Observations of shadow bands at the total solar eclipse of 16 February 1980

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Photoelectric observations of short term light variations (shadow bands) at the 16 Feb. 1980 total solar eclipse have been made using a set of spatially separated PIN diodes. Light variations in a bandpass of 1–500 Hz were detected during the half-minutes preceding and following the total phase. Fourier analysis of the noise spectrum of the variations reveals a sharp drop-off for frequencies above 50 Hz and an overall spectrum quite similar to previously reported power spectra of stellar scintillation. This is consistent with an atmospheric origin for the shadow bands. Cross-correlations between the detector outputs are low, suggesting a short persistence time for the turbulent elements causing the patterns.

I. Background

Undulating patterns of ground illumination, resembling shimmering ripples or bands of light, are frequently observed in the minute or two just before or after totality at a solar eclipse. Although they can be easily distinguished by the naked eye, which perceives moving patterns as enhanced against a stationary background, they are features of intrinsically low contrast (only a few percent of the ambient background in our measurements) and can be detected quantitatively only with great difficulty. Most attempts to make such measurements in the past have failed to record signals at all against the background of solar light and instrumental noise. As a consequence, there are few reliable reports of such observable characteristics as the temporal and spatial frequency distribution of the patterns, the persistence of individual features in the patterns, and the speed of their motion, if any.

The paucity of hard data has in turn led to the proliferation of exotic proposals to explain the shadow-band phenomenon. In the simplest picture, the formation of shadow bands involves the focusing and defocusing of light rays from the narrow crescent of the uneclipsed sun by the turbulent density fluctuations in the earth's atmosphere.[1–3] As such, the shadow band pattern may be regarded as similar to the mottled light pattern observed across the objectives of telescopes when they are illuminated by bright stars.[4,5] These patterns are linked to the phenomenon of stellar scintillation (twinkling); hence the theory of stellar scintillation[6] should also apply to the shadow bands, with the primary difference being that the illuminating source is a point source for stellar scintillation and crescent-shaped for the shadow bands. (It should be noted that the irregularities in the moon's limb may play a role in determining the visibility of development of the bands, also that the shadow bands have been reported at annular eclipses of the sun.[7,8] So the assumption of a crescent source is an approximation at best.)

While this simple atmospheric model of shadow band formation seems quite adequate for explaining the qualitative phenomena, three alternate hypotheses persist. The earliest observers appear to have accounted for them as interference patterns similar to the Fraunhofer patterns produced by a sharp edge when illuminated by a point source.[9] The interference theory has been revived from time to time (most recently by Burgess and Hults[10]), but the speed and spacing of the observed patterns are clearly not in accord with the pattern produced by diffraction at the moon's edge, even were the sun a point source of light.[11] Horn-D'Arturo[7] suggested that the bands were formed by transparency fluctuations, but the observed motions of the shadow bands seem to favor the simpler density fluctuation model. A third alternative, proposed by Stanford[12] and Feldman,[13] invoked a Lloyd's mirror effect; interference was produced by direct rays from the sun and indirect rays bounced off clouds or a hypothetical reflecting layer in the atmosphere. Clearly this model suggests a rather contrived and fortuitous set of circumstances. The shadow bands themselves have been observed under a wide variety of meteorological conditions, often under cloudless skies.

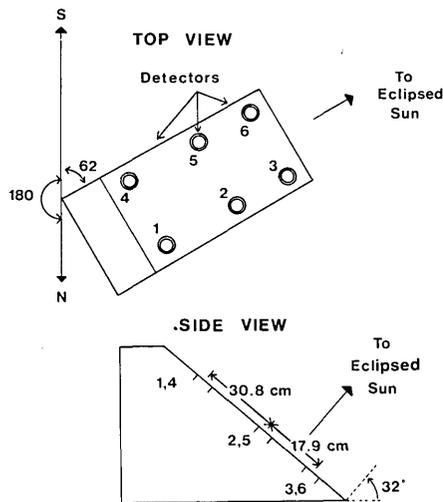Nevertheless the matching of quantitative models,

Fig. 1. Orientation and spacing of the PIN diode detectors used to make observations of the shadow bands at the total solar eclipse of 16 Feb. 1980. Only detectors 2, 4, 5, and 6 were operational.

following Young's methods, with quantitative observations is essential before the matter can be set to rest. The most successful of these observations have been photoelectric.[14-16] In all three of these reports, a frequency analysis of the observed shadow band pattern was carried out.

