

PUBLICATIONS
OF
THE UNITED STATES
NAVAL OBSERVATORY

Second Series
Vol. XVII-Part IV



WASHINGTON : 1955

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OF THE

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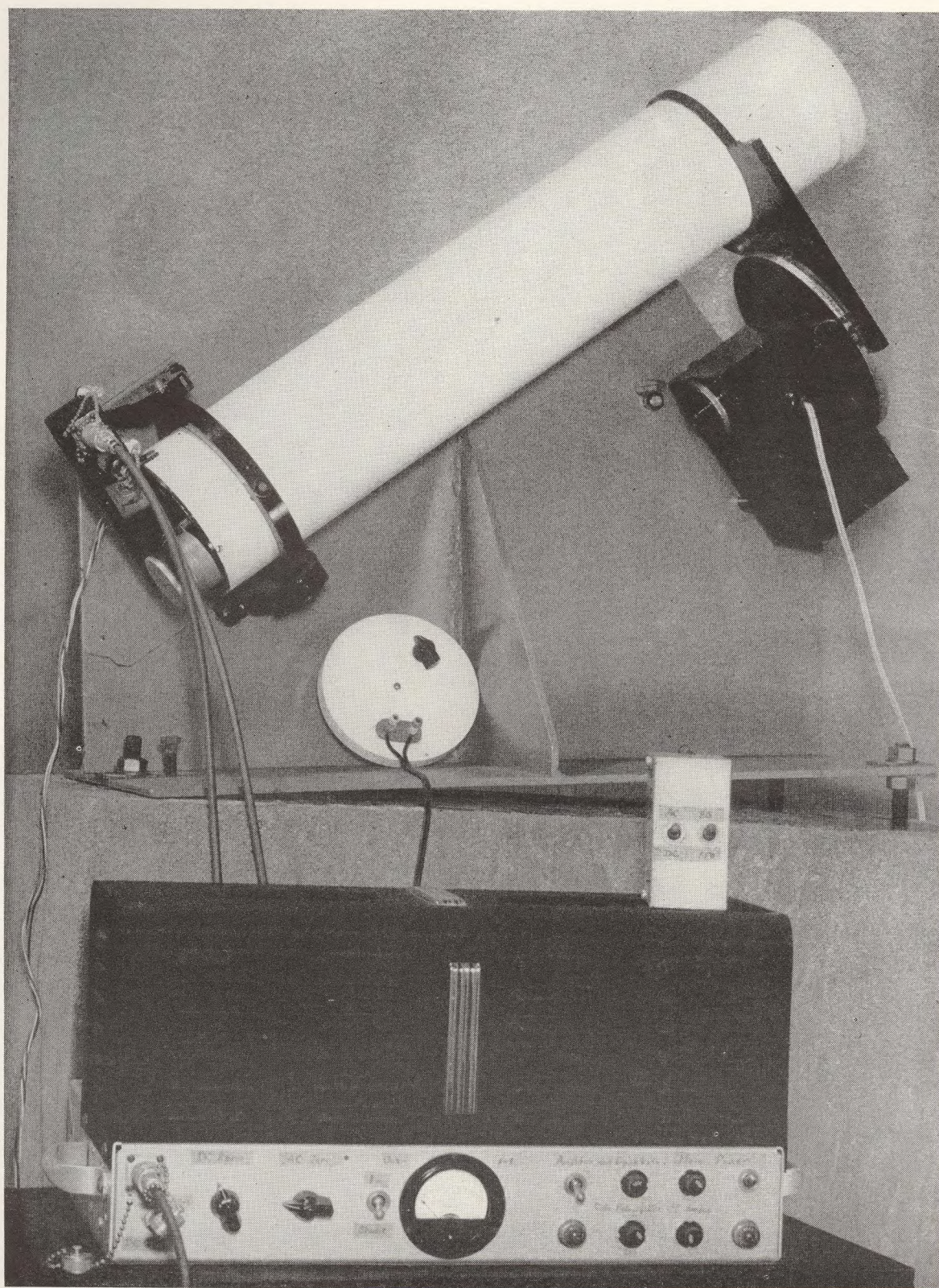
THE SCINTILLATION OF STARLIGHT

By
A. H. MIKESELL

139

TABLE OF CONTENTS

	Page
INTRODUCTION.....	143
PERSONNEL AND ACKNOWLEDGMENTS.....	143
EQUIPMENT.....	144
Optical components.....	144
Electrical components.....	144
Other equipment.....	146
REDUCTION OF OBSERVATIONS.....	146
Calibrations.....	146
Computations.....	147
Comparisons of Methods of Measurement.....	150
Noise meter and wave analyzer—Noise meter and oscillograph—Conclusion.....	150
THE OBSERVATIONS.....	152
Composition and Errors of Observations.....	152
Observing Routine.....	153
List of Observations.....	153
DISCUSSION OF THE RESULTS.....	164
The Shape of the Scintillation Distribution Curve.....	164
Scintillation and Weather.....	165
Seasonal effects of scintillation—Effect of wind on observations of scintillation made with 4-inch aperture—Effect of wind on observations of scintillation made with 15-inch aperture—Discussion of observations of scintillation made with rectangular aperture.....	165
Scintillation and Zenith Distance.....	177
Scintillation and Circular Aperture Size.....	178
Scintillation and Seeing.....	179
Introduction—Available seeing data—Scintillation and 4-inch telescope seeing—Scintillation and observations of latitude—Scintillation and other seeing criteria—Conclusion.....	179
Scintillation of Artificial Sources.....	185
Free balloon flights—Helicopter flight.....	185
POLARIS MONITOR.....	185
Equipment.....	185
Observations.....	187
Preliminary Results.....	187
Comparison with wind—Comparison with seeing.....	187
SUMMARY OF THE RESULTS.....	189
REFERENCES.....	190



THE POLARIS MONITOR.

THE SCINTILLATION OF STARLIGHT

INTRODUCTION

Scintillation is used here to mean only the changes with time of the brightness of the telescopic image of a star or other source. Seeing is construed to mean the degree of change in the position, shape or size of a stellar image. Considerable care was taken to eliminate effects of seeing from the observations of scintillation.

The amplitudes of several harmonic components of scintillation are published and discussed in this report. Each amplitude represents the ratio of the effect produced by scintillation, upon the measuring equipment, to that produced by a fully modulated, sinusoidally varying source of the same average brightness as the source of scintillation. The ratio is expressed as a percentage and is termed the equivalent sine-wave modulation of the starlight. For convenience the terms scintillation amplitude or scintillation are frequently used to denote the above ratio. When scintillation is used to mean the resultant of all frequency components integrated together, the fact is so stated.

The observation of scintillation was undertaken in 1950 for two major purposes: to measure its effects on the accuracy of stellar photometry, and to locate the underlying meteorological causes of scintillation. For secondary goals the program was designed to determine if a relation exists between scintillation and seeing, and to construct equipment which would continuously monitor both scintillation and transparency. The work involved in this project was supported in part by the Bureau of Ordnance, Department of the Navy.

Interest in the effects of scintillation on photometric accuracy arose with the increased application of alternating current methods to stellar photometry. Because early results^{1, 2} fulfilled the first major purpose of the program, most of the study has been directed to the other problems. This has meant systematic observations of scintillation, observations at very low frequencies, the use of artificial stars, and development of monitoring equipment.

The prior information on scintillation was outlined in an earlier report¹ and has since been described in more detail by Nettelblad,³ Epstein⁴ and Protheroe.⁵ This discussion deals, therefore, with the present program.

PERSONNEL AND ACKNOWLEDGMENTS

This program was initiated in September 1949, by John S. Hall. At that time he planned the use of the electronic harmonic analysis of scintillation which, in one form or another, has been retained for all the observations of this report. His interest and guidance have been a part of all phases of the study, including the discussion.

¹ 1 references are listed in the last section of this study.

The observations of January 1951, were made by A. A. Hoag, who also collaborated on the observations of stars through slits.

The author joined the program in 1950 upon the arrival of the first analyzing equipment and, with the above exceptions, has made all of the observations published herein. Mrs. Lucy T. Day, Mrs. Winifred Cameron, and J. L. Gossner assisted in the reductions. The figures were drawn by R. S. Lewis.

The results have depended also upon the exchange of equipment or ideas with many others, especially with Mr. E. Goldstein, Naval Research Laboratory, Washington, D. C.; Dr. E. C. S. Megaw, Royal Naval Scientific Service, England; Dr. A. J. Hynek and the members of the Ohio State University project, Columbus, Ohio; and Dr. A. G. Wilson and his collaborators at the Lowell Observatory, Flagstaff, Arizona. Mr. M. J. West and Mr. J. F. Dibrell of the Naval Bureau of Ordnance kindly assisted in obtaining a substantial portion of the equipment.

EQUIPMENT

OPTICAL COMPONENTS

Scintillation of starlight was examined with many combinations of telescopes and photoelectric photometers. The form of the optical equipment was found to be unimportant as long as the objective aperture was circular and all incident light reached the phototube. Concurrent observations occasionally made with different equipment gave essentially identical results. During the program there were used at various times a 12-inch polar telescope, 15-inch photographic equatorial, a 40-inch reflector, and several small polar, equatorial and alt-azimuth instruments.

Each telescope was equipped with a focal plane diaphragm, as small as was practical, and a field lens behind it which focussed the objective on the photocathode. This eliminated most of the intensity variations of the photometer signal due to gross excursions of the stellar image. However, the flying shadows, or light spots, which appear on objectives of large size still were reproduced at correspondingly varying locations on the photocathode. Since the cathode sensitivity was not uniform, such spottiness appeared as a brightness fluctuation in addition to that due solely to scintillation. This effect, as well as a signal variation which appeared as an objective slit was rotated, was eliminated by the use of a piece of ground glass in front of the phototube.

The photometer generally included means of adjusting the light intensity with an optical wedge and provision for color filters.

ELECTRICAL COMPONENTS

Most of the analysis of the photometer signal was performed at the telescope. This operation has been described for the frequency range of 10 to 1000 cycles per second.¹ The extension of the range to lower frequencies required additional electronic components, resulting in the system shown in outline in figure 1.

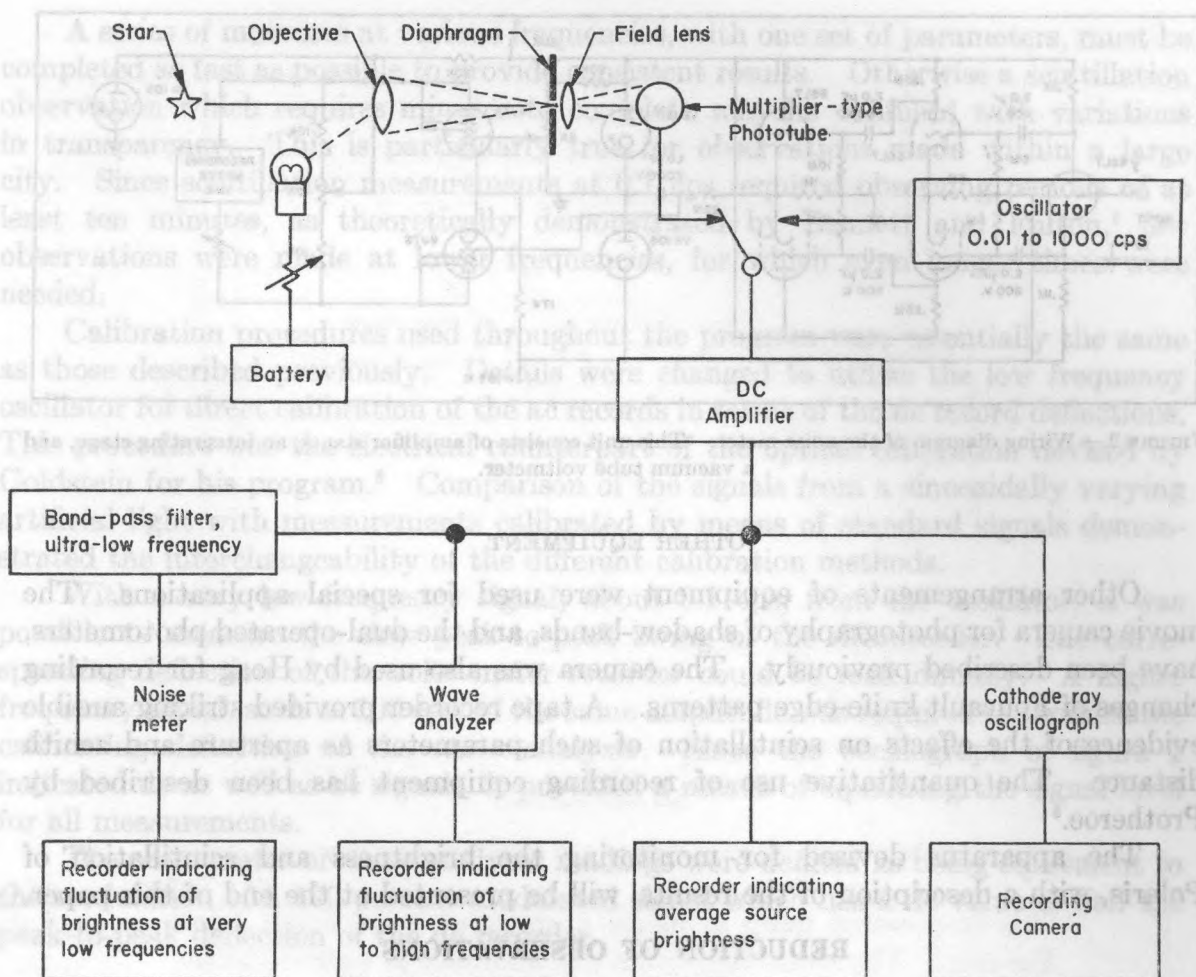


FIGURE 1.—Diagram of the apparatus for observing starlight scintillation.

Below 10 cps the fluctuations were analyzed with a Krohn-Hite type 330-A ultra-low frequency filter of variable bandwidth which has a lower pass limit of 0.02 cps. The filter output was applied to a "noise meter", a special vacuum tube voltmeter represented by the circuit diagram of figure 2. This design was kindly suggested to us by Dr. R. Clarke Jones of the Polaroid Corporation.

The ultra-low frequency oscillator which appears in figure 1 replaced the standard modulated light source of the first report as a calibrating signal source. This was manufactured by the Krohn-Hite Company as their type 400-A, and furnished sine-wave or square-wave signals at frequencies down to 0.01 cps.

The cathode ray oscillograph was essential for monitoring and calibrating. It also was combined with a camera for use as a recording instrument.

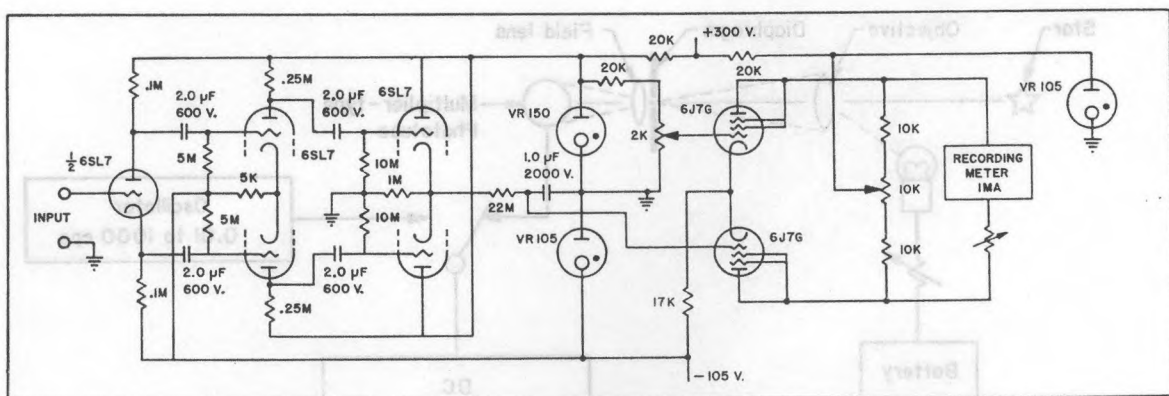


FIGURE 2.—Wiring diagram of the noise meter. This unit consists of amplifier stages, an integrating stage, and a vacuum tube voltmeter.

OTHER EQUIPMENT

Other arrangements of equipment were used for special applications. The movie camera for photography of shadow-bands, and the dual-operated photometers, have been described previously. The camera was also used by Hoag for recording changes of Foucault knife-edge patterns. A tape recorder provided striking audible evidence of the effects on scintillation of such parameters as aperture and zenith distance. The quantitative use of recording equipment has been described by Protheroe.⁵

The apparatus devised for monitoring the brightness and scintillation of Polaris, with a description of the results, will be presented at the end of this paper.

REDUCTION OF OBSERVATIONS

CALIBRATIONS

Calibration of the apparatus was based upon two standards: phototube shot-noise and standard dc and sine-wave signals. The shot-noise established the relative frequency response of the equipment while the standard signals provided the data for calibrating noise measures in terms of sine-wave modulation.

The consistency of the scintillation results depends upon uniformity of shot-noise amplitude with frequency. It has been shown that this premise is valid throughout the audio- and radio-frequency ranges.⁶ With the ultra-low frequency filter and noise meter the relation was tested in the sub-audio range. The observed noise meter deflection produced by multiplier shot-noise varied directly as the square root of the bandwidth down to 0.1 cps. Below this, photomultipliers usually produced more noise than predicted by this relation, depending upon which phototube furnished the noise, how much light shone on it, and its recent history regarding light exposure or dynode voltages. This individuality of phototubes, while significant for the 1P21's, was even more noticeable in four cases of other types and designs of commercial photomultipliers.

A series of measures at various frequencies, with one set of parameters, must be completed as fast as possible to provide consistent results. Otherwise a scintillation observation which requires minutes to complete may be confused with variations in transparency. This is particularly true for observations made within a large city. Since scintillation measurements at 0.1 cps required observing periods of at least ten minutes, as theoretically demonstrated by Bennett and Fulton,⁷ few observations were made at lower frequencies, for which even longer times were needed.

Calibration procedures used throughout the program were essentially the same as those described previously. Details were changed to utilize the low frequency oscillator for direct calibration of the ac records in terms of the dc record deflections. This procedure was the electrical counterpart of the optical calibration devised by Goldstein for his program.⁸ Comparison of the signals from a sinusoidally varying artificial light with measurements calibrated by means of standard signals demonstrated the interchangeability of the different calibration methods.

With a very low frequency signal, about 0.1 cps, from the oscillator, it was possible to measure the slow peak-to-peak swing of the dc recorder. The corresponding deflection of the noise meter recorder could be read directly. A higher frequency signal, such as 100 cps, of the same amplitude was required to produce the calibrating deflection of the wave analyzer. Since the oscillograph of figure 1 indicated dc as well as ac signals, it provided a means of equalizing the signal level for all measurements.

The noise meter or wave analyzer readings were defined as being equivalent to the modulation of a 100 percent modulated signal which has a dc value of half the peak-to-peak deflection of the dc recorder.

COMPUTATIONS

The procedure for the reduction of observations with either the noise meter or wave analyzer involved the following steps:

(1). *Correction for non-linearity of the ac indicating equipment.* The curves of figure 3 indicate that both the low- and high-frequency analyzers were linear in response over wide ranges above the non-linear toe of each curve. It was generally possible to adjust the degree of amplification until deflections were placed in the linear regions of each curve, and then to correct them automatically with zero adjustments.

(2). *Correction for non-linearity associated with frequency.* Variation of the indicated signal with frequency was caused mainly by the time-constant of the phototube circuit. Errors in indicated amplitude which depended upon frequency were determined for the complete equipment simply by measuring the noise produced by a photomultiplier when it was exposed to a constant light source.

(3). *Correction for shot-noise associated with the observed dc signal.* The relation used was

$$(\text{Total noise})^2 = (\text{Scintillation noise})^2 + (\text{Shot-noise})^2.$$

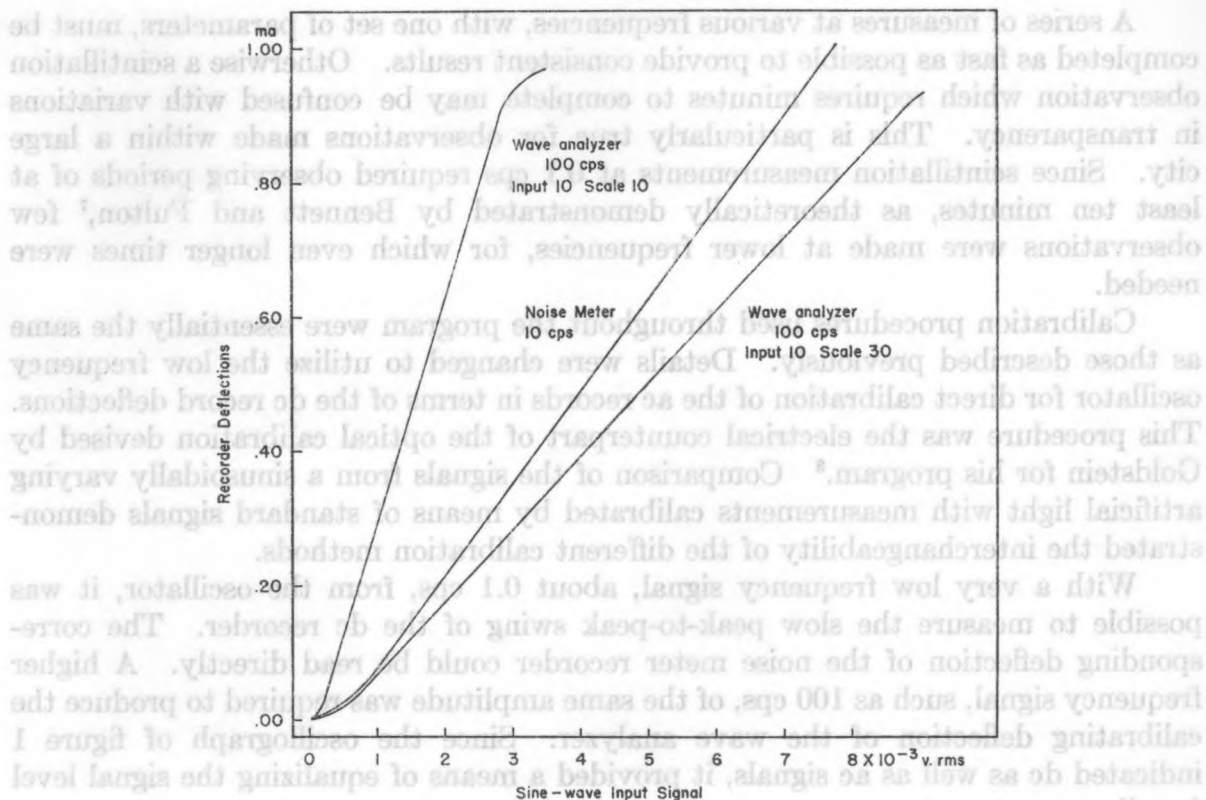


FIGURE 3. Response of the wave analyzer and noise meter to various input voltages.

