Report No. 4

on

Contract AF 19(604)-41

J. Allen Hynek
November 1, 1952

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION

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REPORT

By

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION

COLUMBUS 10, OHIO

Cooperator .... AF CAMBRIDGE RESEARCH LABORATORIES
230 Albany Street, Cambridge 39, Mass.
.... Contract AF 19(604)-41

Investigation of .... FLUCTUATIONS OF STARLIGHT AND SKYLIGHT

Subject of Report .... Progress for the period July 1, 1952

.... to September 30, 1952

Submitted by .... J. Allen Hynek

Date .... November 1, 1952

ABSTRACT

The present report marks the completion of the first year of project work. The problem concerns the manner in which starlight fluctuates in brightness and in color, particularly in the daytime, and likewise how equivalent or smaller portions of the daytime sky behave as sources of light. Observations at various seasons and under a variety of permissible meteorological conditions are stipulated.

Much effort during the first part of the contract year was spent as might be expected, on the design and construction of a suitable stellar photometer, unique in some respects, and on the installation and calibration of associated electronic parts.

Among the significant observational achievements of the latter part of the contract year was the first successful recording of the scintillation of bright stars in full daylight, and the harmonic analysis of this scintillation. The difficulty in such observations is several orders of magnitude greater than for the nocturnal analogue, because of the overwhelming brightness of the daytime sky.

Another significant result has been the determination of the diurnal variation of subaudic frequency components of stellar scintillation and their preliminary correlation with meteorological conditions. It was found that a consistent diurnal variation in stellar scintillation exists and that the total scintillation can be expressed in terms of two parameters: the zenith distance of the star, scintillation varying as $(\sec z)^{1.4}$, and the time of day. It appears that noontime scintillation is about 50 per cent greater than scintillation during twilight. It was also observed that the least over-all scintillation occurs when the observer is on the

west side of a polar "high", shortly after the passage of the center. In addition, greater scintillation appears to be associated with larger violet-to-yellow ratios of zenith skylight.

Scintillation in the daytime is greater when a 6-inch aperture rather than a 12-inch aperture is used. This result, long established for nocturnal seeing, is of significance in that it indicates that the atmospheric disturbances are not significantly larger in linear measure in the daytime than at night. If they were generally larger than six inches, the amount of scintillation observed with the two apertures would not be markedly different.

PERSONNEL AND ADMINISTRATION

There were no changes in personnel and none in the administration of the contract other than that Mr. Protheroe was engaged full time for the summer months.

The slow delivery of equipment continued to be the only matter that hindered the full scope of the work. Facilities at the University were adequate and enough telescope time was available, both night and day, for the prosecution of the work. The telescope and accessories are in good condition.

COMMUNICATIONS

A copy of Report No. 3 was transmitted to the U.S. Naval Observatory, where Drs. Hall, Mikesell, and Hoag are engaged in a closely related phase of the problem of stellar scintillation. From the inception of this project work, we have maintained close cooperation with these gentlemen. They have, in turn, followed the practice of communicating with us whenever they have obtained significant results. During the present report period they communicated to us in advance of publication their results on the scintillation of lights carried to specified heights by helicopter.

With respect to our Report No. 3, communications were received from them pointing out that they had some time ago made measurements on the "aureole" of a star and had presented their results at the Cleveland meetings of the American Astronomical Society last winter (1951-52). Thus, our measurements are confirmatory. Our measurements resulted from the necessity of determining how large a diaphragm it was necessary to use to insure that the total light of the star was admitted to the photocell in the course of measuring the fluctuations in total light. These measurements, therefore, were necessary in any case.

Dr. Heinz Fischer, of the Cambridge Research Laboratories, visited the McMillin Observatory in September for a review of progress to date. He was accompanied by Dr. E. Wahl, who was particularly interested in the meteorological possibilities inherent in the present problem. He and Dr. Keller conferred on problems of atmospheric turbulence.

During the general discussions, the question of terminology with respect to "noise" and "constant noise source" arose. In order to clarify the use of these terms in the present context, Mr. Protheroe has prepared a short discussion (see appendix I).

STATEMENT OF PROBLEM AND
METHODS OF ATTACK

The chief problem under attack is that of the manner in which star-light fluctuates in its passage through the atmosphere of the earth, especially in the daytime. The specific problem is to devise and utilize equipment for the recording and analysis of such fluctuations. The long-range purpose of this work is to seek to utilize optical means of sounding the upper atmosphere.

The work during the present report period, July 1, 1952 through September 30, 1952, can be summarized by stating that the major effort has been shifted from getting equipment to work over to the daily use of the equipment on hand in making the systematic observations needed to obtain trustworthy answers to the questions posed in this contract work.

The telescope has been used for these purposes on virtually all clear days available, and, at the present moment, observations run considerably ahead of "reductions". The aim this summer has been to get consistent observations so that valid intercomparison is assured. This has meant "settling down" to a standard program of observation rather than "trying this and trying that"; a large part of the first year of work was spent in the latter, and necessarily so.

The standardized observations are two-fold. Those carried out by Mr. Hosfeld are concerned with the hourly variation of, primarily, daytime seeing. Here the characteristic "cutoff" of the Brown recorder between 10 and 12 cps. (Fig. 1) is utilized to give the percentage scintillation of a star in terms of its total signal. Since by far the greater portion of stellar scintillation occurs at sub-audio frequencies,

RESPONSE OF BROWN
RECORDER VS FREQUENCY
FOR ONE UNIT THROW.

