THE MEASUREMENT OF LONG-PERIOD OSCILLATIONS AT SACRAMENTO PEAK OBSERVATORY AND SOUTH POLE*

ROBIN STEBBINS

*Sacramento Peak Observatory**, Sunspot, NM 88349, U.S.A.*

and

CHRISTOPHER WILSON***

Department of Physics, University of California at San Diego, La Jolla, CA 92093, U.S.A.

Abstract. A program to measure long-period brightness oscillations at the solar limb has been pursued at Sacramento Peak Observatory for several years. Past improvements in observing technique and data analysis are reviewed. The encouraging results aid in the verification of the reality and the origin of oscillatory signals. However, the main stumbling block to this and other observational programs is the length of observing sequences imposed by the day/night cycle. The South Pole has received considerable attention as a site where extended observations might be possible. Currently, the Sacramento Peak program is developing a South Pole telescope designed for the observing technique and data analysis proven in Sunspot. A review of pertinent South Pole site parameters is given here for other workers who may be considering South Pole observations. Observing sequences longer than 150 hr are possible, though rare. Data sets of this duration are very attractive for solar oscillation studies.

1. Introduction

The history of observations of solar oscillations has been a series of improvements in observational technique, database, and data analysis. Three examples demonstrate this: The first report of global oscillations (Hill and Stebbins, 1975) was a serendipitous byproduct of a novel observing method. The case for the 160 min oscillation rests largely on the vast database compiled by the Crimean and Stanford groups. The analysis leading to the diagnostic diagram revealed the real character of the five minute oscillation (Deubner, 1975). Because of their complex nature and subtle manifestations, future progress in the observational study of solar oscillations will be achieved largely through further improvements in technique, database and analysis.

The program of oscillations study reported here has developed and tested improvements in observing methods and data analysis. The main focus is now on extending the database. While reviewing these efforts, it would be well to keep the three goals of any such study firmly in mind. Initially, the observer will want to demonstrate the existence

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*** Summer Research Assistant at Sacramento Peak Observatory.

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of an oscillatory signal, along with some measure of its robustness. Secondly, the origin of the oscillatory signal must be identified – in particular, whether the signal is of solar rather than terrestrial or instrumental origin and whether the signal is caused by an organized pulsation or some stochastic process. Finally, having established the observation of a solar oscillation, the observer will want to elucidate the properties of the oscillation. While restating these goals may seem trivial, they are frequently overlooked in the excitement of developing new instruments and reporting new results. This paper wil attempt to report progress using these goals for perspective.

2. The Basic Method and Its Generalization

The basic observation senses brightness oscillations in the limb of the Sun. These oscillations are expected to be localized at the extreme limb. The detection is achieved by analyzing the shape of the limb darkening function with the Finite Fourier Transform Definition (FFTD) of the edge of the Sun. This definition of the edge was developed for measuring the solar oblateness (see Hill *et al.*, 1975, for a complete discussion of the FFTD). The FFTD defines the edge of the Sun to be the center of an interval over which a particular Fourier component is missing. For the purposes of this discussion, application of the FFTD involves selecting an interval size, multiplying the limb profile by a prescribed weighting function, and moving the interval until the weighted sum vanishes. The interval size is a free parameter about which more will be said. The weighting function has been chosen to minimize the effects of seeing on the edge location, yet remain sensitive to changes in the limb darkening. Roughly, the weighting function measures a second derivative averaged over the interval. The behavior of the FFTD is documented by a well developed theory and empirical tests.

The FFTD has been previously implemented as part of the telescope requiring the choice of a single interval size. However, the FFTD can be employed more effectively for oscillations studies if multiple definitions with different intervals can be applied simultaneously. A family of edge definitions, with interval size as family parameter, can be used to trace the reality and origin of an oscillatory signal. Since each edge follows an apparent brightness change in the limb profile with a sensitivity dependent on the shape of the brightness perturbation, their relative responses constitute a signature which characterizes the origin of the oscillatory signal. This signature can be examined to test the reality of the power at every frequency without reliance on the broadband statistics of the power spectrum. Further, the signature will also reveal the origins of that power.

