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Report No. 8
Contract AF 19(604)-14
J. Allen Himek November 23, 1953

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Report No. 8

PROGRESS

REPORT

By

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION

COLUMBUS 10, OHIO

To..... AF CAMBRIDGE RESEARCH LABORATORIES

..... 230 Albany Street, Cambridge 39, Mass.

..... Contract AF 19(604)-41

On FLUCTUATIONS OF STARLIGHT AND SKYLIGHT

.....

.....

For the period July 1, 1953 - September 30, 1953

Submitted by J. Allen Hynak

..... Department of Physics and Astronomy

Date November 23, 1953

ABSTRACT

The technique of recording stellar scintillations on magnetic tape has been developed to a satisfactory state and is presented as a potentially useful tool in the study of the atmosphere.

The tool has been used in a comparison of daytime and nighttime stellar scintillation, in a comparison of the scintillation of double stars, and in a comparison of stellar scintillation at opposite ends of the visible spectrum.

The usefulness of "scintillation moduli" to describe numerically the shape of a scintillation curve is being explored, and their application to the variation of scintillation with zenith distance and with telescope aperture has been attempted.

The work on low frequency scintillation variation with telescope aperture and with zenith distance has been completed and is presented in tabular form for reference. These indicate the order of scintillation that results with a given telescopic system, at a given time of day, and at a given zenith distance.

The exploratory survey into the nature of image motion has been completed. The general independence of stellar scintillation and image motion has been established, and values of image motion, in seconds of arc, which might be expected under average conditions have been determined from measures made on 1600 movie frames of stellar image motion during the day as well as the night.

PERSONNEL AND ADMINISTRATION

There were no changes in personnel and the only change in administration was the appointment of Mr. William Protheroe as acting Project Supervisor during September while Dr. Hynek was in Europe. During September Dr. Hynek was officially on leave from the project.

Facilities at the University continue to be adequate for the prosecution of this contract work.

COMMUNICATIONS

A paper on observations establishing the independence of what is ordinarily termed "astronomical seeing" and "twinkling" or stellar scintillation, has been accepted for publication by the Journal of the Optical Society of America. The paper carries the title "Stellar Scintillation and Image Motion" and the author is Roger Hosfeld.

Dr. Keller presented a paper, "Experimental Verification of a Theory of Astronomical Seeing", at the summer meetings of the American Astronomical Society, held at Boulder, Colorado, August 26-28, 1953.

Dr. Hynek discussed the present studies of stellar scintillation in progress at The Ohio State University with many European astronomers and presented talks on this subject at the Stockholm Observatory at Saltsjöbaden, Sweden, at Lund Observatory, Lund, Sweden, and at the University of Helsinki, Helsinki, Finland.

STATEMENT OF THE PROBLEM AND METHOD OF ATTACK

The basic problem remains the same, the study of the effect of the atmosphere on celestial images (a) to obtain harmonic analyses of stellar scintillation and to establish parameters of scintillation which may prove useful in military and meteorological applications and, of course, in the physical study of the atmosphere; (b) to study the manner in which an image moves, in the daytime as well as at night, and to establish a correlation, or lack of it, between scintillation and image motion; and (c) to attempt a theory of atmospheric effects on the stellar image.

SUMMARY OF SIGNIFICANT RESULTS
OBTAINED DURING REPORT PERIOD

1. SCINTILLATION STUDIES

Many significant observational data were obtained during the report period, enabling definite conclusions regarding scintillation and image motion to be drawn, but perhaps the matter of most overall significance was the establishment and "proving-out" by Mr. Protheroe of the technique of recording stellar scintillation on magnetic tape, during both nighttime and daytime. In the matter of a few minutes, a "scintillogram" on tape can be obtained which gives a record of the stellar scintillations characteristic of the atmospheric conditions prevailing at that time. The record can then be "played back" at one's convenience and a detailed harmonic analysis made at leisure.

The chief advantages of this technique are (1) elimination of changing atmospheric conditions during an analysis and (2) availability of as many points on the frequency curve as desired and (3) permanency of record and availability for re-analysis. Item (1) is especially important. To obtain a large number of points on the scintillation frequency curve, such as is necessary in establishing fine structure along the curve, the time needed to make the analysis directly at the telescope is prohibitive, and even if the atmospheric conditions remain identically the same, the zenith distance of the star changes appreciably during the interval of observation. With a tape recording, the observations are made in a matter of minutes, but "play-back" for complete analysis can take the better part of the day.

The tape recording technique now allows an independent approach to the problems already investigated by Mr. Hosfeld, who used the much simpler technique of recording the integrated low frequency scintillations, (0-10 cps) directly on a Brown Recorder. Of greater importance, the new method allows an analysis of scintillation, frequency by frequency, and an extension of studies to the higher frequencies.

Previously Mr. Protheroe had made harmonic analyses of scintillation, including the higher frequencies, but by the more tedious methods of direct recording with a wave-analyzer at the telescope.

It is of interest to list the first applications of the tape recorder technique.

- (1) Comparison of day and night stellar scintillation frequencies.
- (2) Scintillation frequency curves for components of a double star, extending the work of Hosfeld on the incoherency of double star twinkling.

- (3) Scintillation frequency curves for red and violet portions of the spectrum.
- (4) Establishment of variation of scintillation moduli with zenith distance.
- (5) Variation of scintillation moduli with telescope aperture.
- (6) Comparison of star-planet scintillation frequencies.

A large part of the material in the above items comprises original work and some is supplementary and confirmatory to work done previously here or elsewhere.

Before discussing the above items, it will be best to present in outline form also the significant results obtained during the report period.

Since Mr. Hosfeld is to be transferred to another project as of November 1, he devoted a considerable portion of this time to the reduction and compilation of results obtained on the present project. These results are two-fold: those concerning low-frequency scintillation (0-10 cps, in terms of per cent of mean dc signal from the star) of stars during the day and the night, as functions of zenith distance and telescope aperture; and those concerning the motion of the stellar image.

It can be stated that the investigation of integrated low frequency scintillation of stars with respect to star elevation, star color, time of day, and telescope aperture is now essentially completed. Functional relationships have been established to a good degree of finality. Photoelectric techniques were employed in the above. It is felt that additional work on these topics will produce little that is new.

In the second branch of this work, carried out by motion picture photography, a survey of image motion has been completed. Because of the time-consuming observational work, it has been impossible to extend image motion work to correlations with zenith distance, telescope aperture and star color. However, spot checks have been made which indicate the nature of the variation to be expected.

The scintillation and the image motion studies have established beyond all reasonable doubt that the two (scintillation and motion) should be regarded as essentially independent parameters of image behavior.

Returning now to a brief discussion of the individual items covered above:

- (a) In Fig. 1 typical daytime and nighttime scintillation-frequency curves are contrasted. These extend to higher frequencies, the unpublished observations of Hosfeld (for 0-10 cps) that, as a general "rule-of-thumb", maximum daytime scintillation is nearly twice as great as nighttime scintillation. These scintillation curves represent the first records made by magnetic tape of stellar scintillation. Previously Mr. Protheroe had made daytime and nighttime measures using a wave-analyzer directly at the telescope.
- (b) Analysis of tape recordings of the combined scintillation of the components of a double star are shown in Fig. 2. The observed curve is compared with two computed curves, one on the hypothesis that the double star components scintillate coherently, and the other that the scintillation of each of the components is random.

Mr. Protheroe observed each component of the double star separately, and then in combination. The scintillation data for the separate components were combined as though the star scintillated in phase and at random, respectively. These two computations (top two curves on Fig. 2) were then compared with the lowest curve which represents the scintillation arising from both components simultaneously, as observed at the telescope. The latter agrees most closely with the "random" hypothesis. This result confirms findings on the components of Castor (separation $2''.6$) of Hosfeld* who employed essentially the same reasoning but used the integrated scintillation (0-10 cps) technique. Protheroe's results favor the hypothesis of incoherency over the entire frequency range.