% THROW

100
90
80
70
60
50
40
30
20
10
0

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
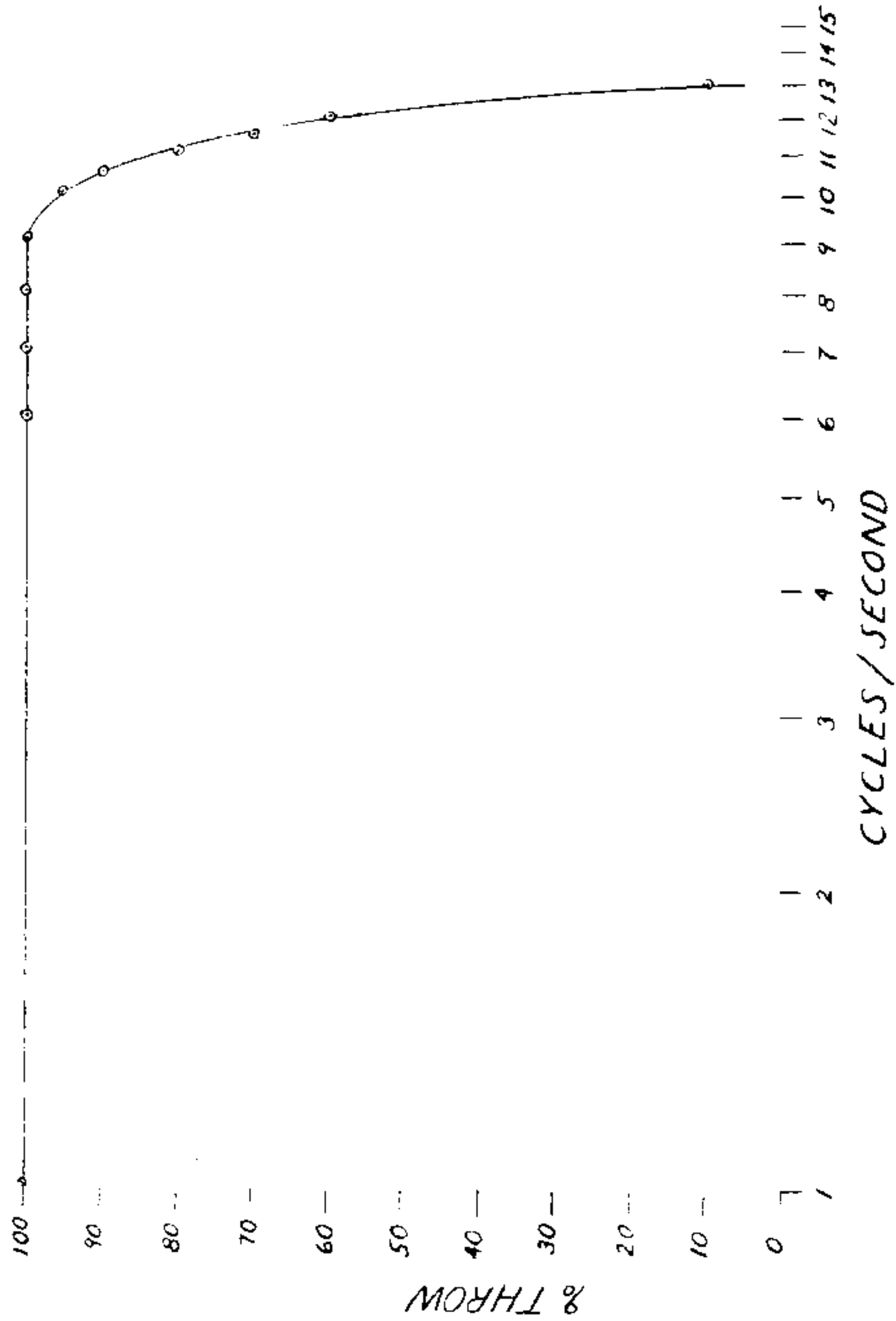
CYCLES / SECOND

FIG. 1

the value of total integrated fluctuations from 0-10 cps seems a particularly good index of seeing to use for an hour-to-hour, day-to-day comparison. The schematic diagram for the apparatus used in this phase of the work is shown in Fig. 2. The star is placed at the center of the field of the 0.50 mm aperture of the photometer, and the gain of the system is adjusted to give an average fluctuation on the Brown recorder of one unit (approximately 1/8 inch on the record). The star is next removed from the field and only the intensity of the adjacent blue sky is recorded. The difference, (sky + star) - (sky), divided into the observed fluctuation (which has purposely been adjusted to be one unit so that the inertia effects of the recorder remain constant) yields the per cent variation of starlight. For example with the fluctuation set at unit value, if (sky + star) reads 75.5 units and the sky alone 71.2 units, the per cent variation is

$$\frac{1.0}{75.5 - 71.2} = \frac{1.0}{4.3} = 23\%.$$

If the sky exhibited measurable fluctuations of the same character as those shown by the star, a correction would have to be introduced. Fortunately, no variations comparable to stellar scintillation are present in skylight.