The dc-powered lamp in figure 1 provided a dc signal equal to that of the star. The associated noise was assumed to be shot-noise.

(4). *Reduction to the equivalent sine-wave modulation for the observing bandwidth.* The previously described calibration process was introduced with the relation:

$$M = 100(i_s/i_c)/(I_s/0.5I_c),$$

where M is the percentage modulation of starlight in terms of an equivalent sine-wave signal, i_s is the noise meter or wave analyzer deflection produced by the star, I_s is the average or dc signal from the star, i_c is the noise meter or wave analyzer deflection produced by a standardized sinusoidal signal, and I_c is the peak-to-peak deflection of the dc-reading meter produced by or associated with i_c . I_s was corrected linearly for any component due to sky light, prior to its use in the above relation.

(5). *Reduction to the modulation which would have appeared if the bandwidth were one cps instead of that actually used.* Goldstein⁹ has demonstrated that when the observing bandwidth is small it is sufficiently accurate to correct the observed data by $(\Delta f)^{-1/2}$, where Δf is the effective observing bandwidth. Figure 4 shows the observed frequency characteristics of the

on limits on the latter were always set, for convenience, to one of the three arrangements shown. The measurements were corrected to unity bandwidth with the quantities given in the figure.

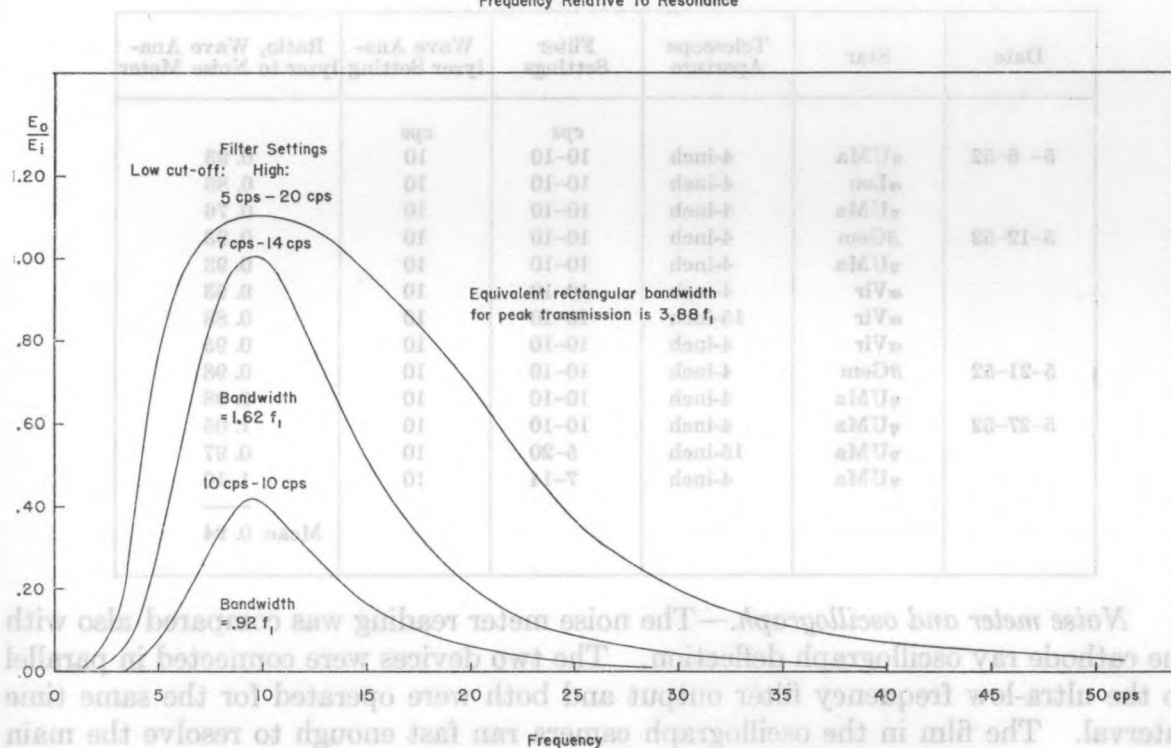
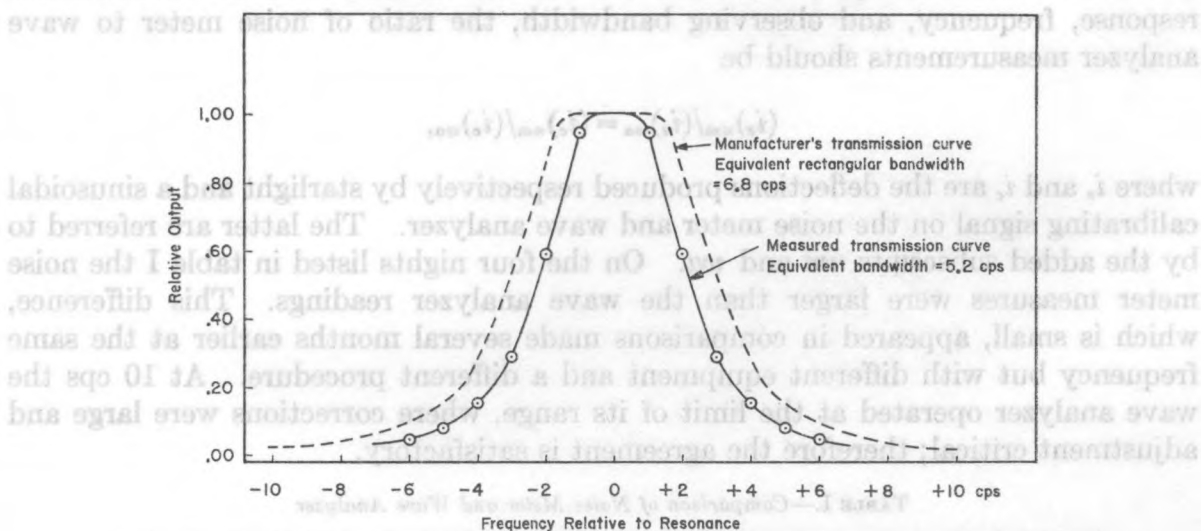


FIGURE 4.—Above. Pass-band frequency characteristics of the wave analyzer. The manufacturer's literature published the dashed curve as representative of the factory tuning of the crystal lattice filter. The solid line was measured at the Observatory after three years of use. Below. Pass-band frequency characteristics of the ultra-low frequency filter. These measured curves are identical in shape to those obtained at any frequency when the same relations are retained between low (f_l) and high cut-off frequency settings.

COMPARISONS OF DIFFERENT METHODS OF MEASUREMENT

Noise meter and wave analyzer.—The wave analyzer was easily compared with the filter-noise meter combination by way of the arrangement shown in figure 1. The same sine-wave signal calibrated both devices at once. After correction for response, frequency, and observing bandwidth, the ratio of noise meter to wave analyzer measurements should be

$$(i_s)_{nm}/(i_s)_{wa} = (i_c)_{nm}/(i_c)_{wa},$$

where i_s and i_c are the deflections produced respectively by starlight and a sinusoidal calibrating signal on the noise meter and wave analyzer. The latter are referred to by the added subscripts nm and wa . On the four nights listed in table I the noise meter measures were larger than the wave analyzer readings. This difference, which is small, appeared in comparisons made several months earlier at the same frequency but with different equipment and a different procedure. At 10 cps the wave analyzer operated at the limit of its range, where corrections were large and adjustment critical; therefore the agreement is satisfactory.

TABLE I.—Comparison of Noise Meter and Wave Analyzer

Date	Star	Telescope Aperture	Filter Settings	Wave Analyzer Setting	Ratio, Wave Analyzer to Noise Meter
			<i>cps</i>	<i>cps</i>	
5- 6-52	η UMa	4-inch	10-10	10	0.93
	α Leo	4-inch	10-10	10	0.86
5-12-52	η UMa	4-inch	10-10	10	0.76
	β Gem	4-inch	10-10	10	0.93
	η UMa	4-inch	10-10	10	0.93
	α Vir	4-inch	10-10	10	0.93
	α Vir	15-inch	10-10	10	0.88
	α Vir	4-inch	10-10	10	0.95
5-21-52	β Gem	4-inch	10-10	10	0.98
	η UMa	4-inch	10-10	10	0.98
5-27-52	η UMa	4-inch	10-10	10	1.05
	η UMa	15-inch	5-20	10	0.97
	η UMa	4-inch	7-14	10	1.10
					Mean 0.94

Noise meter and oscillograph.—The noise meter reading was compared also with the cathode ray oscillograph deflection. The two devices were connected in parallel to the ultra-low frequency filter output and both were operated for the same time interval. The film in the oscillograph camera ran fast enough to resolve the main features of the noise. The displacement of the oscillograph record from its mean value was measured at 150 uniformly spaced points, and the rms value of the fluctuation computed. The spacing of the points was selected so as to avoid discrimination against the frequency of interest. The rms noise was calibrated by recording

sine-wave signals of known amplitude and frequency. Since a rms reading was desired from the noise meter, its deflection was defined as equivalent to 0.707 times the peak-to-peak dc meter swing when calibrated with a sinusoidal signal.

TABLE II.—Comparison of Noise Meter and Oscillograph Records

Date	Star	Filter Settings	Ratio, Oscillograph to Noise Meter
11-29-51	β Ceti	<i>cps</i>	
		0.1 - 0.2	1.03
		.25 - .5	0.88
		.5 - 1.0	0.92
		1 - 2	0.97
		2 - 4	0.96
		4 - 8	0.90
		12 - 12	0.97
5-6-52	η UMa	.1 - .4	Mean 0.95
		1.4 - 2.8	1.09
		10 - 10	0.96
	α Leo	10 - 10	0.92
		1.4 - 2.8	0.99
		.1 - .4	0.91
		10 - 10	0.89
5-12-52	η UMa	10 - 10	0.88
		1 - 4	0.89
	α Vir	.1 - .4	0.95
		.1 - .4	0.92
		1 - 4	1.03
5-21-52	β Gem	10 - 10	0.89
		10 - 10	1.04
		1.4 - 2.8	1.00
	η UMa	.1 - .4	0.96
		10 - 10	0.91
		1.4 - 2.8	1.01
		.1 - .4	0.83
			Mean 0.95

A further correction was required for the noise meter records. It was observed that a sine-wave signal produced 62 percent of the deflection of a square wave of identical frequency and peak amplitude. This was close to the 64 percent which would have been obtained if the noise meter were an average-reading device. According to R. Clark Jones,¹⁰ a meter which measures the average value of a signal and which is calibrated to read the rms value of a sine-wave signal should have its indication multiplied by $2\pi^{-1/2} = 1.13$ in order to obtain the rms value of a noise signal, or of any other voltage with a Gaussian distribution of amplitude. In table II, noise meter measurements corrected in this manner average slightly larger than the oscillograph measurements. The comparisons on November 29, 1951, involved a calibration and a technique which differed in detail from those of the other nights.

Conclusion.—These results indicate that the wave analyzer, noise meter and oscillograph records are equivalent.

THE OBSERVATIONS

The observations represent time-integrated amplitudes of the harmonic components in scintillation noise signals. Photographs of oscillograph tracings of these signals appear in the earlier report.¹ Similar records of the scintillation associated with various observing conditions have been published by Whitford and Stebbins,¹¹ Nettelblad,³ Butler,¹² and Ellison and Seddon.¹³

COMPOSITION AND ERRORS OF OBSERVATIONS

A set of the measures of the amplitudes of the harmonics on a typical night is shown in figure 5. The harmonic content at each of certain frequencies was observed as many times as were required to satisfy the following rules. Two settings at each frequency were the normal minimum. If the amplitude of scintillation was changing considerably in the relatively short time between these two settings, more measures

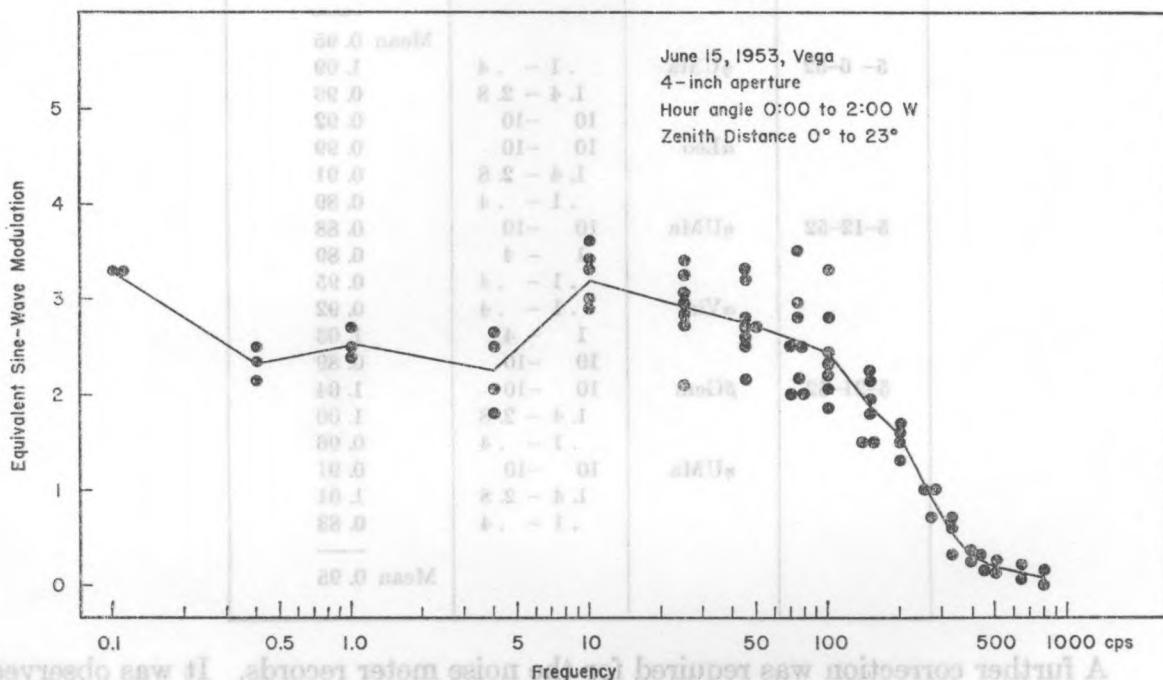


FIGURE 5.—Typical distribution with frequency of the amplitudes of harmonic components of scintillation. were taken until scintillation became constant or a reasonably consistent picture of the pattern had been recorded. When the variation of scintillation showed a general trend in its values, the harmonic amplitudes were averaged over several time intervals, each about twenty minutes long; the data from each interval comprised a separate set of observations, with their own epoch. When the trend of the measures at any one frequency was poorly defined, varying over larger limits than on a night of uniform scintillation, the data were necessarily lumped together for a mean epoch representing the average time of the whole collection of observations. On the nights

of such erratic scintillation, the errors of the mean amplitudes were reduced owing to the larger number of measurements which had been taken at each frequency setting.

Internal probable errors of such data as these have been thoroughly discussed by Protheroe.⁵ He demonstrates that variations of observations, such as appear in figure 5, are due almost entirely to changes of the scintillation and not to other causes. Table III lists the standard deviations of the observed data from the mean values plotted in figure 5.

TABLE III.—*Scatter of Scintillation Observations*Data of June 15, 1953; Vega; hour angle 0^h00^m to 2^h00^m; 4-inch telescope aperture

	Frequency, cps									
	4	10	25	45	75	100	150	200	330	400
Number of Observations	4	5	7	9	8	7	6	5	5	4
Mean Amplitude, %	2.2	3.2	2.9	2.9	2.6	2.4	1.9	1.5	2.5	0.2
Standard Deviation	0.3	0.2	0.4	0.5	0.5	0.4	0.3	0.1	0.2	0.1
Standard Deviation, % of mean	14	6	7	17	19	17	16	7	8	50

OBSERVING ROUTINE

Settings were normally made at the frequency points indicated in figure 5. As will be shown in a later section, little profit would have resulted from setting at closer points for the routine observations. Furthermore, when series of observations with different observing parameters were being compared, it was necessary to complete each series as rapidly as possible before the general scintillation pattern could greatly change. In such cases, a set of observations consisted of measures at only two or three frequencies.

The minimum observing time to produce a complete curve, such as figure 5, was twenty minutes. In this interval the wave analyzer could be set several times on each desired frequency setting in its range; 45 seconds was the minimum observing time for a setting. For the contemporaneous filter-noise meter measurements most of this period was utilized with the setting at 0.1 cps, the remainder of the time being divided between several other settings below 10 cps.

LIST OF OBSERVATIONS

The foregoing comments apply to representative portions of the data obtained during this program, presented in tables IV and V. In order to save space, values of scintillation above 300 cps were omitted from these tables. The higher frequency components were usually small, and above 1000 cps were rarely discernible amidst

the phototube shot-noise. For computation of total noise energy, or for statistical investigation, they may be considered to decline linearly from the value at 300 cps to zero at the cut-off frequency. This latter point of any scintillation distribution is the average lowest frequency at which the signal noise due to scintillation is indistinguishable from the shot noise of the phototube.

Table IV gives data obtained with circular objective apertures. The columns list the date of the evening of the night in which the observations were made, average Eastern standard time of the observational series, zenith distance of the scintillation source at this time, telescope aperture, average percent equivalent sine-wave modulation for unit bandwidth at the listed frequencies, cut-off frequency of the series, and notes, including visual representation of astronomical seeing. Seeing has been described as excellent, good, fair, poor or bad by means of the designations E, G, F, P or B, respectively, with further explanations among the notes.

In table V the same data are given for rectangular apertures; length and width replace telescope aperture and are followed by the position angle of the long dimension.

Notes referred to by number appear at the end of table V. The colon symbol in conjunction with a scintillation amplitude indicates that the value is interpolated from the data at adjacent non-routine frequencies. With cut-off frequencies, the colon signifies that the value was inferred from the trend of lower frequency amplitudes, rather than from zero value observed at higher frequencies.

Observations were made as a matter of routine at 270 and 330 cps, and were averaged to provide the values attributed to 300 cps.

TABLE IV.—Scintillation Observed with Circular Apertures

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation							f _c	Notes	
				0.1	1	10	25	45	75	150			300
1950		Deg.	In.									cps	
3- 5	2310	51	8				1.4	1.0:		0.4:	0.1	600	
4-26	(9)	51	8				3.2	2.5:		1.4:	0.7	800	
6- 2	2140	51	8				1.6	1.1:		0.2	0.1	450	
6- 4	2130	51	5				3.6	3.4:		1.4	0.5	650	
	2140	51	8				1.9	1.6:		0.6	0.2	500	
6- 5	2200	51	8				2.5	1.3:	0.6	0.3	0.1	500:	
6-14	2110	51	8				2.9	2.4:		0.6:	0.2	500	
7- 6	(9)	51	8				2.6	2.1:	2.0	1.0	0.2		
7- 7	(9)	51	8				1.6	1.4:	1.1	0.4	0.1	500	G (6)
7-17	0350	51	8				3.0:	1.4:	0.4	0.1	0.0	400	
7-18	2245	51	8			3.5:	2.7	1.7:	1.1	0.2	0.0	350	(10)
7-25	0150	51	8			2.6:	2.4	2.4:	1.8	0.7	0.2	400	
7-30	2330	51	8			3.0:	2.6	1.6:	0.9	0.2	0.1	400	
8-12	2200	51	8				2.6	2.1:	1.6	0.8	0.2	450	
8-13	0300	51	8				2.7:	2.3:	1.4	0.3	0.2	400	

TABLE IV.—Scintillation Observed with Circular Apertures—Continued

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation								f _o	Notes
				0.1	1	10	25	45	75	150	300		
1950		Deg.	In.									cps	
8-14	2250	51	8				3.6:	3.1:	2.2	0.8	0.1	400	P (6)
	2345	51	8				2.1:	1.8:	1.6	0.4	0.1	350	B (8)
9-14	2150	51	8				3.2:	2.0:	1.1	0.7			(10)
9-18	(9)	51	8				1.6:	1.3:	0.7	0.2		200	(10)
9-30	2200	51	8				1.3:	0.6:	0.4	0.0		150	E (7)
10- 1	2130	51	8			4.8	2.0	0.8	0.3	0.0		200	(2a)
	2230	51	4			7.2	3.2	2.2	0.7	0.0		100	E (7)
10- 2	2045	51	8			2.3	0.8	0.2	0.2	0.0		200:	(10)
10- 4	2350	51	8				2.2:	1.8:	1.3	0.6	0.2	450:	(3a)
	0105	51	4				4.2:	4.1:	3.2	2.6	0.5		(10)
10- 5	2000	51	8				3.8:	2.5:	1.3	0.2	0.1	350	
	2030	51	4				6.5:	5.4:	4.0	1.0	0.4		(4a)
	2300	51	8				2.3:	1.6:	1.0	0.2	0.0	300	
10- 6	2105	51	8				4.0:	1.7:	1.5	0.3	0.0	300:	(3a)
	2145	51	4				6.0:	4.6:	3.0	1.1	0.6	500:	(2a)
10-10	2220	51	4				6.5:	6.0:	3.9	2.0	0.5		
	2250	51	8			3.8	2.8:	2.1:	1.4	0.5	0.0	300	(10)
10-12	2145	51	4				6.8	5.9	5.2	3.6	1.4	650	
	2150	51	8				5.1:	3.7	2.7	0.9	0.5	650	(10)
10-13	1925	51	8				4.9:	3.7:	2.6	1.2	0.4	550:	
	1950	51	4				6.8:	5.8	4.9	2.3	1.2	600	
	2110	51	4				5.9:	5.4	5.0	3.3	1.7	600:	
	2115	51	8				4.1:	3.8	2.8	1.6	0.5	650:	(4a)
10-15	2330	51	4				4.2:	3.1	2.3	0.7	0.2	400:	
	2330	51	8				2.4:	1.4	0.8	0.1	0.0	200	(2b)
10-16	1930	51	4				4.9	3.1	1.9	0.6			
	1945	51	8				2.8:	1.3	0.9	0.2	0.0		(2b)
10-17	2035	51	8				2.2	1.5	1.0	0.3	0.1	350	(1a)
	2035	51	4				4.3	3.7	3.0	1.0	0.4	500	
10-18	1950	51	8				2.3:	2.1	1.7	0.8	0.3	500	
	2000	51	4				3.3:	3.0	2.8	2.1	0.6	650:	
	2340	51	8				2.7:	2.5	2.2	1.3	0.4		(2a)
10-25	(9)	51	8			4.4	3.9:	3.4	1.7	0.8	0.2	400	
	(9)	51	8			3.5	3.0:	2.7	1.3	0.7	0.1	400	
	(9)	51	4			5.4	4.7:	4.8	4.9	2.2	0.4	400	(3a)
10-30	2340	51	8			3.3	2.8:	1.7	0.7	0.3	0.1		
	2345	51	4			5.3	5.2:	4.0	2.9	0.6	0.3		E (7)
10-31	2045	51	8			3.6	2.5:	2.1	1.3	0.5	0.2		
	2105	51	4			5.3	4.9:	3.9	3.3	1.0	0.6		(4b)
11- 4	1910	51	8			5.7	4.9:	2.8	2.2	0.7	0.3		
	1940	51	4			5.3	5.3:	5.4	4.2	2.0	0.6		(4a)
	2110	51	4			6.5	5.4	5.2	4.3	1.4	0.4		
	2115	51	8			5.1	4.1	2.1	1.2	0.3			(5b)
11- 7	1910	51	8			2.9	2.2:	1.8	1.3	0.6	0.3	650	(4a)
	1940	51	4			4.6	3.9	3.6	3.4	1.8	0.2	500	
	2020	51	8			2.9	2.6	2.4	1.4				(10)
11-12	(9)	51	8			2.4	2.1	1.7	1.4	0.8	0.2	400:	
	(9)	51	4			2.9	2.4	3.0	2.6	1.4	0.6	500:	(10)
11-14	2210	51	4			3.3	2.4	2.5	2.2	0.7	0.4		
	2220	51	8			2.6	2.3	1.8	0.8	0.2	0.1		

