X-626-71-189
PREPRINT

NASA TM X- 65545

THE SHADOW BAND PHENOMENON

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MAY 1971

GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Shadow bands are a phenomenon observed during eclipses of the sun and visible only in the minutes immediately preceeding and following totality. Prior to the solar eclipse of March 7, 1970, these bands had never been recorded by an experimental apparatus, accurately measured nor well analyzed. Data were gathered at the site established at Wallops Station, Virginia, in two ways: (1) Recording onto magnetic tape of the output from six collimated photocells whose spectral responses ranged from the ultraviolet to the infrared; (2) visual and mechanical measurement of the orientation and motion of the bands. The recorded data were later processed using the output from a frequency spectrum analyzer. The majority of the energy of the shadow bands ranges between 1 and 25 hz, and appears not unlike plots of scintillation spectra. The onset, amplitude, and duration of the shadow bands seem to be spectrally related to the limb darkening of the sun's photosphere. Other results of the experiment conclusively indicate that the shadow band phenomenon is a manifestation of atmospheric turbulence in the form of air packets of different density from that of their environment (density schlieren), made visible by the light from the crescent sun.

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THE SHADOW BAND PHENOMENON

BACKGROUND

Shadow bands are a phenomenon observed during eclipses of the sun and visible only in the minutes immediately preceding and following totality. In these moments bands of shadows parallel to each other but of different widths and moving at different speeds appear covering every ground surface. Due to their short duration, motion, low contrast ratio, and the relative rarity of observable total solar eclipses, shadow bands had never previously been successfully recorded by an experimental apparatus, accurately measured, or well analyzed.

Pickering, describing the eclipse of 1878 (1), was the first to attribute the nature of the shadow bands to our own atmosphere and not to the edge of the moon. Later, somewhat more than forty years ago, it was postulated that the shadow effect was due to air striae moving with the wind (2). Other publications at the time, however, claimed that there was absolutely no correlation with the wind (3) and even recently, there had been considerable debate as to whether the effect was atmospheric at all or whether it was due to single slit diffraction (4).

To better understand the phenomenon, a site was established at Wallops Station, Virginia, (Figure I), on March 7, 1970 to record and measure any shadow banding that might occur during the solar eclipse predicted for that location (see Table 1). This particular site was chosen because it lay just outside the area of totality providing for uninterrupted observation of the bands.

THE EXPERIMENT

The data used in the analysis of the shadow bands were gathered in two ways:

1. Photoelectric detection. The sensors consisted of six collimated photocells with spectral responses (see Figure II) as follows: Cells I, II, III had peak responses in the green-yellow portion of the spectrum; Cell IV in the blue; Cell V in the ultraviolet; and Cell VI in the infrared. In addition, Cells II and III had plane polarizing filters 90° out of phase with each other. The output from each photocell was amplified and then used to frequency modulate a carrier; the information from each cell was recorded with time and voice onto magnetic tape. These recorded signals were later processed at Goddard Space Flight Center using a frequency spectrum analyzer to:

    (a) produce, on film, a time-frequency-amplitude plot of the light modulation from each photocell.

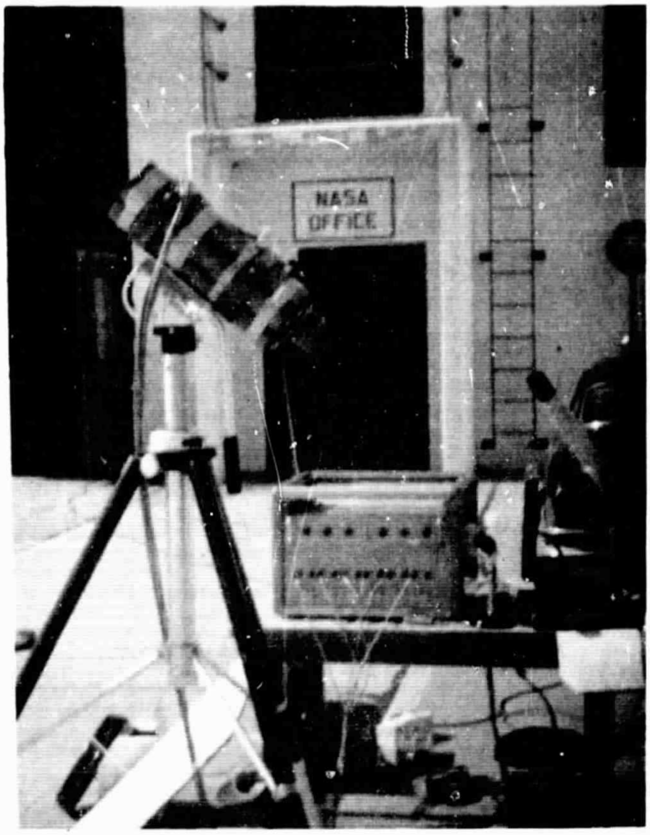


Figure 1. Shadow Band Apparatus on Site at Wallops Station, Virginia

(b) produce, on digital magnetic tape in 50 ms increments, the power amplitudes of the frequencies from 1-26 hz in steps of 1 hz.

2. Visual and mechanical measurement. The motion and orientation of the shadow bands were measured as they moved across two white surfaces, one of which was aligned normal to the sun line.

All information was correlated with data returned from a rawinsonde launched from Wallops Island at 1630 z, approximately two hours before maximum eclipse. Since an eclipse of the sun normally causes a corresponding decrease in temperature and change in wind velocity, exact correlations were not possible.