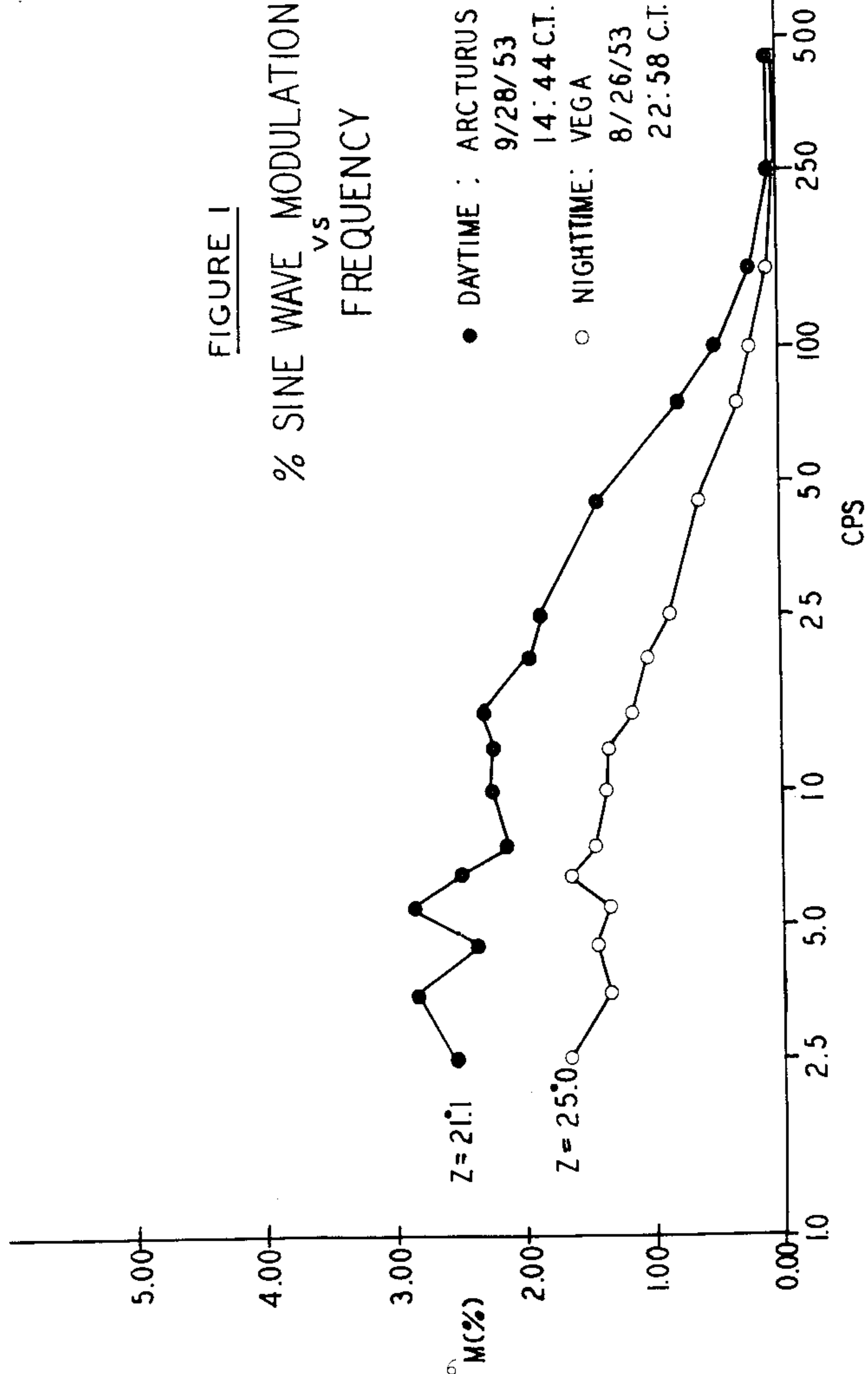
- (c) The phenomenon of twinkling in color, shown to the unaided eye by stars close to the horizon, clearly indicate that, at least in certain instances, scintillation is not color-coherent. This has not, as yet, been established for small zenith distances, an important point, since obvious (to the eye) color scintillation disappears at zenith distance less than 45 degrees.

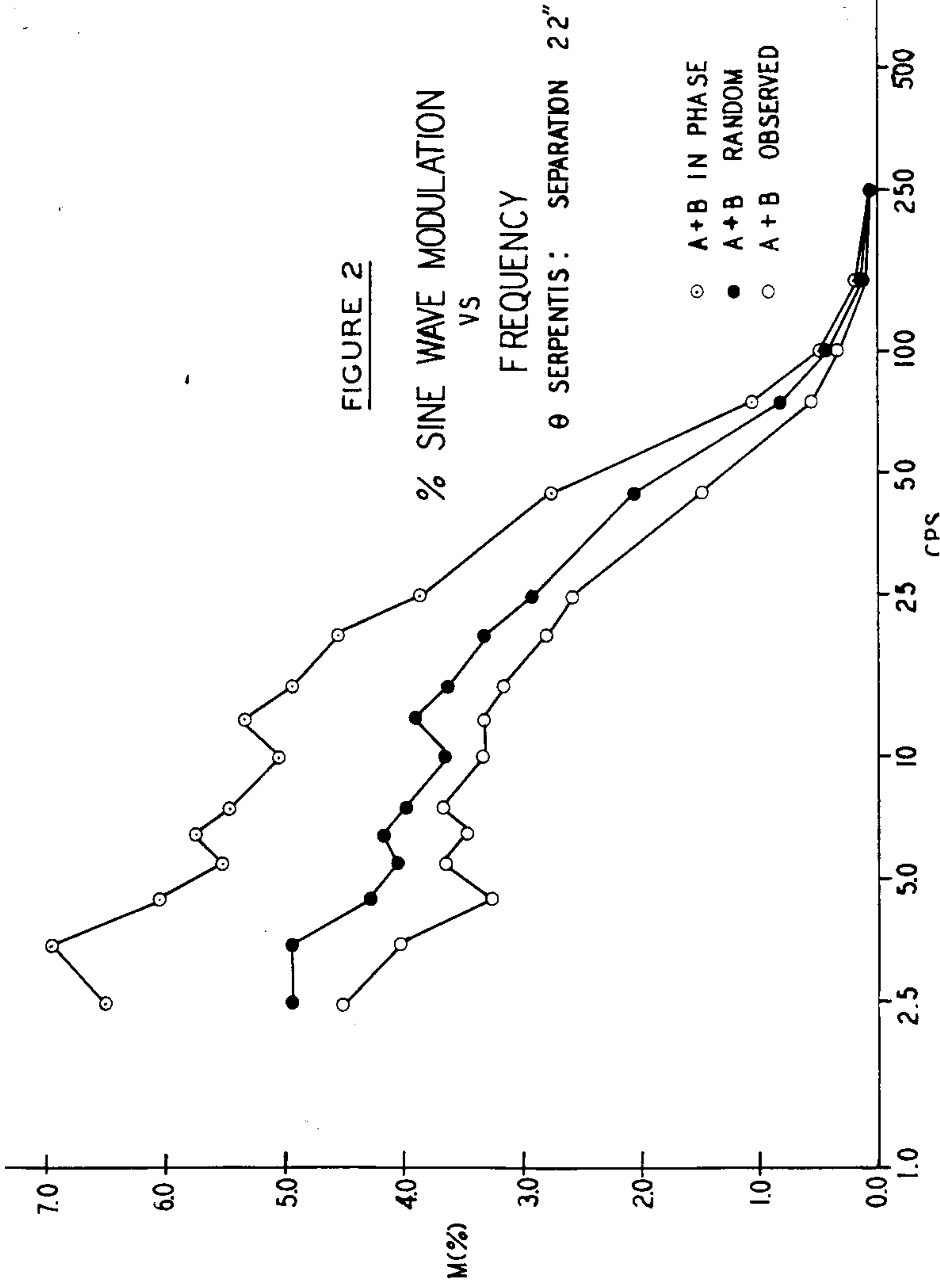
A related question is whether the time-integrated scintillation curves are identical in different colors. Tape recordings of stellar scintillation made through red and ultraviolet filters, using a 12.5 inch aperture, have been analyzed and representative results are shown

*Project Report No. 7 (July 25, 1953)

FIGURE I

% SINE WAVE MODULATION
vs
FREQUENCY





in Figs. 3 and 4. Fig. 3 concerns the twinkling of Vega when very close to the zenith, Fig. 4 that of Arcturus at a zenith angle of 66° .