The observations show that such an index of seeing can be represented, on the average, as a function of two parameters: elevation of the star and time of day. The day-to-day variation depends on meteorological conditions. It has been found, for instance, that the maximum scintillation for a given elevation angle is observed on days with considerable
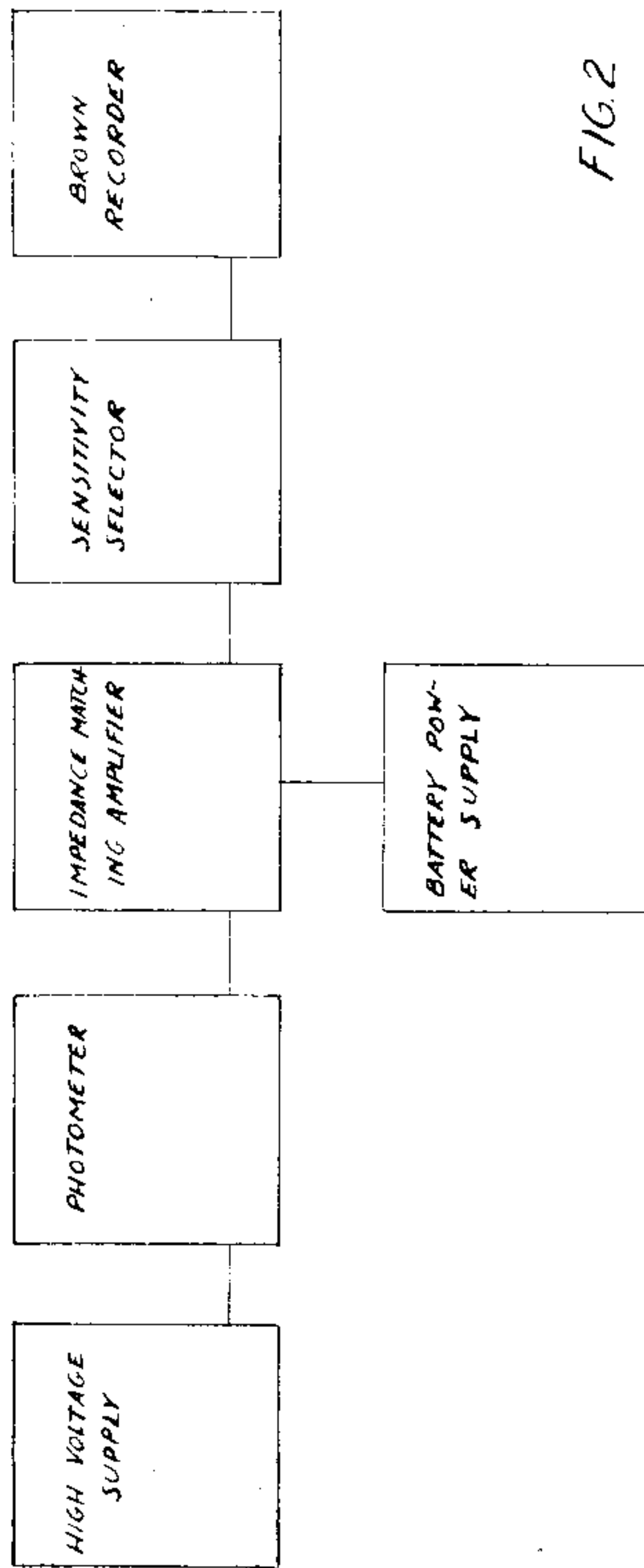
FIG.2

SUB-AUDIO SCINTILLATION
MEASURING SYSTEM

convective activity, as indicated by towering cumulus clouds. Minimum scintillation, correspondingly, has been observed on the west side of polar "highs" shortly after the passage of the center of the "high".

Observations of daytime "seeing" have been carried out from sunrise to sunset. A typical series of "runs", obtained on August 8, 1952, is shown in Fig. 3. These represent the observed percentage scintillation of various stars at different times of day and hence, of course, at various elevations of the stars above the horizon (shown as index numbers at each point on the graph).

When the elevation parameter is isolated, it is found that scintillation varies as $(\sec z)^{1.4}$, where z is the zenith distance of the star.

Conversely, observations corrected to a constant zenith distance show, on the average, a sinusoidal diurnal variation in scintillation, with the peak, at midday, about 50% greater than values at sunrise or sunset.

The change in scintillation with time of day for a given elevation angle is illustrated by the average values (Table I) for Vega and Arcturus during the period July 31, 1952 to August 8, 1952.

TABLE I
Average Scintillation Values, July 31 - August 8, 1952

Mean elevation angle,°	Variation star signal, %		Mean time of day, P.M.	
	Arcturus	Vega	Arcturus	Vega
30		43		4:43
35		36		5:12
40	38	30	2:22	5:41
45	32	25	2:44	6:10
50	27	21	3:09	6:39
55	24	18.5	3:26	7:08
60	21	17	4:06	7:36
65	19	16.5	4:40	8:06
70	16	--	5:40	