Of the three sets of photoelectric data, the Quann and Daly[14] observations at the Mar. 1970 eclipse are the most extensive, enabling a comparison of the observed power spectrum with similar power spectra of stellar scintillation in the 1–20-Hz range. Their results showed a general pattern that is similar to the scintillation spectra over the limited range studied. Our study reported here presents observations made at the Feb. 1980 solar eclipse. The experiment was designed to investigate the power spectrum of the shadow fluctuations over a wider bandpass and at several spatially separated locations.

II. Observations

Measurement of the shadow bands was carried out at the Japal-Rangapur Observatory, 45 km southwest of Hyderabad, India, at the total solar eclipse of 16 Feb. 1980. The detectors consisted of a set of six Bendix 33605-1 PIN diodes arranged in a rectangular array on an inclined surface as shown in Fig. 1. The surface was oriented so that the surface holding the detectors would be perpendicular to the line of sight to the eclipsed sun. Previous observations[17] suggested that the elongation of the shadow bands would be tangent to the moon's shadow and thus that the bands would be aligned with the short side of the array prior to totality. This orientation would thus simplify the analysis of the detector output to determine band motion. Visual observations of the shadow bands before totality indicated an elongation approximately parallel to the short side of the array, as expected. After totality the elongation of the bands lay roughly along the long axis of the array.

The collecting area of each diode was 1 cm in diameter, and the diodes were sensitive over the entire visible spectrum. Unlike Quann and Daly, no colored filters were used to determine wavelength dependence of the pattern contrast. Neutral density filters, however, were employed in the early stages of the eclipse to prevent saturation; the filters were removed several minutes before totality.

Detector output was amplified and recorded on an Ampex FRS-1300 multitrack tape system running at 15 ips. At this speed the frequency response of the recorder was 0–5000 Hz, and the rms signal-to-noise ratio was 42 dB. During the eclipse only four diodes were functioning, 2, 4, 5, and 6 in Fig. 1. Recordings of the light falling on the detectors were made continuously from ~20 min before second contact (the beginning of totality) to ~20 min after third contact. The output of detector 2 was recorded on channel 1 of the recorder, detector 4 on channel 2, detector 5 on channel 3, detector 6 on channel 4. Henceforth we refer only to these recording channels in discussing the data.

Output from the four recording channels was digitized with a sampling frequency of 1 kHz and the accuracy of 12 bits for a period of ~10 min before second contact to 10 min after third contact. Further analysis of the data was then performed on a Burroughs B5900 computer at Gettysburg College.

III. Data Reduction

Since the overall illumination from the sun is continuously changing both before and after the eclipse, and since the bands appear as small modulations of the overall intensity, a normalization procedure was employed to extract the fluctuations. The output from each channel was divided into 8.192-sec segments. Over each segment, it was found that the background light level could be approximated very well with a linear fit to the data. This line was used as the background; the actual signal was normalized to it and expressed as a relative intensity. Fluctuations significantly greater than the noise could be discerned by visual inspection of the data only from ~30 sec before totality until second contact and for ~30 sec after third contact. This was in accord with visual observations made at the eclipse itself.

As a sample of these data, Fig. 2 shows the normalized output from the four detectors plotted for a 1.6-sec interval beginning at 20 sec before second contact. The shadow pattern is clearly visible above the noise; most of the latter is a 60-Hz hum. The fluctuations show a strong resemblance to tracings of stellar scintillation made through a small aperture telescope,[5] an impression borne out by further analysis.