There is no marked difference in the shapes of the scintillation curves in the two colors, either for small or large zenith distances. It appears, therefore, that whether or not instantaneous incoherency in color scintillation occurs near the zenith (as we know it does at large zenith distances) there is no overall difference in the scintillation of a star in different colors, regardless of its zenith distance, for large apertures.

- (d) In order to describe how scintillation curves vary with the several parameters, e.g., zenith distance, Protheroe has adopted "scintillation moduli", as indices of scintillation, to characterize the shape of a scintillation curve.

The scintillation modulus as defined at present is the ratio of the average per cent sine wave modulation in a given frequency range to that in the frequency range 2.5 to 10.5 cps. The frequency ranges in the numerator of this expression have been chosen as 10 to 50 cps and 50 to 400 cps respectively for the purpose of conducting a preliminary study of their usefulness as an index of the shape of the curve.

It should be emphasized that the scintillation modulus is a measure of the shape of the scintillation curve, and not of the amount of scintillation. Thus Fig. 5 indicates the change in shape of the scintillation curve with zenith distance without reference to the amount of scintillation within selected frequency ranges with zenith distance.

In Fig. 5 and 6 the open circles represent nighttime observations and filled circles the daytime observations. In Fig. 5 it is clear that there is in general no change in the shape of the scintillation curve from day to night, whereas Fig. 6 indicates that there is an increase in the amount of scintillation from night to day, even though the scatter is large.

- (e) Fig. 7 shows, in passing, another type of measurement made with the tape technique, that of comparing scintillation from a star with that from a planet. This type of comparison, however, has been done previously, by our observers and by other investigators. The results here are confirmatory.
- (f) Further tape recordings of scintillation were made to supplement previous work, here and elsewhere, on the effects of decreasing aperture upon the nature of scintillation. Circular apertures alone are reported here, although work is in progress on the use of rectangular slits in various orientations. The tape recordings were confined to observations at the zenith.

FIGURE 3

% SINE WAVE MODULATION
VS

FREQUENCY

VEGA: $\bar{Z}=4^\circ$

○ CLEAR

● RED

⊙ ULTRAVIOLET: $\lambda_e 6280, BW 500$

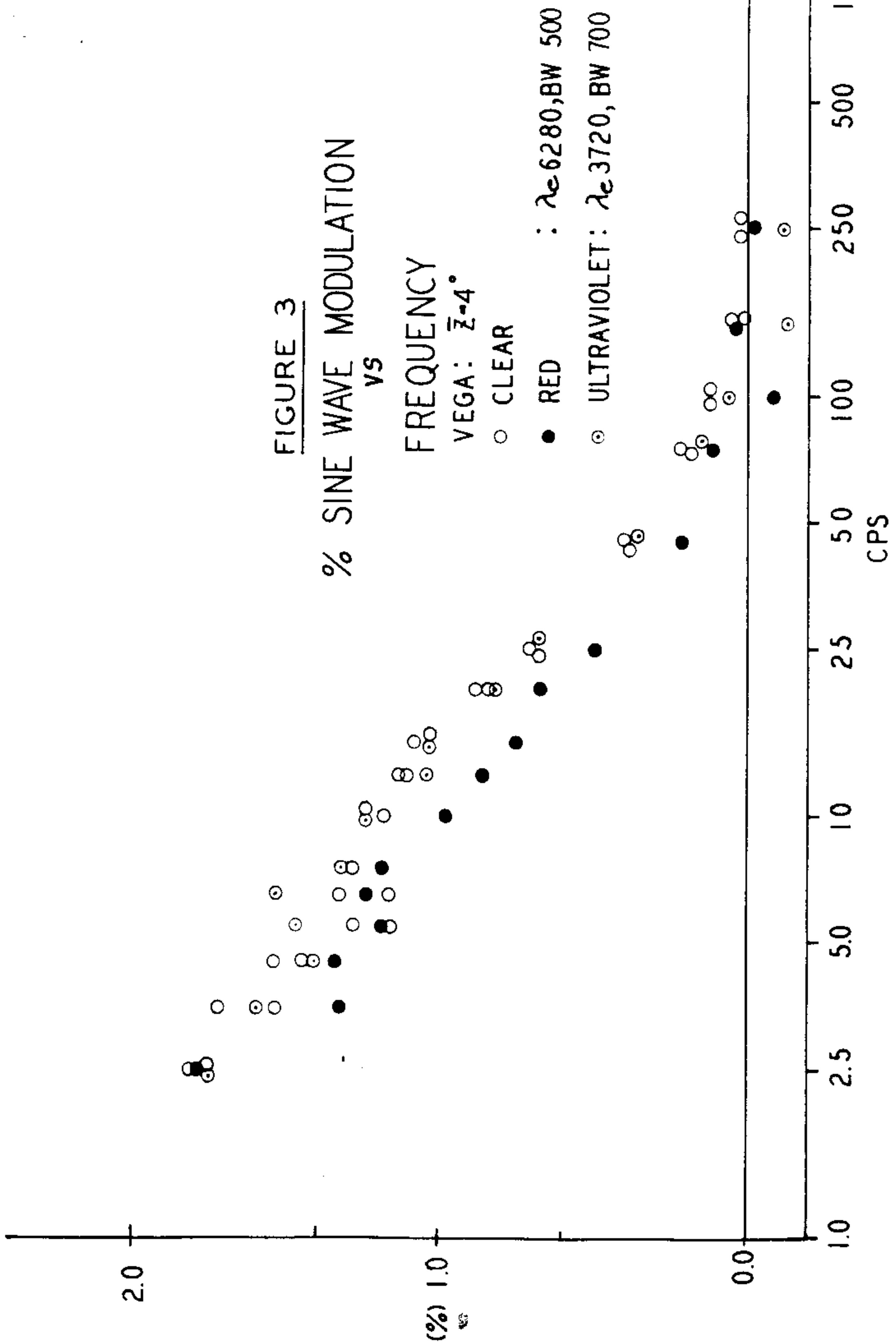
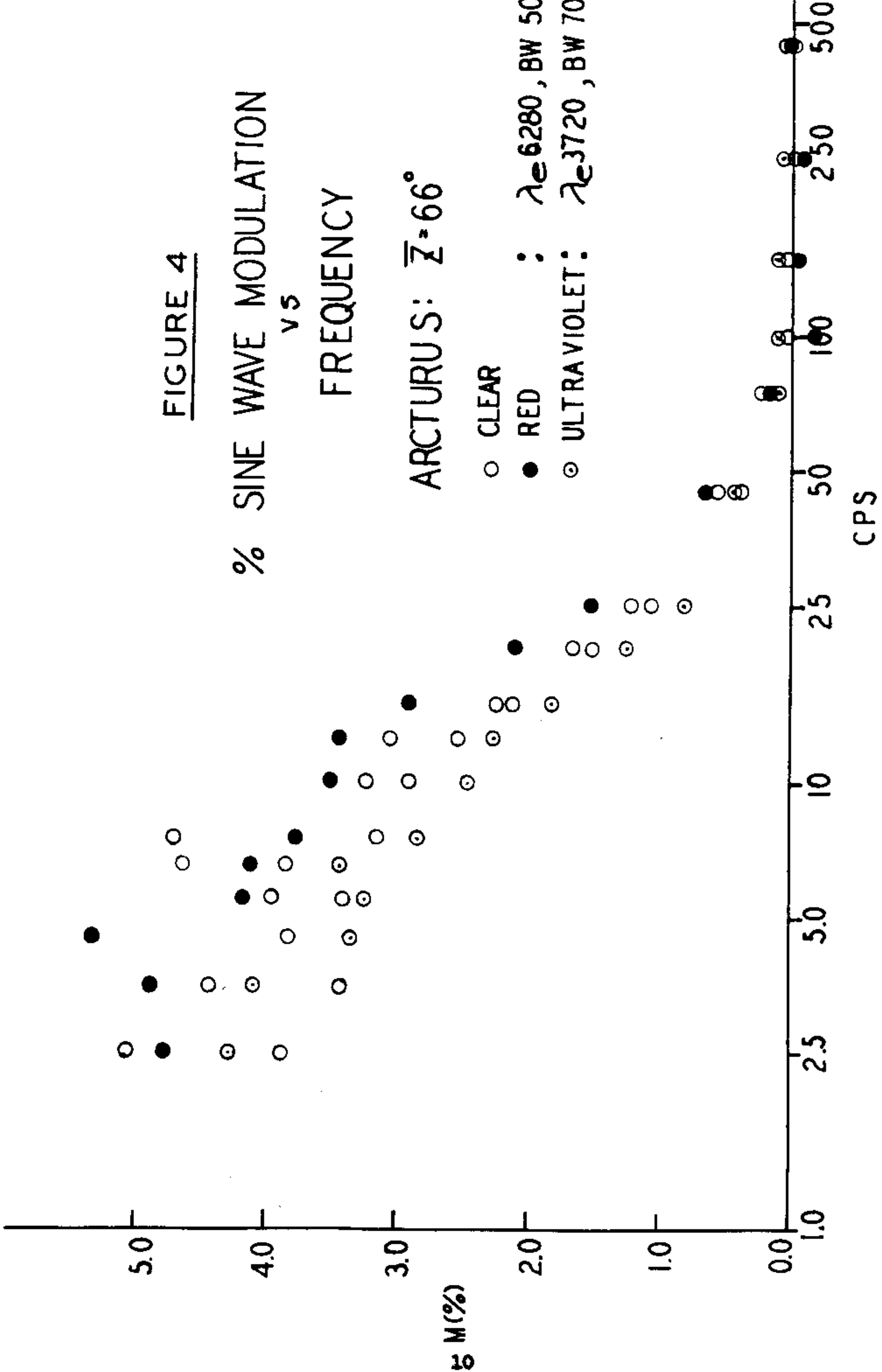