TABLE IV.—*Scintillation Observed with Circular Apertures—Continued*

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation							f _e	Notes
				0.1	1	10	25	45	75	150	300	
1950		Deg.	In.								cps	
11-19	(9)	51	4	2.2	2.6	2.4		2.2	0.6	0.2	400	(11)
	(9)	51	8	2.6	2.3			0.8	0.2	0.0	100	(12)
11-26	2340	55	4	2.7	2.0	1.6	0.1	0.0	0.0	0.0	800	(13)
11-27	2305	55	4	3.0	2.2	1.9	0.2	0.0	0.0	0.0	450	(13)
12- 4	0045	55	4	4.6	3.6	3.6	3.4	2.9	1.4		425	
12- 5	2320	55	4	3.8	2.8	2.4	2.3	2.0	0.6		400	
	2350	55	2	7.4	5.6	4.4	4.0	3.1	0.9		500	(13)
	0000	55	1	12.5	7.6	5.9	5.6	4.2	1.6		250	(14)
12- 9	2325	55	4	4.2	2.4	2.3	1.6	1.0	0.2		350	(2a)
	0055	55	4	2.8	2.2	2.0	2.0	1.3	0.2		400	
12-19	2000	51	4	3.4	3.0	2.4	2.2	0.9	0.0		400	
12-21	2010	19	8	1.0	1.0	1.0	0.6	0.3	0.0		275	
	2010	62	8	4.0	3.7	2.2	0.8	0.2	0.0		350	
	2050	70	8	8.4	5.3	1.5	0.5	0.2			350	
	2105	74	8	7.0	4.2	2.3	1.0	0.2	0.0		400	
	2105	72	8	7.6	4.8	1.9	0.7	0.2	0.0		300	
	2125	0	8	1.8	1.8	1.7	1.0	0.5	0.2		200	
	2200	7	8	1.5	1.6	1.3	0.8	0.3	0.1		325	
	2200	60	8	6.2	5.7	2.7	0.6	0.2	0.0		300	
	2225	5	8	1.2	1.4	1.0	0.6	0.1	0.0		600	
	2235	8	12	0.7	0.7	0.5	0.2	0.0	0.0		1000	
	2250	9	6	1.3	1.4	1.3	1.0	0.4	0.0		400	(1a), (15)
1951												
1- 4	2000	20	15	1.2	1.2	0.9	0.6	0.4	0.3		200	(17)
	2155	10	8	1.6	1.6	1.3	1.0	0.6	0.2		800	(4a)
	2205	11	10	0.8	1.0	0.6	0.5	0.3	0.2		800	
	2315	64	15	4.1	2.8	1.2	0.5	0.2	0.1		300	
	2335	60	6	6.2	5.1	3.8	2.3	0.4	0.0		600	
1- 5	2120	66	15	2.8	2.9	2.5	2.0	1.2	0.2		1000	
1-19	1845	19	40	1.2	1.3	1.0	0.9	0.8	0.7		400	(1a), (15)
	1915	23	1	3.0	3.2	2.6	2.2	1.7	1.0		200	(17)
	1935	27	6	1.2	1.5	1.5	1.2	0.8	0.4		300	(4a)
1-21	0120	63	6	7.5	6.2	4.1	2.4	0.9	0.2		800	
	0135	60	6	7.3	6.5	3.8	1.8				200	(17)
1-22	1905	26	15	1.3	1.2	0.8	0.4	0.1	0.0		300	(4a)
1-26	2200	15	15	1.5	1.2	0.8	0.3	0.2	0.0		800	
	2225	17	4	2.8	2.4	2.3	2.0	1.3	0.9		500	(2a)
	2330	30	4		2.7	2.8	2.2	1.9			500	(2b)
	(18)	(18)	6		2.2	2.0	1.6	1.4			300	F-P (7)
	(18)	(18)	10		1.6	1.1	1.1	0.2			350	(5b)
	(18)	(18)	15		1.2	0.8	0.6	0.2				
2- 2	2000	12	4	2.7	2.4	2.0	1.8	1.4	1.1		800	(4a)
2-11	0045	30	4	4.4	3.7	3.4	2.2	1.1	0.3		400	(5b)
2-12	0445	15	4	2.8	2.9	2.5	2.0	1.0	0.1		600	(4a)
	0500	65	4	9.8	5.6	3.0	1.3	0.1	0.0		250	(4a)
2-18	2135	68	4	9.7	8.1	6.2	4.9	3.0	0.8		500	(5b)
	2155	34	4	4.3	4.2	4.3	3.8	2.6	0.4		500	(2a)
	2200	11	4	1.4	1.5	1.5	1.0	1.0			300	(2b)
	2240	29	4	3.8	4.0	3.8	3.1	1.8	0.0		300	F-P (7)
	2310	73	4	3.2	4.5	4.1	3.1	2.3	0.2		350	(5b)

TABLE IV.—Scintillation Observed with Circular Apertures—Continued

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation								f _c	Notes
				0.1	1	10	25	45	75	150	300		
1951		Deg.	In.									cps	
2-22	2150	58	4			4.1	4.2	3.6	2.8	1.4	0.2	450	(19)
	2240	38	4			3.6	3.5	3.3	1.6		0.2	450	(20)
	2315	22	4			3.5	3.4	2.6	2.4	0.8	0.0	300	(21)
	2345	75	4			5.5	4.8	4.2	3.0	1.4	0.2	500	(28)
	0040	38	4			4.8	4.4	3.3	2.2	1.4	0.2	500	(22)
2-23	0220	19	4			4.0	3.5	2.8	2.0	1.0	0.2	500	(23)
	0055	61	4			4.8	4.3	4.0	3.0	1.9	0.1	350	(24)
	0130	49	4			5.6	4.6	2.8	2.2	1.4	0.3	500	(25)
	0205	54	4			4.6	3.6	3.2	2.5	1.3	0.1	350	(26)
	(9)	51	4			5.3	4.8	3.7	3.2	2.0	0.4	550	(27)
(28)	0310	11	4			2.7	2.4	2.3	1.8	1.3	0.3	400	F (7)
	(9)	75	4			5.3	4.8	4.2	3.0	1.4	0.2	500	(28)
	3- 5	2300	28	4		1.5	1.2	1.0	0.8	0.3	0.0	300	(1a)
	0105	71	4			7.2	6.4	5.3	4.6	2.6	0.6	500	
	0125	12	4			3.2	2.8	2.3	2.4	1.8	1.1	650	
3- 8	0150	58	4			5.8	5.0	3.8	2.6	1.5	0.0	270	(29)
	0210	0	4			2.3	2.4	2.2	2.0	1.4	1.0	500	
	2000	15	4			2.7	2.3	2.1	2.0	1.6	0.8	500	(2a)
	2045	23	4			4.5	4.0	3.5	2.9	1.6	0.7	850	
	3-11	0000	32	4		6.1	6.5	5.2	4.9	3.3	1.5	650	(5b)
3-22	2030	59	4			7.0	7.7	6.5	5.4	3.0	0.8	500	
	2135	28	4			4.4	5.4	4.1					
	2155	24	4			2.8	2.8	2.5	2.3	1.4	0.8	330	(2a)
	2130	54	4			9.0	8.1	6.9	5.1	2.6	0.6	500	
	2200	21	4			7.7	7.0	5.8	4.0	2.3	1.0	500	(2a)
4-20	2250	65	4			13.0	7.2	3.3	1.3	0.4		300	
	2335	14	4			2.8	2.6	2.6	2.3	1.8	0.4	350	P (7)
	4-23	2130	18	4		3.0	3.4	3.0	2.5	1.4	0.1	350	
	2205	68	4			10.4	6.8	5.6	1.6	0.2		200	
	2235	10	4			2.8	2.8	2.6	2.4	1.7	0.4	400	
6- 5	2145	50	4			0.8	0.4	0.2	0.1	0.0	0.0	150	(30)
	2220	50	4			5.5	6.4	5.6	4.4	1.4	0.2		(4a)
	7-14	2100	36	4		2.4	2.2	1.6	1.1	0.4	0.1	350	(2a)
	2225	50	4			3.8	3.2	2.2	1.6	0.4	0.0	300	F (7)
	9-15	0205	69	4		5.1	4.6	4.1	3.2	1.1	0.0	350	
9-20	(9)	>30	4			3.6	3.6	2.7	2.2	1.2	0.0	270	
	9-21	2035	29	4		3.1	2.5	1.8	1.4	0.5	0.0	250	
	9-23	2100	25	4		3.4	3.5	3.0	2.6	1.7	0.3	400	
	9-26	2020	65	4		8.4	7.4	6.4	4.0	0.8	0.0	200	(10)
	10- 9	2320	42	4		3.9	3.4	2.4	1.9	1.4	0.7	600	
10-13	2115	69	4			7.6	5.6	3.4	1.6	0.4	0.0	200	
	11- 5	2345	58	4		3.8	3.6	4.0	3.4	2.8	1.0	500	
	11-20	1945	58	4		5.9	4.7	3.9	3.1	2.6	2.0	500	
	(9)	44	4		3.5: 4.3								
	11-29	2115	59	4		5.3: 4.1							
12-13	2100	3	4			2.7	2.4	2.1	1.5	1.2	0.8	650	
	12-19	2050	22	4		1.7	1.7	1.5	1.6	1.8	0.7	600	
	12-22	1840	42	4		4.0	4.0	4.4	3.8	2.8	1.2	650	
	1952												
	1-10	1820	28	10		0.9	0.9		0.8	0.2	0.0	350	
(7)	0000	15	4			1.8	1.8		2.2	1.8	0.2	350	

TABLE IV.—*Scintillation Observed with Circular Apertures—Continued*

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation								f_c	Notes
				0.1	1	10	25	45	75	150	300		
1952		Deg.	In.									cps	
1-15	1930	18	4			1.8	2.0	1.4	1.0	0.6	0.0	300	
1-16	1820	28	10			0.9	0.9	0.9	0.8	0.2	0.0	350	
	2020	15	4			1.8	1.8	1.9	2.2	1.8	0.2	350	
1-23	2045	20	4			4.0	4.4	4.0	3.2	2.3	1.0	600:	
1-30	2110	19	4			2.6	2.6	2.3	1.6	0.6			
	2310	49	15				2.1:						
	2310	49	10				2.5:						
	2310	49	8				3.0:						
	2310	49	4				5.3:						
	0010	62	4			5.4	4.8	3.6	2.6	0.4	0.0	250	
1-31	1940	24	4			3.0	3.4	3.2	2.6	1.0	0.0	200	
3-19	2110	33	4			2.4							(31)
3-20	0115	27	4			2.2							
3-25	(9)	4	4	2.0	1.6	1.4	1.2						
4-8	0020	17	4		2.6	2.1	1.8	1.7	1.2				
	0245	25	15		1.6	2.0	1.2	1.1	0.7				
	0430	66	15	5.8	5.7	5.4	2.3	0.7	0.2				
	0515	66	4	6.0	4.4				1.0				
4-9	1955	66	4	7.4	5.1	5.0	3.6	2.6:		0.6			
	2055	72	15	7.7	4.7	4.6	4.8	3.6:	1.2	0.2			
	2250	15	15	1.4	1.3	1.2	0.8	0.5:	0.3	0.2			
	2310	15	4	2.4	2.2	2.2	1.8	1.7:	1.4	0.6	0.2	400:	
4-17	2030	72	4			5.8							
	2030	72	15			4.8							
	2125	56	4			5.4							
	2125	56	15			2.6							
5-6	2200	70	4		6.8:	6.4	6.0:	4.4:	2.1				
	2240	11	4		2.0:	2.0	2.0	1.8	1.6	1.2	0.6	800:	P (7)
	2325	72	4		5.9:	4.6	4.8:	3.8:	2.4	0.9	0.2	700:	
	0025	19	4		2.5:	2.5	2.1:	2.0:	1.6	1.2	0.5	800:	
5-12	2210	70	4		6.4:	5.8	4.4	2.6	1.6	0.8	0.1	350	
	2255	12	4		3.2:	2.7	2.8	2.7	2.4	1.6	0.6	700:	P (7)
	0030	61	15		4.3:	3.5	3.0	1.4	0.5	0.2	0.0	250	
	0035	61	4		6.5:	5.9	5.7	4.8	3.0	1.0	0.2	350:	
5-21	2045	60	4		5.8:	4.8	4.4	2.9	2.9	0.6	0.1	500	
	2225	16	4		3.8:	3.4	3.4	2.7	2.7	1.5	0.4	500:	
5-27	2115	12	4		2.8:	2.4	1.9	1.4	0.9	0.3	0.2	350	
	2115	12	15		1.2:	0.8	0.5	0.2	0.1	0.0		150	
6-2	2010	20	4				4.6:						
8-17	2010	48	4			2.6	2.4	1.7	1.2	0.6	0.2		
	2040	5	4			1.9	1.7	1.4	1.0	0.8	0.2	400:	
8-26	2040	4	4			3.6	2.2	1.7:	0.9	0.1	0.0	250	G (8)
9-3	2030	5	4			1.8	1.8	1.4	1.2				
9-4	2230	32	4			2.5	2.2	1.7	1.4	0.9	0.0	300:	
9-10	2135	15	4	2.5	2.4	2.0	2.2:	1.2	0.2	0.0		250	
	2250	15	15		1.1	0.8	0.4	0.2	0.1	0.0		150	
9-11	2205	20	4	2.3	1.8	2.0	1.8	1.3	0.8	0.3	0.0	350	
	2245	15	15		0.9	0.6	0.4	0.2	0.0	0.0	0.0	150	
9-12	2245	26	4	1.4	1.6	1.6	1.4	1.0	0.6	0.2	0.0	250	
9-13	2050	18	4	2.2	2.2	2.0	1.8	1.6	0.8	0.3	0.0	250	F-G (7)

TABLE IV.—Scintillation Observed with Circular Apertures—Continued

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation								f _c	Notes
				0.1	1	10	25	45	75	150	300		
1952		Deg.	In.									cps	
9-14	2000	43	4			2.9	3.2			0.7			
9-26	0300	24	4	3.1	2.8	3.4	3.2	2.2	1.4	0.8	0.0	350	B-P (7)
9-27	2040	27	4		2.4	2.6	2.4	1.6	0.8	0.1		200	
10- 1	2255	20	4		1.5	1.4	1.4	1.1	1.0	0.4	0.1	550	G (7)
10- 3	2245	14	4			2.6	2.7	2.4	2.2	1.5	0.3	400	P (7)
10- 6	2120	22	4		1.6	1.5	1.4	1.4	1.4	1.0	0.4	600	E-F (7)
11- 6	0110	15	4	2.8	2.7	2.6	2.5	2.4	2.2	1.7	1.0	>1000	B (7)
11-13	1840	18	4		1.2	1.2	1.2	1.2	1.0	0.6	0.0	300	
11-14	2000	43	4			2.9	3.2			0.7			
11-16	2100	44	4	3.5	4.8	3.6	3.1	2.7	2.0	0.6	0.0	400	
11-22	2155	16	4	2.4	2.4	2.5	1.8	1.7					
11-24	1930	24	4		2.4	2.4	2.2	1.9	1.5	0.8	0.3	650	
11-28	2300	15	4	2.5	2.1	2.2	2.4	2.3	1.8	1.6	0.9	1000:	
11-30	2000	20	4	1.2	2.2	2.3	2.1	2.1	1.8	1.0	0.4	1000:	
12- 6	2230	23	4	3.9	3.6	3.8	3.2	2.6	2.5	2.0	0.6	800	F-P (7)
12-11	2125	23	4	4.7	4.1	6.1	4.4	3.9	3.7	1.9	0.4	800	B (7)
12-16	2010	39	4	5.0	6.2	5.6	5.4	4.6	3.6	1.7	0.2	800	P (7)
	2100	30	4	3.5	4.1	4.6	4.0	4.2	3.6	1.0	0.2	1000:	
	2140	23	4	3.3	2.6	2.8	2.8	2.5	2.2	0.8	0.1		
	2255	46	4	3.3	3.7	4.1	3.6	3.6	2.6	0.6	0.1	500	
	2345	7	4	1.9	2.0	2.3	2.0	1.8	1.2	0.4	0.1	400	
1953													
1-12	2305	15	4			2.2	2.0	1.7	1.7	1.0	0.5	1000:	
1-26	1945	49	4				3.0		2.0	0.8			
1-28	2320	28	4			3.5	3.5	3.4	3.0	2.1	0.9	>1000	
	0020	16	4			3.5	3.2	3.0	2.4	2.0	0.8	800	P (7)
	0035	10	15			1.5	1.1	1.1	0.6	0.3	0.0	270	
2- 3	1915	13	4			1.7	1.3	1.2	1.1	0.6	0.2	650	
2- 4	1855	9	15			0.8	0.6	0.3	0.2	0.1	0.0	400:	
	2050	7	4			2.4	2.2	1.9	1.4	0.7	0.2	500:	
2-10	2000	46	4			2.2							
2-13	2015	7	4	2.2	2.3	2.4	2.2	2.1	2.0	1.6	0.8	800	
	2055	10	15	1.9	1.2	1.2	1.2	1.0	0.8	0.2	0.1	500	
2-16	2340	21	4			3.3	3.2	3.1	2.5	1.8	0.9	600:	
2-17	2120	13	4	3.0	2.4	3.1	3.0	3.5	2.4	1.8	0.8	800	
	2210	12	15		1.1	1.2	1.0	0.6	0.4	0.2	0.1	600:	
	2250	16	2	3.9	3.6	4.2	3.8	3.4	3.0	2.4	1.2	650	
	2315	21	4	1.2	2.9	3.4	3.0	2.8	2.4	1.9	0.6		
2-18	1945	10	4	1.6	1.9	2.1	2.1	2.1	1.6	1.2	0.6	700	
	2000	13	15		1.0	0.8	0.6	0.5	0.4	0.1	0.0	270	
2-26	2200	34	15	0.6	1.1	1.2	1.1	0.8	0.5	0.2	0.0	270	
	2235	31	4	2.9	3.1	3.5	3.0	2.7	2.2	1.4	0.6	800	
3-17	1950	14	4	3.9	3.2	2.6	2.6	2.7	2.8	2.5	1.4	>1000	G (7)
3-19	2325	16	4	4.2	4.4	4.0	3.6	2.8	2.6	1.8	0.7	650	P (7)
	0020	14	15	2.3	1.8	1.2	1.0	0.8	0.6	0.2	0.0	350	
	0130	21	4	4.6	4.4	4.0	3.8	3.7	2.4	1.9	0.6	800	
3-20	2200	29	4	2.4	1.6	1.7	1.6	1.5	1.2	1.1	0.4	650	P (7)
	2300	18	4	1.8	1.8	1.8	1.4	1.3	1.0	1.1	0.4	800	P (7)
	2330	16	15		1.1	0.8	0.6	0.5	0.3	0.2	0.0	350	P (7)
	0000	15	4		2.5		2.4			1.5			B (7)