The generalized application of the FFTD has two other advantages. First, since the relative motions of the edge are found by differencing all the edges against one chosen as the reference, oscillations can be detected by observing only one edge of the Sun. In previous applications of the FFTD where the edge on one side of the Sun is referenced to the edge diametrically opposed, Fossat *et al.* (1981) have suggested that the observed oscillations were due to atmospheric differential refraction changes. This point has been forcefully contested (Hill, 1979). However, a measurement based on a single limb rather than a diameter renders the objection moot. The single-limb approach does have a disadvantage for deconvolving the actual brightness (Knapp *et al.*, 1980). The second advantage lies in the ease of implementation. By digitizing and recording a portion of the limb, minimal specialized hardware is required to implement the FFTD. The definitions can be chosen and applied numerically as part of the data reduction process. The instantaneous value, the average value, and the power spectrum of the seeing can also be derived from the reduction procedure. This will give average values and power spectra for a data set. This will be useful in identifying the source of an oscillation.

The observation, as described, consists of digitizing and recording a patch of the solar limb at regular intervals. The data reduction consists of computing the locations of each edge, and then subtracting the location each from a chosen reference edge. The difference between two edge locations reflects only brightness changes and hence is called a brightness signal. The Fourier transform and power spectrum of each of these brightness signals are generated in the conventional way (see Stebbins, 1980, for details). For display purposes, the power spectra are converted to amplitude spectra.

3. Results

Sixteen data sets comprising 156 hr were gathered over a span of two years. For each data set, an amplitude spectrum was computed for each brightness signal. These amplitude spectra can be thought of collectively as a single amplitude function of two variables, frequency and interval size. To concentrate on the simplest portion of the solar acoustic spectrum (above the *g* mode band head and in the least dense region of the *p* modes), the amplitude function is averaged from 0.45 to 0.6 mHz, and this cut in frequency is averaged for all data sets. The resultant signature, that is amplitude vs interval size, is shown in Figure 1, along with one standard deviation error bars. Clearly, there is a distinctive and statistically significant signature. The amplitude is clearly peaked toward small interval sizes, indicating a brightness fluctuation concentrated at the extreme limb. Further, the phases of all these brightness signals are very nearly the same, -0.94 ± 1.01 degrees. The interpretation of these facts has been given elsewhere (Stebbins, 1980), but will be reviewed and extended here.

Clearly, the signature and phases are not random. What is the origin of this systematic signal? The differential nature of the measurement eliminates most telescope problems. The signature clearly shows an apparent brightening change, and the phase uniformity indicates that it must be concentrated within a few arc seconds, half the smallest interval size, of the intensity onset. Exotic sensitivity variations in the photo-diodes near the limb could produce such a signature. However, discontinuities in the brightness signal should appear when the periodic recalibration is done. No significant discontinuities are seen.

As mentioned previously, atmospheric differential refraction does not affect the brightness signals. Seeing changes will alter the shape of the limb profile, particularly within a few arc seconds of the intensity onset. However, the amplitude of the brightness signal most sensitive to seeing is more than twice that which would have been caused by the actual seeing changes alone. Further, the signature is the wrong shape for seeing.