% VARIATION VS.
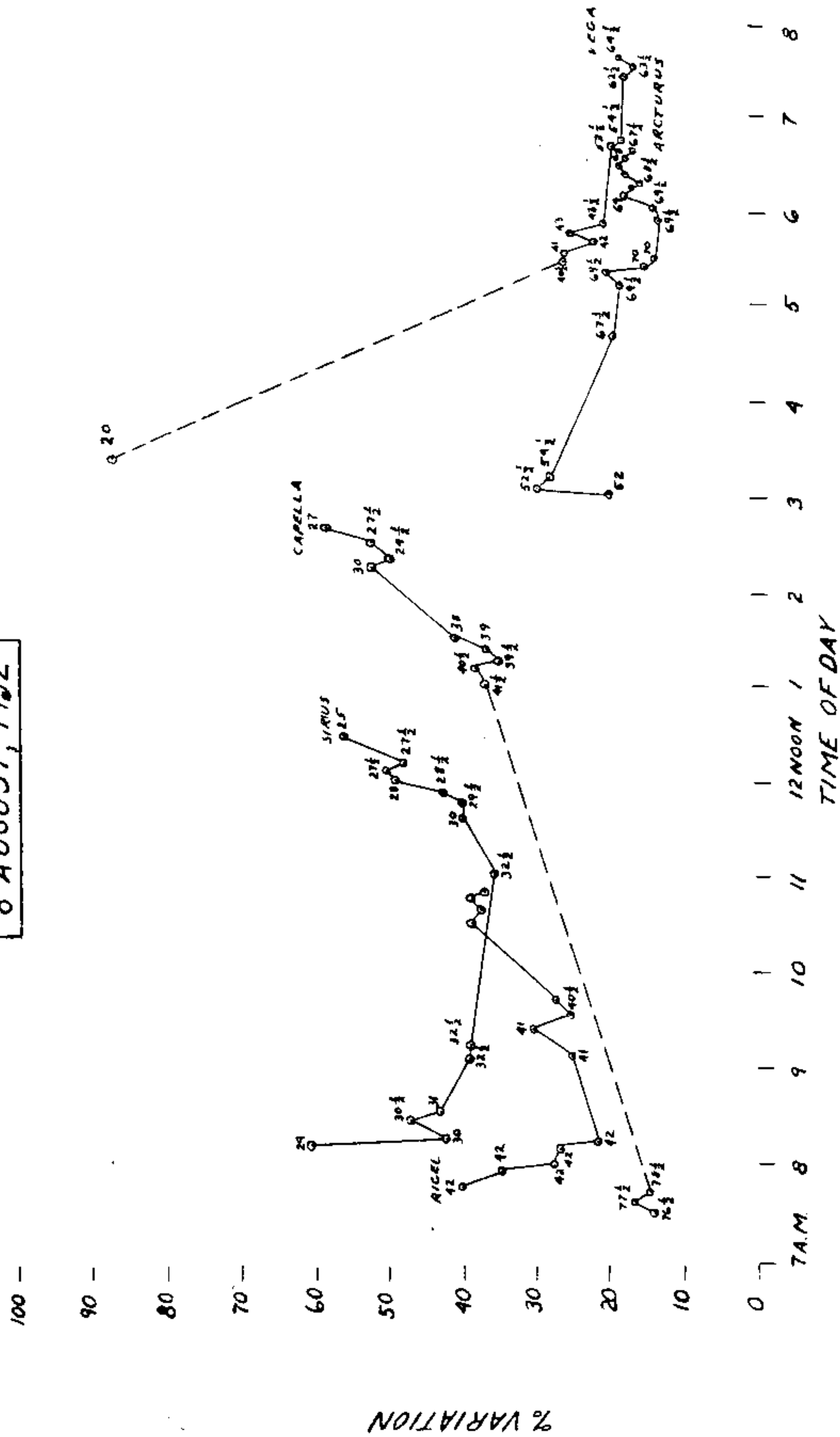TIME OF DAY
8 AUGUST, 1952

FIG. 3

TIME OF DAY

% VARIATION

Observations are being extended to include all hours from sunrise to sunset, and a direct comparison with nocturnal values is planned. The present limited data, however, show clearly that for any given constant elevation angle, the closer to midday the observation is taken, the greater the per cent scintillation.

Although Vega and Arcturus differ somewhat in brightness and considerably in spectral class, there is no evidence from observations so far that either a significant magnitude or color effect exists.

Summarizing the principal facts concerning _daytime_ scintillation of stars, to be regarded at present as preliminary results which may be modified after considerably longer runs have been completed, we have:

(1) Noontime scintillation, for a given elevation angle, is about 50% greater than at twilight.

(2) Scintillation increases rapidly with increasing zenith distance and is about 2.5 times greater at 60° than at 0°.

(3) Scintillation in daytime is greater for a 6-inch aperture than for a 12.5-inch aperture, a result which has been long established for nightime scintillation. This result is of more significance than might at first be surmised for, if the turbulent elements in the daytime atmosphere were significantly larger (in this case, larger than 6 inches), there would be little difference in the amount of scintillation observed with either of the apertures.

(4) The greatest diurnal scintillation is observed when the air mass has much convective activity, such as that which produces towering cumulus clouds in the daytime sky.

(5) The steadiest traces are obtained on the west sides of polar "highs".

(6) Greater scintillation is associated with larger violet/yellow zenith skylight ratios. Although this has not previously been mentioned, systematic observations of zenith skylight through various filters have been carried out along with the regular photoelectric measures. A simple exposure meter, sturdily mounted in the open, has been employed.

The observations lead to two other preliminary generalizations:

(a) The brighter the total sky radiation, the smaller the proportion of violet light to yellow light.