TABLE IV.—Scintillation Observed with Circular Apertures—Continued

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation								f _s	Notes
				0.1	1	10	25	45	75	150	300		
1953		Deg.	In.									cps	
3-24	2045	32	4	3.8	4.5	4.9	4.5	4.1	3.4	2.4	1.2	800	81-9
	2115	39	15	1.8	1.8	1.9	1.6		0.8	0.3	0.2	650	82-9
3-30	2015	14	4	3.6	3.2	3.6	3.2	2.9	2.6	2.1	1.1	800	72-8
	2055	22	15		1.8	1.4	1.1		0.7	0.3	0.2	500	1-01
4-11	0015	11	4			3.2	3.0	2.8	2.4	1.7	0.6	800	2-01
4-14	2330	45	4			4.6	4.0	3.6	2.5	1.6			8-01
5-1	2245	46	4				3.8		3.4	2.7	1.2	600	8-11
5-26	2330	15	4	3.8	3.9	4.7	4.2	3.9	3.5	2.6	1.0	>1000	31-11
	2330	15	15		1.6	1.6	1.2		1.0	0.6	0.2	500	41-11
5-28	0030	10	4	2.0	2.4	2.7	2.5	2.6	2.2	1.8	1.0	1000	01-11
	0055	13	15		1.3		0.6		0.6	0.2			22-11
6-2	2325	30	4	2.4	2.7	3.4	2.8	2.7	2.4	2.0	0.8	1000	15-11
6-4	2250	21	4	2.4	2.6	2.5	2.5	2.0	2.0	0.8	0.2	500	22-11
	2325	27	4		2.0		2.0			0.6	0.4		02-11
	0000	21	4		2.2		2.2			1.0	0.0	300	3-11
	0015	19	8		2.2		1.2			0.2	0.0	350	11-11
	0035	20	15		1.2	0.9	0.8	0.5	0.2	0.1	0.0	300	31-11
	0055	11	4	3.3	2.8	3.0	2.8	2.6	2.1	1.1	0.2	650	
6-15	0315	15	4	3.3	2.5	3.2	2.9	2.7	2.6	1.8	0.7	1000	
	0315	15	15		1.2		0.8		0.4	0.2			
	0330	18	8		1.5		1.6		0.6				
6-22	0235	13	4	2.5	2.0	3.0	2.6	2.5	1.8	1.0	0.0	300	80-1
	0235	13	15		1.2	1.1	0.8		0.2	0.0	0.0	150	21-1
	0310	30	4		2.5		3.2		1.9	1.1			(4a)
	0330	69	4	7.4	5.6	5.7	5.5		3.3	0.7	0.0	270	22-1
6-23	2200	30	4	4.2	3.1	3.1	2.7	2.3	1.8	0.6	0.1	500	
	2220	54	4	3.8	5.8	5.7	5.2		1.7	0.3	0.1	350	
	2240	11	4	2.3	2.0	2.6	2.0	1.6	1.2	0.4	0.0	350	6-2
	2300	14	15		1.6	1.3	0.8		0.2	0.0		100	1-2
7-13	2210	14	4	3.6	2.4	2.4	2.4	2.1	1.5	0.8	0.2	500	
	2230	27	4		4.9		2.3			1.1			01-2
	2240	70	4		10.0	8.2	4.8		0.9	0.1	0.0	200	21-2
	2255	1	4		2.7		2.3			1.0			02-2
	2305	2	8		1.6		1.2		0.6	0.3			04-2
	2325	5	15		1.0	0.6	0.4		0.1	0.1			05-2
	2355	9	4		1.9	1.7	1.7	1.6	1.0	0.8	0.1	400	71-2
7-14	2210	12	4	2.7	1.9	1.8	1.6	1.5	1.1	0.7	0.0	350	
	2235	6	8		1.4		0.8		0.4	0.2	0.0	250	
	2300	3	15		1.0		0.4		0.2	0.1			21-2
	2320	2	4		2.2		1.7		1.1	0.8		350	
	2330	35	4		2.4		2.1			0.9			02-2
	2340	63	4		8.1		4.8			0.6			03-2
	2345	6	4		1.6		1.4			0.6			71-2
7-23	2315	9	4	4.0	3.2	3.0	2.8	2.2	1.4	0.4	0.1	400	P (7)
	2355	15	8		2.0		1.2		0.3	0.0			
	0000	16	15		1.4		0.6		0.2				
	0020	20	4	4.2	4.4	3.7	3.6	2.8	2.0	0.4	0.2	400	G (7)
8-11	2045	9	4	3.3	2.7	2.0	1.8	1.7	1.5	0.9	0.1	400	
	2125	0	15		1.2		0.5		0.2	0.1			
	2135	2	8		1.8		1.2		0.5	0.1			

TABLE IV.—*Scintillation Observed with Circular Apertures—Continued*

Date	EST	Z	Aper.	Percent Equivalent Sine-Wave Modulation								f _o	Notes
				0.1	1	10	25	45	75	150	300		
1953		Deg.	In.									cps	
8-25	2040	2	4	2.2	2.2	2.1	1.5	1.0	0.5	0.1	0.0	250	F (7)
	2110	9	8		1.2		0.5						
	2120	10	15		1.1		0.5			0.0			
	2140	14	4		1.9		1.2		0.4				
	2145	30	4		2.6		2.1		0.5				
	2200	18	4		2.4		2.0		0.7				
8-27	2020	0	4	2.9	2.8	4.8	4.0	3.4	2.3	0.4	0.0	350	(4b)
9-1	2210	6	4	3.6	3.4	3.6	2.6	1.6	0.8	0.0	0.0	250	(2b)
9-10	2140	8	4	3.2	2.7	3.9	3.3	3.0	2.8	1.2	0.1	400	(1a)
9-18	2110	26	4	2.8	2.5	3.3	2.8	2.0	1.0	0.2	0.0	300	(5b)
9-22	2240	23	4	2.8	2.0	2.8	2.7	2.2	1.6	1.1	0.2	400	(4a)
9-28	2020	6	4	3.0	1.7	2.4	2.2	1.8	1.8	0.8	0.1	450:	(2a)
	2040	14	15		1.0	1.1	0.6	0.4	0.2	0.1			
	2135	15	8		1.4		1.4	1.1	0.6	0.2			
	2145	18	4		2.1		2.1	1.8	1.6	0.8			
	2155	42	4		3.6		3.8			0.4			
10-1	2010	6	4	1.2	1.5	2.0	1.7	1.3	0.6	0.2	0.0	200	(3a)
	2120	15	8		1.4		1.2		0.3				
	2120	15	4		2.2		2.2		0.7				
10-7	1945	6	4	2.0	2.3	3.5	3.2	3.1	2.5:	1.7:	0.8	>1000	(4a)
10-9	2035	14	4	2.5	2.1	3.7	3.2	3.0	3.0	2.4	0.8	>1000	(1a)
10-31	0145	40	4			3.3	3.3		1.9:	1.7			
	0320	20	4			2.0	2.5		2.2	1.6	0.2	350	
1954													
4-20	2125	31	4			3.4	3.0	2.0	1.0	0.4	0.2	500:	
4-21	2345	12	4			2.6	2.4	1.9	1.1	0.2	0.1	400:	
4-22	2140	25	4			3.6	4.0	2.7	1.9	0.5	0.1	350:	
6-5	2145	14	4	5.4	5.6	4.2	3.0	2.5	2.0	1.0	0.2	500	G (7)
7-8	2310	8	4	5.8	6.7	3.7	2.6	2.4	1.8	0.9	0.3	500	F (7)
7-27	2145	8	4			3.9	3.2	2.4	1.7	0.6	0.0	270	
	2310	59	4			7.5	5.2	3.9	3.4	1.1	0.0	400:	
	0025	65	4			9.3	5.9	4.5	2.0	0.4			
8-3	2105	11	4			4.2	3.8	4.1	3.2:	3.2	0.7	700:	
	2125	74	4			0.9	0.4	0.3	0.1:			100	(30)
	2150	71	4			10.1	8.7	7.3	5.4	1.6	0.3	500:	
	2215	69	4			1.2	0.5	0.2	0.2			100:	(32)
	2255	61	4			8.4	6.9	5.7	5.0	2.3	0.2	600:	
	2330	20	4			4.5	3.8	3.6	3.2	2.3	0.2	600:	
9-1	2140	19	4			4.6	3.8	3.3	1.9	0.4	0.0	250	
	2240	55	4			9.1	6.6	4.7	2.5	0.3	0.1	400:	

347447-55-4

TABLE V.—Scintillation Observed with Rectangular Apertures

Date	EST	Z	Aper.	P. A.	Percent Equivalent Sine-wave Modulation						f _c	Notes
					10	25	45	75	150	300		
1950		Deg.	In.	Deg.							cps	
10- 2	2115	51	4×8	0	3.5	2.0:	0.7:	0.2				
	2125	51	4×8	90		2.2:	0.8:	0.4	0.1			
	2140	51	2×8	90		3.3:	1.5:	0.6	0.2			
	2155	51	2×8	0		2.6:	1.1:	0.4				
10- 5	2115	51	2×8	0		3.9:	3.5:	3.0	1.3	0.3		
	2145	51	2×8	90		4.0:	2.7:	1.3	0.2		200	(4a)
	2320	51	2×8	135		3.9:	3.2:	3.3	2.0	0.8	400	
	2325	51	2×8	45		3.7:	2.4:	1.9	0.7	0.0	270	
	2325	51	2×8	90		4.0:	2.9:	1.8	0.3	0.0	270	
	2340	51	2×8	0		4.5:	3.2:	2.0	1.3	0.0	270	
10-10	0055	51	2×8	0		2.9:	2.8:	2.3	1.3	0.5	500:	(10)
10-12	0000	51	2×8	0		5.0:	4.0:	3.7	2.6	1.3	800	
	0000	51	2×8	90		5.2:	4.5:	3.2	1.4	0.7	650	
10-13	2030	51	2×8	0		4.9:	4.1	4.3	2.8	1.3	800	(4a)
	2030	51	2×8	90		5.4:	4.2	3.3	1.5	0.8	650	
10-15	2330	51	2×8	0		2.9:	2.2	1.4	0.7		250:	(2b)
	2335	51	2×8	90		4.0:	2.2	1.1	0.3			
10-16	1940	51	2×8	0		3.5:	2.5	2.0	0.9	0.4		(2b)
	2000	51	2×8	90		3.3:	2.0	1.1	0.6	0.3		(10)
10-17	2035	51	2×8	0		3.3:	2.3	2.2	0.8	0.3		
	2100	51	2×8	90		4.4:	2.4	1.4	0.7	0.5		(1a)
10-18	2010	51	2×8	0		2.5:	2.3	2.1	1.4	0.7	650	
	2020	51	2×8	90		3.0:	2.3	2.0	1.0	0.5	650	(2a)
11- 4	1950	51	2×8	0	5.0	3.8	3.9	3.3	1.1	0.4	550	(4a)
	2040	51	2×8	90	6.9	5.3	4.3	2.7	0.8			
11- 7	1955	51	2×8	0	3.3	2.6	2.6	2.3	1.4	0.0	250	(4a)
	1910	51	2×8	90	5.7	3.2	2.6	1.7	0.8	0.1	350	(10)
11-14	2310	51	2×8	0	2.0	1.7	1.6	1.6	0.7	0.0	250	
	2310	51	2×8	90	2.7	2.5	1.9	1.2	0.6	0.4		
12-21		7	1/4×13	0	0.8	1.0	1.0	0.9	0.9	0.1	500	
		7	1/4×13	90	2.4	1.8	1.4	0.6	0.2	0.0	350	
		11	1/4×13	0	1.1	1.0	0.8	0.6	0.5	0.4	700	
		16	1/4×13	90	2.9	2.8	2.8	1.9	1.2	0.7	1000	
1951												
1-16	2010	18	1×13	45		2.8		2.0	1.9			
	2015	18	1×13	135		5.4		2.4	1.2			
	2200	10	1/4×7	135	2.8	3.2		2.4	0.8			
	2200	10	1/4×7	135	2.8	2.8		2.0	0.8			
	2205	10	1/4×7	135	2.8	3.7		2.6	1.2			
	2205	10	1 1/4×7	135				1.5	0.4			
	2210	10	1/4×7	135	3.3	3.8		2.6	1.3			
	2210	10	1 1/4×7	135				1.4				
1-21	2225	12	1×7	90	1.9	1.2		0.8	0.6			
	2230	12	1×7	0	1.4	1.0		1.0	0.6			
3-24	0005	16	1×15	90	2.2:	3.8	2.4	2.7	1.9	0.0	350	
	0015	16	1×15	0	3.2	2.9	2.0	2.8	1.8	1.0		
3-26	0135	30	1×15	45	1.4	1.6	1.6	1.4	1.4	0.9	700	
	0135	30	1×15	135	2.8	2.8	2.4	1.4	0.7	0.2	500	
	0215	20	1/4×15	45	1.2	1.4	1.6	1.4	1.0	0.4		
	0215	20	1/4×15	135	2.2	2.1	1.9	1.6	0.4	0.0	250	

TABLE V.—Scintillation Observed with Rectangular Apertures—Continued

Date	EST	Z	Aper.	P. A.	Percent Equivalent Sine-wave Modulation						f_0	Notes
					10	25	45	75	150	300		
1951		Deg.	In.	Deg.							cps	
3-26	0245	21	6×15	135	1.8	2.3	1.8	1.0	0.2			
	0250	21	6×15	45	1.6	1.8	1.4	1.1	0.6			
	0320	34	1×15	45	1.8	2.3	1.8	1.6	1.2	0.7	650	
	0320	34	1×15	135	2.5	3.0	2.2	1.8	0.7	0.1	400	
4-5	2015	64	1×15	40	4.8	5.4	4.8	4.1	2.6	0.7		
	2015	64	1×15	130	5.8	5.2		1.6	0.4	0.3		
	2025	65	3×15	45	5.2	4.5	4.1	3.7				
	2025	65	3×15	135	7.4	4.3	2.9	1.3				
	2040	67	6×15	45	5.4	4.5	4.4					
	2040	67	6×15	130	6.7	3.6	2.6					
	2055	69	1×15	40	5.2	6.1			3.6:	1.4		
	2055	69	1×15	135	5.8	5.6		1.2:				
	2220	23	1×15	0	2.5	2.2	1.9	1.2	0.6	0.0	250	
	2220	23	1×15	90	1.7	1.4	1.5	1.3:	1.1	0.7	1000:	
	2110	72	1×15	35	5.3	7.4	5.6	3.5	1.8	0.5	800:	
4-6	2110	72	1×15	125	7.0	6.1	2.5	0.8	0.4:	0.1	350	
	2140	82	3×15	35	8.0	8.5	5.6	3.0				
	2140	82	3×15	125	7.4	6.1	2.4	1.1				
	2225	23	1×15	25	1.6	1.6	1.5	1.6	1.3	0.4	600:	
	2225	23	1×15	115	2.6	2.6	2.3	1.6	0.4	0.1	500:	

Notes

1a.—Seeing excellent according to a contemporary visual observation of this star, made with a 4-inch telescope and magnification of about 800 diameters. The rings of the diffraction pattern were well defined, several could be seen; motion was slow, about 1".0 from side to side.

2a.—Seeing good when determined in the manner described in note 1a. Diffraction pattern was not sharp, but one or two rings were visible; motion was slow, about 1".0 from side to side.

2b.—Seeing good, as in 2a, except motion was fast, about 1".0 from side to side.

3a.—Seeing fair when determined as described in note 1a. Definition poor, but the observer saw the central image and used it to estimate extent of motion; motion was slow, less than 3".0 from side to side.

4a.—Seeing poor when determined as described in note 1a. Image was large and fuzzy; motion was slow, less than 3".0 from side to side.

4b.—Seeing poor as in 4a, but the image was sharply defined, with a fast motion about 4" from side to side.

5a.—Seeing bad when determined as described in note 1a. Image very large and fuzzy; motion was slow, greater than 3".0 from side to side.

5b.—Seeing bad as in 5a, but motion was fast.

6.—Contemporary visual observations with the 6-inch transit circle. Seeing was reported on an excellent (E) to bad (B) scale, equivalent to a 1 to 5 scale, that considers both definition and motion of the star image with respect to parallel reticle wires 6 seconds of arc apart.

7.—Subjective estimate of seeing, considering definition and motion, made with moderate magnification at the telescope with which scintillation was observed.

8.—Contemporary estimate of seeing with the 26-inch or 40-inch telescopes.

9.—Data regarding epoch of observation not available. Epoch is either near that of adjacent observations, or is in the evening.

10.—Occasional clouds. No observation was made through clouds.

11.—Observation from a site near the 13-inch telescope at the Lowell Observatory, Flagstaff, Arizona, at altitude 7250 feet. With a 4-inch telescope, 800 diameters magnification, Polaris appeared as a very sharp image with 3 to 5 rings, and having a motion at moderate speed, 1".6 from side to side. Seeing deemed fair by local observers.

12.—Equipment and site as noted in 11. The image of Polaris was sharp, with rings, moving rapidly 4" 5 from side to side. Local observer noted a light NE wind and poor seeing.

13.—Equipment and site as noted in 11. The star image appeared large and fuzzy; no rings were visible; motion was fast and large.

14.—Equipment as noted in 11. Observations made at "Snow Bowl", west slope of San Francisco Mountains, above Flagstaff, at 9030 feet elevation. The star image appeared to be very large, but instead of being fuzzy it was full of detail, looking like pieces of a diffraction pattern, in rapid relative motion.

15.—Yellow Corning No. 3384 filter in the light-path.

16.—Blue Corning No. 5543 filter in the light-path.

17.—Seeing, observed with Polaris, in the category of note 2b.

18.—Aperture effects observed with constant frequency runs over several hours. Mean epochs and zenith distances are given.

19.—Azimuth 18°.

20.—Azimuth 25°, seeing F according to the standard of note 7.

21.—Azimuth 61°.

22.—Azimuth 90°.

23.—Azimuth 11°.

24.—Azimuth 286°.

25.—Azimuth 72°.

26.—Azimuth 264°.

27.—Azimuth 358°.

28.—Azimuth 37°.

29.—Double Star, α Gem.

30.—Saturn.

31.—Noise meter observation.

32.—Mars.

DISCUSSION OF THE RESULTS

THE SHAPE OF THE SCINTILLATION DISTRIBUTION CURVE

A typical distribution of scintillation amplitude with frequency is shown in figure 5. Never, throughout the whole program, did a particular frequency stand out significantly. This statement is not in contradiction with the findings of other observers, such as Nettelblad,³ Butler,¹² or Ellison and Seddon.¹³ It is rather a further description of the noise-analyzing equipment for which the phase, the amplitude, and the frequency of a dominant signal would have to be constant if the signal were to be recorded as outstanding. Even though scintillation energy might have been concentrated for several minutes at one frequency, the fact was not observed because of the length of time spent observing at other settings of the distribution pattern. The procedure furnished no distinction between the short-term dominance of a particular frequency component and a brief enhancement of scintillation at all frequencies. Since the observing process was a smoothing process, it was rarely profitable to set on closer-spaced frequencies than are indicated in figure 5, or to base conclusions on short-term measurements.

The observations of Protheroe⁵ were obtained within eight-minute intervals upon a magnetic tape recorder. They agree with the above generalization concerning the scintillation distribution, if their much smaller smoothing is considered.

Knowledge about scintillation such as provided by figure 5 has proved useful, however. It indicates frequencies above which scintillation noise will not appear and demonstrates a low-frequency saturation, which will be considered further in connection with the effects of aperture and zenith distance. It formed a basis for John S. Hall's² studies of the intrinsic errors of photoelectric photometry.

Goldstein^{8,9} represented the scintillation curve by an analytic expression in order to compute the effects of signal noise on other signal modulation. His expression is $M = kf^{-n}$, where M is the equivalent sine-wave modulation for unity bandwidth at a frequency f , and k and n are numerical coefficients. For horizontal light-paths he found k and n to average 6.0 and 1.6 respectively. Other possible representations of the curve have been discussed by Protheroe.⁵

The manner in which the scintillation distribution also represents the distribution of turbulent eddies in the atmosphere has been discussed theoretically by Megaw,^{14,15} Little,¹⁶ Chandrasekhar,¹⁷ Keller,¹⁸ and van Isacker.¹⁹ The sensitivity of scintillation to gross meteorological effects will be described in the following paragraphs.

SCINTILLATION AND WEATHER

The following discussion is based upon the scintillation of stars observed near the zenith on one hundred nights from 1951 to 1954.

Seasonal effects of scintillation.—In figure 6, which uses observations obtained with 4-inch apertures, there can be seen a seasonal variation in scintillation, which is largest at the high frequencies.

Wind speed and height of the tropopause are meteorological circumstances known to vary seasonally. Therefore, recourse was made to the nightly observations of these factors which were available in the rawinsonde and radiosonde

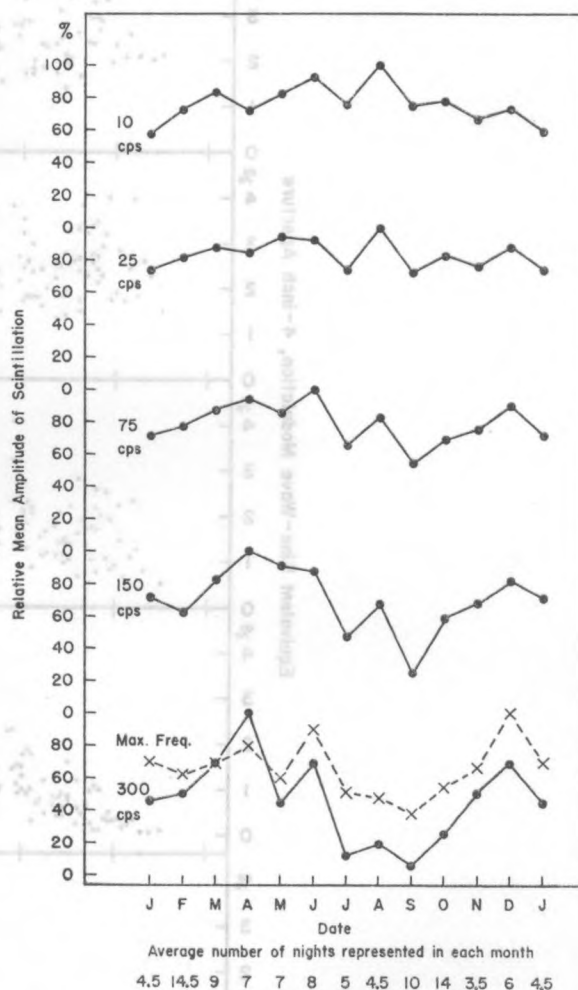


FIGURE 6.—Seasonal changes in the scintillation at different frequencies. A 4-inch aperture was used to observe the stars which were near the zenith. The points are relative mean amplitudes in terms of the highest monthly average in one category, which is defined as 100 percent. Data are used from the nights between the sixteenth of the preceding month and the fifteenth of the indicated month.

data procured at the Silver Hill, Maryland, Weather Bureau Station. This station is located about ten miles southeast of the Naval Observatory, on the other side of Washington. Since on most clear nights winds were westerly, the air through which scintillation was observed often was close to that carrying the sounding balloon.