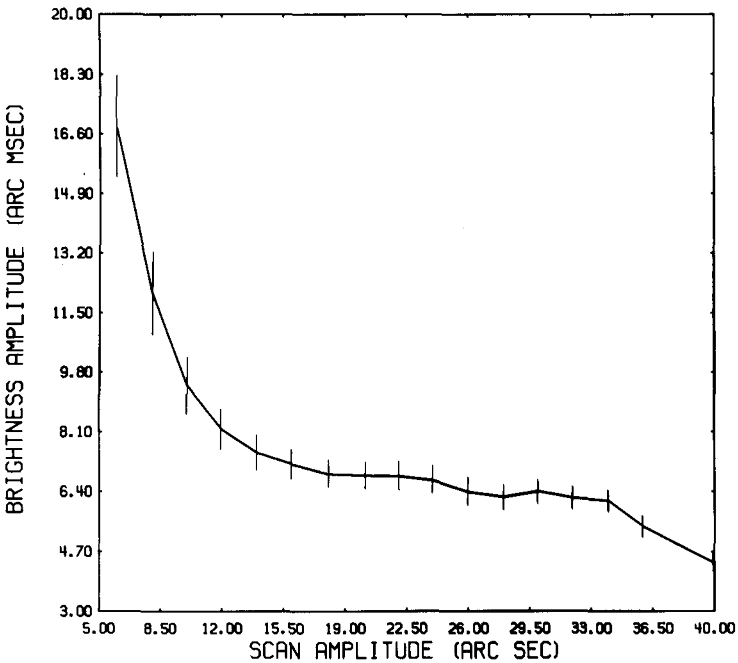

Fig. 1. The reality and origin of a solar oscillation are demonstrated by the signature, the oscillatory amplitude versus interval size. (Scan amplitude is one half of the interval size.) This signature has been averaged over sixteen data sets and 0.45 to 0.60 mHz. Error bars are shown at each value of interval size.

The seeing signature is essentially flat with a minimum at 8 arc sec, and a slight turn up at 6 arc sec.

If the observed signal is not of instrumental or atmospheric origin, could it not be from brightness features on the solar surface moving through the aperture or enduring while in the aperture? Brightness features rotating into the interval of each edge definition would cause the phases to be delayed by 250–720 degrees from one brightness signal to the one with the next largest interval size. So, brightness features rotating into the apertures are clearly inconsistent with the observed phases. Since the contrast of surface features declines toward the limb, evolutionary effects would be most pronounced at the inner boundary of the FFTD interval. This leads again to large phase shifts between brightness signals which are not observed.

Long-period oscillations could explain the observed signature and phases. Knapp *et al.* (1980) show evidence for a limb brightening sharply peaked within 6 arc sec of the intensity onset. Although no widely accepted calculation of the brightening exists, the effect should be most evident at the limb, and all of the brightness signals should respond in phase. Hence, the signature and the phases have established the reality of an oscillatory signal and indicated its origin as being a solar pulsation.

A signature, such as shown in Figure 1, could be drawn for every frequency point of every amplitude function and every data set. To demonstrate this, Figures 2a and 2b