RESULTS

A. The orientation of the shadow bands is tangent to the non-eclipsed crescent of the sun, the direction changing in direct relation to the change in the

Table I

GMT			SOLAR OBSCURATION (%)		NEAREST UMBRA (km)
HR	MN	SEC	Diameter	Area	
18	32	52	94.98	94.56	168.54
18	33	52	96.24	96.12	126.09
18	34	52	97.47	97.59	84.87
18	35	52	98.62	98.88	46.31
18	36	52	99.57	99.77	14.51
* 18	37	52	99.985	99.998	0.507
18	38	52	99.56	99.77	14.61
18	39	52	98.61	98.87	46.58
18	40	52	97.46	97.57	85.37
18	41	52	96.22	96.09	126.89

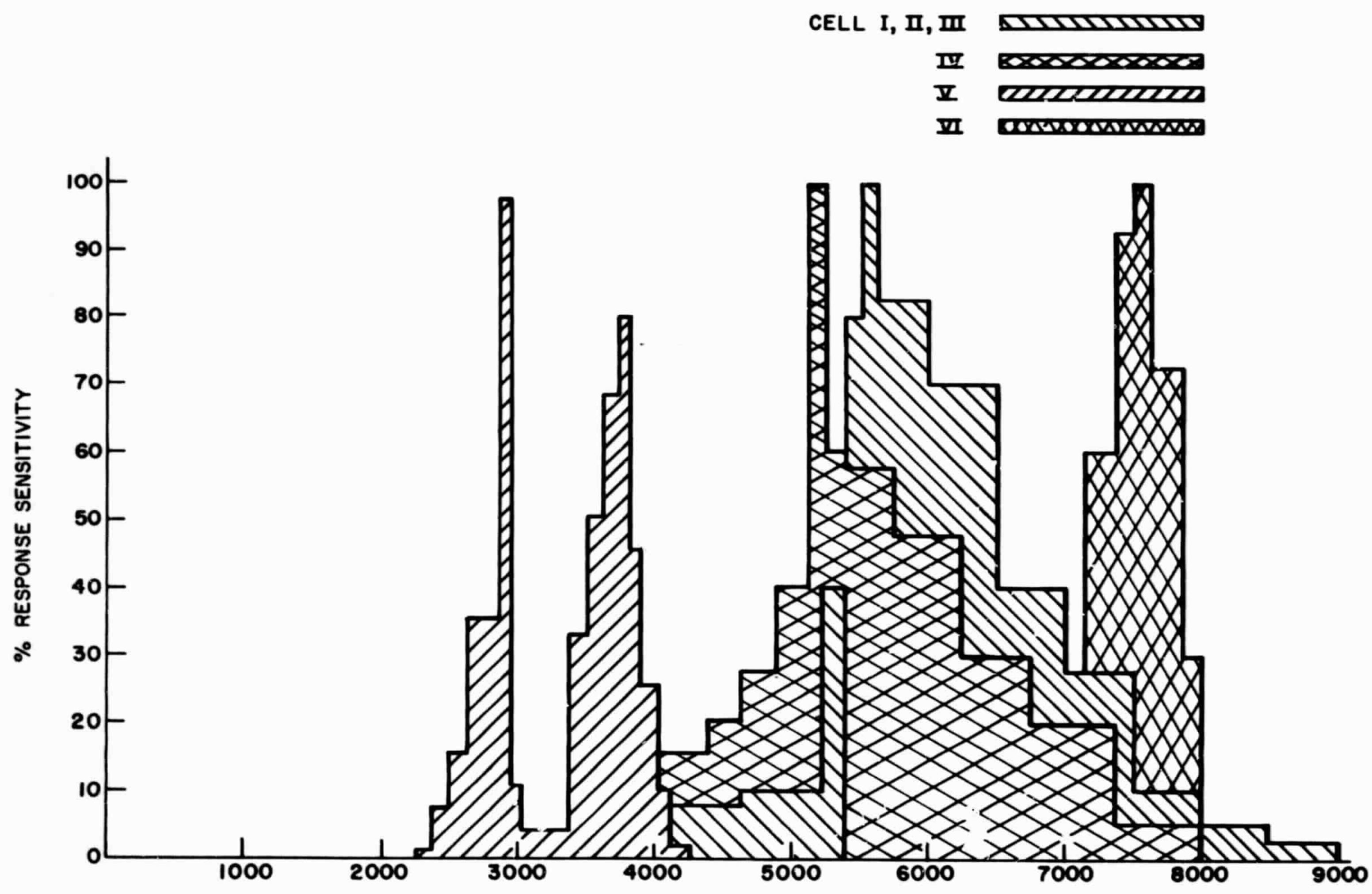
* Maximum eclipse

Site location:

Ø = 37° 55' 43'' N

λ = 75° 28' 29'' W

H = 0



λ (ANGSTROMS)

Figure II. Spectral Response of Photocells orientation of the crescent. With respect to the location of the experiment at Wallops Station, between the times of 1836 z and 1839 z the crescent of the sun rotated from an initial angle of 12° (measured from celestial north) to an angle of 283° . . . a rotation of almost 90°. This corresponded to the measured rotation of the bands through the same angle.

B. While the orientation of the shadow bands could be measured to a reasonable accuracy, the direction of travel of the bands could not. The most that can be said with certainty is that they moved from west to east. The winds aloft as measured from a rawinsonde show the winds at all altitudes to 134,000 feet to be out of the west (Figure III).

C. Two distinct types of shadow bands quite different in width, separation, and velocity were simultaneously visible at the site:

(1) Width of bands: 1 foot; distance between bands: 6 feet; velocity as projected onto the viewing plane: 50 feet/second.

(2) Width of bands: 1.5 inches; distance between bands: 3 inches; velocity as projected onto the viewing plane: 10 feet/second.

Of these two types which were readily distinguishable, the former was the more intense, beginning earlier and lasting longer than the latter.

D. Recorded frequencies range from 1-50 hz with the higher frequencies beginning later and terminating earlier than the lower frequency components. (See Figures IV - VII).

Plots of the power spectrum of the data (Figure VIII), i.e. relative power amplitude vs. frequency, show that the majority of the energy is concentrated in the lower frequencies and appears not unlike plots of scintillation spectra (5).