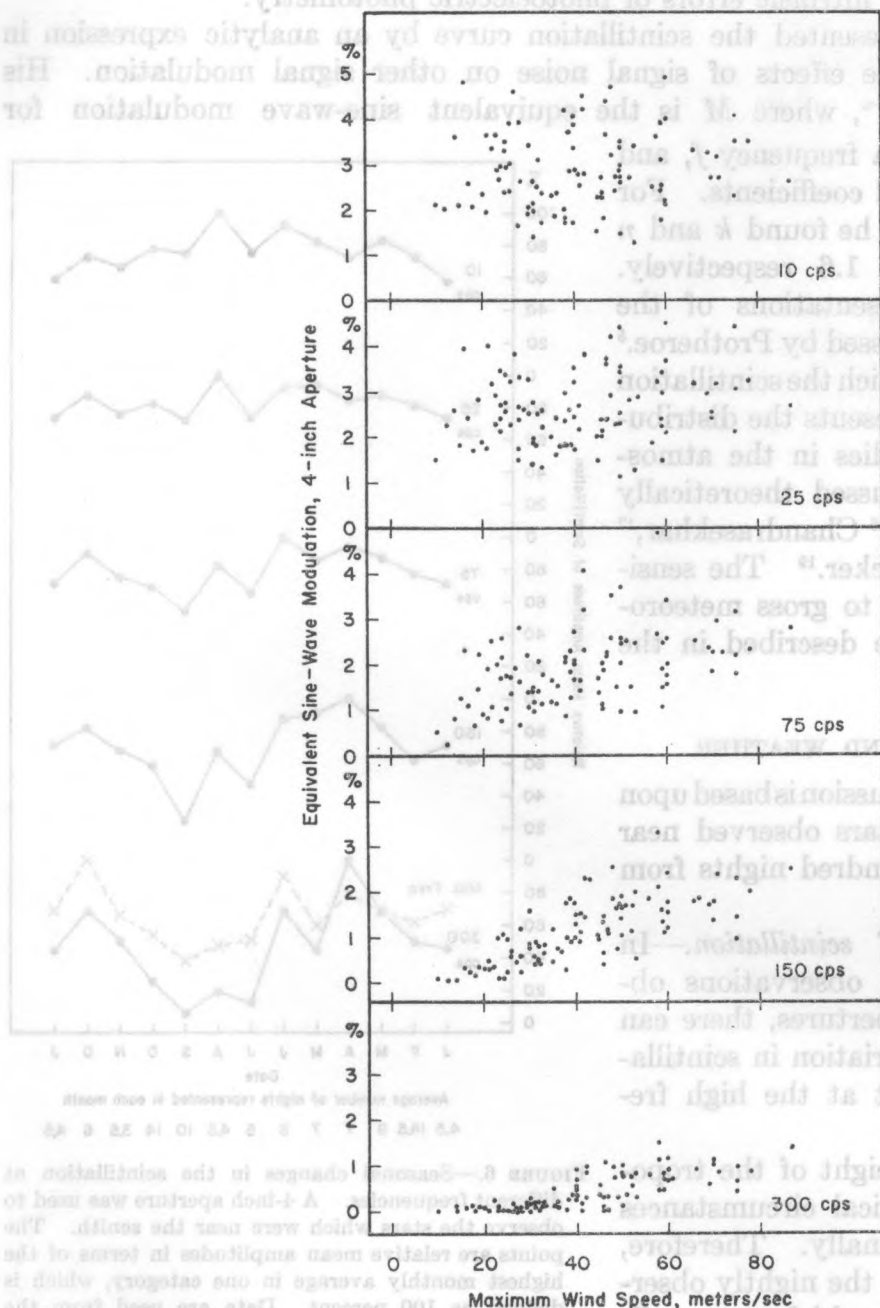


FIGURE 7.—Scintillation and maximum wind speed. These are observations of stars near the zenith obtained on nights when wind data were available from altitudes at least as high as 10 km. Each point in each plot refers to a separate night.

For each comparison with scintillation the weather data were taken from the balloon flight closest in time to the epoch listed in tables IV and V.

For purposes of the following discussion the tropopause is the lowest level of a radiosonde flight at which the decrease of temperature with height consistently starts its inversion to the temperature of the stratosphere. It occurs at various levels between 7 and 16 km.

We are indebted to the U. S. Weather Bureau for furnishing the wind and temperature data used in this report.

Effect of wind on observations of scintillation made with 4-inch aperture.—In figure 7 scintillation observations at several different frequencies are compared with maximum wind speed, considered without regard to the height at which it was observed. There is no correlation evident at 10 or 25 cps, but definite correlation at 150 cps and higher. Plots of the 150 cps scintillation against wind speed at various heights, figure 8, show the best correlation at levels from 8 to 14 km high.

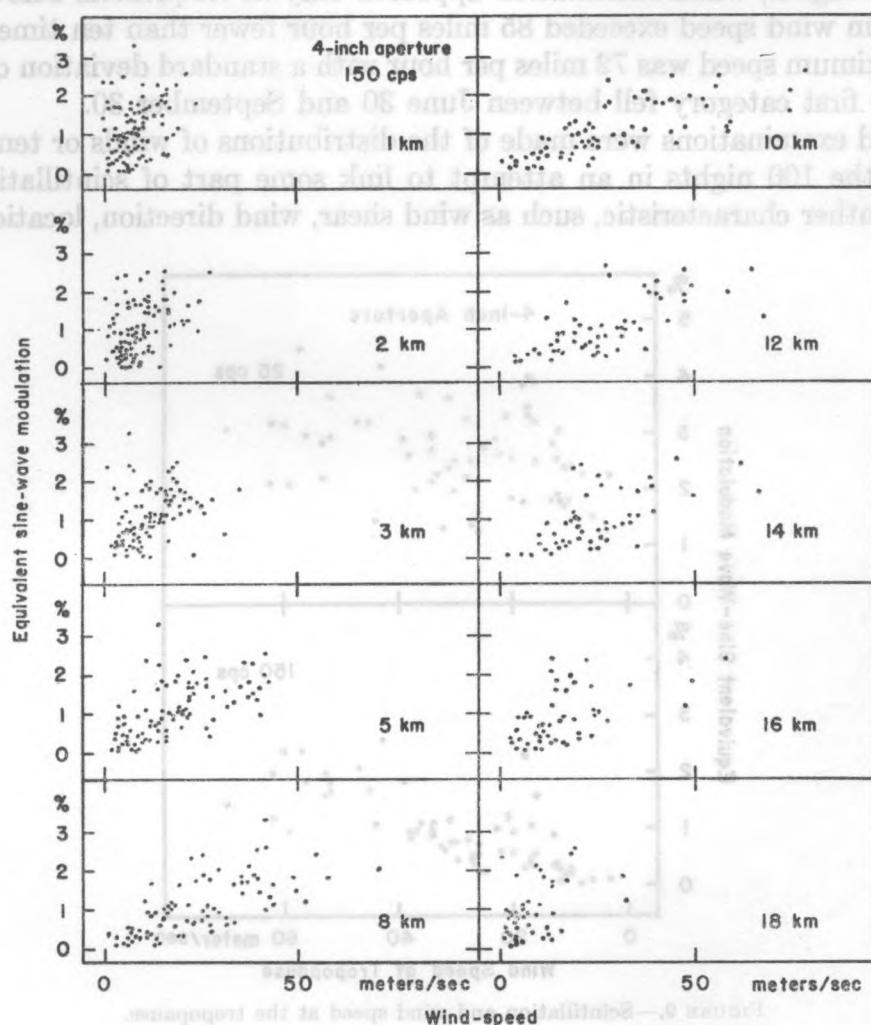


FIGURE 8.—Scintillation and wind speed at various levels.

Since this region of the atmosphere is that which generally contains the tropopause, there is some interest in ascertaining the relative roles of both tropopause and wind in scintillation formation. The combination of the two, represented in the plot of scintillation against wind speed at the tropopause, figure 9, indicates a correlation little better than that shown in figure 7, where height of wind was not primarily a factor. In figure 10, in which scintillation and maximum wind speed, respectively, are plotted against the height of the tropopause, one can see little evidence of correlation in either diagram. Scintillation, then, is no more associated with tropopause height than is wind speed, and the tropopause does not appear to be an independent agent in its formation.

At frequencies higher than 150 cps the action of wind speed is more striking. On 38 nights when scintillation was observed at frequencies above 550 cps the maximum reported speed aloft was always above 85 miles per hour. The average maximum speed on these nights was 128 miles per hour, with a standard deviation of 27. On the other 62 nights, when scintillation appeared only at frequencies below 550 cps, the maximum wind speed exceeded 85 miles per hour fewer than ten times, and the average maximum speed was 72 miles per hour with a standard deviation of 23. No night of the first category fell between June 30 and September 30.

Detailed examinations were made of the distributions of winds or temperatures on each of the 100 nights in an attempt to link some part of scintillation with a common weather characteristic, such as wind shear, wind direction, location of wind

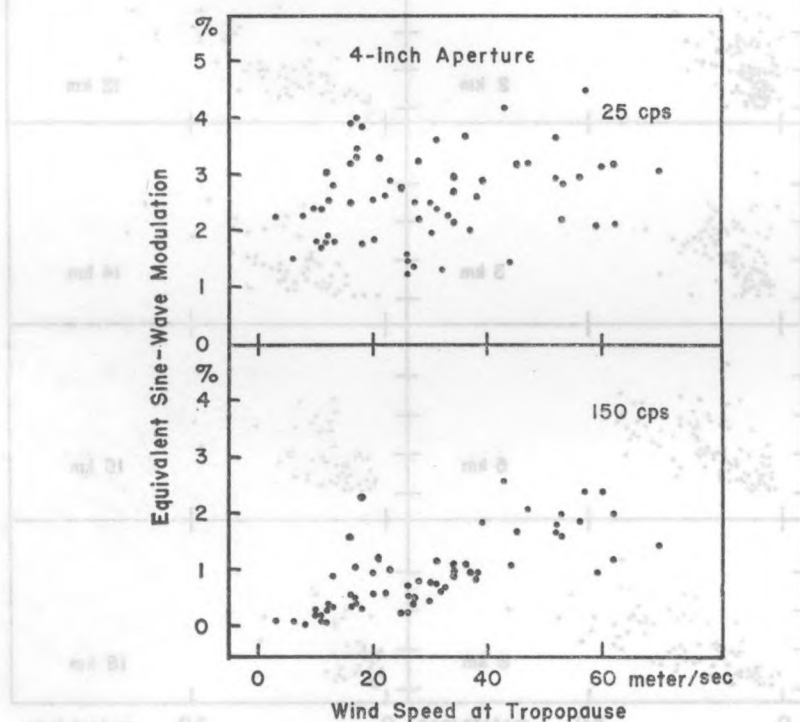


FIGURE 9.—Scintillation and wind speed at the tropopause.

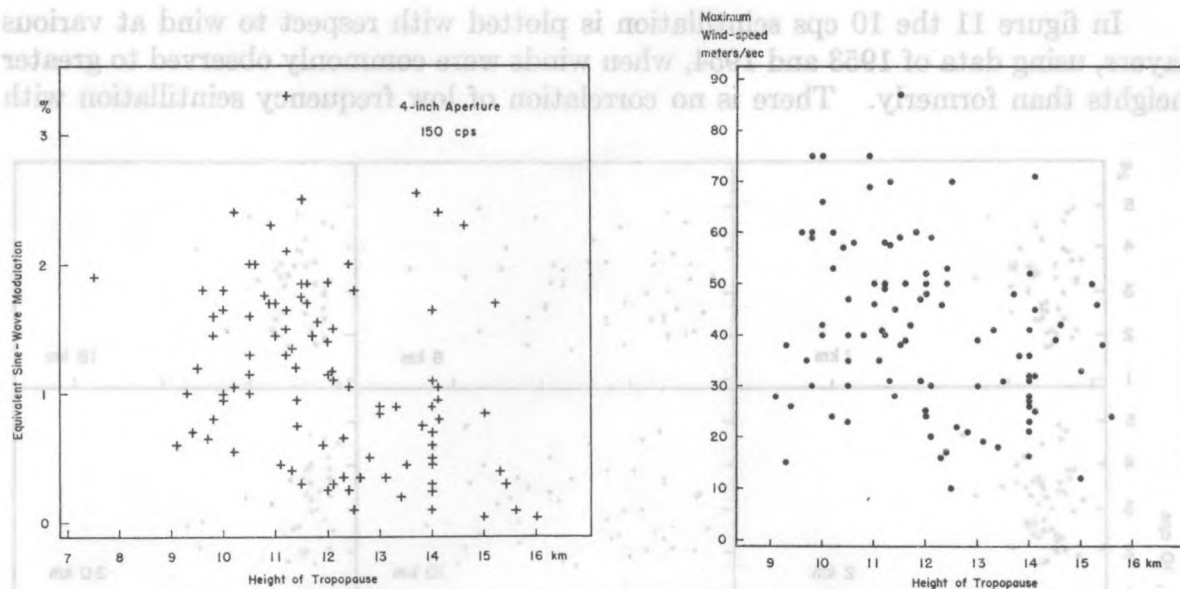


FIGURE 10. Left. High frequency scintillation and the tropopause height. Right. Maximum wind speed and the height of the tropopause, for the same dates.

maximum or minimum, intermediate temperature inversion, location or minimum value of the stratospheric temperature, or temperature lapse rate. No correlation was found except that noted with wind speed.

On the basis of figure 7 low frequency scintillation has been treated separately from high frequency scintillation. The seasonal trend of 10 cps scintillation is not statistically strong in figure 6 but it also has been noted by Protheroe⁵ in his observations. Its tendency to a larger amplitude in the summer suggests a correlation with wind opposite to that of the high frequency scintillation; that is, the larger values of scintillation are associated with lower wind speeds. There is also theoretical basis for an *a priori* expectation that the strong temperature inversions, such as the tropopause, produce significant scintillation mainly at low, rather than high, frequencies. Gifford²⁰ has discussed the Naval Observatory observations for the twenty-four nights for which the most uniform wind data were available. He found some correlations between wind speed and both 25 and 150 cps scintillation at a 1.4 km height. This is the average height of the "frictional inversion" at the top of the daytime planetary boundary layer. He also found correlation between wind speed at the average tropopause height and 150 cps scintillation, but none with 25 cps scintillation.

In figure 11 the 10 cps scintillation is plotted with respect to wind at various layers, using data of 1953 and 1954, when winds were commonly observed to greater heights than formerly. There is no correlation of low frequency scintillation with

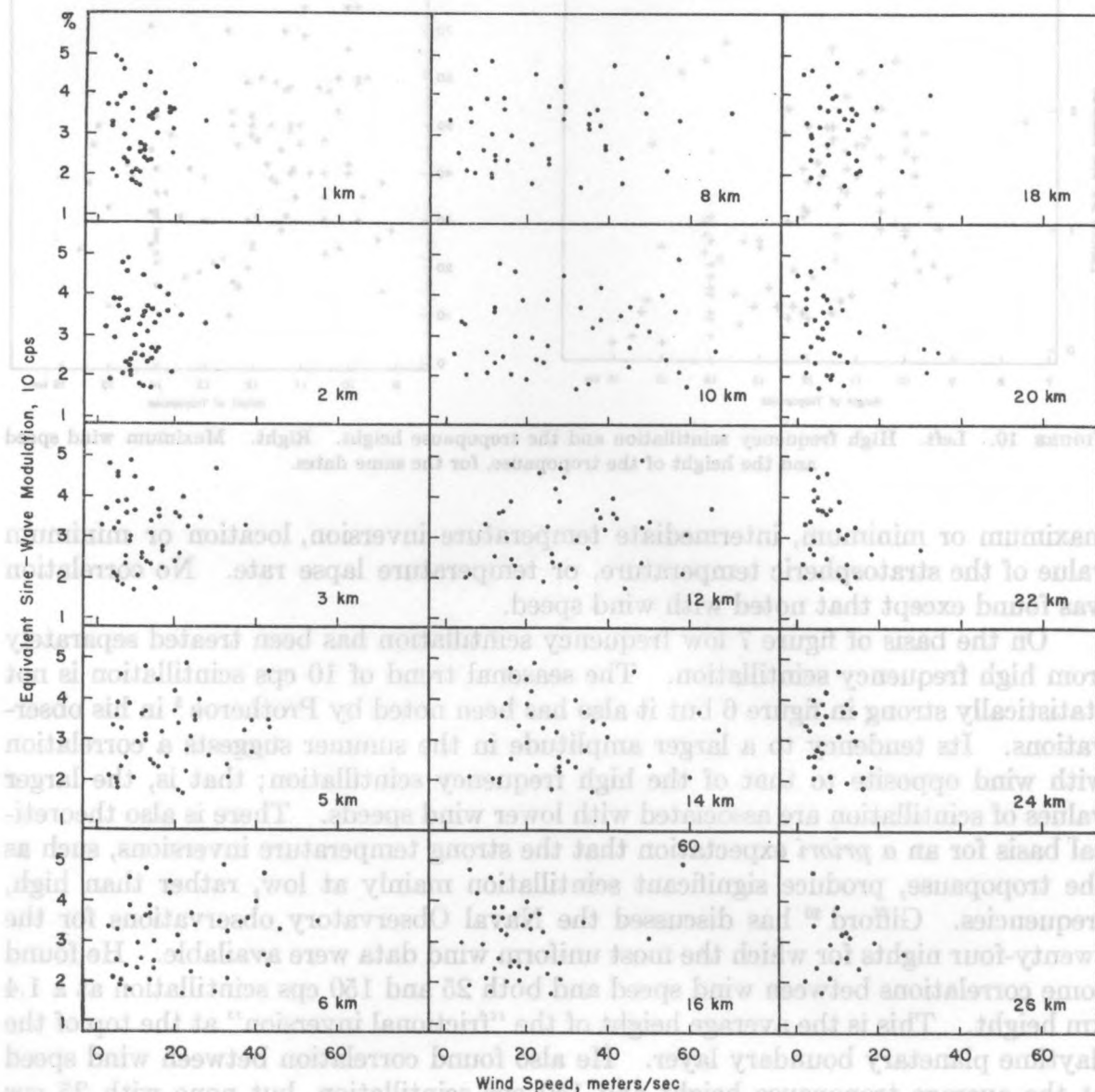


FIGURE 11.—Scintillation and wind speed at various levels. These plots represent 10 cps scintillation observed with a 4-inch aperture. The same zenith stars were used as for 150 cps data, figure 8. Points represent separate nights.

wind speed at any height. Figure 12 shows that there is also no correlation between low frequency scintillation and tropopause height on the same nights.

Effect of wind on observations of scintillation made with 15-inch aperture.—The ways in which different apertures affect observations of the phenomenon is demonstrated in figure 13, where the contemporaneous observations of the same star near the zenith, using 4- and 15-inch apertures, are compared. With the small aperture,

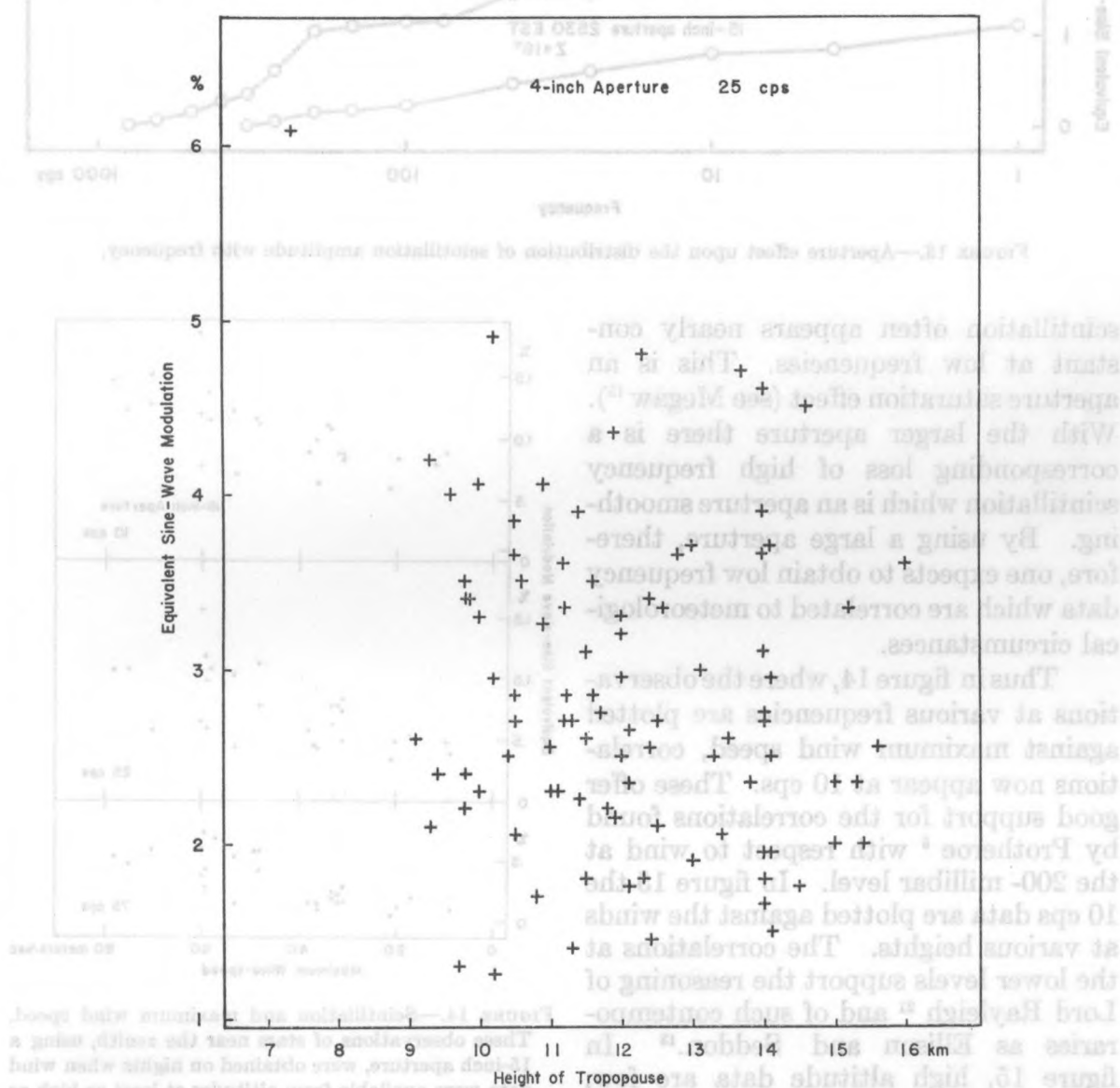


FIGURE 12.—Low frequency scintillation and tropopause height.

