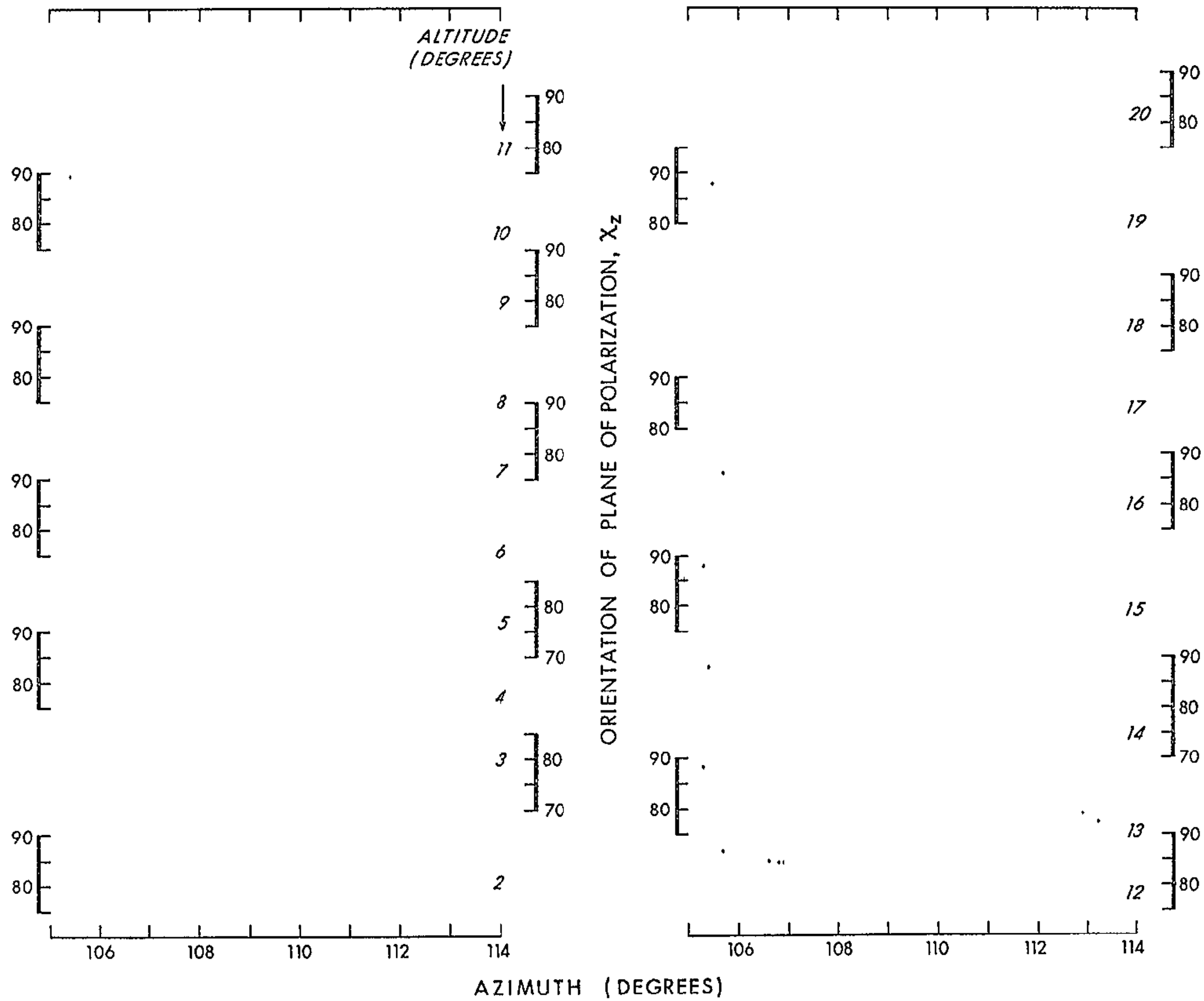

ALTITUDE (DEGREES)
ORIENTATION OF PLANE OF POLARIZATION, X_Z
AZIMUTH (DEGREES)
106
108
110
112
114
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
70
80
90

FIG 18

FIG 19