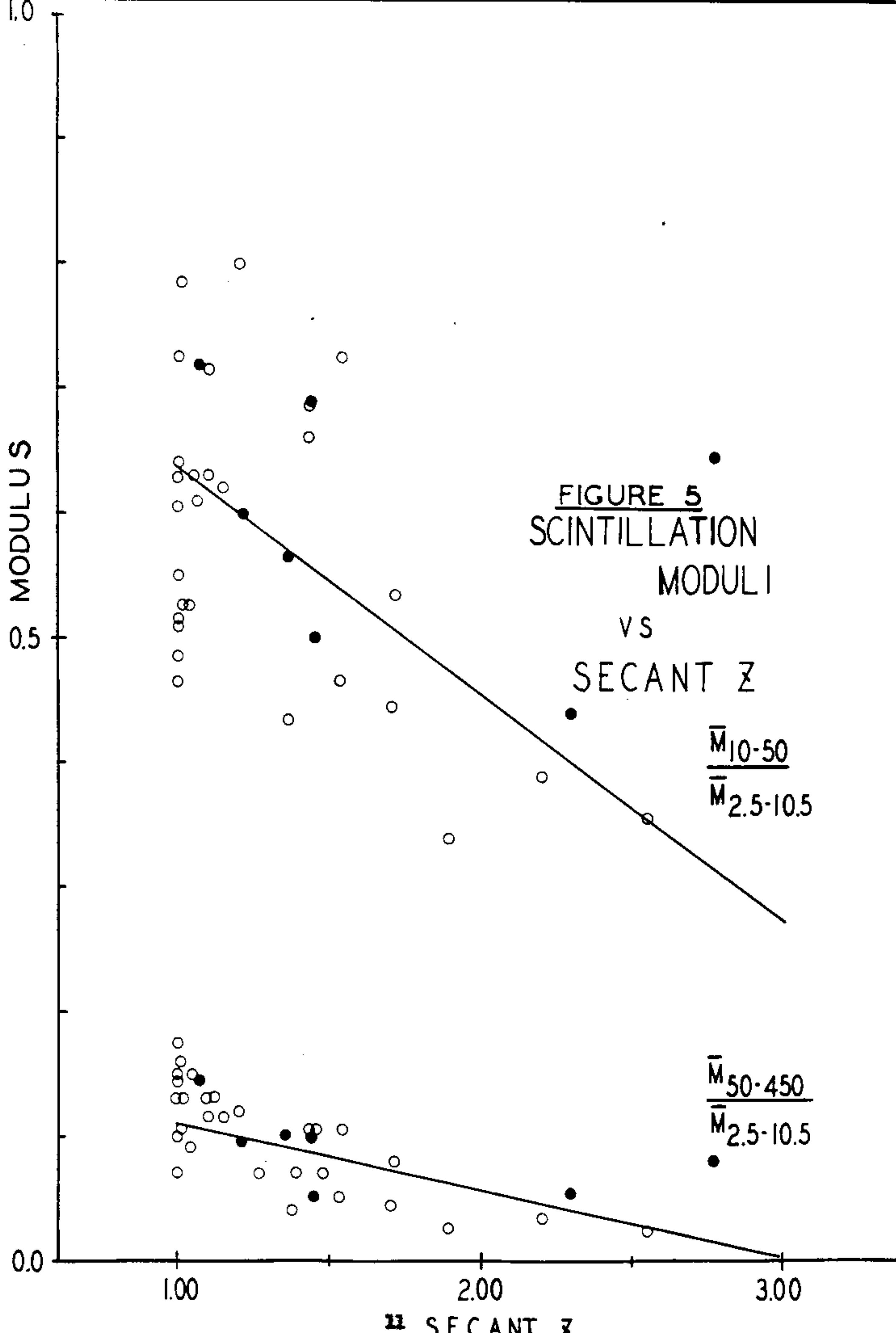
FIGURE 4

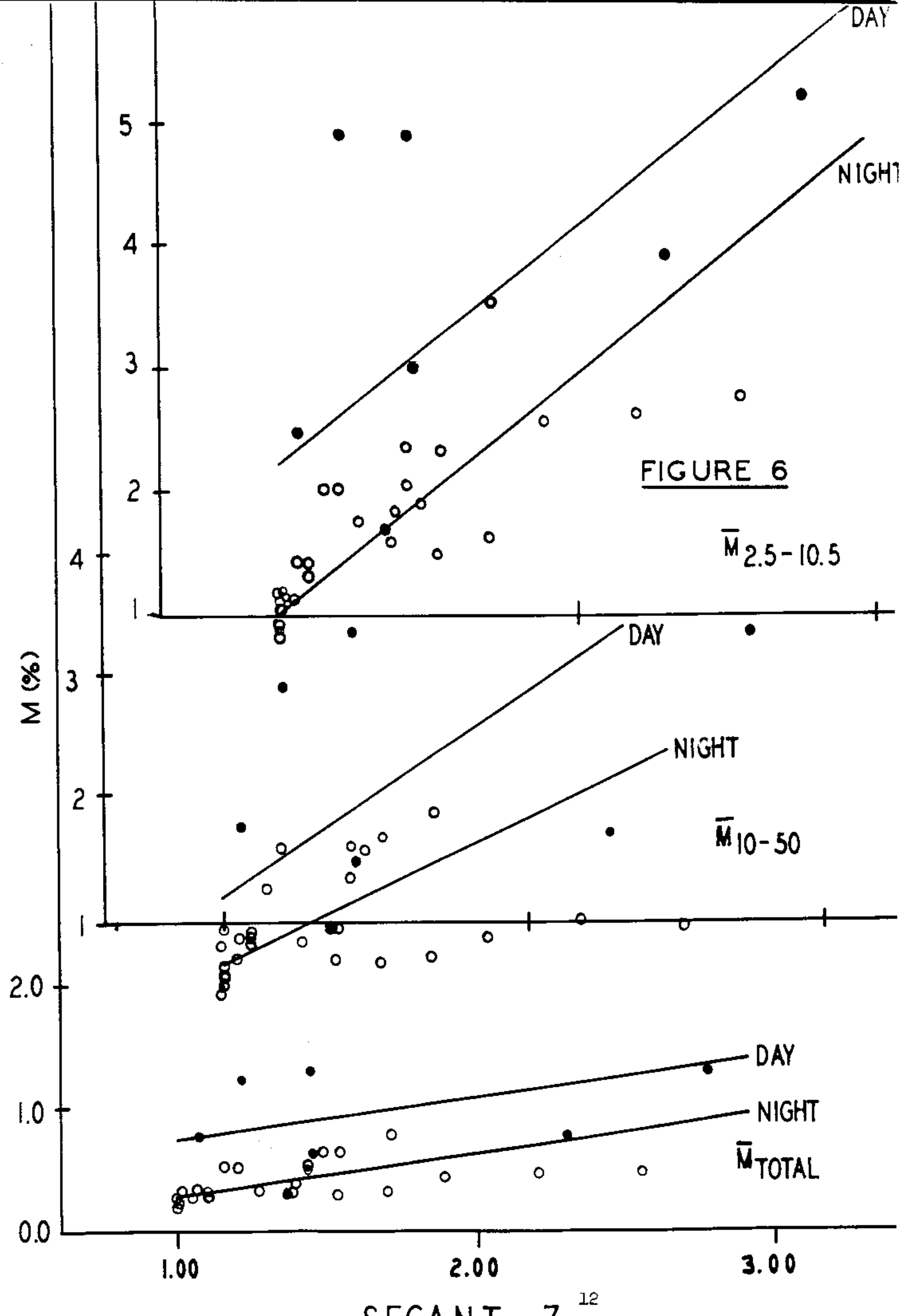
% SINE WAVE MODULATION
vs
FREQUENCY

ARCTURUS: $\bar{\lambda} = 66^\circ$

- CLEAR
- RED : $\lambda_e 6280, BW 500$
- ⊙ ULTRAVIOLET: $\lambda_e 3720, BW 700$







2.00

M (%)