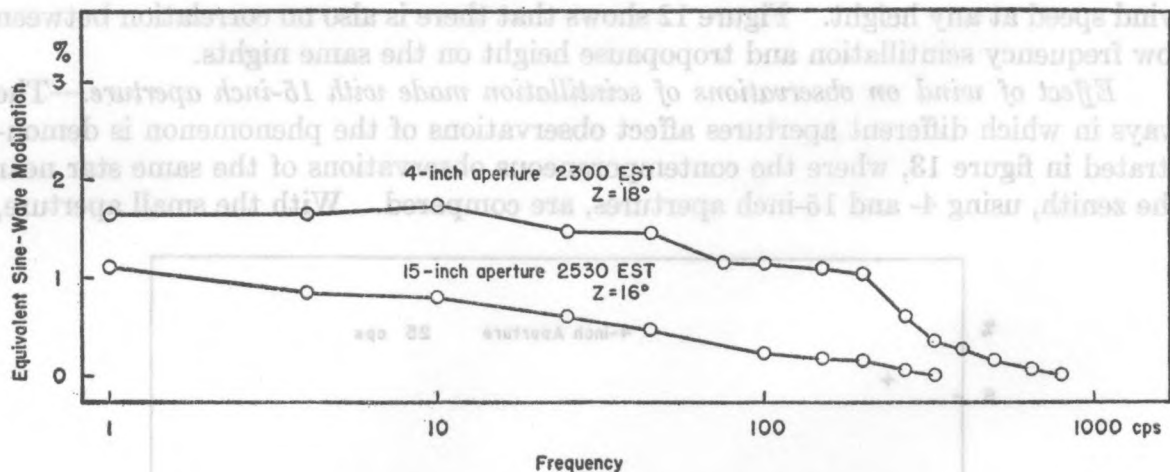


FIGURE 13.—Aperture effect upon the distribution of scintillation amplitude with frequency.

scintillation often appears nearly constant at low frequencies. This is an aperture saturation effect (see Megaw¹⁵). With the larger aperture there is a corresponding loss of high frequency scintillation which is an aperture smoothing. By using a large aperture, therefore, one expects to obtain low frequency data which are correlated to meteorological circumstances.

Thus in figure 14, where the observations at various frequencies are plotted against maximum wind speed, correlations now appear at 10 cps. These offer good support for the correlations found by Protheroe⁵ with respect to wind at the 200-millibar level. In figure 15 the 10 cps data are plotted against the winds at various heights. The correlations at the lower levels support the reasoning of Lord Rayleigh²¹ and of such contemporaries as Ellison and Seddon.¹³ In figure 15, high altitude data are few, and the plots can merely reflect in this

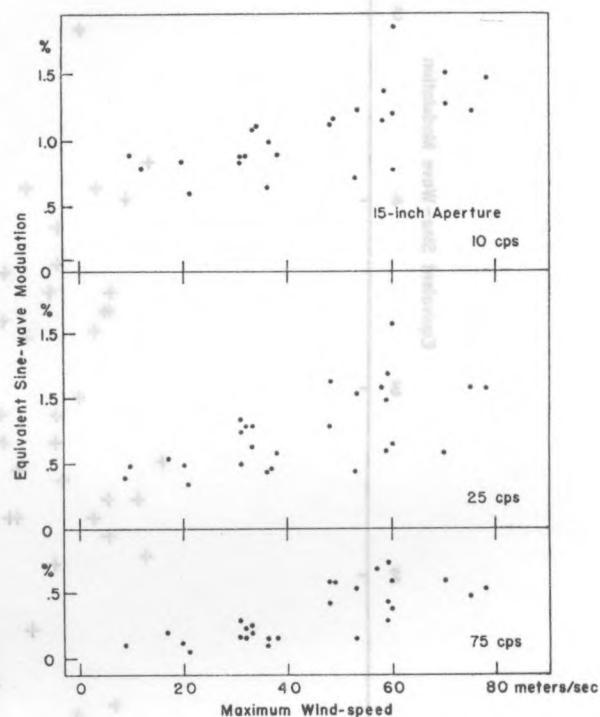


FIGURE 14.—Scintillation and maximum wind speed. These observations of stars near the zenith, using a 15-inch aperture, were obtained on nights when wind data were available from altitudes at least as high as 10 km.

instance the selection of nights on which the overall winds were slow enough for the weather balloon to be followed to high altitudes. Such a selection implies also a selection of summer nights, and of nights when atmospheric turbulence might be caused less by horizontal winds and more by convection currents.

In other respects, the observations with 15-inch apertures tend to show associations similar to those shown by observations made with 4-inch apertures. Scintillation is plotted against the tropopause wind speed for several frequencies in figure 16. In figure 17 the plot of scintillation against tropopause height shows no apparent correlation.

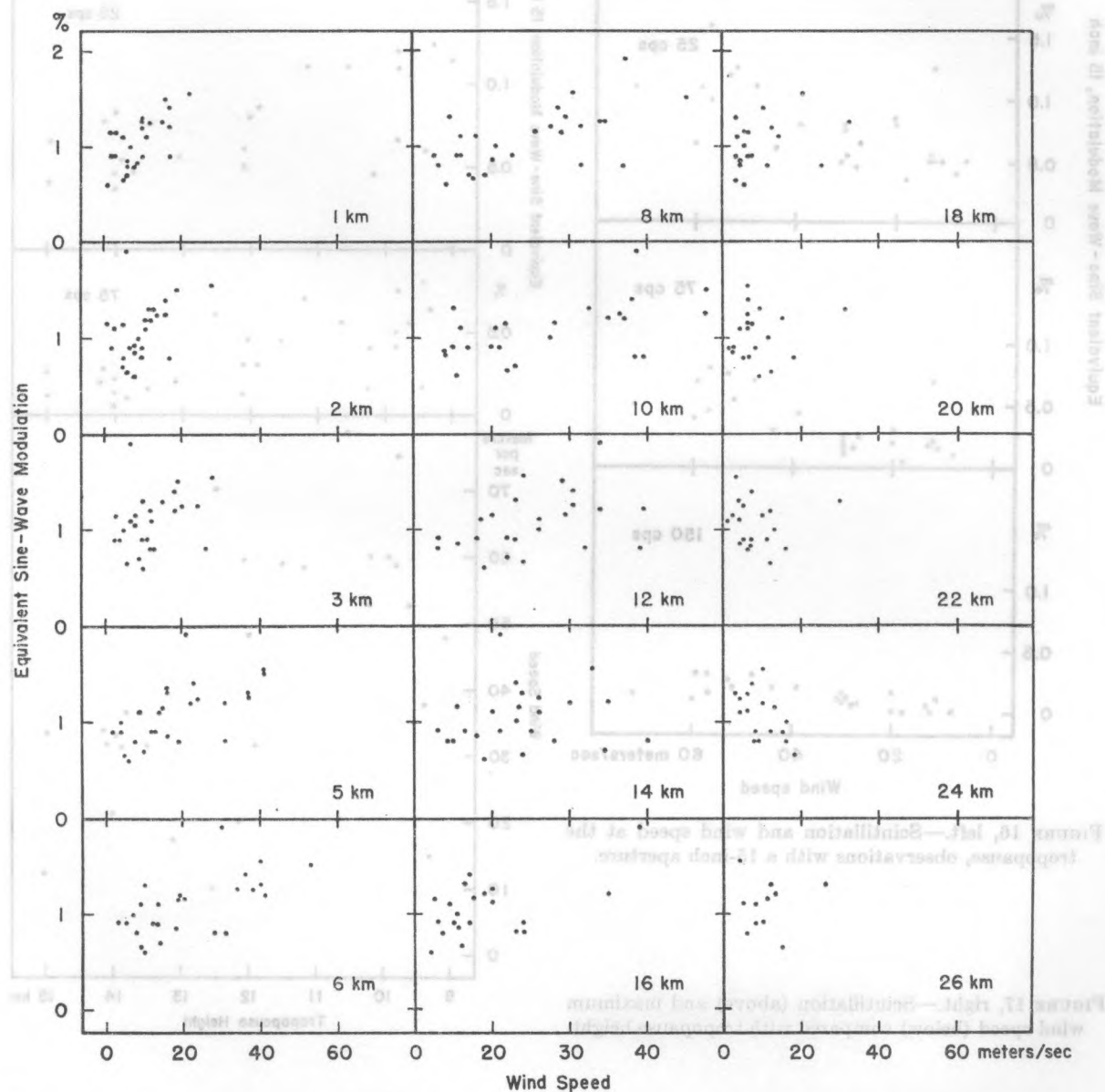


FIGURE 15.—Scintillation at 10 cps and wind speed at various levels. A 15-inch aperture was used for these observations of stars near the zenith.

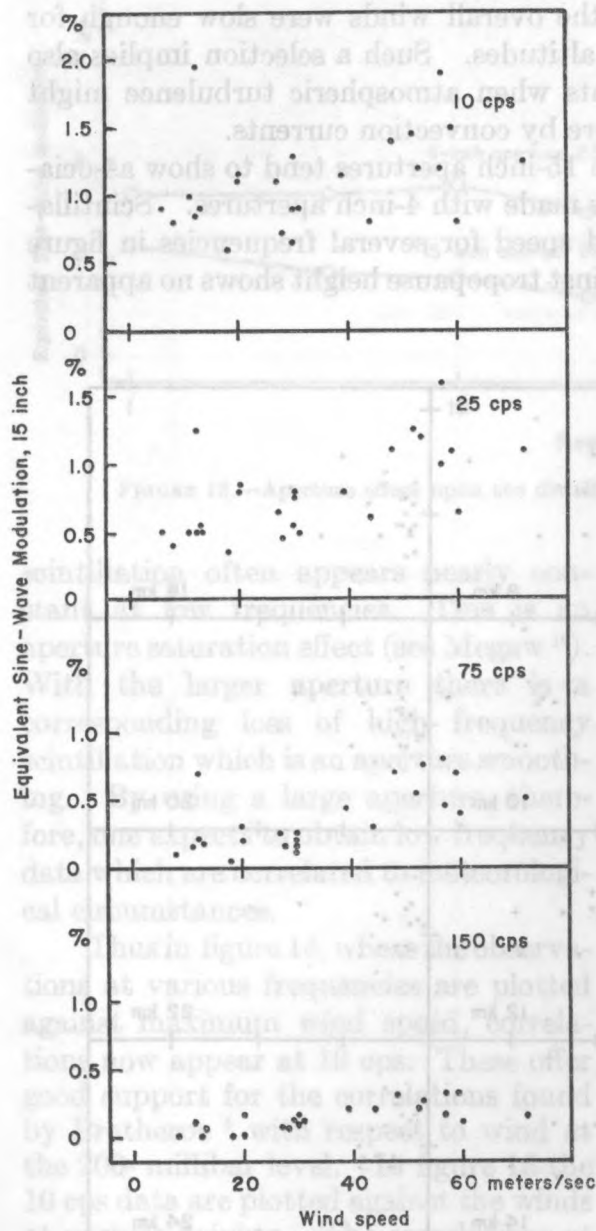


FIGURE 16, left.—Scintillation and wind speed at the tropopause, observations with a 15-inch aperture.

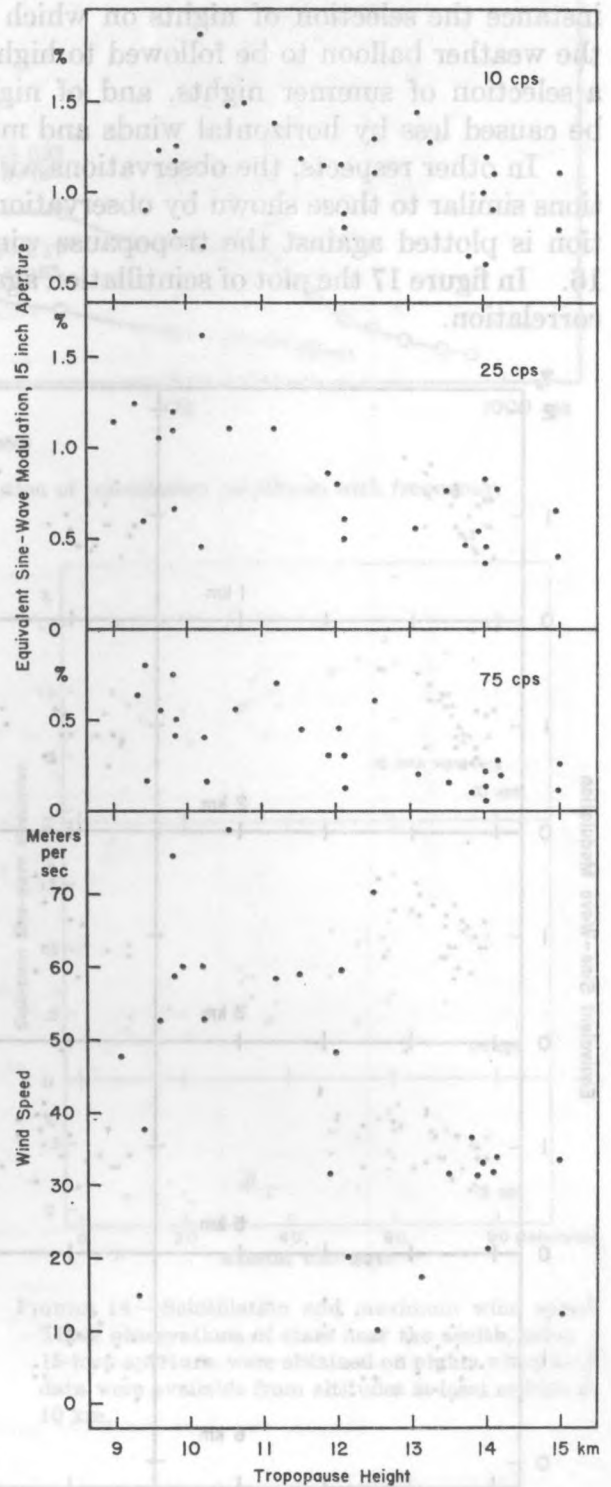


FIGURE 17, right.—Scintillation (above) and maximum wind speed (below) compared with tropopause height.

Hence, within the limitations of the data, the wind speed appears as the predominant factor in the production of low as well as high frequency scintillation. Relatively large telescope apertures are required, however, to study the effects of various parameters on low frequency scintillation.

Discussion of observations of scintillation made with rectangular apertures.— Since wind data have recently become regularly available from much higher altitudes than were reached at the outset of this program, the rectangular opening has developed into an interesting and specialized device for scintillation analysis. It has been

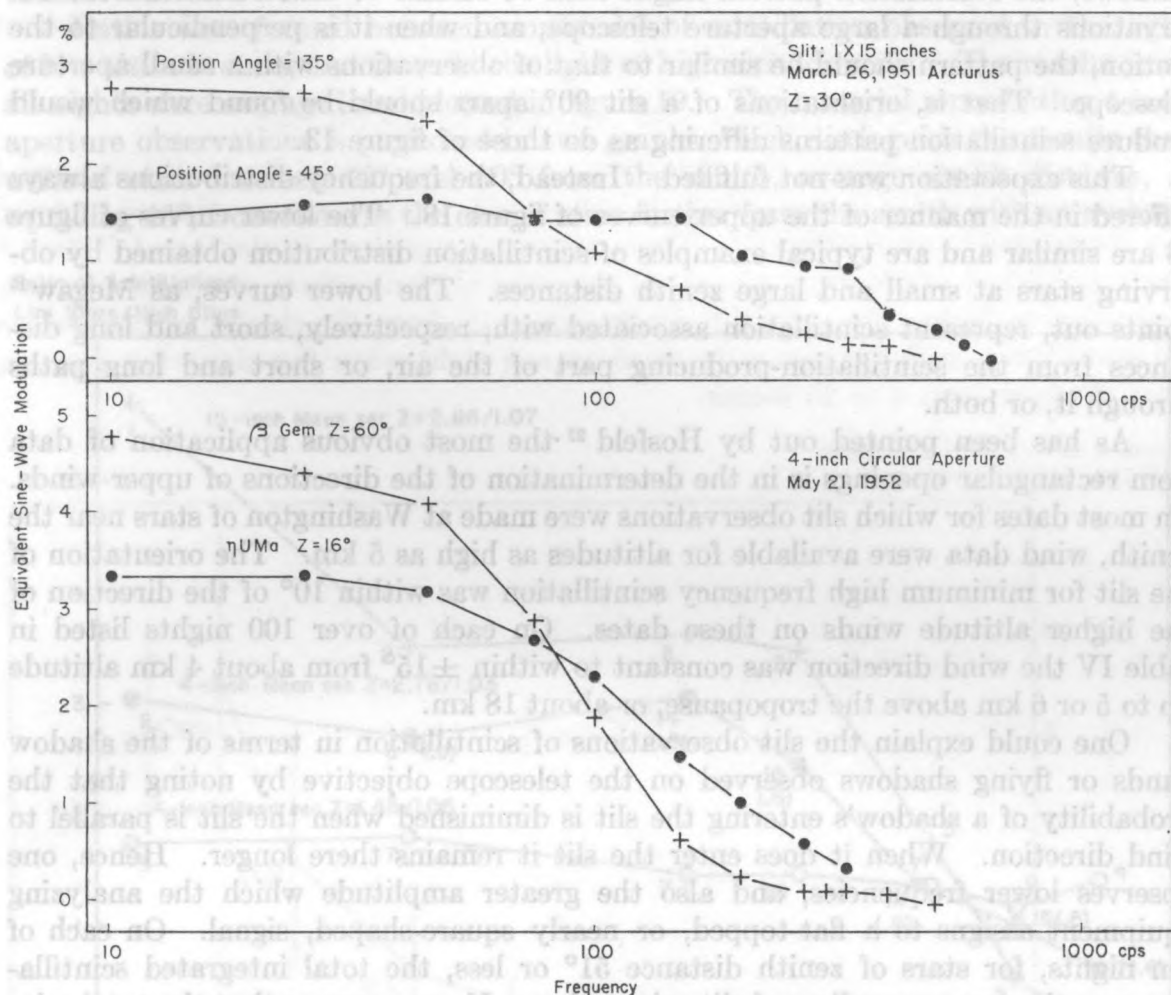


FIGURE 18.—Above. Typical change in the scintillation distribution pattern as a slit over the telescope objective is rotated. Below. Effect of zenith distance upon the shape of the pattern obtained when observing with a circular aperture.

explored briefly here, and in more detail by the Ohio State group which combined the appropriate theoretical investigation of Keller¹⁸ with original observing techniques of Hosfeld²² and Protheroe.^{5,31}

If a large slit is placed in front of the telescope objective one might expect that the patterns of scintillation will be different for different orientations of this slit. The expectation would be based upon observations of the apparent motions of the "flying shadows" across the starlight-illuminated objective, and an assumption that scintillation is associated with these. When the slit is parallel to the motion of the shadows, the scintillation pattern might then be similar to that obtained with observations through a large aperture telescope, and when it is perpendicular to the motion, the pattern should be similar to that of observations with a small aperture telescope. That is, orientations of a slit 90° apart should be found which would produce scintillation patterns differing as do those of figure 13.

This expectation was not fulfilled. Instead, the frequency distributions always differed in the manner of the upper curves of figure 18. The lower curves of figure 18 are similar and are typical examples of scintillation distribution obtained by observing stars at small and large zenith distances. The lower curves, as Megaw¹⁵ points out, represent scintillation associated with, respectively, short and long distances from the scintillation-producing part of the air, or short and long paths through it, or both.

As has been pointed out by Hosfeld²² the most obvious application of data from rectangular openings is in the determination of the directions of upper winds. On most dates for which slit observations were made at Washington of stars near the zenith, wind data were available for altitudes as high as 5 km. The orientation of the slit for minimum high frequency scintillation was within 10° of the direction of the higher altitude winds on these dates. On each of over 100 nights listed in table IV the wind direction was constant to within $\pm 15^\circ$ from about 4 km altitude up to 5 or 6 km above the tropopause, or about 18 km.

One could explain the slit observations of scintillation in terms of the shadow bands or flying shadows observed on the telescope objective by noting that the probability of a shadow's entering the slit is diminished when the slit is parallel to wind direction. When it does enter the slit it remains there longer. Hence, one observes lower frequencies, and also the greater amplitude which the analyzing equipment assigns to a flat-topped, or nearly square-shaped, signal. On each of ten nights, for stars of zenith distance 51° or less, the total integrated scintillation was the same regardless of slit orientation. If one assumes that the total scintillation is proportional to the obscuration per unit of time which the telescope objective suffers from shadows, then these shadows must be fairly uniformly distributed and not greatly elongated. This is also the conclusion of Hosfeld²² after he photographed the shadow patterns with different exposure times, and of Protheroe³¹ after he analyzed scintillation observed through pairs of small holes in front of the telescope objective.

SCINTILLATION AND ZENITH DISTANCE

Changes in scintillation produced by viewing stars at different zenith distances were described in the first report,¹ and are introduced with figure 18 in this discussion. They have been treated quantitatively by several investigators, especially by Nettelblad,³ Protheroe,⁵ Butler,¹² Megaw,¹⁵ and Siedentopf and Elsässer.²³ From the results of the previous section it is obvious that all comparisons for computing the effect of zenith distance must be of observations not only on the same night but as nearly at the same epoch as possible. The requirement was followed in the computations described here.

