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Facility

GONG* site evaluation program at Udaipur Solar Observatory

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Abstract. Helioseismology provides a very good tool for probing the internal structure and dynamics of the sun. For its success, it is essential to observe the sun on near continuous basis during 24-hour period, covering many days. The Global Oscillation Network Group (GONG) proposes to make helioseismic observations from several ground-based sites distributed over the globe, in order to reduce the diurnal cycle encountered at a single location. A site evaluation program was started in 1986 at the Udaipur Solar Observatory for accurately determining the daytime fraction of clear sky or duty-cycle at Udaipur. In this paper, various statistical parameters related to solar visibility, such as, average daily duty cycle, clear and dark time distributions, average transparency power spectrum and extinction coefficient are presented for the Udaipur site using sunshine data base for the period November 1986-March 1991. Importance of this site, leading to its selection for the six-site GONG network from 15 candidate sites, is also discussed.

Key words : helioseismology—GONG network—solar duty cycle—site survey

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*GONG (Global Oscillation Network Group) is community-based helioseismology project proposed by the National Solar Observatory, Tucson and sponsored by the National Science Foundation, USA. Site evaluation program at Udaipur is being carried out under an Indo-US joint cooperative program.

1. Introduction

'Helioseismology' is a new, developing technique in Solar Physics for determining internal structure and dynamics of the sun using measurements of its surface oscillations. It utilizes 'seismic' waves propagating in the interior of the sun, which get affected by its internal physical parameters, such as, density, temperature, angular rotation etc. Most of our present understanding of the solar interior rests on theoretical models constructed by using just the global properties, i.e., radius, mass, luminosity composition and age. Comparison of oscillation periods predicted from solar models with actual observations is expected to refine these models and resolve various fundamental problems, such as, helium abundance, solar neutrino deficit, cosmological models of the early universe etc. (Deubner & Gough 1984; Christensen-Dalsgaard *et al.* 1985; Leibacher *et al.* 1985; Brown *et al.* 1986; Toomre 1986; Hill, Deubner & Isaak 1991).

One major difficulty in achieving goals of helioseismology is imposed by interruptions in solar observation due to the day-night cycle at a single observing site. This periodic interruption of the observed time series contaminates the power spectra with side-lobes at the harmonics of 1/day, *i.e.*, 11.6 microHz. This results in a crowded structure in power spectra, introducing uncertainty in identification of oscillation frequencies in addition to concealing low amplitude oscillations. Moreover, it is essential to obtain sufficient frequency resolution in order to correctly identify and define frequency of a particular mode, uncontaminated by modes with slightly different frequency. Toomre (1986) has shown that frequency resolution of the order of 0.3 microHz is needed. This implies uninterrupted solar observations over a period covering around 39 days—clearly not achievable from a single site due to the inevitable day-night cycle.

Several data processing techniques have been suggested to fill data gaps, *e.g.*, Maximum Entropy Method (MEM), interactive deconvolution etc. (Fahlman & Ulrych 1982, Scherrer 1986, Brown & Christensen-Dalsgaard 1990), but none of these meet the requirements of helioseismology. Numerical simulations of a maximum entropy gap filling procedure have shown that a minimum of 80% duty cycle, *i.e.*, a continuous solar coverage of around 19.5 hr, is required to accurately and fully recover the solar oscillation spectrum.

The following alternate observational strategies are available to overcome the problem of diurnal cycle (Hill 1990):

(i) *Observation from geographic south pole during austral summer period* (Grec *et al.* 1980, 1983; Duvall *et al.* 1988; Gelly *et al.* 1988): It has not been possible to obtain more than 5-7 days continuous solar observations due to severe Antarctic weather conditions.

(ii) *Observation from space-borne platform* (Noyes & Rhodes 1984, Noyes 1988, Domingo 1988): This method is clearly free from degrading effects of the earth's atmosphere and daily sunrise-sunset cycle of a ground-based site, but involves highly sophisticated and expensive technology.

(iii) *Observation from a network of ground-based solar observing sites*: This alternative is quite promising and interesting results have already started emerging from some existing networks which are all based on the measurement of integrated solar light, *i.e.* un-imaged sun. Birmingham Network (Aindow *et al.* 1988), and IRIS (Fossat 1988) are such networks and cover modes with *only* low spherical harmonic degrees $l \leqslant 3$.

These low l modes are important for diagnostics as they encompass nearly entire solar volume. However, good depth resolution is not available unless these are combined with low-degree gravity modes (Delache & Scherrer 1983, Palle 1991). As the spectrum of gravity modes is found to be quite crowded and much longer time sequences are required to resolve the g-mode spectrum due to their long periods, they are rather difficult to observe. If imaged, or spatially resolved solar observations are used instead of integrated sunlight, one would be able to observe higher-degree p-modes allowing to probe the solar interior over a large range of radius with higher depth and latitude resolutions.