ANALYSIS AND CONCLUSIONS

The onset, amplitude, and duration of the shadow bands seem to be spectrally related to the limb darkening of the sun's photosphere. The shorter the wave length, the sooner the bands appear and the longer they last. (Figure IX). In the cases of both the blue and the UV cells, maximum banding occurred on both sides of maximum eclipse (18:37:52 z). At maximum eclipse both these cells experienced a cut-off with the dead time for the UV cell lasting for twice that of the blue cell. The duration of the shadow bands as seen by the green-yellow photocells was somewhat in excess of four minutes, while that recorded by the blue and UV cells exceeded seven minutes. No bands were detected by the IR cell.

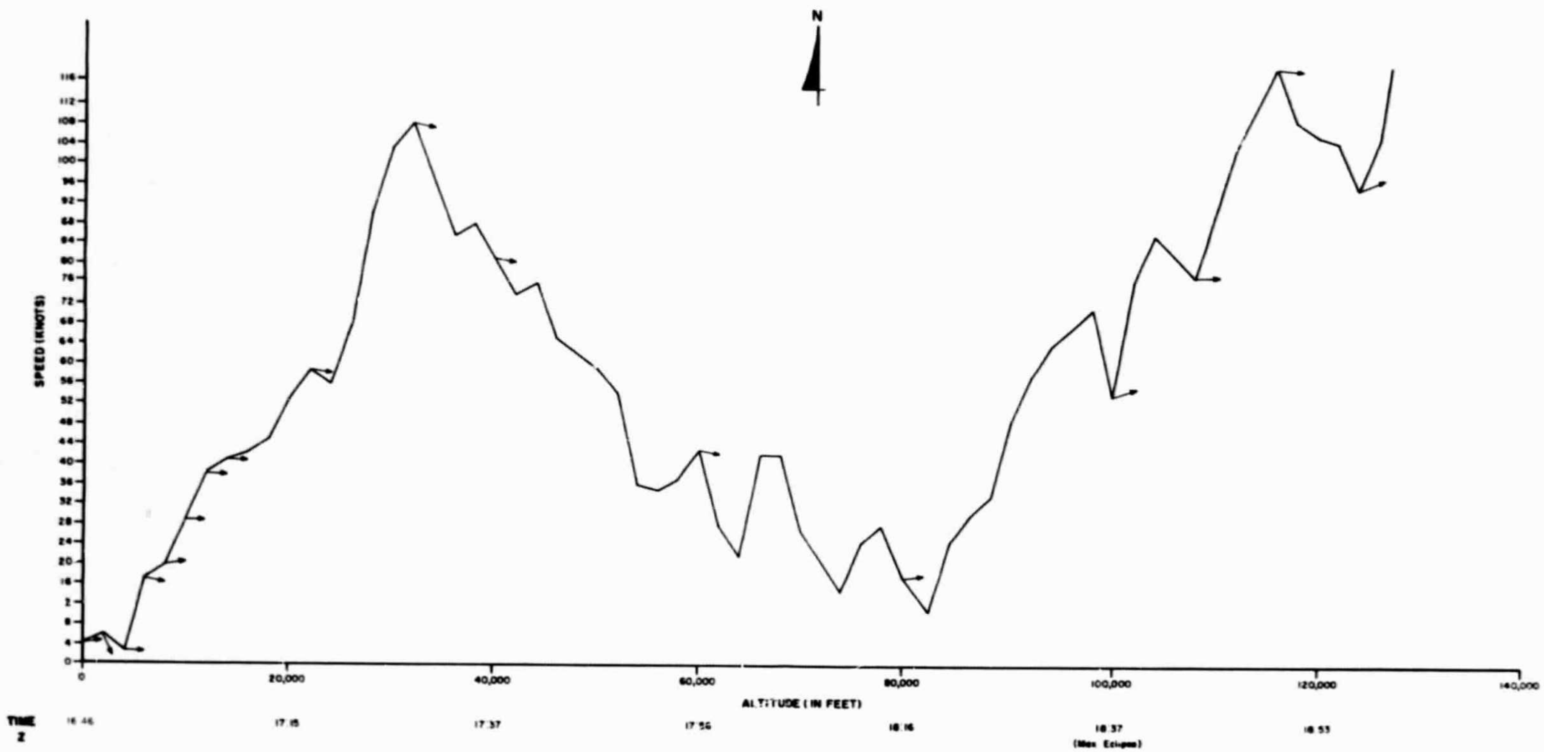


Figure III. Wind Profile as Measured from Rawinsonde

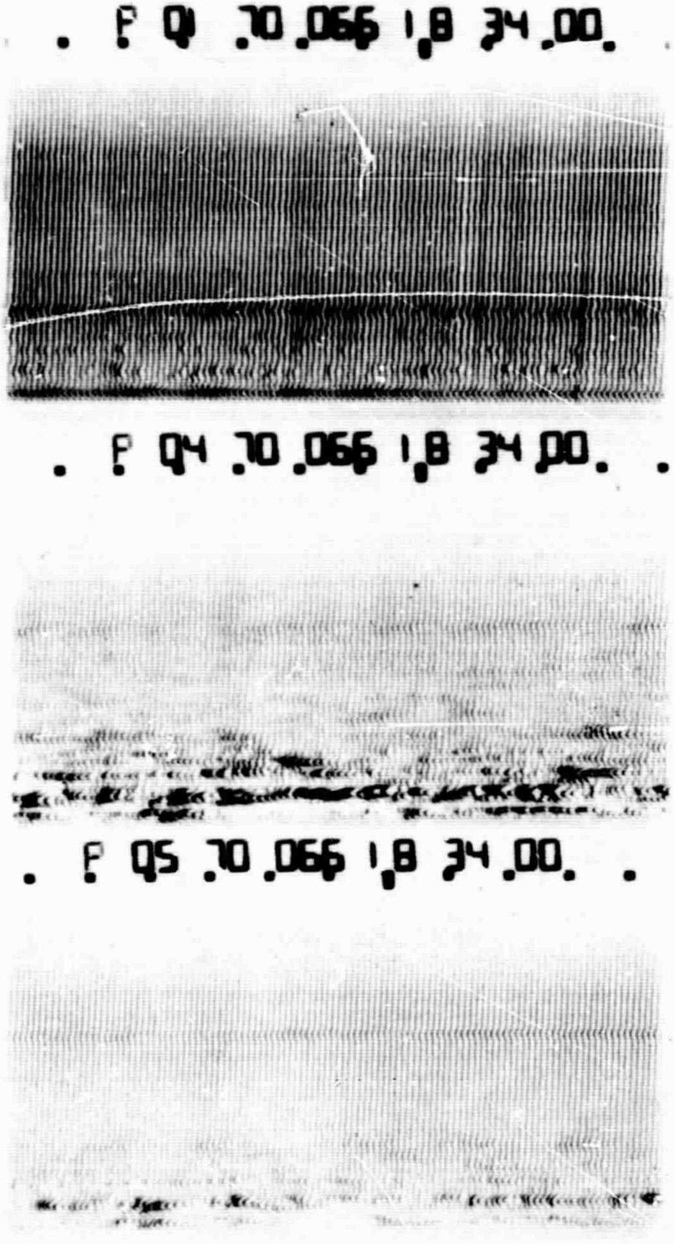


Figure IV. Top to bottom: Plots of time-frequency-amplitude for Channels I, IV, and V respectively. Time is 1834z, almost four minutes prior to maximum eclipse. Frequency range is 0 - 50 hz (bottom to top). Time is advancing from left to right, each marker representing 1 second. Channel I is quiescent, while Channels IV and V are detecting low frequency bands.

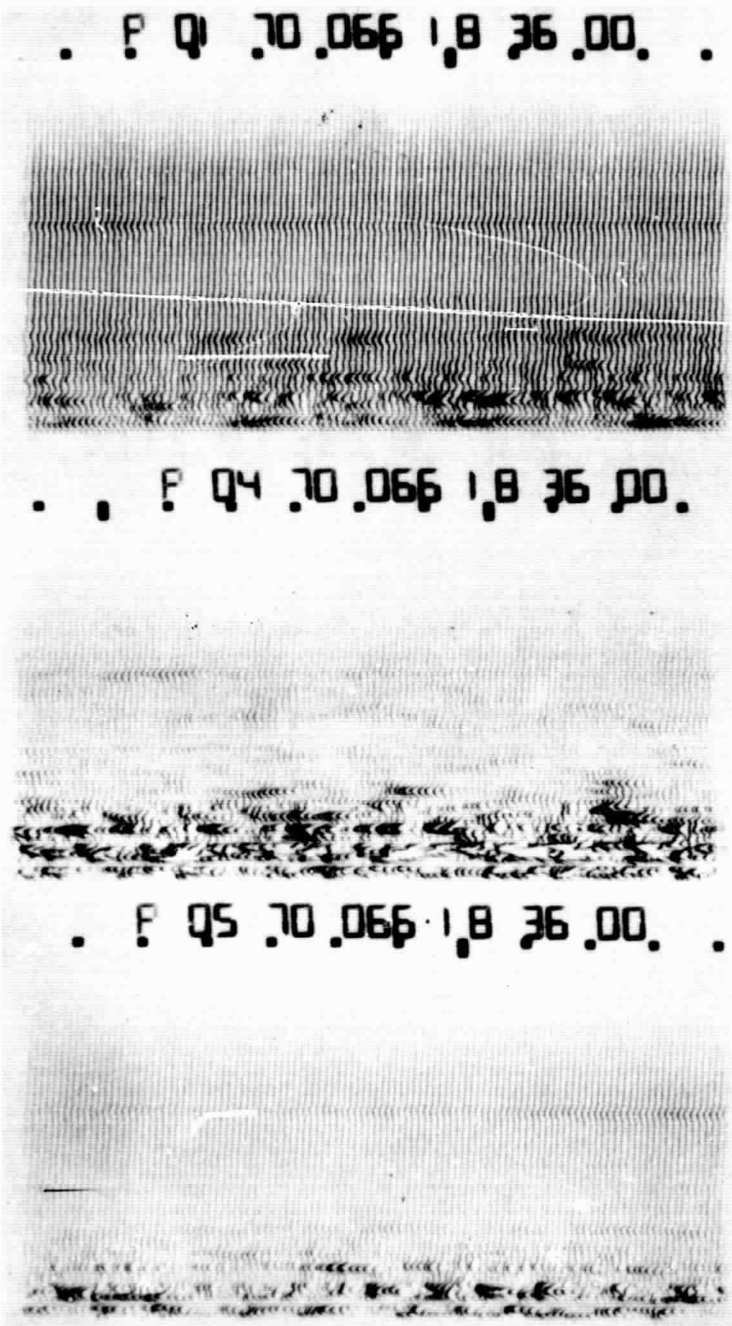


Figure V. Time is 1836z, approximately two minutes prior to maximum eclipse. Channel I is beginning to detect low frequency bands; Channels IV and V remain active.