The dc background was subtracted from each 8.192 segment of signal. Spectra were then computed using a fast Fourier transform algorithm.[18] The instrumental noise spectrum was determined by sampling data during periods far from totality, when no shadow signal was present. The instrumental noise was then subtracted digitally from each computed power spectrum.

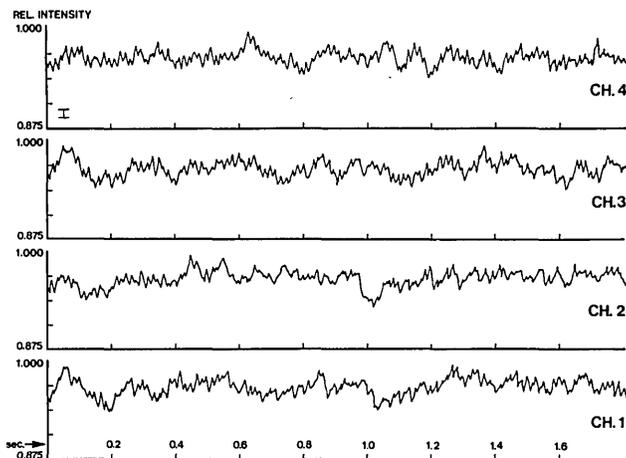A distinctive power spectrum of the shadow bands

REL. INTENSITY

Fig. 2. Normalized signals from four detectors (channel 1 = detector 2; channels 2–4 = detectors 4–6) for a period beginning 20 sec. before second contact. Root mean square noise is shown by error bars on channel 4.
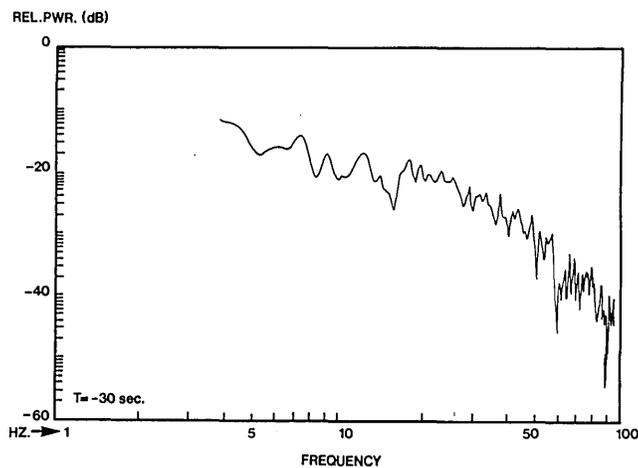
REL.PWR. (dB)

Fig. 3. Power spectrum (average of four channels) for a period of 8.192 sec beginning 30 sec before second contact.
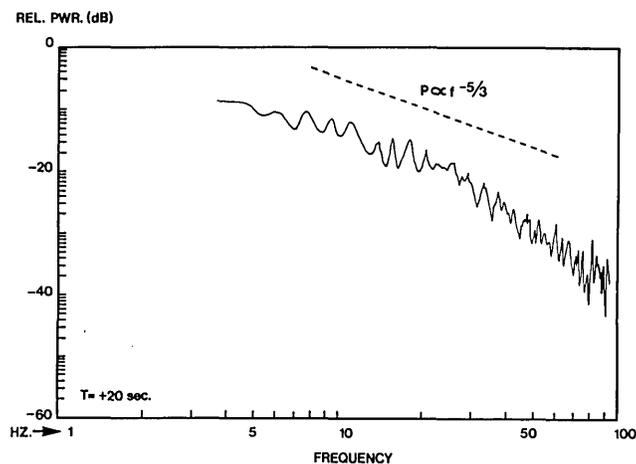
REL. PWR. (dB)

Fig. 4. Power spectrum (average of four channels) for a period of 8.192 sec beginning 20 sec after third contact. A line representing the relation $P = kF^{-5.3}$ is shown for comparison with the results of Quann and Daly.[14]

appeared clearly only in the samples taken from 30 sec before second contact until totality and from third contact until 26 sec after totality. There was no appreciable change in the shape of the spectrum over this time nor was there a significant difference between the spectra in each of the four channels. An average power spectrum from the four channels for a period beginning 30 sec before totality is shown in Fig. 3. A similar spectrum for the period beginning 20 sec after totality is shown in Fig. 4. During totality, and at all times before and after the periods mentioned above, no indication of shadow band activity was present in the spectra. This strengthens the case that we are seeing a real illumination effect, not just instrumental noise. It is also in disagreement with the observations of Klement,[16] who noted activity in his power spectra during totality at the 1973 eclipse.