2. Global Oscillations Network Group (GONG) Project

The Global Oscillation Network Group (GONG) project is an international group of scientists whose aim is to study internal structure and dynamics of the sun by measuring waves that penetrate throughout its invisible core. As distinguished from existing helioseismology networks, GONG proposes to use spatially resolved solar images. It has been originally proposed as a community activity by the National Solar Observatory, Tucson (U.S.A.) in 1984 and is sponsored by the National Science Foundation, U.S.A. Under this project, it is planned to make imaged solar observations from six observing stations placed uniformly around the world in order to reduce the problem of diurnal cycle and to obtain much longer, near continuous observations than can be made from the South Pole. Identically similar GONG instruments will be installed at each of these sites. These instruments will essentially yield Dopplergrams to obtain solar disk velocity field images at spatial resolution of around 8 arc-second and it is expected to precisely detect modes with spherical harmonic degree l of up to 350 (Harvey 1988).

3. GONG site evaluation program

It has been found by a computer model that a well-chosen six-site network would be able to achieve an overall duty cycle of about 94% (Hill & Newkirk 1985). Here duty cycle is defined simply as the ratio of the length of solar visibility to the total. Hill and Newkirk have considered a statistical model of cloud coverage at various geographic locations on the earth. However the results critically depend on the adopted value of the mean probability or fraction of clear sky, ρ, for a given site. For the success of the GONG project, it is crucial to obtain accurate values of this parameter, hence a site evaluation was considered essential. In view of this, it was proposed to place sunshine monitors at several potential GONG sites. From these, the final six sites have been selected in April 1991, after completion of more than 4 years of the site evaluation program. Table 1 lists 15 candidate sites where site evaluation program was undertaken. Their geographic longitude, latitude and date when the site survey instruments became operational are also tabulated. Distribution of these sites is shown on a world map in figure 1—the selected six sites forming the GONG network are underlined. These sites were selected primarily on the basis of their longitudes, facilities and local interest in helioseismology. It is also required that sites should be located such that at least two stations are potentially observing the sun at all times. If this is not so, diurnal sidelobes will reappear as soon as the single site covering a given longitude zone encounters bad weather or instrumental failure (Hill & Newkirk 1988).

Table 1. GONG candidate sites

Site	Longitude	Latitude	Start Date
Haleakala, Hawaii	−156°15.4′	+20°42.4′	7 Dec 1985
Mauna Kea, Hawaii	−155°28.3′	+19°29.6′	10 Dec 1985
Mauna Loa, Hawaii	−155°35.8′	+19°28.0′	25 May 1989
Big Bear, California	−116°54.9′	+34°15.2′	26 Aug 1985
Mt. Wilson, California	−118° 3.6′	+34°13.0′	9 Sep 1985
Yuma, Arizona	−114°30.0′	+32°40.0′	16 Jul 1985
Tucson, Arizona	−110°56.9′	+32°14.0′	17 Jun 1986
Cerro Tololo, Chile	−70°48.9′	+30°9.9′	8 Mar 1986
Las Campanas, Chile	−70°42.0′	+29°1.5′	7 Mar 1986
Izana, Canary Islands	−16°29.8′	+28°17.5′	23 Sep 1985
l'Oukaimeden, Morocco	−7°51.4′	+31°11.6′	Mar 1989
Riyadh, Saudi Arabia	−46°43.9′	+24°38.3′	11 Oct 1988
Udaipur, India	−73°42.8′	+24°35.1′	8 Nov 1986
Urumqi, China	−87°38.0′	+43°43.0′	19 Dec 1987
Learmonth, Australia	−114°6.1′	+22°13.2′	2 Dec 1985

Considering the importance of scientific goals of the project, the Udaipur Solar Observatory accepted to become part of the GONG site evaluation network. This observatory was established in 1975 at Udaipur on a lake-site after an extensive site survey program covering Rajasthan and Gujarat states. This site survey was conducted with prime objective of selecting a suitable location in India for obtaining high resolution solar observations. However, accurate quantitative values of the parameter ρ, important for the success of GONG project, were not obtained. Though high spatial resolution is certainly desirable for various studies undertaken at USO, it is not essential consideration for the GONG project, which plans to install instruments having rather coarse spatial resolution of 8 seconds of arc.

A sunshine monitor was placed over the roof of the observatory office building at Udaipur in October 1986 with the aim of accurately determining the solar duty cycle at this site. After initial adjustments of the instrument, regular sunshine monitoring at Udaipur site commenced from 1986 November 8. At Udaipur, sunshine data is now available for a continuous period of more than 4 years. This data provides statistically valuable information about solar duty cycle from Udaipur, both in single site mode and in the six-site GONG network.