(b) Larger violet-to-yellow zenith sky brightness ratios are found on the east side of polar "highs" than on the west side.

HARMONIC ANALYSIS OF DAYTIME
STELLAR SCINTILLATION

An independent but closely correlated aspect of the work is the frequency analysis of daytime stellar scintillation being carried out by Mr. Protheroe. It is expected that this work will constitute a portion of Mr. Protheroe's doctoral dissertation in Astronomy at The Ohio State University.

At the close of the present report period, Mr. Protheroe succeeded in obtaining the first measures of the frequency components of stellar scintillation in bright daylight. Again, the results so far are preliminary; indeed, the magnetic tape recorder intended to be an integral part of this program has not yet been received.

The present instrumental arrangement for making these observations is illustrated schematically in Fig. 4.

The photometer and the high-voltage supply have been described in previous reports and are also the same as used in the "subaudio" system (Fig. 2).

The photometer output is fed to an attenuator and bias control. The latter derives its bias voltage from a flashlight battery and is used to cancel out most of the d-c input signal, thereby allowing a high gain d-c amplifier to be used. The amplifier used in this work
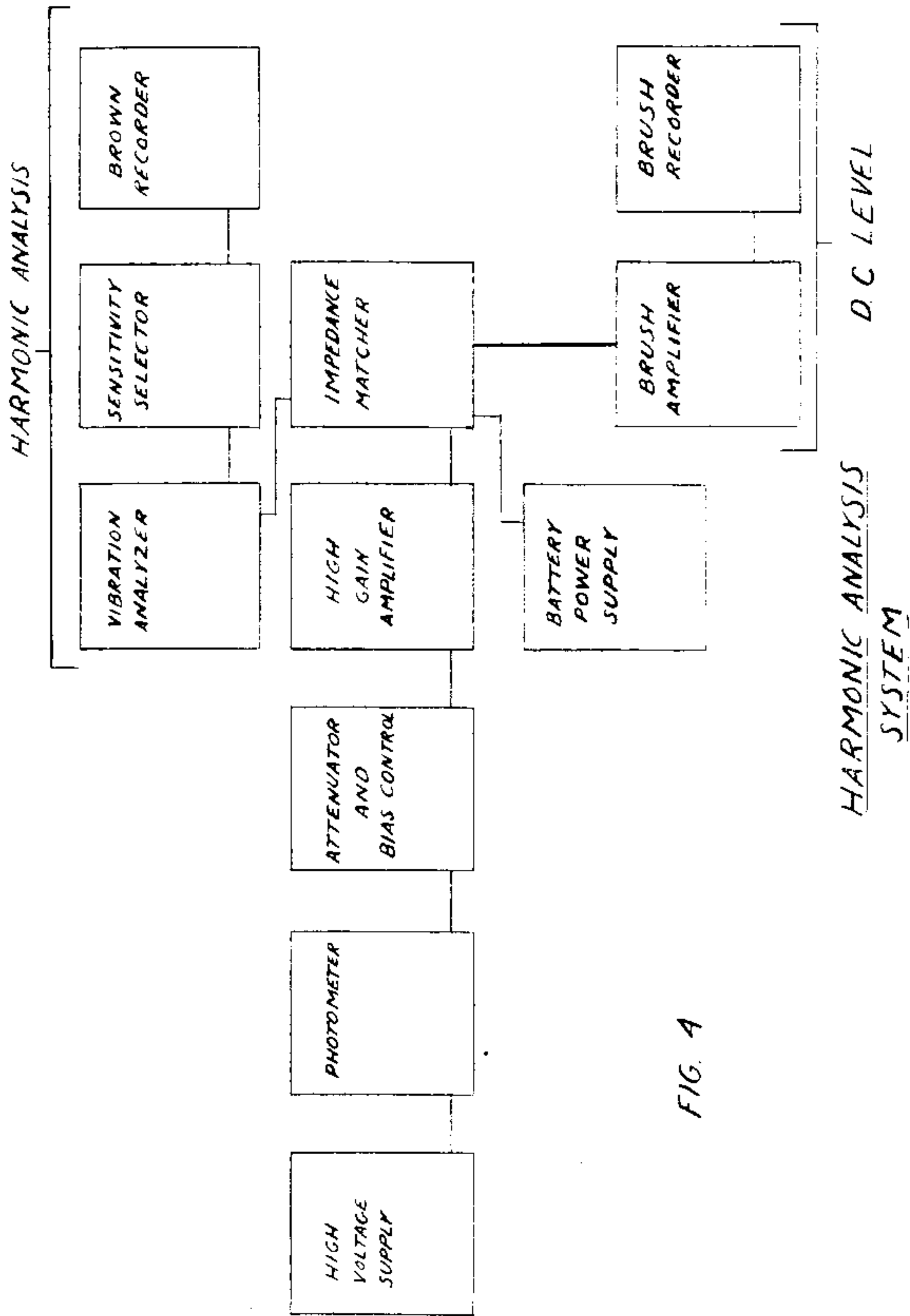
FIG. A

is a Tektronix Direct-coupled Type 112 Amplifier having input and output impedances of 10^6 ohms and 10^5 ohms respectively.

In order to permit the operations of several pieces of equipment at the output of the amplifier, an impedance matcher must be used. To accomplish matching for the Vibration Analyzer, a simple cathode follower used; a simple resistive attenuator suffices for the d-c level signal.