Ratios were formed between amplitudes of scintillation observed in the light of low altitude stars, and those in the light of high altitude stars. The results from all nights were averaged and plotted in figure 19. The material representing 4-inch aperture observations is presented in two graphs which distinguish the results that utilized stars between 40° and 50° from the zenith, average zenith distance, z , equalling 46° , from those in the case of stars farther from the zenith with an average

Ratio of Scintillations
Low Stars/High Stars

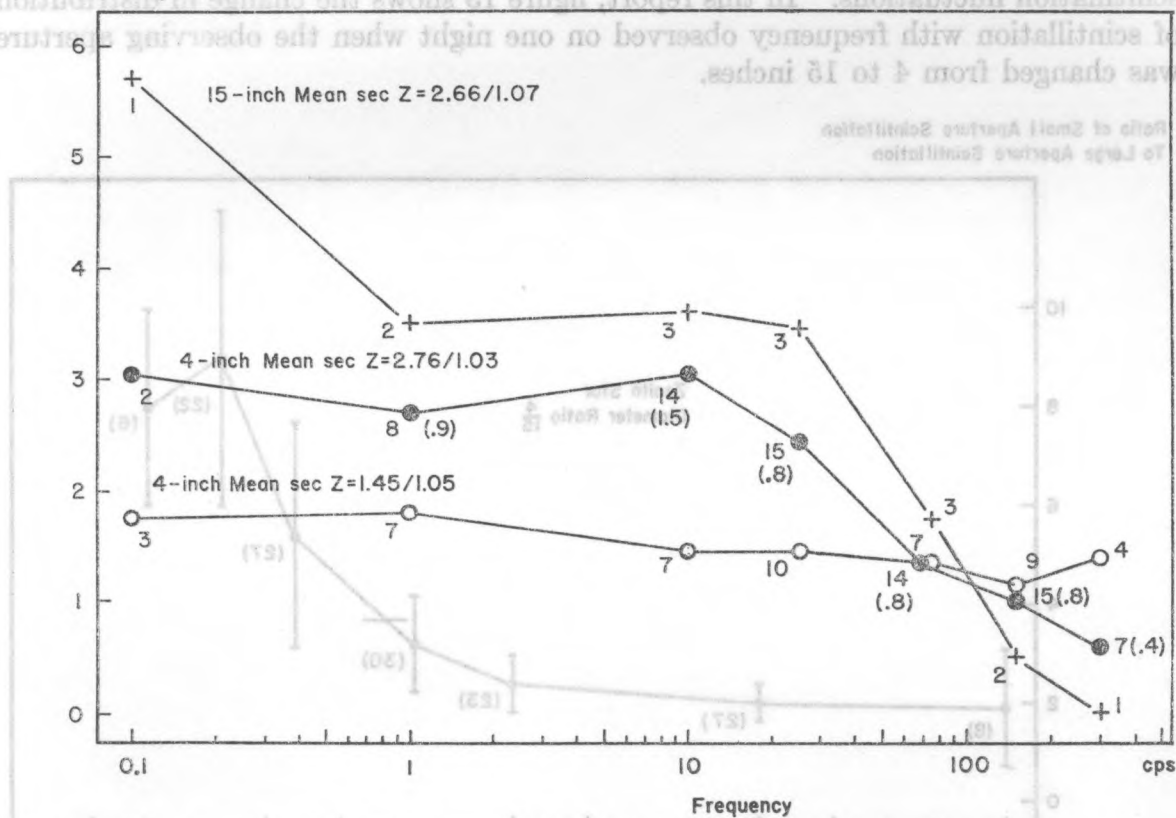


FIGURE 19.—Summary of the effect of zenith distance on scintillation. Numbers in parentheses are the standard deviations of the data of the adjacent points. The other numbers are the nights represented by the points.

z of 69° . A large scatter in the ratios depending upon low altitude stars is to be expected for at least two reasons. One is the known fact that scintillation variation with $\sec z$ is non-linear when z is large; the other is the unknown dependence of the above ratios upon wind-speed and other meteorological conditions.

The comparisons show that for sources at large zenith distance, scintillation harmonic content is greater at low frequencies and smaller at high frequencies than for stars near the zenith. This effect is illustrated by the lower curves of figure 18. Of practical significance, figure 19 indicates that the tilting of the scintillation distribution curve has not occurred for stars 46° from the zenith. One need not extrapolate this information much farther to expect that Polaris would have about the same relative frequency distribution of scintillation as that of a zenith star.

SCINTILLATION AND CIRCULAR APERTURE SIZE

The effect of aperture upon scintillation was discussed briefly by Whitford and Stebbins¹¹ and in the first report of this program.¹ It has been considered in detail by Nettelblad³ and Protheroe.⁵ These authors, as well as Butler¹² and Ellison,¹³ have published oscillograph records of the most obvious effects of aperture on the scintillation fluctuations. In this report, figure 13 shows the change in distribution of scintillation with frequency observed on one night when the observing aperture was changed from 4 to 15 inches.

Ratio of Small Aperture Scintillation
To Large Aperture Scintillation

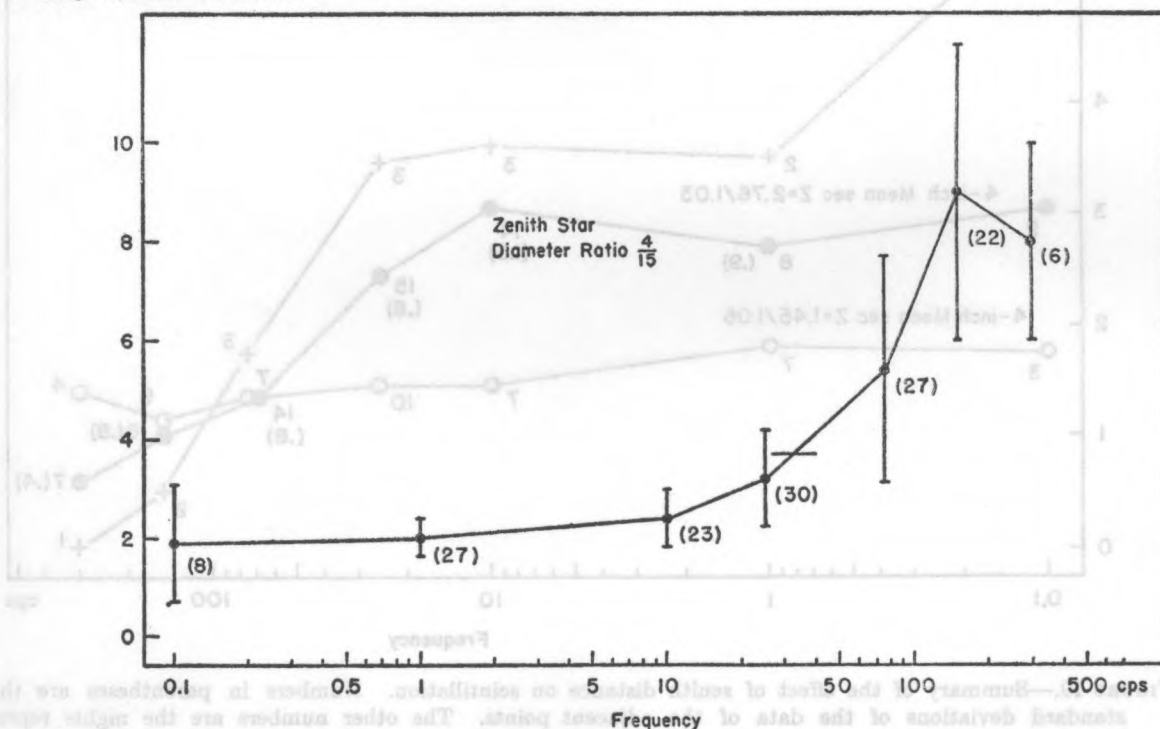


FIGURE 20.—Ratios of scintillation observed with small and large apertures. The number of nights represented in each point is in parentheses. The vertical lines are twice the standard deviations, and the horizontal line marks the ratio of the apertures.

In figure 20, the ratios of scintillation amplitude, using apertures of 4 and 15 inches, are plotted against frequency. The stars were within 30° of the zenith, a range within which the variation with zenith distance was found to be unimportant.

The frequency at which ratios of scintillation amplitudes equal the reciprocals of the respective aperture diameters is roughly constant for small to moderate apertures. For 4-inch to 8-inch, and 6-inch to 12-inch aperture observations of zenith stars, the frequency is 25 cps. For 4-inch to 8-inch aperture observations of Polaris, it is 40 cps, and in figure 20 it is 33 cps. Megaw²⁴ computed that the amplitudes of scintillation observed with an oscillograph, using a short time constant, should vary inversely as the diameter of the observing aperture.

SCINTILLATION AND SEEING

Introduction.—Observers differ most in their attempts to relate seeing and scintillation, yet this particular relation is the most interesting of all to astronomers because scintillation is the only naked-eye manifestation of clear-air observing conditions. The variety of opinions implies that the following parameters are involved in the definition of seeing:

(1). *Criteria for seeing:* A common standard of seeing is the image motion of a star observed with a small telescope. Image definition is also commonly used, but is affected by telescope aperture and magnification; as a seeing index, it generally reflects specific observing situations. The Pickering scale²⁵ and Hosfeld's cinematographic Hartmann tests²⁶ are two attempts to make it impersonal. Hosfeld has also shown that both image definition and dancing affect the light curve obtained as the focal image of a star drifts past a knife-edge.* He proposes the use of this fact to register automatically the seeing of Polaris.²⁷

(2). *Geographical location:* Observations of Polaris with standard high-power telescopes have been made at several locations by the California Institute of Technology, reported by Anderson,²⁸ and by the U. S. Naval Observatory. These sets of data represent opposite coasts of the United States and very different altitudes, weather patterns, and atmospheres.

Basic image quality for the two sets of seeing observations was so generally different that they can hardly be deemed comparable. Western observations, in Southern California, consistently listed sharp diffraction patterns with two rings well contrasted;²⁸ on only a handful of nights did observers find the pattern completely blurred-out and seriously enlarged. The eastern observers, who were within 200 miles of Washington, rarely saw clear-cut, sharply defined diffraction patterns, and seldom could observe more than one or two rings. The diffraction pattern was always completely blurred-out during the first clear night or two after a storm.

The above differences in image appearance became evident through the use, in the eastern survey, of Mount Palomar site-testing equipment and methods.

*The principle of this method was implicit in the microphotometry of photographic star trails which Minnaert and Houtgast described in 1935 in the *Zeitschrift für Astrophysik*, volume 10, page 86. On the basis of the gross irregularities of their star trails they assumed that brightness variations along the trails were due almost entirely to scintillation. Subsequent studies, such as Hosfeld has reported in reference 26, demonstrate that they were measuring mainly the effects here included in the definition of seeing.

These two series of unpublished observations showed no marked differences in image motion.

(3). *Local circumstances*: In each region some local stations provided generally worse seeing than others, and were dropped after several months of operation. On the other hand some as much as 100 miles apart consistently showed similar results on the same nights. The writer is indebted to Dr. J. A. Anderson of the California Institute of Technology for the opportunity to examine the data of the Mount Palomar site-testing survey.

Available seeing data.—Four categories of seeing observations are available here for discussion:

(1). Visual observations of Polaris using a magnifying power of 800 diameters with a 4-inch telescope;

(2). Similar observations for stars while they were being used as scintillation sources;

(3). Internal agreement of time and latitude observations of the Ross photographic zenith tube (PZT);

(4). Subjective estimates of seeing by the 6-inch transit circle observers.

Scintillation and 4-inch telescope seeing.—(1) and (2), above, both depend upon visual magnification of a star image large enough to show diffraction rings and image motion. The latter was measured in terms of the size of the central disk. The visual data at high power have been summarized in footnotes to tables IV and V in terms of image definition, speed of image motion, and extent of image motion. These effects were further condensed to categories numbered 1 to 5 where 1 represents the sharpest image and smallest motion, and category 3 means a somewhat fuzzy image with at least one ring still visible, and moderate motion (less than 3 seconds of arc). Under this system most seeing appeared to be 2 or 4.

Seeing that was thus classified for stars near the zenith on thirty-one nights is compared, in figure 21, with scintillation of zenith stars as observed with a 4-inch telescope. A weak correlation is apparent for every phase of scintillation here considered. Small scintillation specifically has been observed simultaneously with very bad seeing. The reverse situation occurred once during the program, as shown in figure 21. However, on several occasions the star image as seen in the 8-inch guiding telescope suddenly blew-up to condition 5 at its worst, with simultaneous and proportionate increase in all parts of the scintillation record. There were, of course, similar associations of improvement in seeing with decrease of scintillation, though never as rapid.

It was found that inclusion in figure 21 of data from stars at greater zenith distances weakened the correlations. No correlation between scintillation and seeing appeared on eleven of the twenty-one nights in 1950 when Polaris was observed with 4-inch aperture. More numerous observations of this star were made later with a different technique and during a different season. They will be discussed on page 187.

Equivalent
Sine-Wave
Modulation

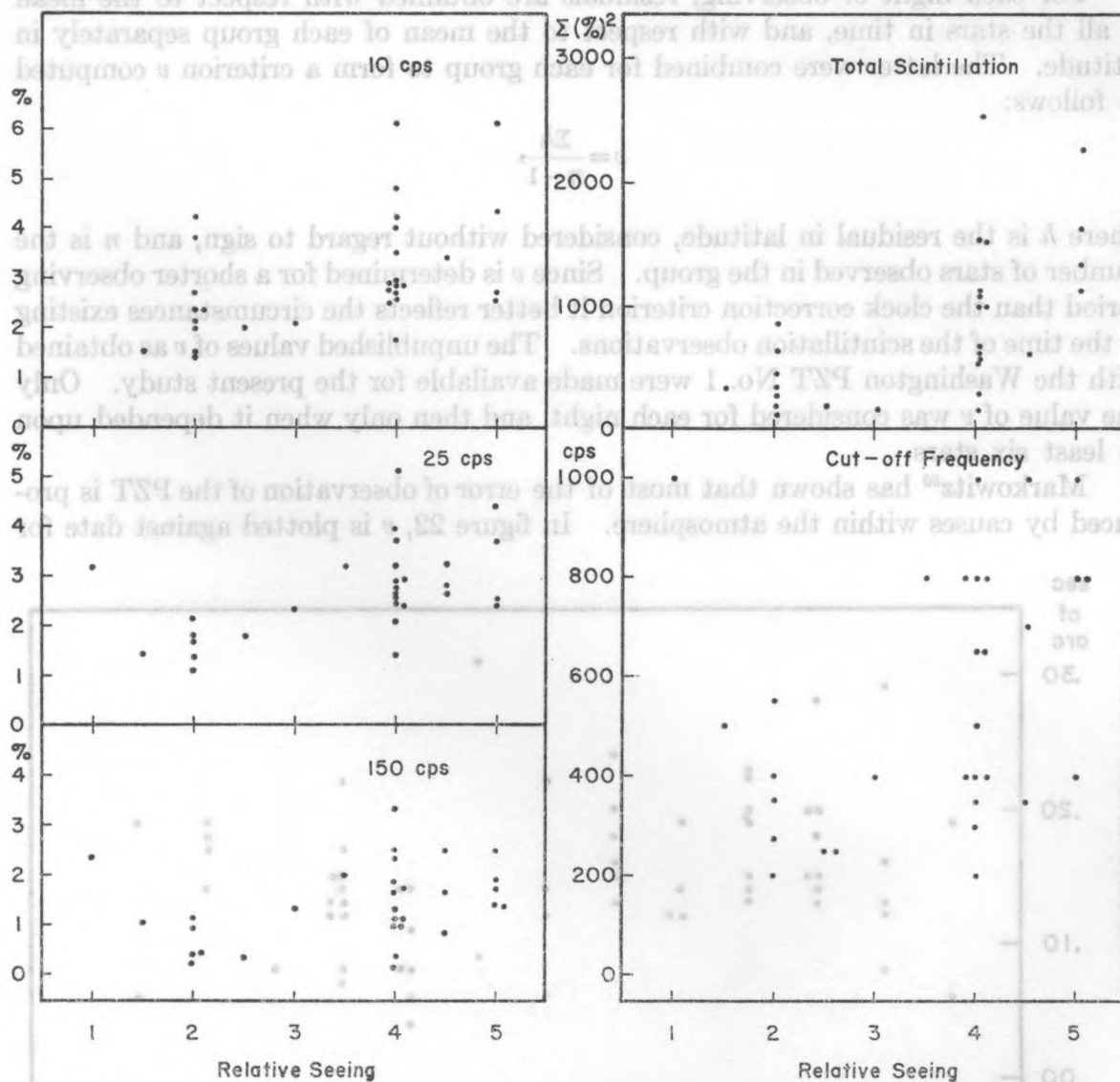


FIGURE 21.—Scintillation and seeing. Plots on the left compare amplitudes at the indicated frequencies with visual seeing of the stars while they were observed for scintillation. The total scintillation is proportional, for each night, to the area under a curve which represents the distribution with frequency of the squares of the scintillation amplitudes.

Scintillation and observations of latitude.—The photographic zenith tube, or PZT, has been described elsewhere.²⁹ It is used by the Time Service of the U. S. Naval Observatory for regular observation of stars which transit very near the zenith. Two groups of nine stars each are observed during each night, with the

data of each star furnishing an independent measurement of both clock correction and variation of latitude.

For each night of observing, residuals are obtained with respect to the mean of all the stars in time, and with respect to the mean of each group separately in latitude. The latter were combined for each group to form a criterion v computed as follows:

$$v = \frac{\sum h}{n-1},$$

where h is the residual in latitude, considered without regard to sign, and n is the number of stars observed in the group. Since v is determined for a shorter observing period than the clock correction criterion it better reflects the circumstances existing at the time of the scintillation observations. The unpublished values of v as obtained with the Washington PZT No. 1 were made available for the present study. Only one value of v was considered for each night, and then only when it depended upon at least six stars.

Markowitz³⁰ has shown that most of the error of observation of the PZT is produced by causes within the atmosphere. In figure 22, v is plotted against date for

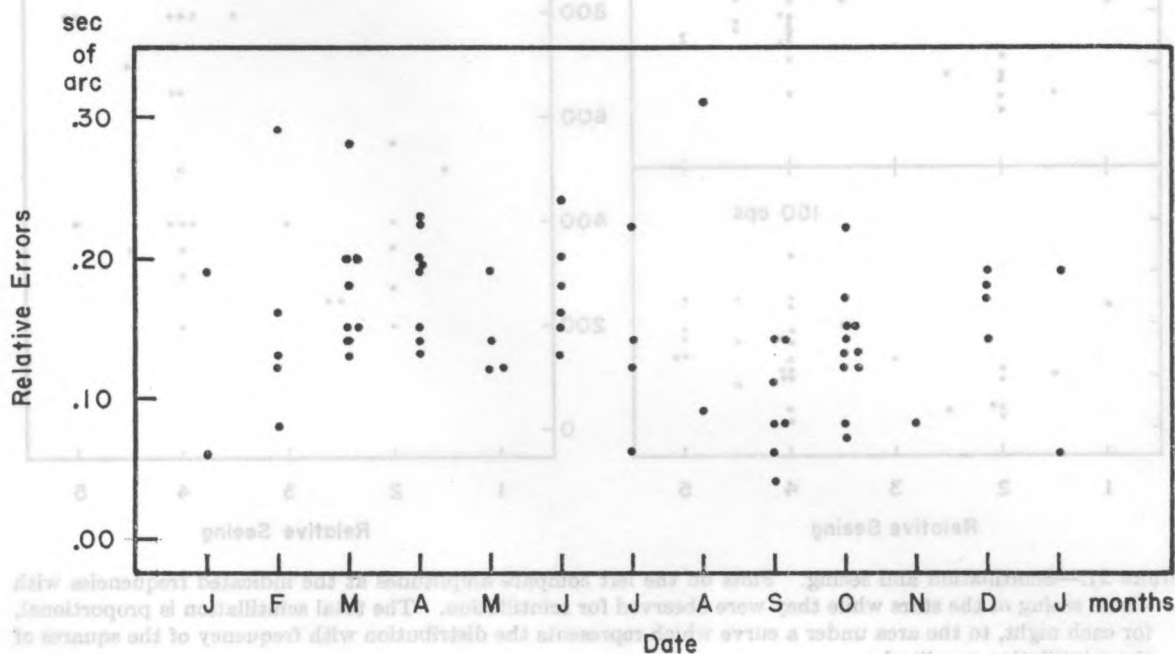


FIGURE 22.—Seasonal variation of the PZT criteria. The corresponding seasonal effect in scintillation is shown in figure 6.

sixty-four nights in 1950 to 1953; it shows a seasonal variation analogous to that of high frequency scintillation in figure 6. In figure 23 these same v 's are plotted against contemporaneous scintillation data. There is evidence of correlation between v and the scintillation at both 25 and 150 cps, but no correlation between v and the cut-off frequency. In general the comparisons agree with the results obtained using visual seeing data, figure 21, and show that the probable error in latitude obtained with the PZT tended to be smaller on the nights when scintillation was smaller.

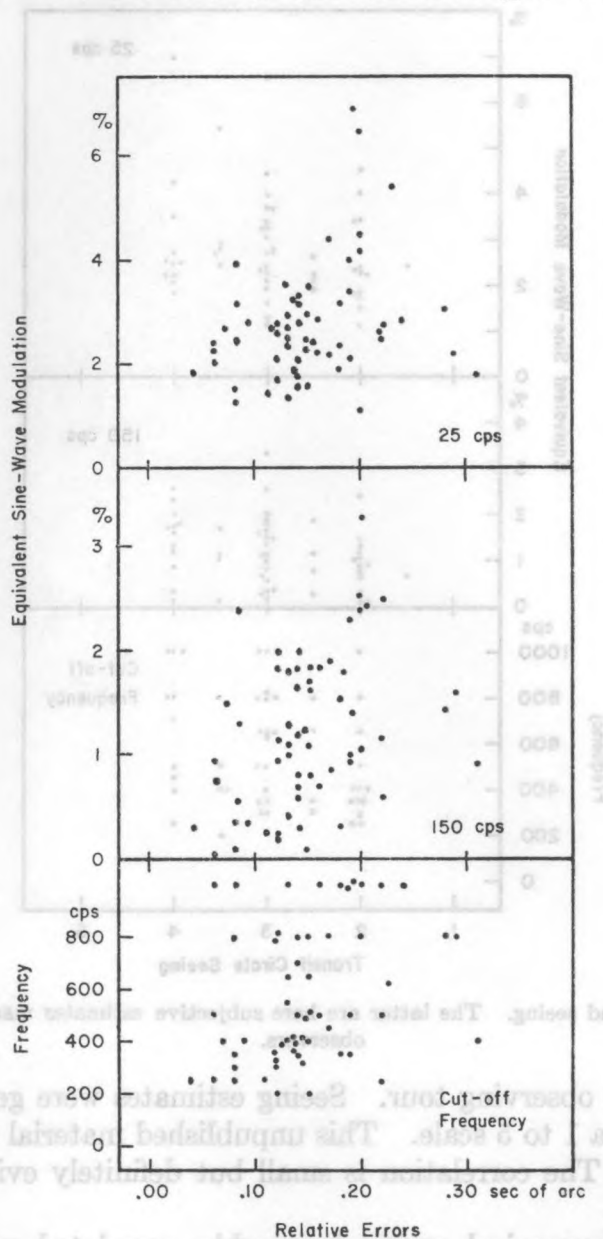


FIGURE 23.—Scintillation and seeing. The latter is here the criterion of quality of variation of latitude measurements obtained by the Time Service with a photographic zenith tube. Scintillation data were taken of stars near the zenith with a 4-inch aperture.