(a) *The GONG site evaluation instrument*

The site evaluation instrument consists of two parts : (i) sun tracker and (ii) data acquistion system, or the data logger (Fischer *et al.* 1986). The sun tracker is a normal incidence pyrheliometer, manufactured by Eppley Laboratories, with a field of view of 5°43′ (figure 2). It is a pointed thermopile, mounted on a polar equatorial clock drive, which measures solar radiation with an accuray of 1%. The pyrheliometer converts incident solar radiation into voltage—conversion constant of the Udaipur instrument being $9.05 \times 10^{-6} \mathrm{V/Wm^2}$. The signal is routed through a cable to the data logger. Data logger consists of a digital voltmeter (DVM), a programmed HP-41 CX calculator and a

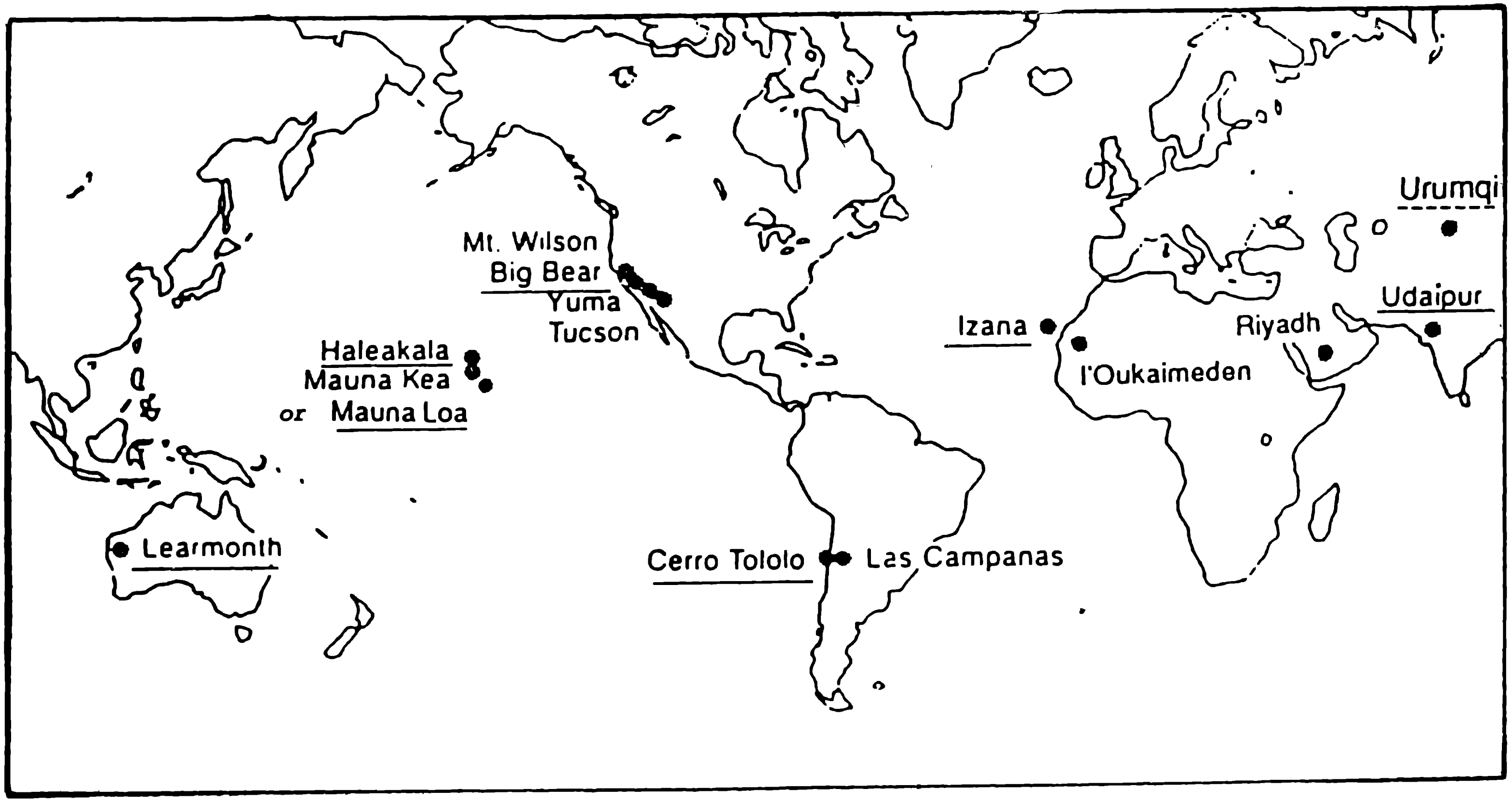


Figure 1. The candidate sites which participated in GONG site evaluation program, shown in a world map. The selected six sites to form the GONG network are underlined.