By means of the resistive attenuator, part of the signal is sampled by the Brush recorder to indicate the d-c component of the light signal falling on the photomultiplier, which corresponds to the level of illumination.

The output of the cathode follower is applied to the Vibration Analyzer which indicates the relative rms voltage at selected frequencies. The analyzer has a band pass that is 3.2% of the center frequency.

Finally, the output of the analyzer is fed to the Brown recorder via the sensitivity selector. The absolute noise voltage is determined by a calibration of that part of the system which follows the photometer.

The actual technique of measurement is given in Appendix 2.

The harmonic analysis of daytime star scintillation had been barely got under way at the close of the present report period (September 30, 1952). The first complete "run" was made on Arcturus September 13, 1952, shortly before noon. The resulting frequency analysis is shown in Fig. 5. Because of the preliminary nature of the work to this stage, a comparison with the work of Hall, Mikesell, and Hoag on the frequency analysis of nocturnal stellar scintillation will not be made at this time.

HARMONIC ANALYSIS OF
DAYTIME STAR SCINTILLATION
STAR: ARCTURUS (0.24, K0)
DATE: SEPTEMBER 12, 1952
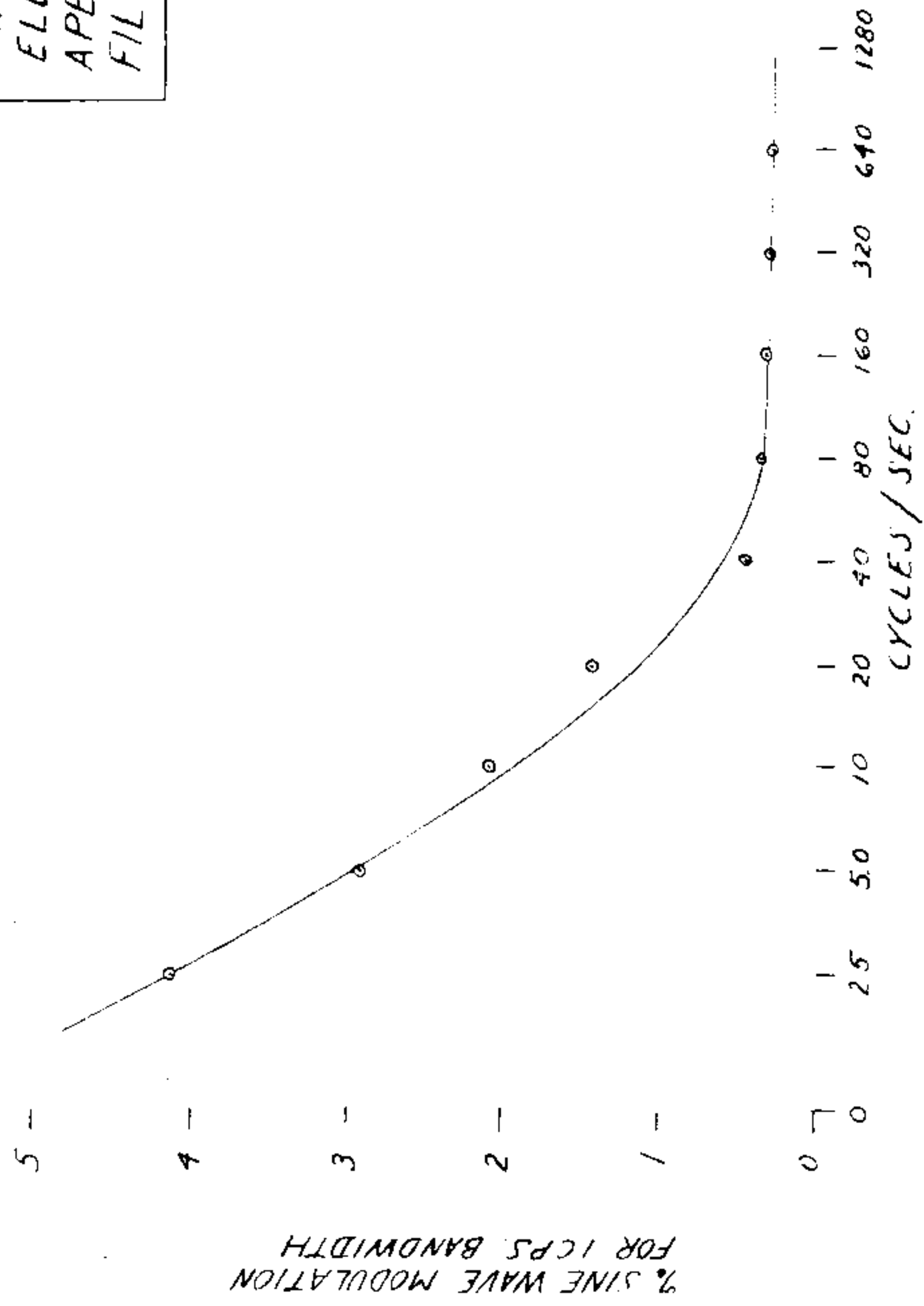TIME: 11:20 A.M.
ELEVATION: 35°
APERTURE: 0.50 mm
FILTER: CLEAR

FIG. 5

CYCLES/SEC.