1.00

0.00

ALDEBARAN $Z=43.5$
03:31 EST

FIGURE 7

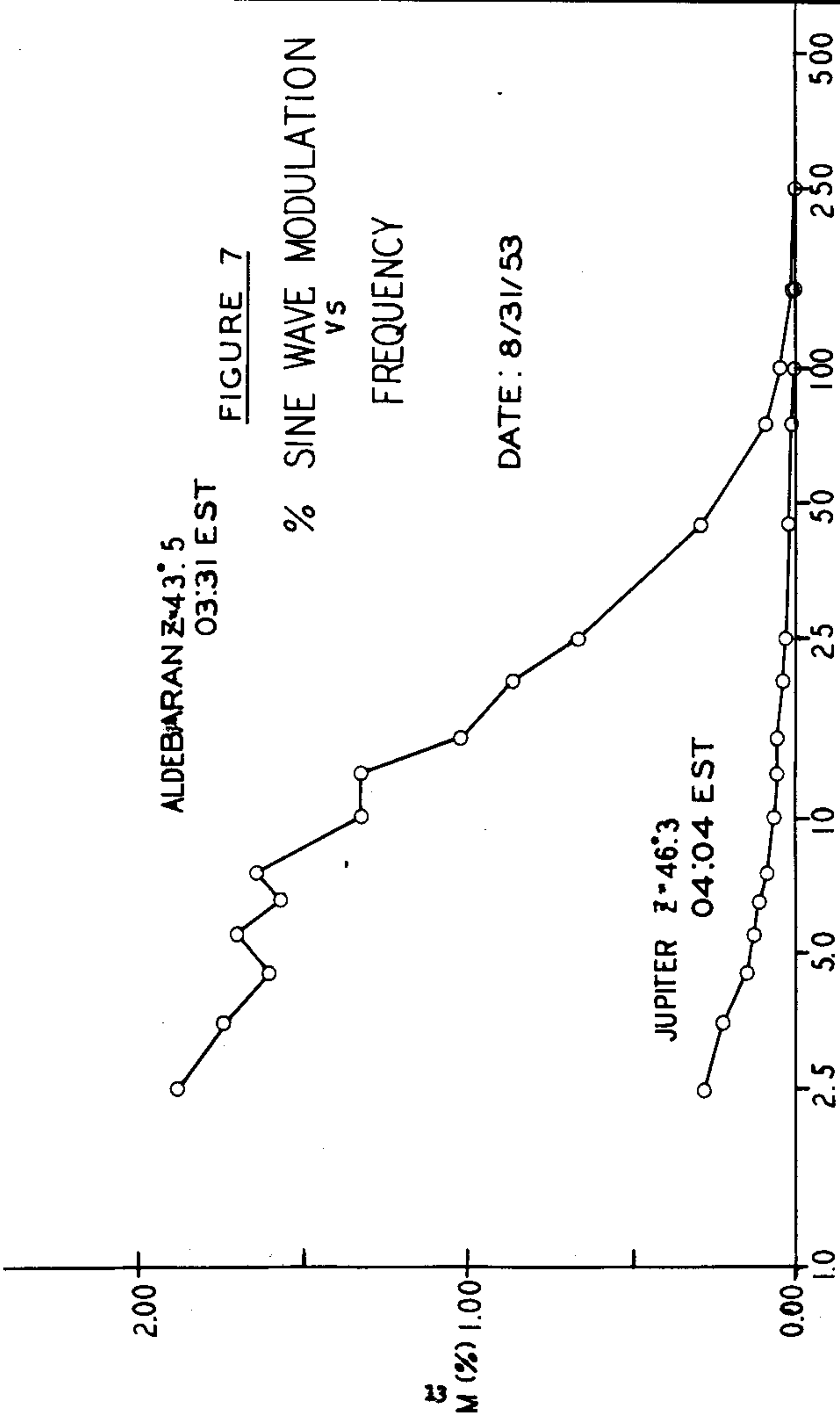
% SINE WAVE MODULATION
vs
FREQUENCY

DATE: 8/31/53

JUPITER $Z=46.3$
04:04 EST

CPS

1.0 2.5 5.0 10 25 50 100 250 500



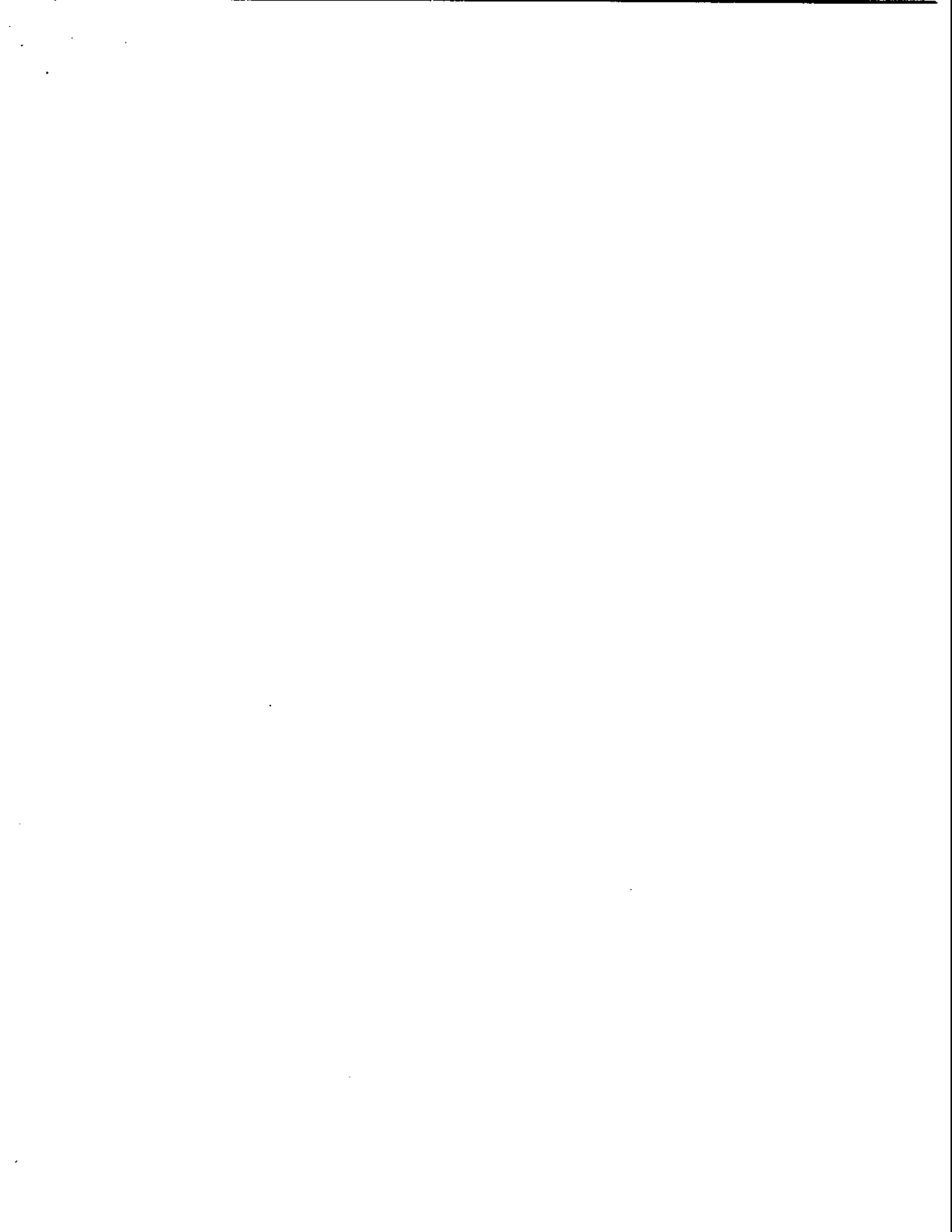