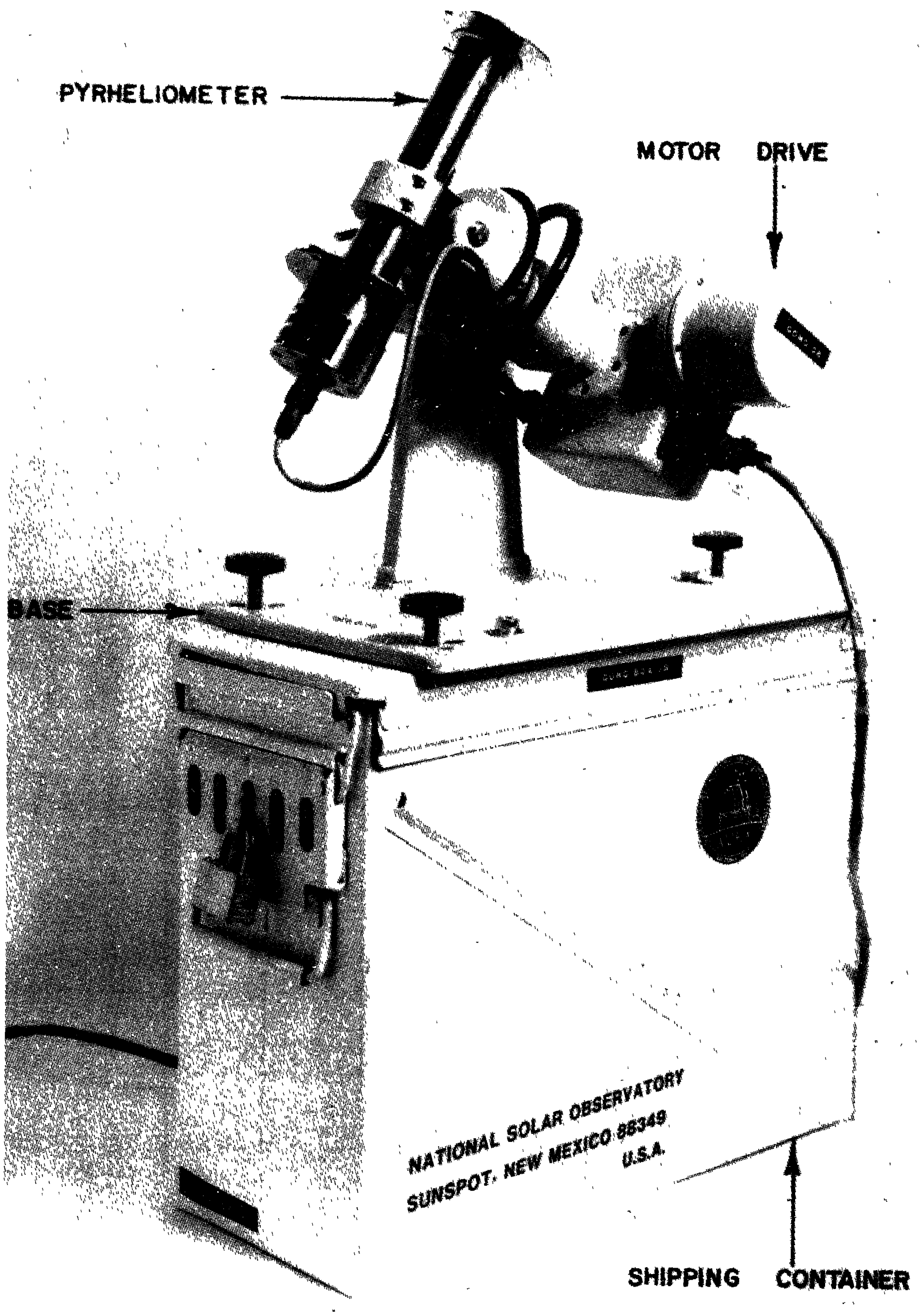


Figure 2. The tracker for sunshine monitoring.

micro-cassette recorder. It also contains a power supply system which provides backup power to the logger components to operate up to 5 hours without external power. However, no backup power was originally provided to the tracker with the aim of recording the number of times the mains power is interrupted. The tracker ceases to follow the sun when a mains power interruption occurs, requiring operator intervention to correct solar pointing as soon as power is resumed. Recognizing the unreliability of the power supply situation at Udaipur, an un-interrupted power supply (UPS) was later installed to supplement the mains supply, which has reduced the need of frequent operator interventions.