% SINE WAVE MODULATION
FOR 1 CPS BANDWIDTH

FUTURE WORK

The project during the coming year will be concerned with a series of systematic stellar scintillation measures to assure that continuity is maintained throughout several seasons and varied meteorological conditions.

It is anticipated that, in addition, measures on the over-all size of the tremor disc of a star will be made. Dr. Keller's theoretical investigations, which will soon be published, lead to the conclusion that such measures can yield more immediately useful "soundings" of the upper atmosphere than can scintillation measures alone.

It may be necessary to construct an auxiliary photometer for this purpose. Nonetheless, the present daytime scintillation measures will be continued, with the added feature that scintillation records will be made on tape and analyzed with an audio spectrograph.

APPENDIX I

SHOT NOISE IN A CONSTANT LIGHT SOURCE

In the course of making measurements with the present equipment (Fig. 4), it has been observed that a noise signal exists even when the photomultiplier tube is illuminated by a lamp operated at a constant level of illumination for a period of time long in comparison with the time needed for a single measurement. The Naval Observatory workers, Mikesell, Hoag, and Hall[1], in their work with nighttime scintillation, have recognized this noise as a shot noise, and in reducing their stellar observations they take this into account by illuminating their tube with a "standard noise source" bulb, which is merely a dc-operated lamp adjusted to the same level of illumination as that given by the object measured.

In order to clarify the terminology used in these project reports and to obtain a physical picture of the process by which the noise in question originates, the following discussion, based upon measurements made with our present equipment, may be helpful.

Let us consider first one specific observation. The dc lamp illuminating the phototube was operated at a light level such that, with 360 volts across the photomultiplier tube, an anode current of 2.3×10^{-7} amperes was measured. This corresponded to a light flux on the cell cathode of the order of 2×10^{-6} lumens. The measured noise at 20 cps was 7.36 microvolts.

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1. A. H. Mikesell, A. A. Hoag and J. S. Hall, J.O.S.A. 41, 689, (1951).

We wish to determine which of the following possible sources of noise is responsible:

    a. Thermal noise in the input resistor.

    b. Current noise in the input resistor.

    c. Amplifier and circuit noise.

    d. Shot noise arising from anode current electrons.

    e. Shot noise due to discrete pulses arising from photoemission caused by effective photons striking the cathode of the photomultiplier. [The dark current, or thermal emission of electrons at the photo cathode, also adds to the noise, but in exactly the same manner as a photoemission; it can therefore be discussed as a part of (e).[7]

We discuss these separately.

(a) To indicate the magnitude of the thermal noise, a simple calculation using the familiar formula of Nyquist shows that the noise attributable to this source is many times smaller than that observed. The Nyquist formula states that

$$E^2 = 4\ R\ K\ T\ \Delta f$$

where
- E = rms voltage
- R = ohmage of the resistor
- K = Boltzmann constant
- T = resistor temperature (Kelvin)
- Δf = frequency bandwidth of measuring apparatus.

In the present instance, $T = 300°K$, $R = 0.62 \times 10^6$ ohms, and $\Delta f = 0.64$ cps. Therefore the noise voltage at 20 cps, if of thermal origin alone, should be only 0.08 microvolt, a negligible amount.

The above is valid only when the resistor is not carrying a current.

(b) (c) When the resistor carries current, the possibility of current noise must be checked. In the present instance, a precision carbon type resistor is used and the current noise would be expected to show somewhat the same statistical nature as thermal noise, arising

from changes in resistance at the faces of adjacent carbon particles under current flow.

Such noise can easily be checked by supplying, from a battery to the input circuit of the system, a dc signal equal to that given by the photomultiplier. This was done in this particular instance, with the result that the noise output was too low to give a reliable reading; this source can therefore be excluded in our example. This same measurement also indicates that the amplifier and associated circuits are not responsible for the observed noise.

(d) Shot noise is now left as the remaining possibility. This noise arises because of the random arrival of discrete pulses at a measuring device. When applied to the case of discrete electrons in a current flow it is often called the Schottky effect. The analysis of the effect, in which one assumes pulses of charge M and arrival rate K, leads to the expression[2]

$$I^2 = 2 M^2 K \, \Delta f$$

Here I represents the root mean square current fluctuations in the pass band Δf. If one considers a pulse to be one electron, this expression becomes the Schottky formula:

$$I^2 = 2 e \overline{I} \Delta f$$

where $\overline{I}$ is the average direct current and e is the charge on the electron.

If this expression is applied to the case under consideration, a noise due to the discrete electrons in the anode current of the order of

2. Goldman, Stanford, Frequency Analysis, Modulation and Noise, p. 311 (McGraw-Hill Book Company, Inc., New York, 1948).

2.2 x 10^{-13} amperes is found, corresponding to a voltage of 0.14
microvolts. This again is too small to be considered as a major
contribution to the observed noise.

(e) If one now returns to the general expression

$$I^2 = 2 \, M^2 \, K \, \Delta f$$

and replaces $\underline{M}$ by $\underline{m} \, \underline{e}$, where $\underline{m}$ is the multiplication of the tube and $\underline{e}$
the charge on the electron, their product being simply the terminal
pulse size due to one effective photon at the cathode, it can be written
as

$$I^2 = 2 \, m \, e \, \overline{I} \, \Delta f.$$

The randomness in the electrical pulses is determined by the randomness
in the arrival of the effective photons at the cathode. In the present
case, for a 1P21 photomultiplier operated at 38 volts per stage, the
RCA Tube Manual indicates an average multiplication, m, of the order of
3000. Calculating the noise current from these data, one now finds

$$I = 1.16 \times 10^{-11} \text{ amperes.}$$

This corresponds to a noise voltage of 7.14 microvolts, and agrees with
the measured noise.