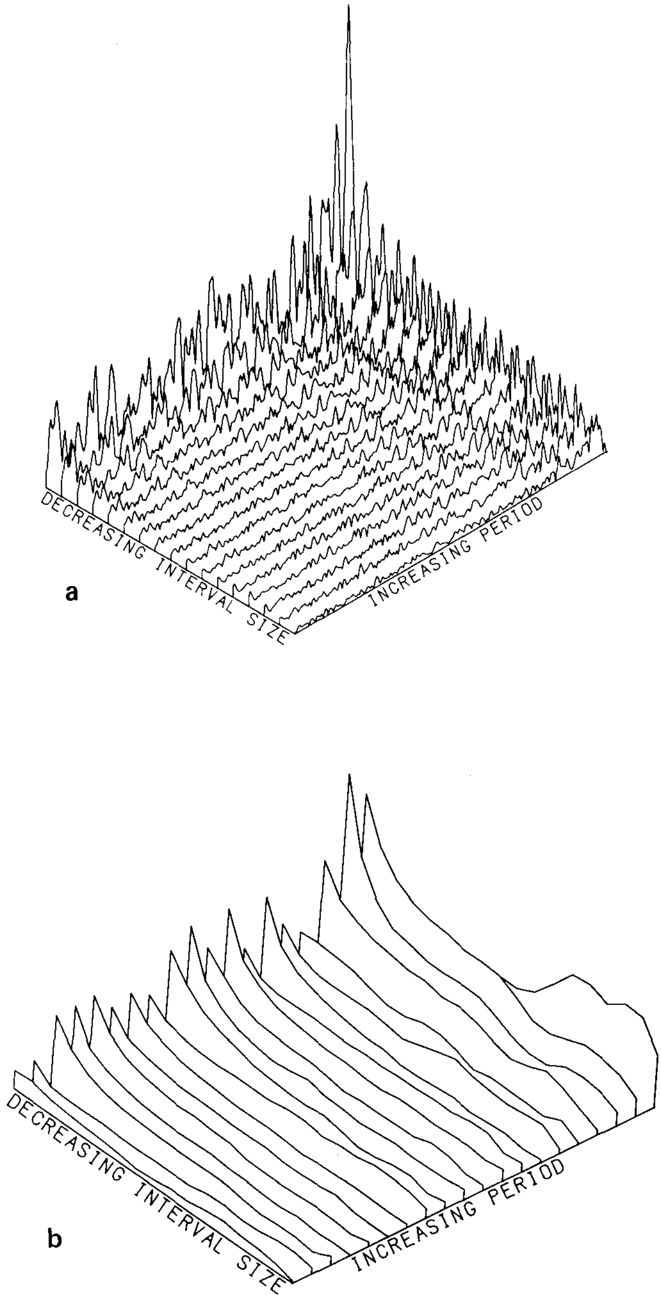

Fig. 2. Isometric plots depict the amplitude function. (a) Cuts along constant interval size are just the amplitude spectrum for each relative edge. (b) Cuts along constant period, at arbitrarily chosen frequencies, show the signature at each frequency. Period increases to the right, from 300 s to infinity. Interval size decreases to the left, from 80 to 12 arc sec.

show isometric plots of the amplitude function for one data set. Figure 2a shows a series of cuts along constant interval size, and Figure 2b shows a series of cuts along constant frequency. The latter demonstrates particularly well the presence of a pronounced signature, peaked toward small interval size. The cuts in Figure 2b were chosen at a fixed frequency spacing rather than for the presence of peaks. The conclusion to be drawn is that there is power from solar pulsations at many frequencies, not just the highest peaks.

4. A Telescope for the Antarctic

For the purposes of this review, these Figures 2a and 2b are presented to show the benefits of the improvements in observing technique and data analysis. The generalization of the FFTD does give new and better information about the reality and the origin of oscillations. The signature analysis brings out that information. What is lacking here is a database with enough time strings of sufficient length to resolve individual modes. One would ideally like frequency resolution characteristic of a 10-day-long observing sequence. The actual data set need not be 10 days long, but the longest gap should not exceed the longest continuous sequence during that period. To put the situation simply, long observing sequences can be acquired either by going to the appropriate space platform, employing a globe girdling network of ground based stations, or going to the polar regions in the right season. The last is the easiest of a difficult lot. Of the two polar regions, the Arctic offers poor weather, no land at the pole, and dismal accessibility; the Antarctic has reputedly good weather, a scientific station at the pole, and adequate assessibility. As a result, a telescope has been built especially for using the above-mentioned techniques at the South Pole (see Stebbins, 1981, for an extensive discussion).

The design goals of this telescope are the formation of a stable, high quality image, the digitization of a portion of the solar limb, assembly and operation in a polar climate, and portability appropriate to the logistical system. A cross-sectional diagram is shown in Figure 3 and a picture of the telescope on site at the South Pole in Figure 4.

The telescope has been tested at South Pole during the austral '80–81 summer. Several instrumental problems prevented the acquisition of any useful data on oscillations. The instrument has been shipped back to Sacramento Peak Observatory for further testing there. Although the first season was disappointing, it did provide an opportunity to evaluate the South Pole site firsthand. Considering the importance of long observations to the study of solar oscillations, the results of this evaluation are presented for other workers in the field who may be contemplating observations at South Pole.

5. South Pole Site Survey

Little data (Pomerantz, 1981a; Wyller, 1970) exists on the suitability of the South Pole for doing astronomy. Available meteorological observations, with one notable excep-