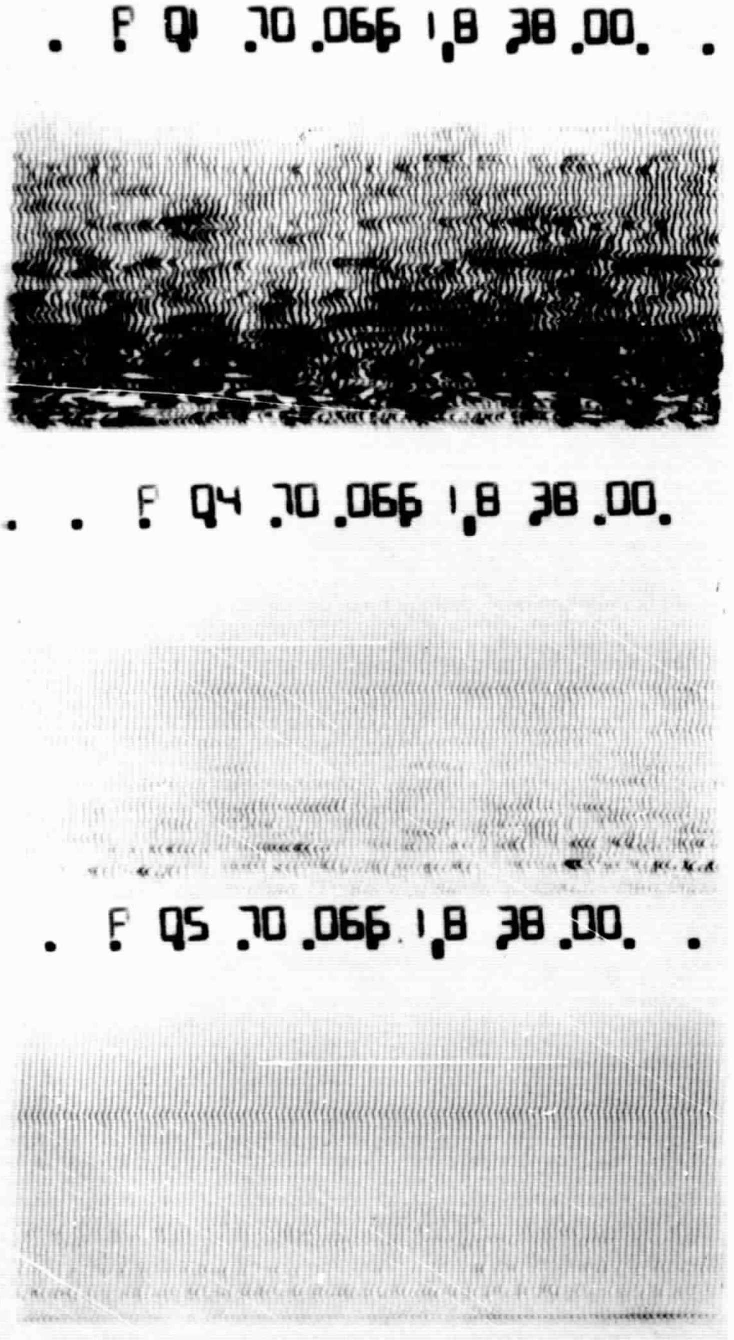


Figure VI. Time is 1838z, a few seconds after maximum eclipse. Channel I is very active and detecting strong bands; Channel IV is just beginning to react after experiencing a cut-off; Channel V is quiescent.

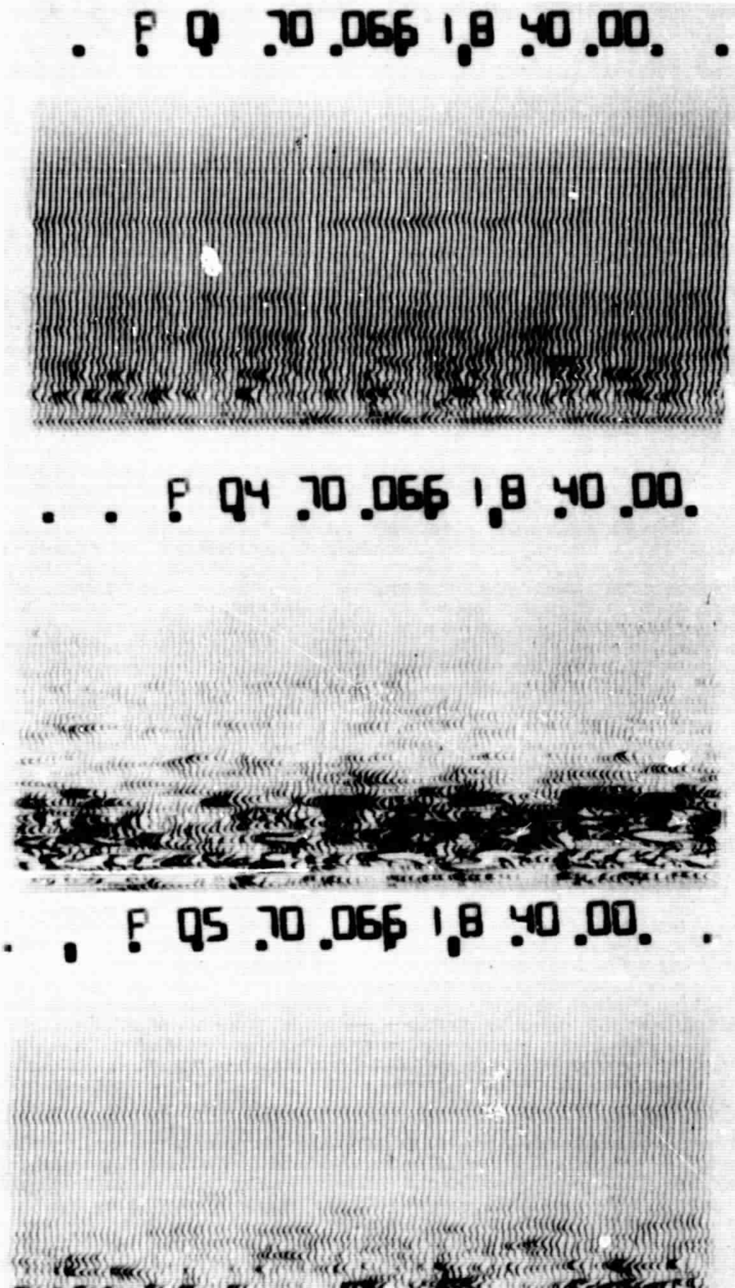


Figure VII. Time is 1840z. Channel I is becoming quiet; Channels IV and V are detecting strong bands.