The small difference between the observed and calculated
value is probably due to the assumed multiplication factor of the
tube. Actually, one may reverse the above procedure to obtain $\underline{m}$ from
the observed noise. Adoption of m = 3100 rather than 3000 brings the
observed and calculated values into agreement. In passing, it may be
noted that this method affords a simple technique for measuring the
multiplication of a photomultiplier tube.

For the sake of completeness, it should be mentioned that the contribution of the phototube dark current (3×10^{-11} ampere) to noise production in this instance is negligible, amounting to only 0.011 microvolt.

Since all the noises considered here are random, with the exception of possible instrumental noises, they add quadratically. Thus, all but the shot noise associated with the arrival of photons at the cathode are, in effect, negligible. It is well to emphasize this point: the measured noise in properly functioning photomultiplier equipment is predominantly a function of the photon arrival rate.

The agreement between noise calculation and observation has been checked at other frequencies and illumination levels; the agreement persists.

In order to correct for the shot noise in the combined signals from skylight and starlight in daytime measurements, arising from the constant components of the two sources, a dc lamp, operated at a constant level equal to the average level of the measured total signal, is used to determine the equivalent shot noise components in the measured starlight. This bulb will henceforth be referred to as the " standard noise source", in keeping with the terminology of Mikesell, Hoag, and Hall[3].

It is interesting to note one consequence of the expression

$$I^2 = 2 \, m \, e \, \bar{I} \, \Delta f.$$

Since the average anode current, $\bar{I}$, is proportional to the illumination

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3. Loc. cit.

level on the cathode, the absolute level of the noise increases as $\sqrt{F}$, where F is the light flux falling on the cathode. Under normal circumstances, one is interested in the signal-to-noise ratio that is present; this, of course, increases as $\sqrt{F}$ for increasing illumination levels. That is, there is an apparent decrease in noise relative to the signal as the illumination from a source which behaves as a dc-operated lamp increases.

The present equipment used in daytime scintillation observations measures absolute noise, and thus the ordinary situation does not obtain; the apparent shot noise _increases_ as the " dc" illumination level increases.

APPENDIX II

TECHNIQUE USED FOR THE MEASUREMENT
OF NOISE MODULATION OF STARLIGHT

A. Observation

1. Level of sky illumination is measured.

2. Sky signal is biased out and amplification is increased to permit larger scale recording of star noise.

3. Amplifier output is analyzed with wave analyzer; at least two minutes is devoted to each selected frequency measured.

4. The star is removed from the entrance diaphragm of the photometer and the adjacent blue sky signal alone is analyzed; identical instrumental settings are used.

5. The photomultiplier tube is separately illuminated by a dc lamp adjusted to the same level of illumination as the sky and the signal is analyzed as in (3) and (4).

6. The system is calibrated with known input voltages at selected frequencies, dc voltages are used to calibrate levels of sky and star illumination.

B. Recording of Data

The output of the wave analyzer is presented by means of ink traces on a Brown recorder sheet. Noise traces at a constant frequency are variable owing to the random nature of the noise. The dc measurement is presented by means of an ink trace on a Brush recorder, which also serves as an indicator of any radical changes in the star signal, such as might be caused by variable transparency, while observations are in progress.

C. Reduction of Observations

1. Averages of the Brown recorder traces for the (sky + star), sky, and artificial source, respectively, are determined for each observation.

2. The relative voltage for each frequency component is read from calibration curves relating deflection on the recorder to relative voltage.

3. Relative voltage is converted to actual r m s voltage, using calibration from (6) of observation procedure.

4. Observations are reduced to unit bandwidth by dividing the measured noise by the square root of the bandwidth. This procedure introduces negligible errors, since the original bandwidth is small, approximately 3.2% of the mean frequency setting.

5. The star scintillation signal is obtained by reducing the (sky + star) signal to (star) signal:

$$(\text{star signal}) = \sqrt{(\text{total signal})^2 - (\text{sky signal})^2}.$$

Likewise sky scintillation signal, that is, modulation above shot noise if such exists, would be detected by reducing the sky signal:

$$\text{sky signal} = \sqrt{(\text{sky signal})^2 - (\text{dc lamplight})^2}.$$

Here, signal means the effective r m s value at a given frequency for 1 cps bandwidth.

6. All results are corrected for attenuation due to finite input capacitance.

7. The dc input voltages are evaluated from the dc calibration.

8. Results are expressed as per cent sine wave modulation

$$M = 1.414 \frac{\overline{F_f}}{F_{dc}}$$

where $\overline{F_f}$ = average r m s voltage at frequency f, and

$$F_{dc} = \text{dc signal voltage.}$$

Note: The dc signal used for the star computations is the excess of the star over the sky value. If this value is large compared to the sky signal, the procedure is modified. The dc lamp is set at the (star + sky) level as well as the (sky) level. These data are then used to reduce the observations. Furthermore, if any sky scintillation signal is detected the star scintillation signal is corrected accordingly.