(b) *Data acquisition*

Basic functions of the data acquisition program consist of a continuously running clock and an interrupt which alerts the calculator to read the DVM every 10s, which continuously measures voltage generated by the pyrheliometer. Mean voltage is computed and stored every minute in the registers of the calculator. Every 30 minutes, if the average voltage of any minute is greater than 0.5 mV, the accumulated average data points are written to the micro-cassette along with flags identifying potential data problems due to power failures, operator intervention etc. An operator intervention and service is required every alternate day to unwind the cable connecting the pyrheliometer tube to the drive-base. The operator is also required to adjust declination axis of the instrument as the sun follows the ecliptic, and to correct pointing of the pyrheliometer. The calculator is programmed to flag such operator interventions, power interruptions etc. Although the tracker is operated 24 hour continuously, no data is written to the cassette during night-time. Each replaceable micro-cassette stores around 500 such averged data points, lasting 2-3 weeks depending on weather conditions. A duplicate cassette is then sent to the GONG project, National Solar Observatory, Tucson (U.S.A.) which also receives such data cassettes from other candidate sites, for the analysis of network performance.

Figure 3a shows an example of the raw solar irradiance data covering period of one week of good weather at Udaipur during October 1989. In the figure, local sunrise and sunset times are marked on the abscissa as circles. The characteristic extinction profile over the period of sunrise-sunset is evident. Sharp drops of voltage near rise and set marks are caused by obscuration at eastern and western horizons by a terrace of a nearby building and a hill, respectively. Very small amplitude fluctuations in the extinction curves are perhaps caused by high altitude dust clouds. These may be attributed to sand storms over Thar desert, separated from Udaipur by Aravali hills in the north-east direction. Passage of clouds through the field of view of the tracker is recorded as sharp fluctuations while extended cloudy periods are conspicuous as prolonged dips in the extinction curve. Figure 3b shows an example of a completely cloudy week in January-February 1990.

4. Data analysis and results

Prior to further analysis, the raw data as shown in figure 3 is subjected to various corrections for clock errors, atmospheric extinction etc. (Hill *et al.* 1988). A sunshine window for a site is created by assigning the value of 1 to each clear minute and a value of 0 to each dark minute. Using this window, fraction of clear time available in a day during sunrise to sunset, or daily duty cycle, is computed. The distribution and statistics, *e.g.*, mean, standard deviation, maximum and minimum lengths of continuously clear and dark time are also calculated. One may define a completely clear or dark day if $\rho > 0.95$ or $\rho < 0.05$, respectively. Similarly, a complete instrumentally broken day is defined when more than 95% time in the day had instrumental problem. Obviously, sky