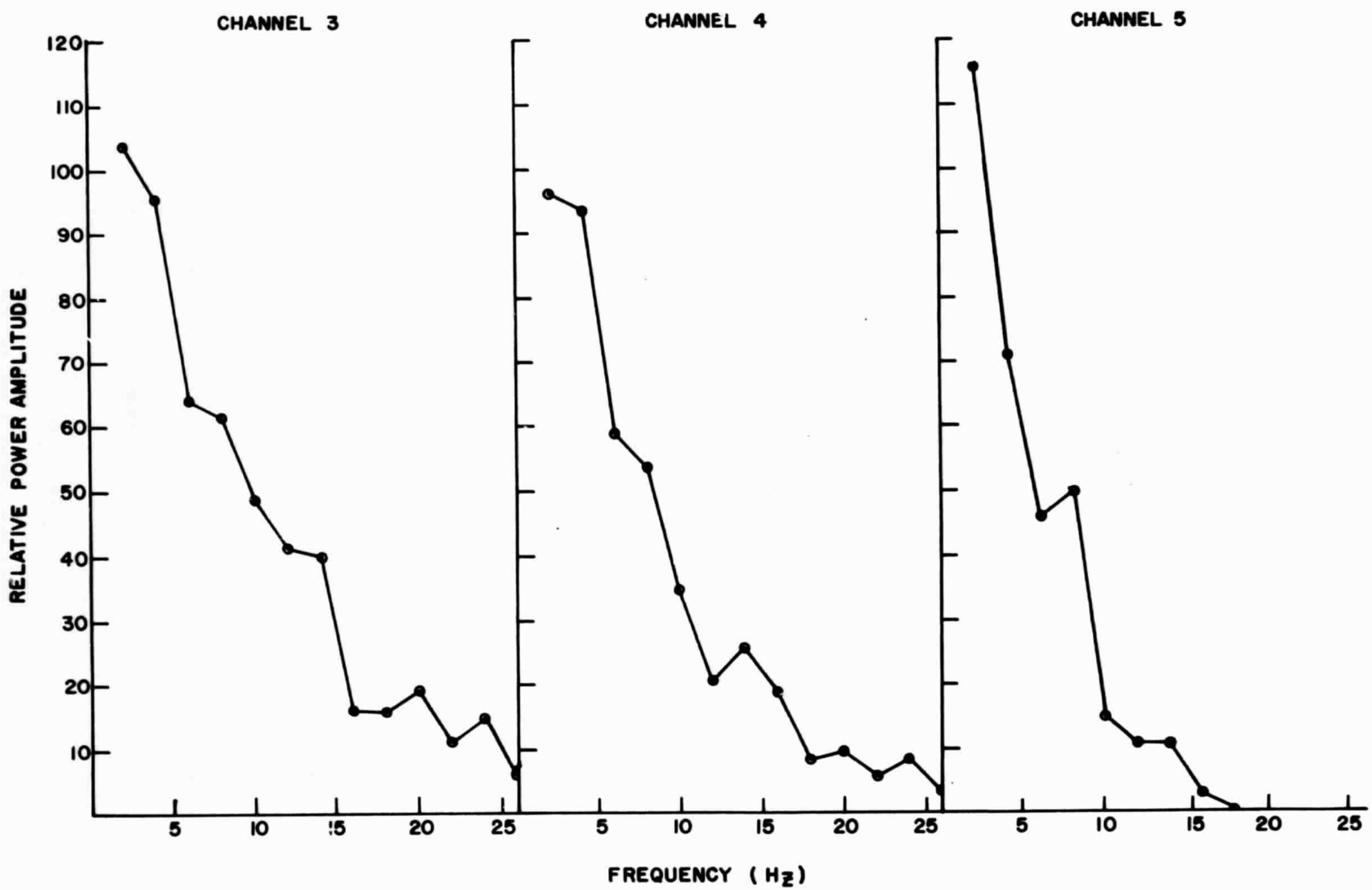


Figure VIII. Power Spectra of Shadow Bands from Channels III, IV, and V

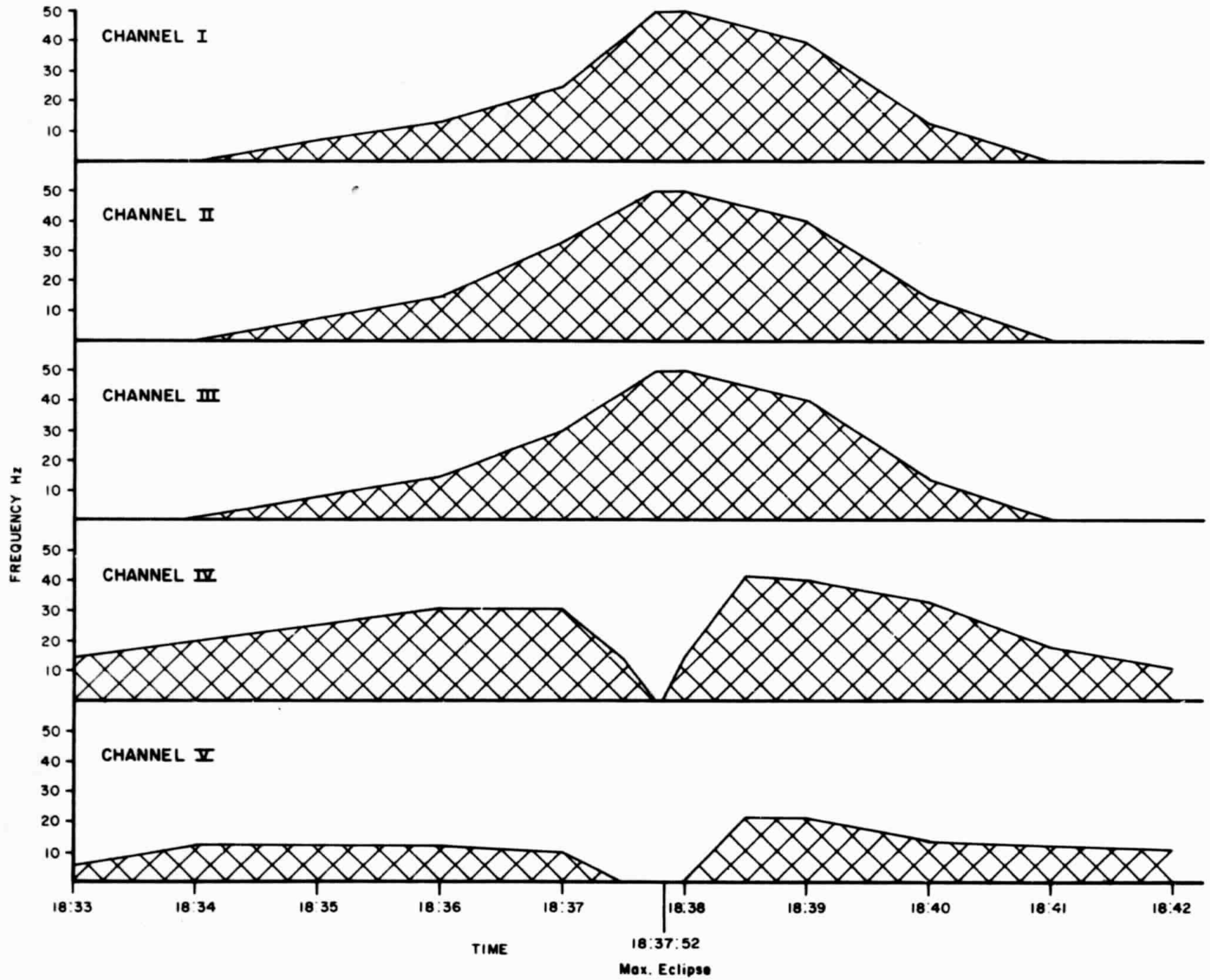


Figure IX. Frequency vs Time for Channels I, II, III, IV, V, VI

The fact that there exist individual bands that move independently of each other nullifies the theory of single slit diffraction.

Calculations based upon the effective width of the crescent sun at 99.5% eclipse, the point at which the first bands became both visible and measurable, reveal that those shadow bands separated by 3 inches could be generated at altitudes no greater than 500 feet; those shadow bands separated by six feet could be generated at altitudes no greater than 12,000 feet. This is arrived at in the following manner. Ref. Figure X a.

$$m = 2(1-\text{magnitude})$$

$$x^2 + y^2 = 1^2 \qquad \frac{r\ \text{moon}}{r\ \text{sun}} = 1.038$$

$$(x + .038 + m)^2 + y^2 = (1.038)^2$$

$$1 - x = \frac{m^2}{2(.038 + m)} + \frac{(1.038)\ (m)}{.038 + m}$$

at visible onset of bands @ 99.5% eclipse

$$m = 2(1-.995)$$

$$m = .01 \text{ and } 1 - x = .2173 \text{ (radius)}$$

or .1086 (diameter).

Assuming effective light is from 50% of the crescent, then: (Ref. Figure X b)

$$\frac{.054}{100} = \frac{\text{distance between bands}}{h}$$

Bands generated at higher altitudes would be unresolvable.