Scintillation and other seeing criteria.—Seeing estimates associated with the 6-inch transit circle observations are, of course, very personal. They reflect the difficulty of the observers in keeping star images centered between wires, 6 seconds of arc apart, which are automatically driven to follow the stars. During 1951 and 1952 observers' notes referred to individual stars, and the data could be selected according to epoch and zenith distance. In recent years the observer's estimate

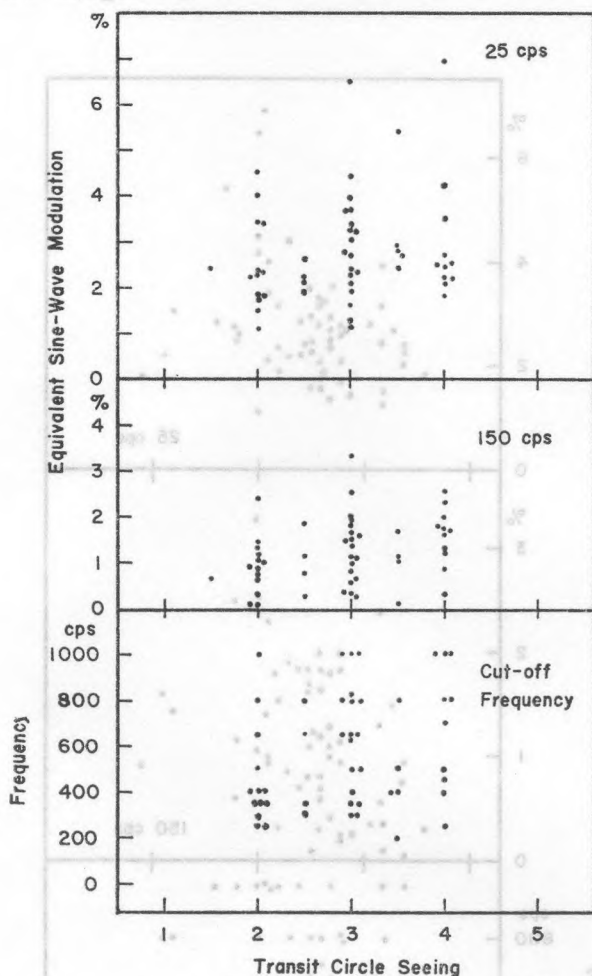


FIGURE 24.—Scintillation and seeing. The latter are here subjective estimates made by 6-inch transit circle observers.

referred to the whole observing tour. Seeing estimates were generally represented on the equivalent of a 1 to 5 scale. This unpublished material was plotted against seeing in figure 24. The correlation is small but definitely evident in the case of 150 cps scintillation.

Conclusion.—Astronomical seeing is roughly correlated with scintillation at frequencies between 10 and 150 cps.

SCINTILLATION OF ARTIFICIAL SOURCES

Observations of artificial sources at the Naval Observatory have been conducted jointly with A. A. Hoag and John S. Hall. Measurement of scintillation of artificial sources over horizontal paths was the basis of a study directed by Goldstein.^{8,9} Over horizontal paths only several hundred yards long no scintillation was detected at the Naval Observatory. Neither was any found in the light of sources carried by captive balloons up to heights of 1000 feet and as distant as 2500 feet. These sources were lamps with filaments 1 to 2 mm long.

Free balloon flights.—After preliminary experiments, flights of free balloons were made successfully on 31 October 1953, using reserve-type batteries to furnish power to 6-volt lamps with filaments 3 mm long. In one case data were obtained from a light about 25,000 feet high. For each flight observations were started when the source was around 10,000 feet high and near the zenith. Horizontal winds carried the balloons rapidly to low zenith distances. Scintillation at 10 or 25 cps was about one-third that of adjacent stars. This relation remained about constant as the zenith distance increased, and was not independently affected, apparently, by the increasing height of the balloon. These experiments are being continued.

We were greatly aided in the procurement and use of the balloons and other materials required for these flights by Mr. H. W. Rahmlow of the Radiosonde Section, Instrument Division, of the U. S. Weather Bureau. Mr. G. R. Wright and Mr. N. B. Foster, also of the Instrument Division, kindly assisted in the procurement of lights and batteries. All balloons were launched from the grounds of the Silver Hill Weather Bureau Station.

Helicopter flight.—A small-filament lamp was carried to a height of 8000 feet over the Naval Observatory in July, 1952. Its scintillation was observed to be less than one-tenth that of an adjacent star.

POLARIS MONITOR

EQUIPMENT

The apparatus pictured in plate II was constructed for the routine monitoring of the nighttime scintillation and brightness of Polaris. This equipment was put into operation in February, 1954. Figure 25 shows the arrangement of the components. The lens has a 120 mm aperture and 600 mm focal length. In the focal plane diaphragm there are two holes, one on the axis for the star and one slightly off-axis for measurement of the sky background. A disk in front of the diaphragm is driven intermittently by a motor, completing a revolution in 15 two-minute steps. In certain positions it blocks the starlight; in one of these, light from adjacent sky only is allowed to reach the 1P21, while in another, only light from a radium-activated source produces a signal. The field lens transmits both star and sky-light to very nearly the same part of the 1P21.

Polaris is followed by changing the direction of the axis of the telescope, a suggestion of A. A. Hoag. One end of the tube is supported by gimbals and the other carries roller bearings resting upon, and against the side of, a large disk which is turned one revolution per sidereal day. The disk is mounted off-center on its shaft by an amount equivalent to the polar displacement of the star. The telescope drive motor operates continuously, but the other units are powered through a time switch.

The dc amplifiers use series-balanced circuits and the tuned amplifier has two stages with bridged-T filters. Half-amplitude bandwidth is about 4 percent of the pass-band frequency. The noise meter has been described in figure 2. Switching of the circuits is synchronized with the position of the occulting disk, as indicated in figure 25. For the two monitors now in use this operation is performed by relays at the amplifiers, which are controlled by switches at the telescope. One recorder serves for all measurements; these can be cycled to suit the observational needs.

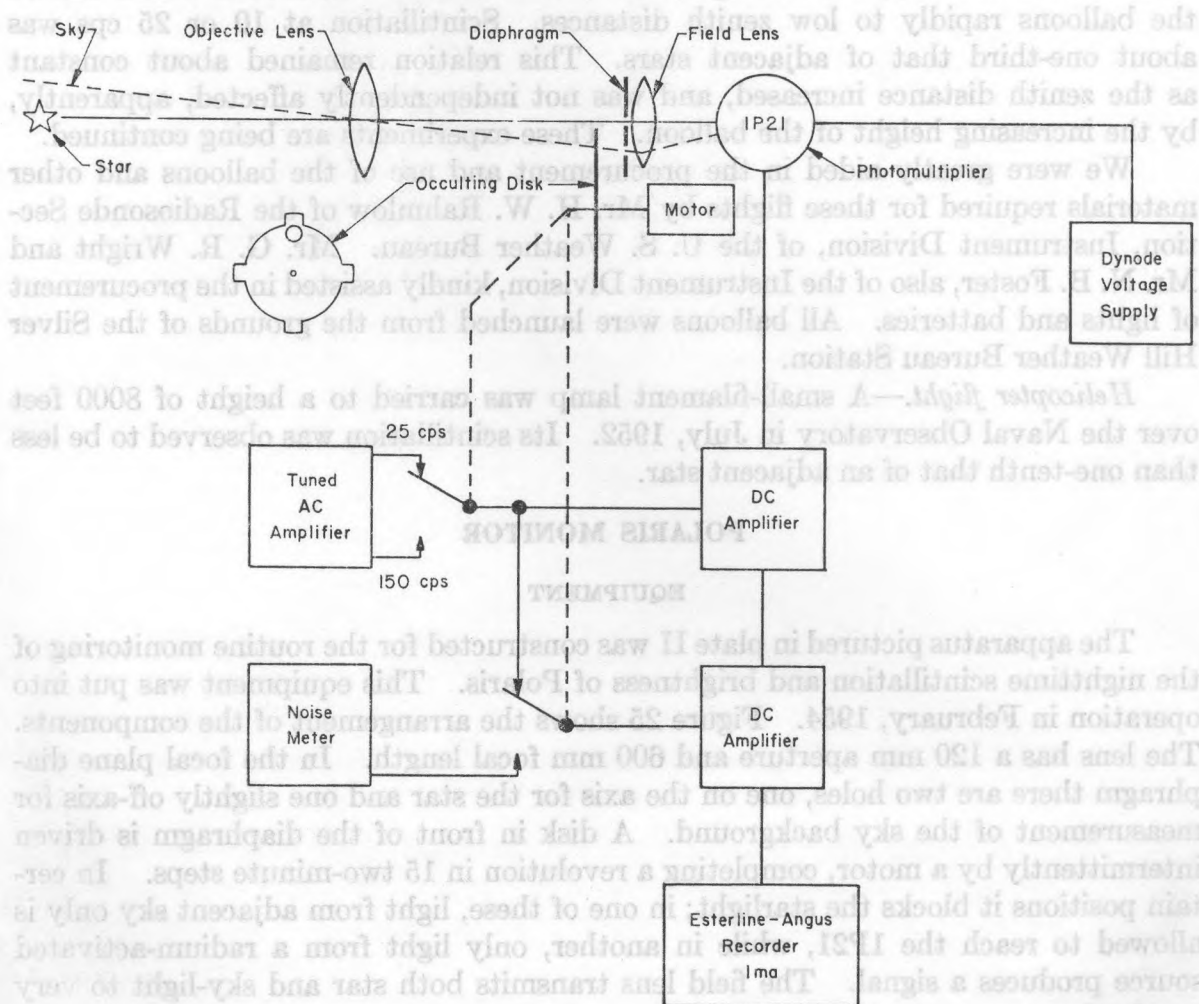


FIGURE 25.—Components of the Polaris Monitor.

OBSERVATIONS

The list of 2-minute observations made at present during one 30-minute cycle is as follows:

- (1) Brightness of radium-activated source,
- (2) Amplitude of scintillation at 25 cps,
- (3) Amplitude of scintillation at 150 cps,
- (4) Brightness of Polaris,
- (5) Amplitude of scintillation at 25 cps,
- (6) Amplitude of scintillation at 150 cps,
- (7) Dark current reading of dc channel,
- (8) Brightness of sky,
- (9) Amplitude of scintillation at 25 cps,
- (10) Amplitude of scintillation at 150 cps,
- (11) Dark current reading of ac channel,
- (12) Brightness of Polaris,
- (13) Amplitude of scintillation at 25 cps,
- (14) Amplitude of scintillation at 150 cps,
- (15) Dark current reading of dc channel.

The amplitudes of scintillation can be normalized with respect to the star brightness to provide indications of relative scintillation. Calibrations similar to those already described in connection with the general equipment may be used to reduce the measurements to equivalent sine-wave modulation whenever this is desired. The monitors have been adjusted to have about equal deflections at 25 and 150 cps on average nights.

PRELIMINARY RESULTS

Comparison with wind.—In figure 26 the maximum speed of the winds aloft is compared for each night at Washington with the relative scintillation at both 25 and 150 cps. The only data used were the scintillation measures recorded between 9:30 and 10:30 pm EST, and rawinsonde results from the balloon flight launched at that time from Silver Hill, Maryland. Correlation is evident at 150 cps but absent at 25 cps. Correlations shown in figure 27, where the wind speed is that at 13 km only, resemble those in figure 26. These results agree with previous conclusions based upon data obtained from stars near the zenith.

Comparison with seeing.—Figure 28 shows the scintillation compared with contemporaneous visual seeing measurements of Polaris made at a power of 650 diameters with a 4-inch telescope. The seeing criteria were the same as those discussed earlier: definition or size of image, speed of image motion, and extent of image motion, summarized into a scale of 1 to 5. Only a few minutes were involved in each seeing observation; the scintillation data were the same as used in figure 26. Both the scintillation monitor and seeing telescope were within four feet of the ground. However, while the scintillation observations were made automatically

at the Naval Observatory, the seeing was observed from a suburban location four miles northwest of the Observatory. The correlations are stronger than those described earlier that related to the observations of zenith stars for which seeing and scintillation were viewed from the same site. These data indicate that some factor at high levels affects both scintillation and seeing.

Only a small part of the available data has thus far been analyzed. A more complete report will be made at a later date.

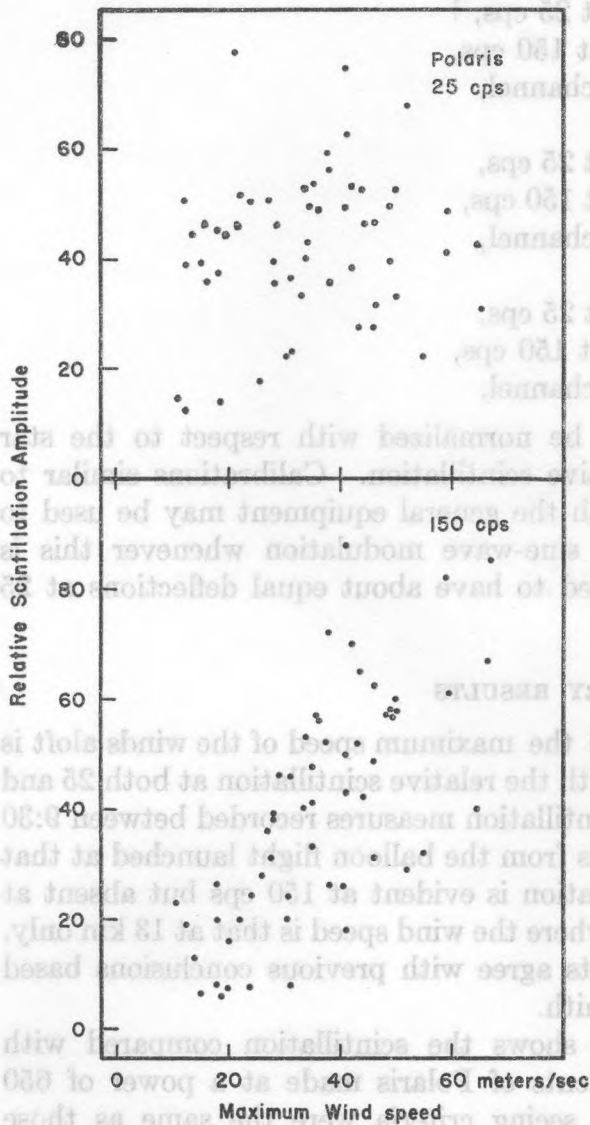


FIGURE 26.—Scintillation of Polaris and maximum wind speed. Wind speeds were observed to altitudes of at least 10 km on each night. Data are from June 4 to September 29, 1954.

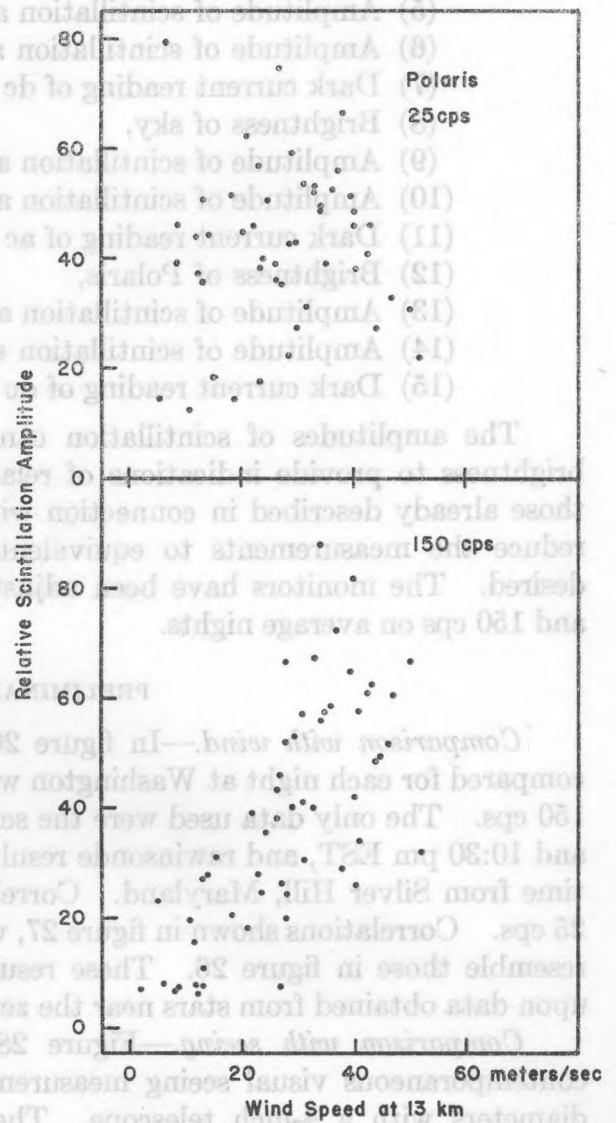


FIGURE 27.—Scintillation of Polaris and the wind speed at 13 km for the same dates.

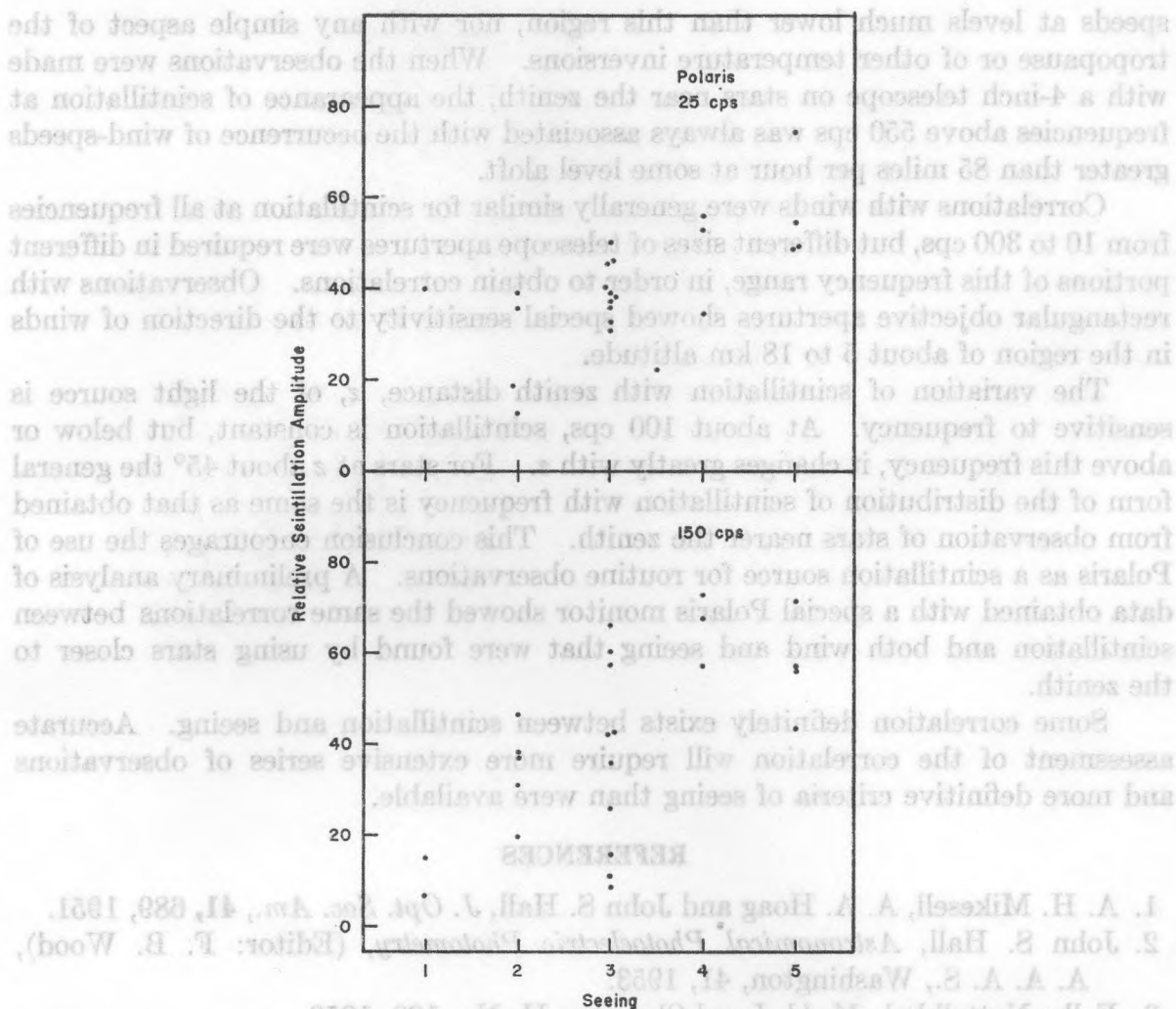


FIGURE 28.—Scintillation and seeing with Polaris as a source. Observations were contemporaneous but made with equipment four miles apart. The period of observation was the same as for figure 26.

SUMMARY OF THE RESULTS

In the preceding discussion of scintillation data obtained at the Naval Observatory the following conclusions were evident:

Harmonic components of scintillation decrease with frequency roughly uniformly from 0.1 cps to about 500 cps. Concurrent observations made with the telescopes of different sizes produce different distributions of scintillation with frequency. A small-aperture distribution is often relatively flat below about 40 cps, while a large-aperture distribution is lost at high frequencies, above about 150 cps. At approximately 40 cps the scintillation amplitude varies inversely with the diameter of the telescope objective, within the size range of 4 to 15 inches.

Scintillation is correlated with the maximum speed of winds aloft, especially with winds in the region from 8 to 16 km high. It is not well correlated with wind-

speeds at levels much lower than this region, nor with any simple aspect of the tropopause or of other temperature inversions. When the observations were made with a 4-inch telescope on stars near the zenith, the appearance of scintillation at frequencies above 550 cps was always associated with the occurrence of wind-speeds greater than 85 miles per hour at some level aloft.

Correlations with winds were generally similar for scintillation at all frequencies from 10 to 300 cps, but different sizes of telescope apertures were required in different portions of this frequency range, in order to obtain correlations. Observations with rectangular objective apertures showed special sensitivity to the direction of winds in the region of about 5 to 18 km altitude.

The variation of scintillation with zenith distance, z , of the light source is sensitive to frequency. At about 100 cps, scintillation is constant, but below or above this frequency, it changes greatly with z . For stars at z about 45° the general form of the distribution of scintillation with frequency is the same as that obtained from observation of stars nearer the zenith. This conclusion encourages the use of Polaris as a scintillation source for routine observations. A preliminary analysis of data obtained with a special Polaris monitor showed the same correlations between scintillation and both wind and seeing that were found by using stars closer to the zenith.

Some correlation definitely exists between scintillation and seeing. Accurate assessment of the correlation will require more extensive series of observations and more definitive criteria of seeing than were available.

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