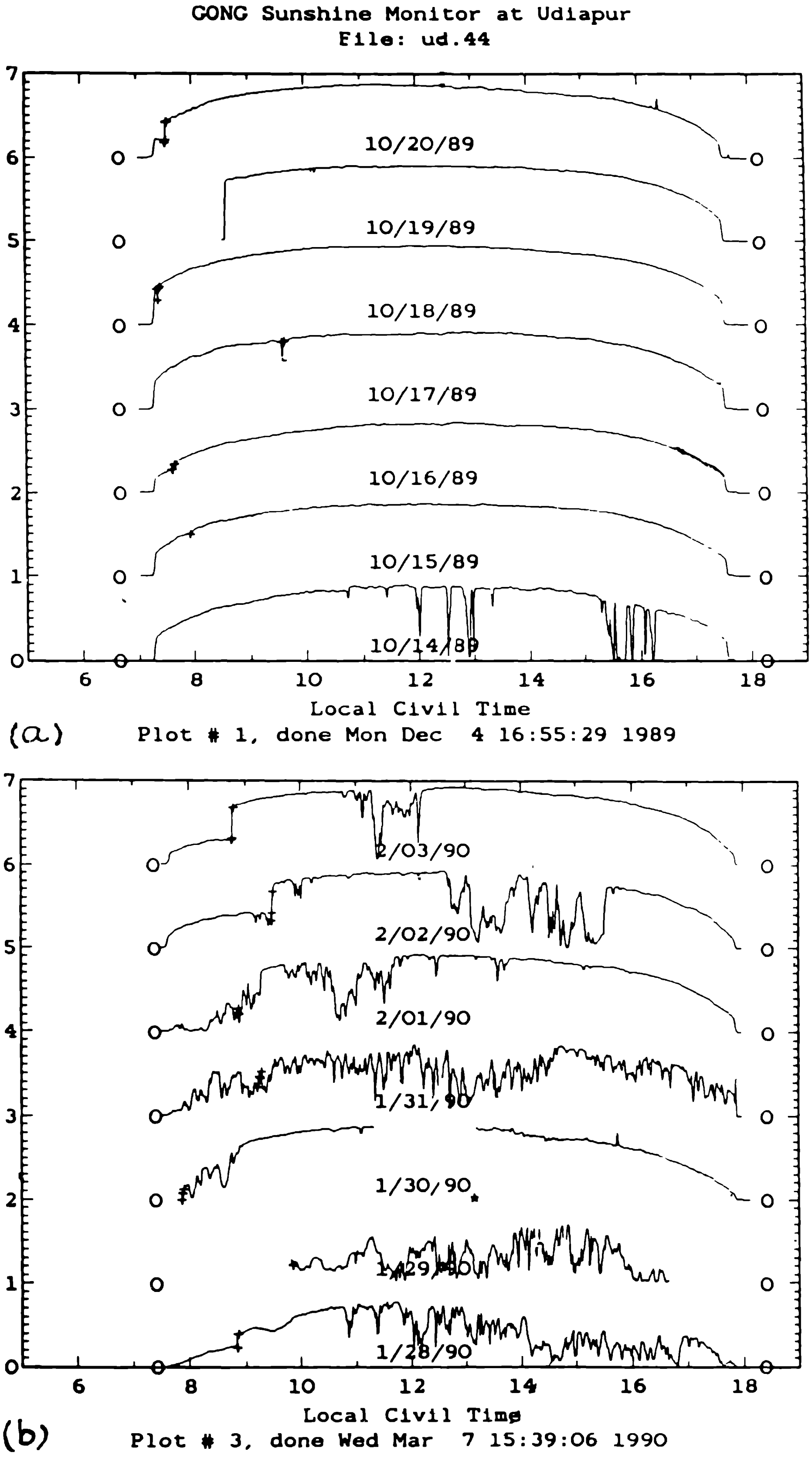


Figure 3. Examples of raw solar irradiance profiles during (a) a week of good weather, and (b) a cloudy week.

could have been clear or dark, but as no recorded data would be available, the observer's daily logbook may be used to ascertain the sky conditions during the broken periods.

Sunshine window for Udaipur site, covering November 1986-March 1991 period, is shown in figure 4. In this figure, a background grid has been plotted in which each box is 1 hour wide. The grid is 72 hour wide *i.e.*, 3 days are plotted along one column. A box in the grid is filled black if the sun was not visible at the corresponding time. Nights are marked by sweeps of 3 dark bands running horizontally in the figure. Seasonal variation of the length of day is also evident. Daily, or hourly solar visibility may be inferred instantly from the window covering more than 1587 days with a total of 15962 possible sunshine hours. It is found that there were 519 completely clear days with $\rho > 0.95$. Also, there were 223 days with $\rho < 0.05$, considered as completely dark days; most of them being during Indian monsoon period of July-September. Longest string of consecutive clear days of 13 days length started on October 19, 1987. Longest string of continuous dark days of 14 days length commenced on July 30, 1988—in fact this was the longest string of dark period found in the whole network. There were 43 instrumentally broken days due to UPS breakdown, or tracker or logger malfunctions. Monthly average values of daily clear time fraction is shown in figure 5 for the period covering the sunshine window of figure 4. On an average, Udaipur is measured to have clear skies around 63% of the times. Not surprising for south-eastern longitudes, a significant seasonal variation in the duty cycle is observed—marked by four prominent dips. These dips correspond to the cloud coverage over Udaipur site during the months of Indian monsoon.

In figure 6 is shown histograms of clear and dark time distributions in bins 1 hour wide. These give maximum length of unbroken clear (or dark) time of length 11.13 hr (11.37 hr). Percentage of continuously clear time of 9-12 hr duration is around 23%, which increases to 65% if continuous clear time longer than 4 hr but less than 12 hr are considered. This implies that one could expect to have around 238 days in a year at Udaipur when at least 4 hours of continuous sunshine is available. Clearly, it will rise much higher, above 83%, for periods of continuous sunshine of 1 hour or more. We have listed in table 2 the site performance records for Udaipur as compared to the best and the worst performances in the GONG network of candidate sites.

A measure of the amount of sunlight absorbed by the earth's atmosphere is given by the so-called "extinction coefficient" defined by the fraction of incoming radiation which is absorbed at perpendicular incidence. Alternatively, the fraction of light which is transmitted unabsorbed through the atmosphere is termed as "transmission or transparency coefficient". Monthly average extinction coefficients are plotted in the sequence of panels in figure 7 for each calendar month at Udaipur. Various statistical parameters of interest, *i.e.*, the averge and standard deviation of the data are listed in the panels. The quantities P_1, P_2 and P_3 are the percentages of time that the extinction coefficient was greater than 0.1, 0.2 and 0.3, respectively. Lower extinctions (< 0.20) have been obtained around the winter months, *i.e.*, November-February, while higher extinctions (> 0.22) are obtained around the summer months, *i.e.*, April-July. We estimate an overall average extinction coefficient of 0.2071 with standard deviation 0.0488 using the complete data base spanning more than 4 years.