FIGURE 8

% SINE WAVE MODULATION
VS
FREQUENCY

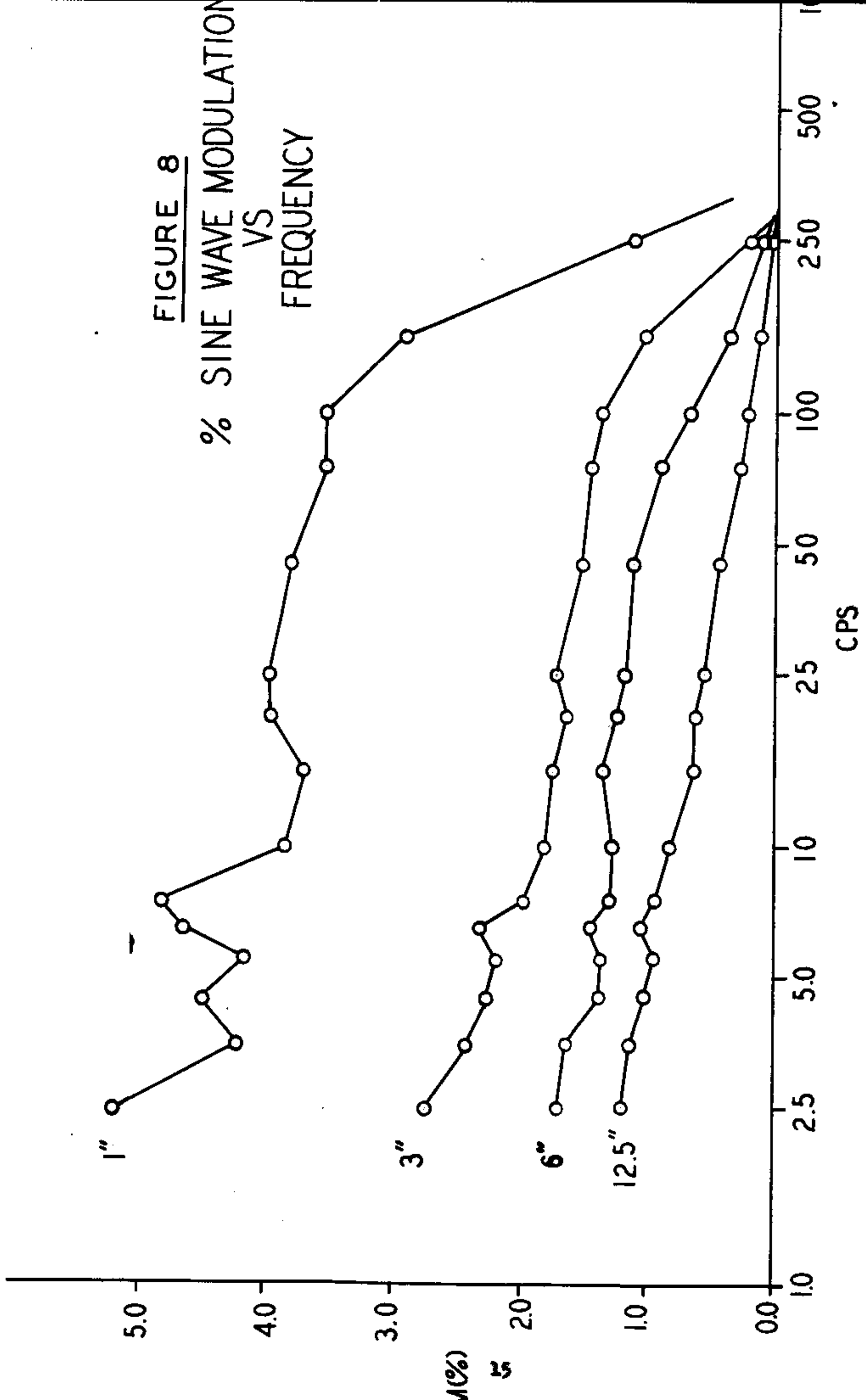


FIGURE 9

RELATIVE SCINTILLATION
VS
APERTURE

- $\overline{M(\%)}$ 2.5-10.5 CPS
- △ $\overline{M(\%)}$ 10-50 CPS
- $\overline{M(\%)}$ TOTAL