The wind speeds as determined from the rawinsonde at these altitudes are in basic agreement with the measured speeds of the shadow bands.

The differences in visibility and intensity of the shadow bands is readily explainable: As the sun's crescent diminishes in size, it approaches a linear source which lessens the smearing effect upon the shadows. More bands separated by shorter distances, which were not previously distinguishable became narrower and more intense.

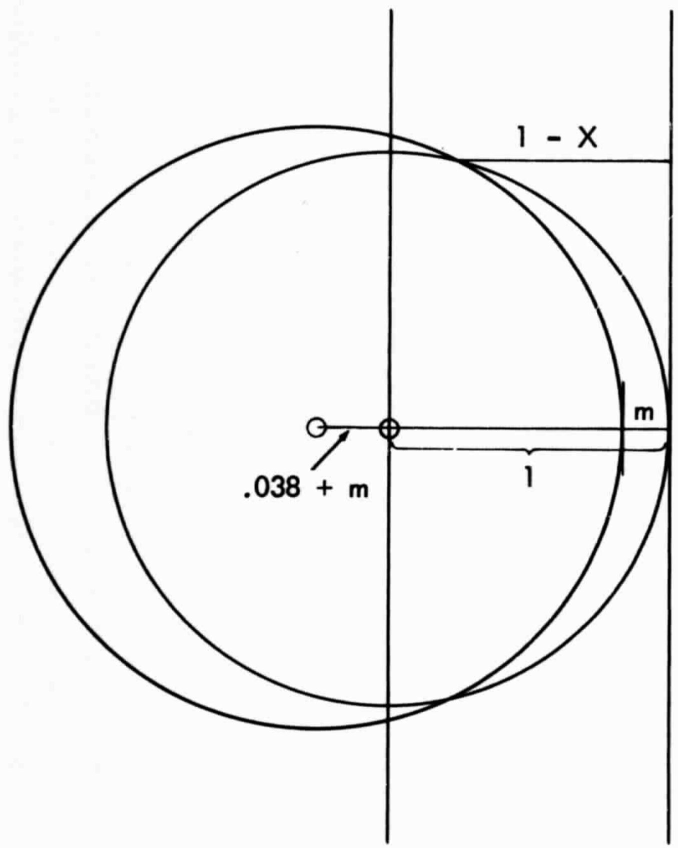
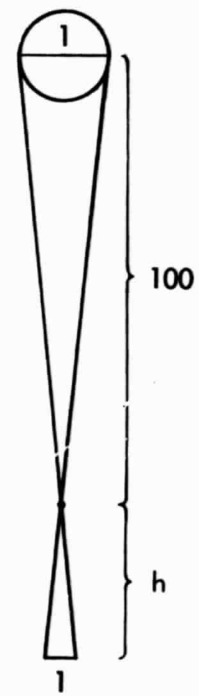


Figure Xa. Relationship of Moon to Sun



DIAMETER OF SUN 866,000 mi
1 AU 92,900,000 OR ≈ 1/100

Figure Xb. Relationship of Diameter of Sun to Separation and Height of Shadow Bands

Kolmogoroff, in 1941, developed the similarity theory of locally isotropic turbulence (6). Stated in terms of spectral energy density F, viscous dissipation ϵ, and wave number (frequency) k

$$F \sim \epsilon^{2/3} \quad k^{-5/3}$$

otherwise termed the -'5/3 power law'. (7, 8). There is general agreement that the low frequency ranges contain the bulk of the energy, while the viscous dissipation is negligible (9). Thus, the log of the energy is directly proportional to -5/3 the log of the frequency. If we were now to replot the shadow band spectra (presented in Figure VIII) onto a log/log grid, we find that the -5/3 power law does indeed fit the general shape of the data (Figure XI).