In order to evaluate detectibility of solar *p*- and *g*-modes, it is desirable to compare avarage atmospheric transparency power spectrum with the average power contained in the frequency-bands of these modes. We have obtained power spectra of the monthly

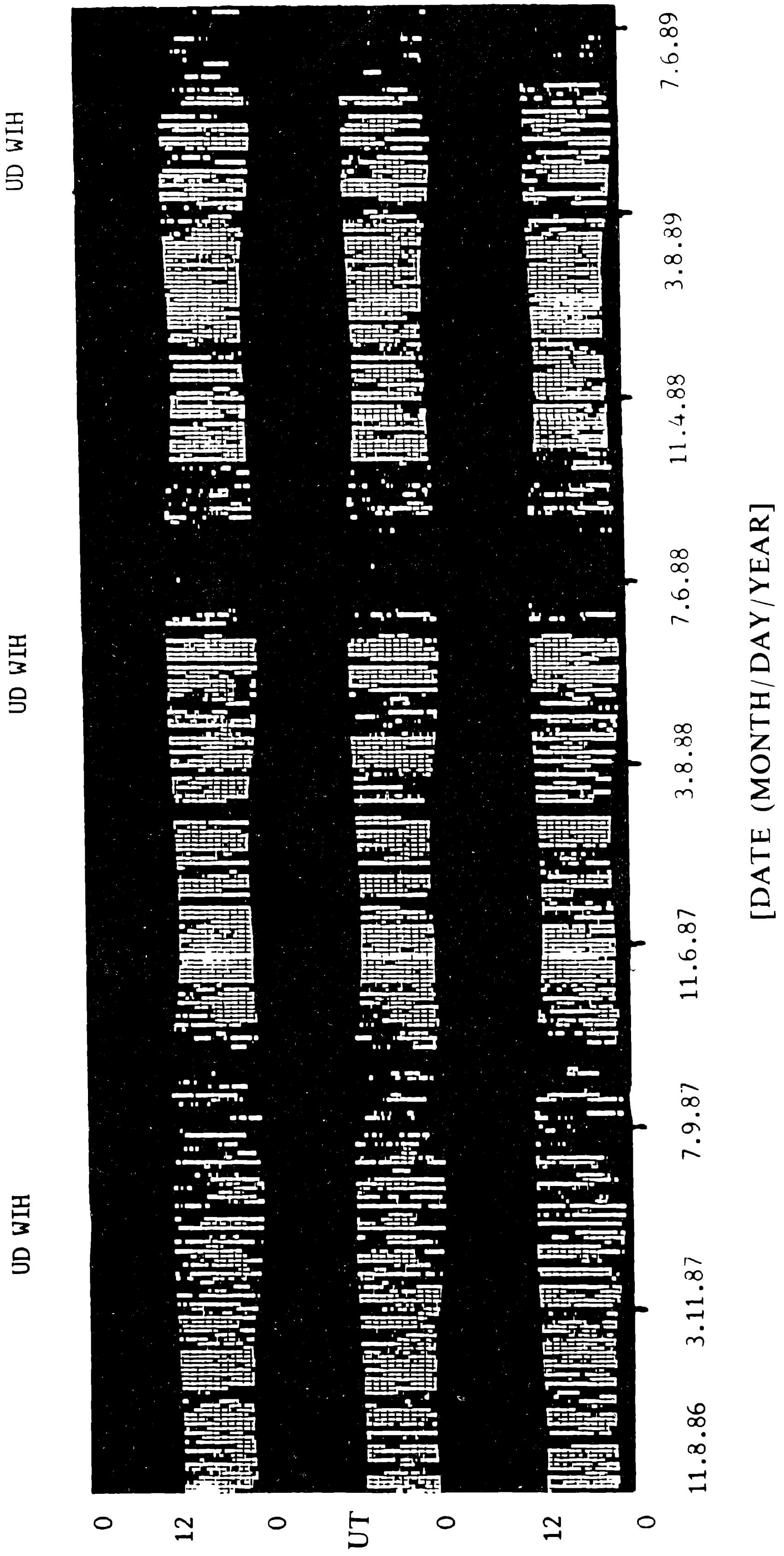


Figure 4. Sunshine window for Udaipur.