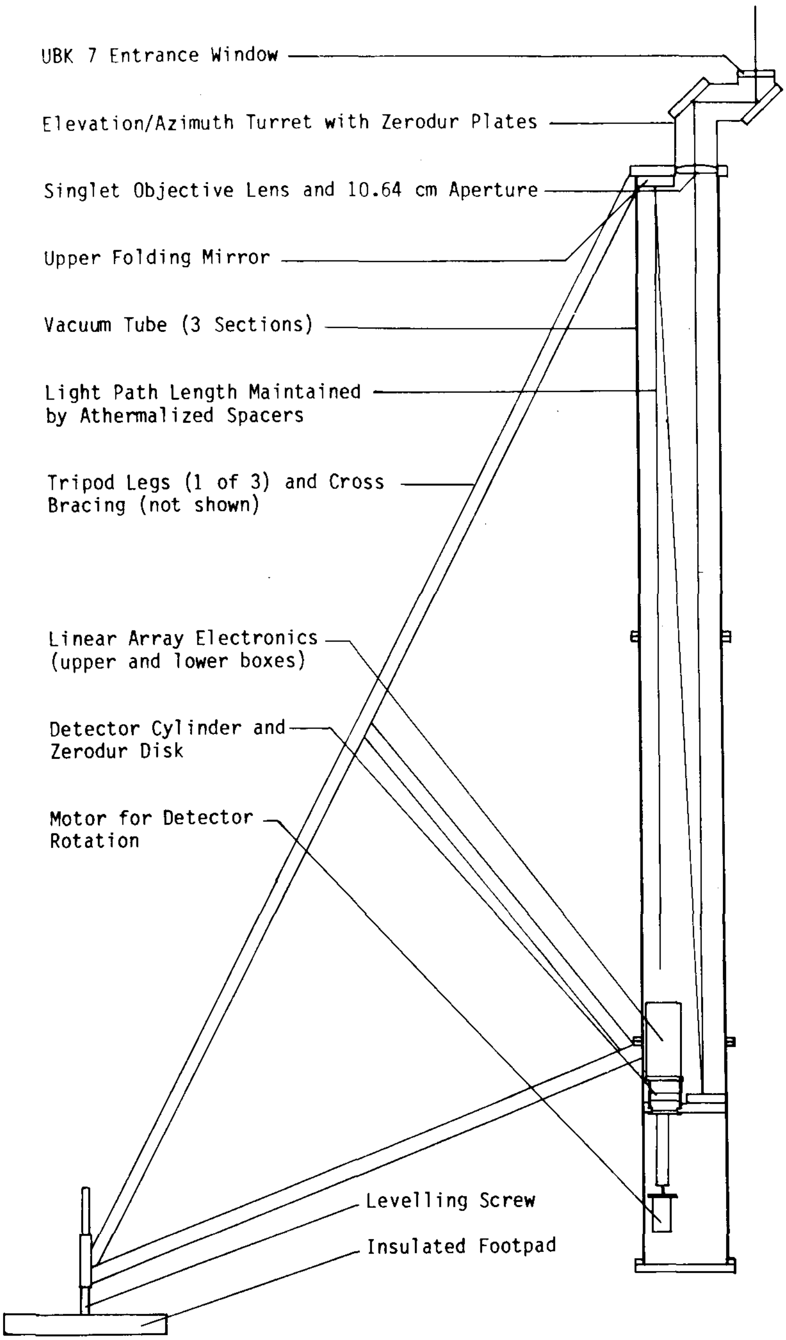

Fig. 3. A schematic cross-section of the Antarctic telescope.

tion, are not terribly useful, and the bulk of the evidence is in the form of casual observation. Since no one has spent the entire season for many years at South Pole, even personal experiences are limited. Herewith is a summary of all the available quantitative information about the suitability of the South Pole as an astronomical site. The quality and quantity of the information about most parameters is woefully lacking.