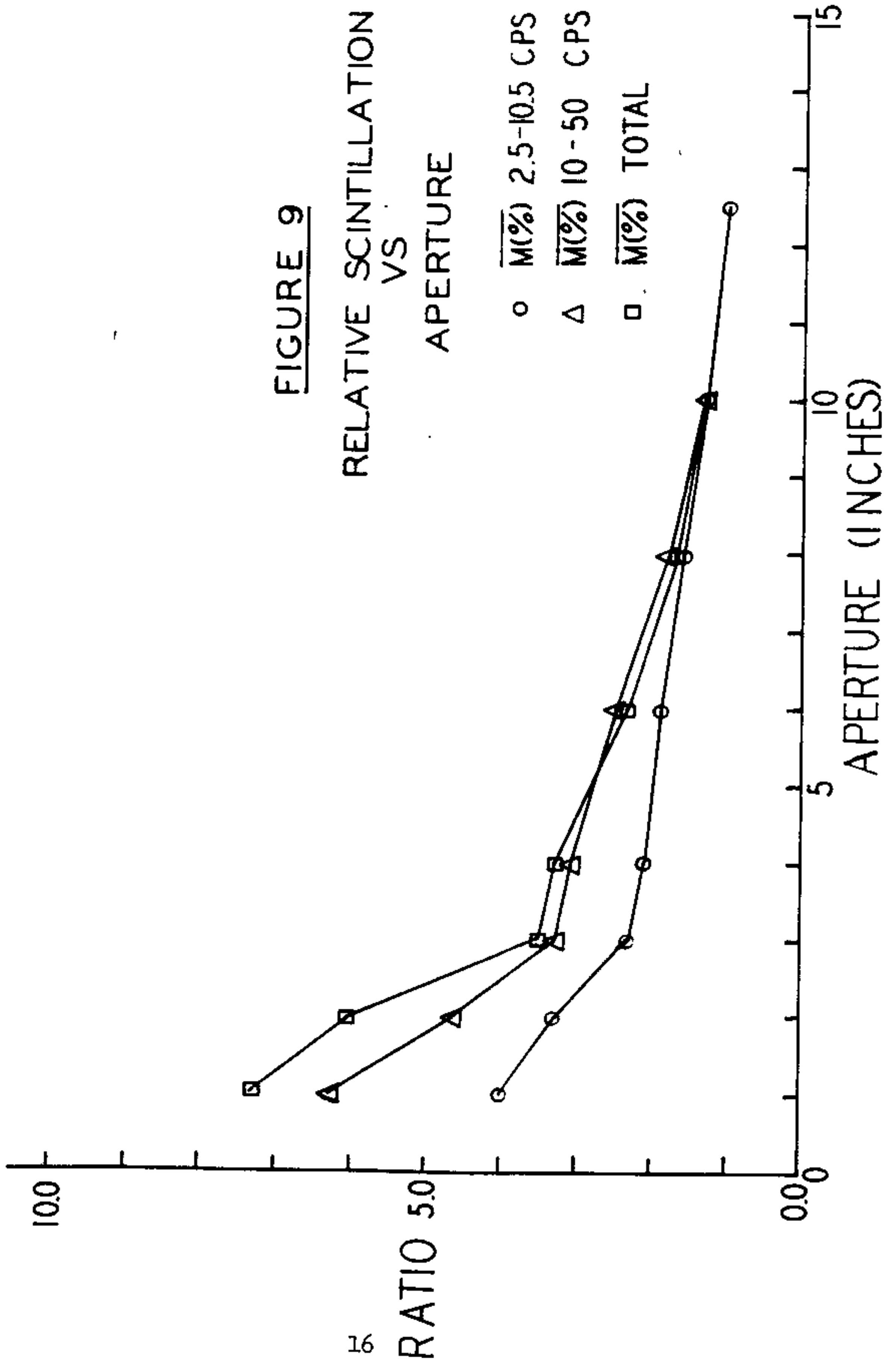


FIGURE 10

SOLID = OBSERVED ZENITH SCIN.
DOTTED = CALCULATED $\frac{\text{APERTURE}}{\text{APERTURE}}$

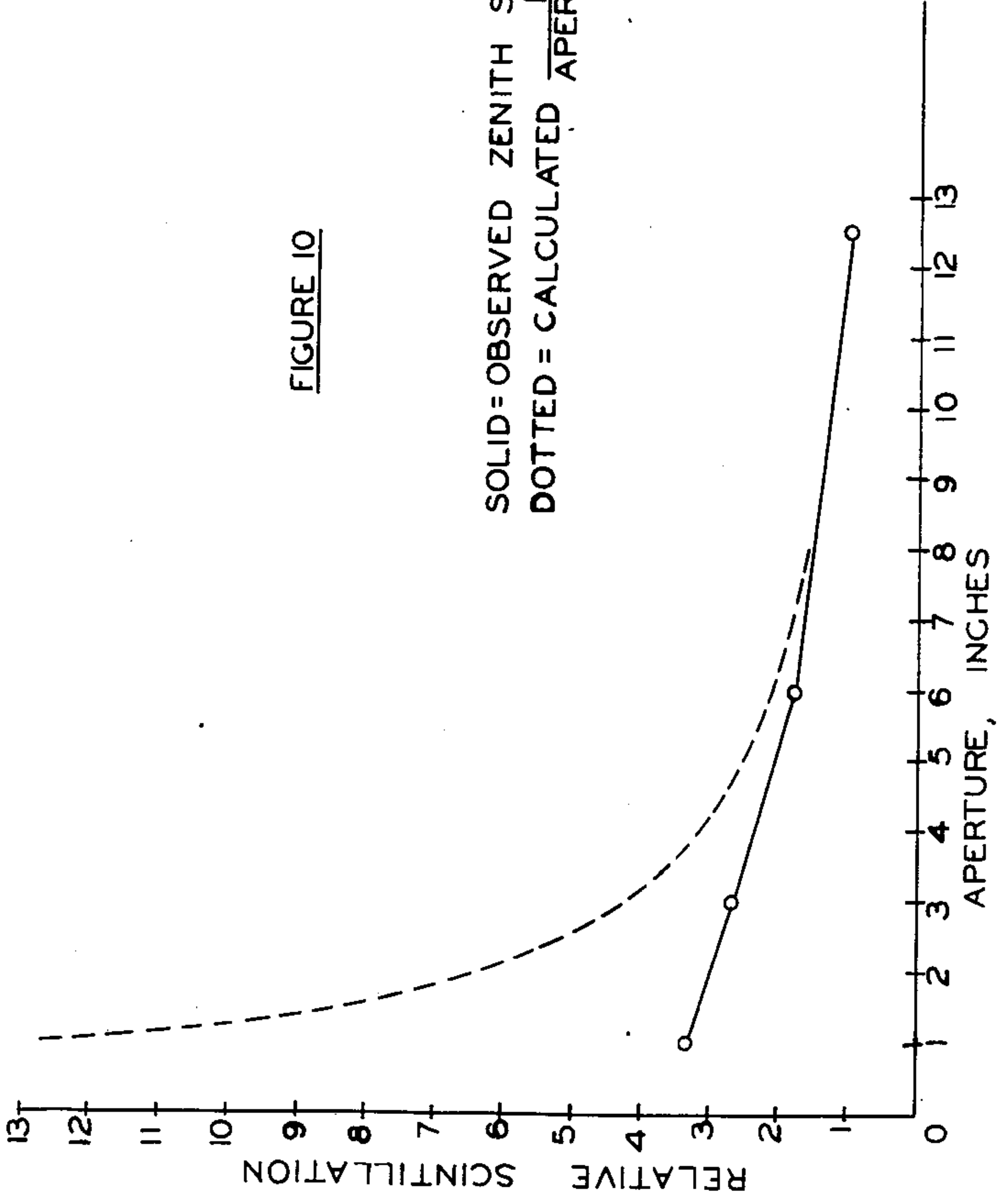


TABLE 1

STELLAR SCINTILLATION, 0-10 cps (PER CENT OF MEAN de STELLAR SIGNAL)

| Zenith Distance of Star Degrees | Aperture of Telescope (circular) | | | |
|------------------------------------|----------------------------------|--------|--------|--------|
| | 12-1/2 inch | 6 inch | 3 inch | 1 inch |
| 0 | 19 | 34 | 51 | 63 |
| 30 | 24 | 41 | 60 | 74 |
| 45 | 31 | 50 | 68 | 90 |
| 60 | 50 | 75 | 95 | 125 |
| 70 | 85 | 120 | 145 | -- |

TABLE 2

INCREASE OF SCINTILLATION OVER FULL 12.5 INCH APERTURE

| Zenith Distance of Star Degrees | Aperture of Telescope (circular) | | |
|------------------------------------|----------------------------------|--------|--------|
| | 6 inch | 3 inch | 1 inch |
| 0 | 1.8 | 2.7 | 3.3 |
| 30 | 1.7 | 2.5 | 3.1 |
| 45 | 1.6 | 2.2 | 2.9 |
| 60 | 1.5 | 1.9 | 2.5 |
| 70 | 1.4 | 1.7 | -- |

The factors in Table 2 prove to be independent of the time of day, i.e., a 3-inch aperture at 45 degrees zenith distance can be expected to give 2.2 times as much scintillation as the 12.5 inch aperture, regardless of time of day or night.

2. IMAGE MOTION STUDIES

A second phase of the work done by Mr. Hosfeld, has now also been completed. This is a motion picture study of image motion.

The photocell is admirably suited for scintillation studies but for studies of the motion of the image the motion picture camera is far better.

In previous reports, accounts of the progress of this work has been given (see especially Progress Report No. 7). Mr. Hosfeld has been collating this material on the subject, with the express purpose of summarizing his results on the total amount of image motion to be expected.

Unfortunately, much more labor is required to obtain exact functional relations between image motion and time of day and zenith distance than between these parameters and low frequency scintillations. Time has not permitted a long investigation of image motion. Nevertheless, Table 3 presents the analysis of 1000 motion picture frames. Each entry represents a summary of image motion measures on 100 frames. The two columns are, respectively, the total range of motion (in seconds of arc) shown by the image in 100 frames, taken at about 1 frame per second, and the mean motion of the image if the ten per cent of frames showing greatest deviation, and the ten per cent showing the least motion are neglected. That is, the second column is a measure of the image motion to be expected generally, with the "high" and "low" fringes omitted.