Cross-correlations between the detector outputs were also computed in hopes of determining the speed of motion of the shadow pattern across the detector array. No strong correlation of the detector outputs was noted, however. In this case we were hampered by noise in the recorder (probably a perodic variation in the capstan speed) at ~5 Hz. This noise had a period roughly equal to the time (200 msec) a typical shadow pattern should have taken to travel from one detector to another, at a speed of a few m/sec, typical of speeds previously reported in the literature.[7]

Examination of the shadow band fluctuations themselves shows dramatically why they are so difficult to detect. The fluctuations are only a few percent of the background illumination (Fig. 2), but they are clearly visible above the noise. (Signals at other times showed primarily the 60-Hz hum noticeable in the figure. The hum, the major noise source, was used to set the error bar at the top left of Fig. 2.)

The computed power spectra of the shadow fluctuations are clearly quite consistent during the entire period when shadow bands were observed visually during the 1980 eclipse. These power spectra are in good agreement with the data studied with a narrower bandpass by Quann and Daly.[14] Both sets of data show a good fit to the minus five-thirds power law (see Fig. 4) expected for light from a small source propagating through a turbulent atmosphere.[6,19,20]

Since the detectors' collecting area was similar to that of a telescope of 1-cm aperture, the overall spectra might be expected to resemble the power spectra of stellar and planetary scintillation seen through a small telescope. A comparison with the published data of Young[6] shows that this is indeed the case with a flattening of the curve for frequencies less than ~10 Hz (a phenomenon evident, but not noted, in Quann and Daly's results) and a steeper drop-off in energy beyond ~40 Hz.

The power spectrum analysis is quite clearly in accord with an atmospheric scintillation model for the shadow bands. So, of course, is the absence of shadow band activity during totality, for then, clearly, there is no longer a source of illumination. The anomalous results of Klement[16] may simply be due to unaccounted systematic effects in his detection system. The presence

of airborn sand is noted in that report, and it is possible that light reflected from sources other than the sun may have contaminated the signal.

The absence of a strong cross-correlation between the detectors makes it impossible to determine the speed of motion of the bands or to estimate the effects of systematic atmospheric motions in producing the apparent motion. Nevertheless this result is in accord with the common observation that the shadow pattern of stellar scintillation is coherent over a length of only ~10 cm. Since our detectors were separated by ⁔17 cm we might expect few shadow patterns to remain coherent long enough to be detected in more than one detector. A reduction in the capstan noise at future eclipses will help settle this issue.

IV. Conclusions

Detection of weak (2–3%) fluctuations in the ground illumination from the almost-eclipsed sun has been made at the total eclipse of 16 Feb. 1980. Analysis of these fluctuations provides strong confirmation that the process of formation of the shadow bands is similar to the process of stellar scintillation. Power spectra of the shadow fluctuations are in accord with similar power spectra of stellar scintillations, and the fluctuations themselves may be uncorrelated over lengths of at least 17 cm.

Although shadow bands are at best a curious epiphenomenon of nature, like the rainbow, we intend to continue our investigations in several directions. (1) The observed width of the bands was about equal to that of our detector aperture. New detectors with much smaller apertures have been constructed in an attempt to increase the contrast of the detected fluctuations. (2) To investigate more fully the spatial coherence of the shadow pattern, an array of detectors with a wider range of spacings will be employed, sampling points from 1 to 20 cm apart. (3) To investigate the effects of solar-limb darkening on the pattern contrast, a series of measurements at various visible wavelengths will be made. This follows up the suggestive results of Quann and Daly[14] indicating stronger shadow band activity at shorter wavelengths.

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