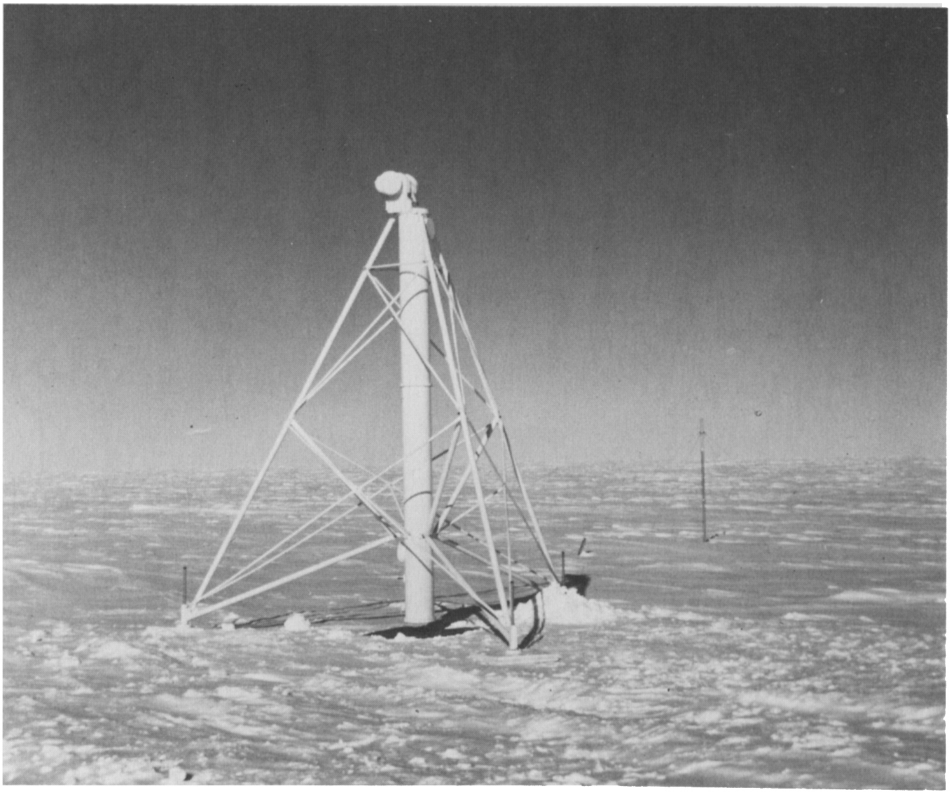

Fig. 4. The Antarctic telescope on location at the Amundsen–Scott South Pole Station.

The most important facet of an observing site for solar oscillations work is the cloud cover, specifically, the frequency and length of uninterrupted views of the Sun. The National Oceanic and Atmospheric Administration's Geophysical Monitoring for Climatic Change Program has operated a device called the Normal Incidence Pyroheliometer (NIP) at South Pole for over 4 years. The NIP measures solar irradiance every minute. Sample data is shown in Figure 5. These data have been accumulated into a histogram (Figure 6a) which shows the frequency of occurrence of uninterrupted viewing segments of different lengths. The threshold defining unacceptable cloud cover is a drop in intensity of 30% for one minute. There were three segments lasting longer than 90 hr in four year period (November through January, 1977–1981), the longest

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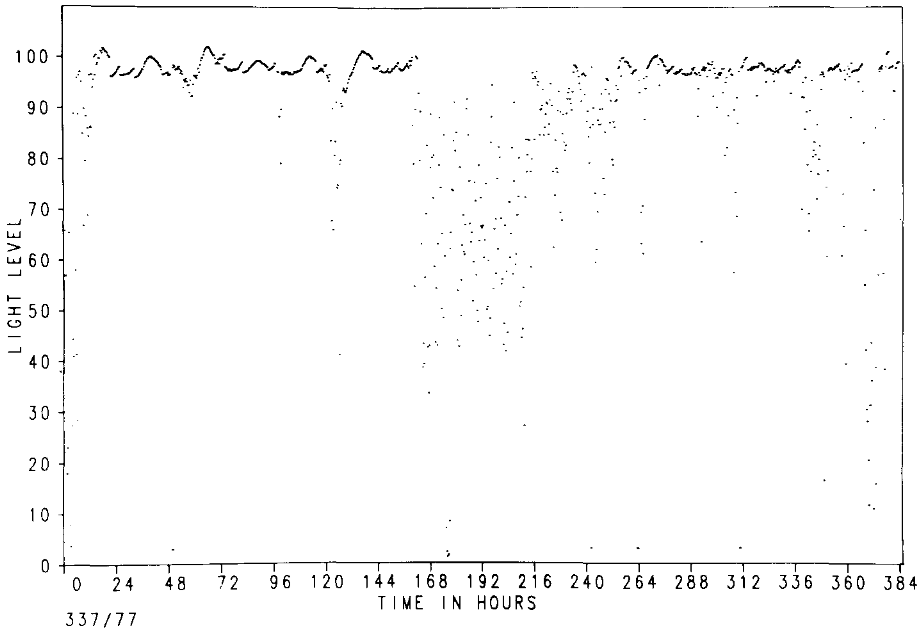