TABLE 3

| Time | Date | Star | Total Range | "Average Motion" |
|------------|--------------|----------|-------------|------------------|
| 8:45 A.M. | 29 September | Castor | 3.5 | 3.2 |
| 9:15 A.M. | 24 September | Capella | 5.8 | 3.2 |
| 9:22 A.M. | 27 September | Castor | 7.1 | 3.5 |
| 9:35 A.M. | 7 September | Capella | 3.3 | 2.0 |
| 10:30 A.M. | 29 August | Capella | 5.8 | 3.3 |
| 10:45 A.M. | 30 August | Capella | 4.4 | 2.4 |
| 1:15 P.M. | 24 September | Arcturus | 5.6 | 3.4 |
| 2:35 P.M. | 6 September | Arcturus | 10.1 | 5.8 |
| 3:35 P.M. | 1 October | Vega | 5.3 | 2.4 |
| 4:10 P.M. | 1 October | Arcturus | 7.7 | 3.5 |
| 6:10 P.M. | 29 August | Arcturus | 3.4 | 1.2 |
| 6:40 P.M. | 29 August | Vega | 2.7 | 1.2 |
| 8:20 P.M. | 7 September | Vega | 2.6 | 1.9 |
| 8:45 P.M. | 7 September | Arcturus | 6.0 | 2.6 |
| 10:40 P.M. | 6 September | Vega | 5.1 | 2.2 |
| 10:50 P.M. | 26 August | Vega | 5.4 | 2.9 |

All observations were made at zenith distances of approximately 30 degrees except the evening observations of 7 September. In that case Vega was less than five degrees from the zenith and Arcturus was 65 degrees away. It appears, from limited evidence, that image motion does not obey the same law of increase with zenith distance that scintillation does.

It should be pointed out that two 3-inch apertures separated by 9 inches center-to-center were used in studying image motion. Each 3-inch aperture forms its own stellar image and when examined out-of-focus (as in the Hartman test), the two separated images can be seen describing relatively independent motions. These independent motions result in fairly rapid changes in image spacing, being sometimes close together, sometimes widely separated. Photographs of 1/25 second exposure time were taken at 1 to 2 second intervals until 100 samples of the image separation were obtained for each run.

These 100 separations were then measured to the nearest 0.1 second of arc and the resulting frequency distribution and cumulative frequency distribution were plotted for each run as illustrated in Fig. 11. Circles and crosses represent independent measures on the same data. If the incident wavefront at the telescope were undisturbed, all image pairs would have the same spacing, but if the wavefront is distorted by its passage through the earth's atmosphere, and if that distortion is changing rapidly, the separations will be different from photograph to photograph, with the degree of distortion being reflected in the spread of observed image separations. Two measures of this spread of separation values are given in Table 3. The first measure is the total range over which the spacing changes; e.g., if the closest pair of images shows 4 seconds of arc separation and the greatest spacing is 10 seconds of arc, the range, or total change in separation, is 6 seconds of arc. Since this criterion is determined by the two extreme values obtained during the run of 100 observations, a single fortuitously large or small value might give a range which would not be representative of the entire run. For this reason a second measure of the spread is included, obtained from the cumulative frequency plot, which is the separation at the 90th percentile minus the separation at the 10th percentile. This particular choice of values was dictated by the fact that the lower upper and upper lower "wings" of the cumulative frequency plot begin to flatten at about the 10th and 90th percentile respectively so that these values are relatively stable and yet include the bulk of the observed spacings (80%).

It should be noted that the number of seconds of arc over which an image in a 3 inch telescope can be expected to move is about one half of the value reported in the "range" column, since the closest spacing of the images can be expected when both move toward each other by the maximum amount of individual motion and the farthest spacing when each moves away by the maximum displacement.

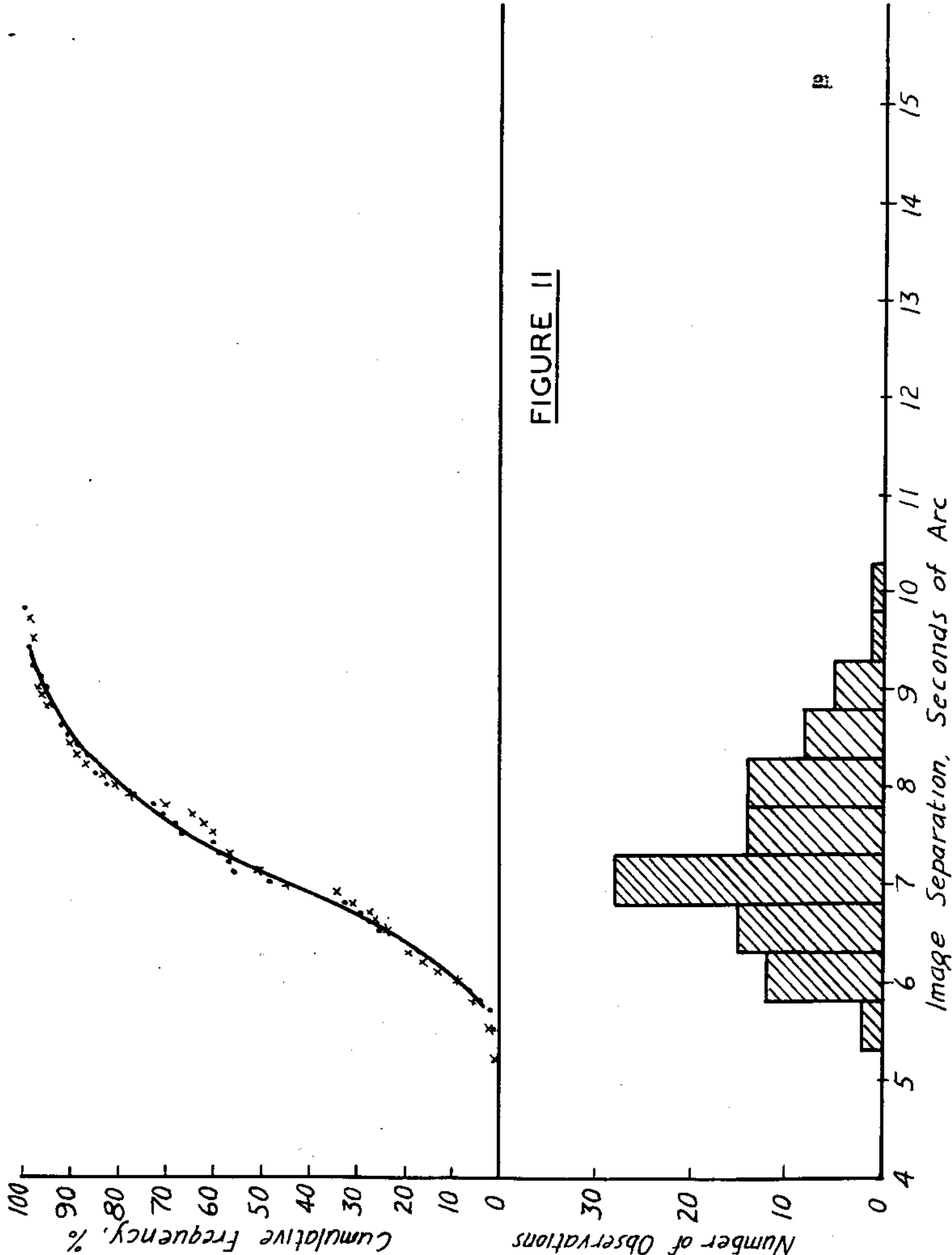


FIGURE II

Similarly, for telescopes of large aperture where the individual portions of the total image are subject to the displacements measured by the two 3 inch areas, the image will be spread over an area half the diameter of the values reported in Table 3.

FUTURE WORK

Under the limited extension of the present contract, effective October 1, 1953, Mr. Protheroe is to carry on and complete his present program of tape recording of stellar scintillation with the purpose of "tying down" quantitatively the variation of scintillation frequencies with zenith distance, time of day, and general meteorological conditions. Mr. Protheroe will also examine a series of scintillation curves for "fine structure"; that is, for periodicities or preferential frequencies in stellar scintillation.

At the close of the extended contract it is hoped that the technique of magnetic tape recording of stellar scintillation will have been established as a standard and usable adjunct to atmospheric studies.

Investigator..... Date.....

Ernest Hosfeld

Supervisor..... Date.....

For The Ohio State University Research Foundation

Executive Director..... Date.....