The results of the experiment conclusively indicate that the shadow band phenomenon is a manifestation of atmospheric turbulence, in the form of air pockets of different density from that of their environment (density schlieren), made visible by the light from the crescent sun. Light passing through these areas of abnormal density gradient is refracted, and, dependent upon the size, spacing, altitude, and density of the packets, forms distinct patterns of alternating shadow and brightness upon the ground. The schlieren appear to move through the air in waves and have a horizontal velocity component similar to that of the wind. Good qualitative measurements of either the direction or speed of motion of the packets, however, is hampered in that the incident illumination is from an elongated source, causing all shadows which are formed to be aligned parallel to the orientation of the source. Only the projection of that component of motion at right angles to the direction in which the shadow bands are orientated can be measured.

SUMMARY

The purpose of this experiment, as designed and conducted, was to produce a better understanding of an unusual phenomenon associated with an eclipse of the sun. This was accomplished with some degree of success, and the level of knowledge concerning shadow bands was raised one step. A total solar eclipse can be regarded as a unique opportunity for the unaided observation of anomalies in atmospheric density. These anomalies could indicate turbulence due to thermal discontinuities, wind layers, billows as well as a host of other atmospheric conditions. Further investigations will be able to use this information as input and perhaps raise the baseline of knowledge concerning turbulence one step.

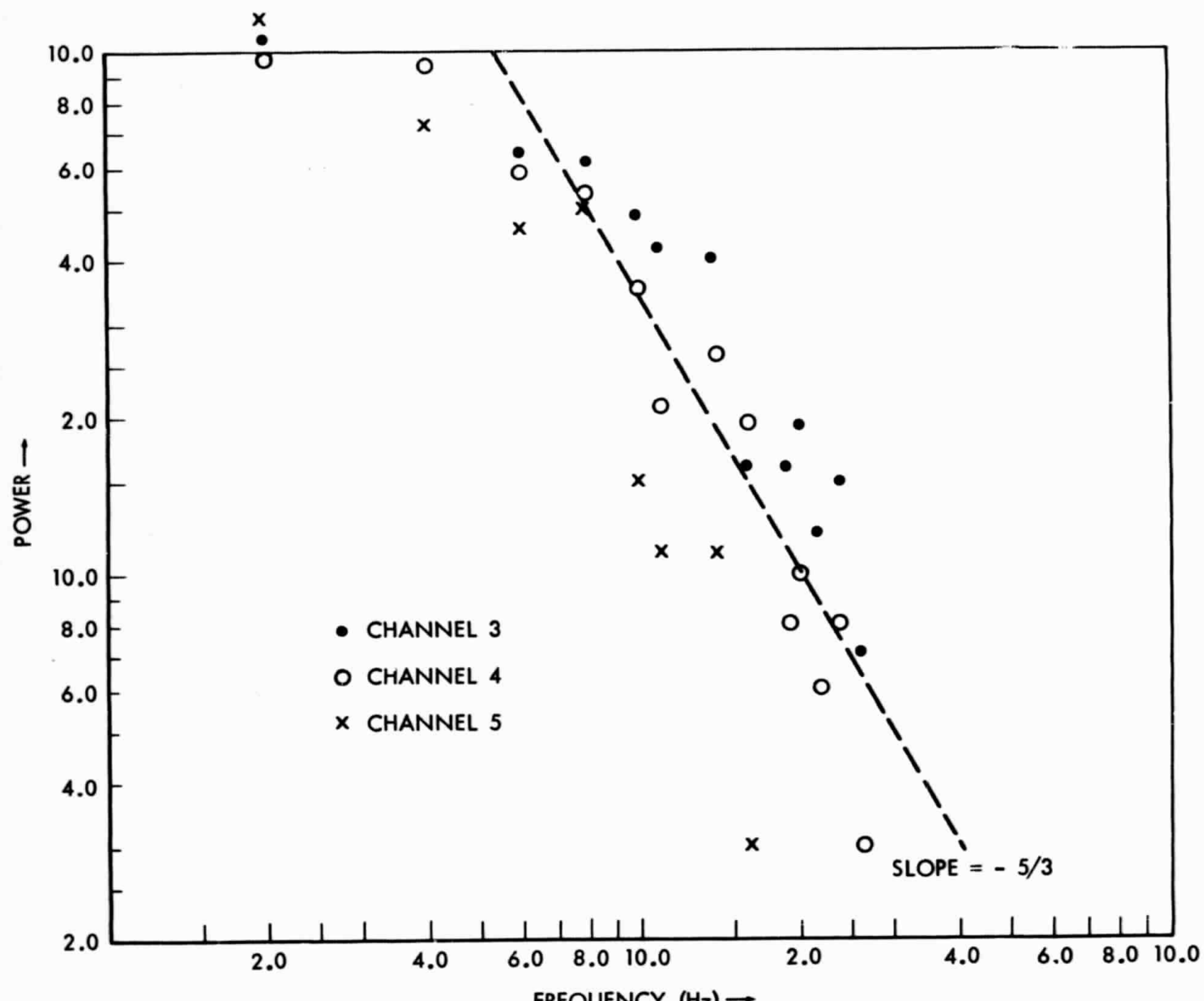


Figure XI. Log/Log Plot of Power vs Frequency Demonstrating Fit to -5/3 Power Law

ACKNOWLEDGEMENTS

The authors would like to thank A. Gault, P. Rickard, F. Wulff and C. Harvey of Goddard Space Flight Center and A. Young of Jet Propulsion Laboratory for their excellent assistance in the shadow band experiment.

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