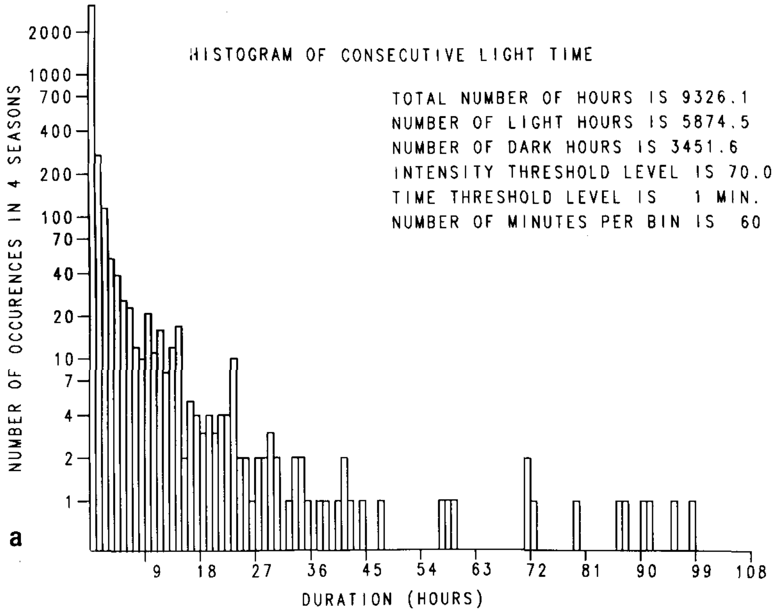
Fig. 5. Sixteen days of sample data from the NIP instrument are shown. The span begins at 00 : 00 GMT, 3 December, 1977. Only every twenty-fourth point is plotted because of the one-minute sampling interval. Brief intensity drops which result from the shadows of nearby instruments can be seen, but are excluded from the analysis. Both clear and cloudy weather can be seen.

being 98 hr. For a threshold of 50%, there are three segments longer than 100 hr, the longest being 133 hr.

A light level drop for one minute is an overly severe criterion for most observations. Figure 6b shows a similar histogram where light level drops lasting 60 min or less are ignored. In this circumstance, there are ten segments lasting longer than 100 hr in a four year period, the longest being 155 hr. If the dropout threshold is reduced to 15 min, there are only six such long spans, the longest being 152 hr.

The lesson from these data is that observing runs lasting from 100 to 150 hr, depending on the selection criteria, are possible at South Pole. It may be possible to link together phases over a much longer time span with correspondingly higher frequency resolution. However, practical considerations, such as start up time and instrument down time, will degrade these uninterrupted viewing periods. While one might like a longer time base for this analysis, these NIP data are a high quality measure of an important site parameter which does not exist for any conventional astronomical site.

The next site parameter to be considered is seeing. While not important for the observations described here, it will be of interest to other workers. Normally, the standard deviation of the atmospheric transfer function could be derived from the FFTD analysis. Lacking the anticipated electronic limb data, substitute photographic data was obtained by placing 35 mm film in the image plane of the telescope. The



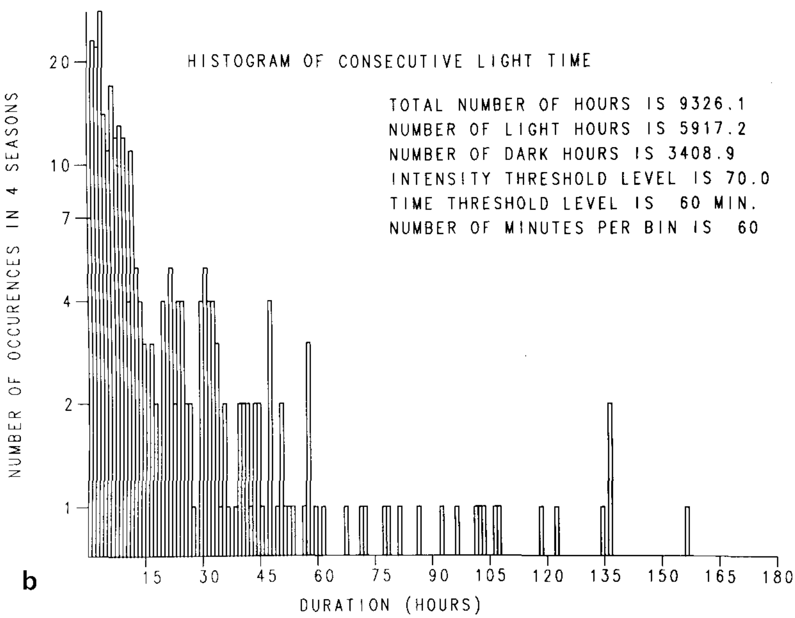


Fig. 6. The frequency of occurrence of clear skies with a given duration are shown in these histograms. The threshold defining clear skies is about 70% of normal light level. (a) An intensity drop below the threshold in any one-minute sample delimits a period of clear skies in this histogram. (b) An intensity drop lasting longer than 60 min delimits clear skies in this histogram. Four Antarctic summers (November, December, and January, 1977–78 to 1980–81) are shown here.

resulting images of the limb were microdensitometered, converted to intensities, and averaged to yield a limb profile. These profiles were then subjected to the FFTD analysis in order to obtain an upper limit on the seeing. (Only an upper limit can be found, owing to the vagaries of the photographic process which contribute to a blurring of the limb profile.) The result is a standard deviation of 2.26 arc sec, a seeing disk with a full width at half maximum of 5.34 arc sec, assuming a Gaussian transfer function. A direct visual check of the solar image at the same time suggested a full width at half maximum equal to 2 arc sec, consistent with the quantitative upper limit. These results stem from samples spanning not more than an hour of time. A much longer monitoring of the seeing is in order. However, the stability of the polar meteorology and the colder-than-air snow surface would lead one to expect long term good seeing.

The next parameter to be considered is the sky brightness, of interest in coronal observations. Using a visual sky photometer (Evans, 1948), the sky brightness was measured to be 20 millionths of the central disk intensity at 1.6 solar radii. For lack of clear weather, this measurement could only be made once. Again, a much longer baseline of observation is desireable. It might also be noted that the clear skies at South Pole are most impressive looking – no visible aureole around the Sun can be seen most of the time. The sky brightness measurement is less impressive. The objective measurement and the naked eye observation could be resolved by the fact that ice crystals in the air are the dominant scattering source (recall that there is no vegetation and essentially no local sources of pollutants). These ice crystals constitute high angle scattering centers, and consequently the whole sky may be brighter without the customary aureole caused by low angle scatterers such as dust and pollution. In support of that contention is the fact that the horizon is oftentimes imperceptible, the white snow graduates into the blue sky.

Other atmospheric phenomena of interest to astronomers are the precipitable water vapor, the ice crystals, and ambient temperature and winds. The precipitable water vapor hovers around 0.45 mm in the summer (Pomerantz, 1981b). The ice crystals, an everpresent phenomenon to greater or lesser extent, give a clear sky a sparkling appearance. Their effect on astronomical observations will probably depend on the particular measurement. The ambient temperature ranges from -20 to -32 degrees centigrade over most of the South Pole summer. Some consideration needs to be given to equipment design and to anticipated human activities (see Stebbins, 1981, for example), but the environment is not insurmountable. The winds are extremely constant, averaging 10 knots along the 20 degree east longitude meridian. The winds are never absent and never exceed about 30 knots, assuring a continuous wash of air over a telescope.

Some miscellaneous points of interest to observers contemplating an Antarctic observation: equipment transport can be extremely hazardous, and every precaution must be taken in packing fragile instrumentation. As befits a site as remote as the South Pole, maintenance and spare parts are hard to acquire. Finally, an Antarctic tour can tax an observing team far more than a conventional site.

In summary, the South Pole appears to be a good site for extended viewing of the

Sun when viewed as a compromise between limitations of a mid-latitude site and the effort needed to construct a grid of stations or a space platform. Providing that the observation is compatible with the weather, most of the other difficulties can be coped with.

6. Conclusions

Advances in the means of collecting and analyzing data have yielded better information about solar oscillations. A novel technique has been developed and tested at Sacramento Peak Observatory. The encouraging results have led to application at the South Pole, where longer data sets can be had. Although no results on oscillations are available yet, a preliminary review of the site indicates that extended observations will produce another advance in the understanding of solar oscillations.

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