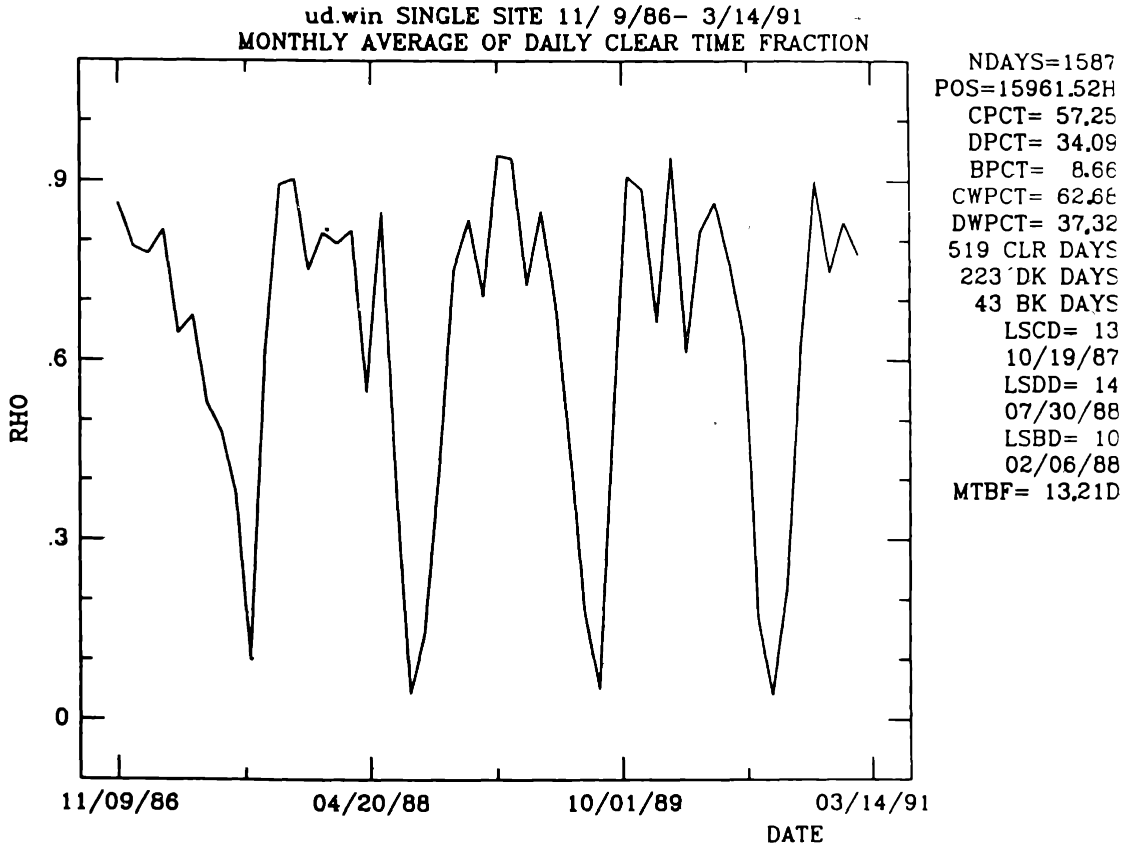


Figure 5. Monthly average of clear time fraction for Udaipur.

average transparency for each calendar month. In the panels of figure 8, solid curves are monthly average power spectra which are plotted along with the dotted curve representing average spectrum obtained from the entire USO data base covering 1986 November 9-1991 March 14. Here, the quantity NSPC is number of spectra that have been averaged together in the plot; GP is the average power in a "g-mode" frequency band between 80 and 200 micro Hz; *PP* is the average power in a "p-mode" band between 2000 and 4000 microHz. A total of 384 spectra have been used to obtain the dotted, overall average power spectrum which shows nearly monotonic decrease of power, from 2E-04 to 4E-08 $(I/Ic)^2/\text{Hz}$ in the frequency band 40-9000 microHz. The overall average g-mode and p-mode powers are obtained as 8.19E-05 and 3.43E-07, respectively, which are greater than the atmospheric transparency power in their

Table 2. Site performance record of Udaipur in the GONG network

	Highest	Lowest	Udaipur
Duty cycle (including downtime)	76.78	33.40	57.25
Percentage of clear weather	82.06	40.63	62.68
Percentage of completely clear weather (30 days)	99.66	4.03	4.03
Percentage of instrumental downtime	41.86	2.01	8.66
Meantime between failures (in days)	52.03	0.75	13.21
Longest length of continuous clear time (in days)	32	—	13
Longest length of continuous dark time (in days)	14	—	14

respective frequency bands, demonstrating the detectibility of the solar global oscillation modes from the Udaipur site.

A power spectrum for the site can be obtained by Fourier transform of the resulting sunshine window function. This power spectrum provides an amplitude spectrum that is convolved with the real solar spectrum, *i.e.*, each real solar frequency is surrounded on both sides by an image of the window spectrum. In order to discuss the quality of the spectrum in quantitative terms, three figures of merit may be defined, which are ratios of the DC component power in the window spectrum to average power in (i) the frequency band of 0 to 60 microHz, (ii) 1 microHz band centered on the first diurnal side-lobe, and (iii) 1 microHz bands centered on the first five side-lobes, respectively. They are thus roughly equivalent to signal-to-noise ratios and reflect the relative effect of the window on a solar frequency. The power spectrum of the first 60 microHz of the window at Udaipur site is shown in figure 9 along with these figures of merit, SNRB, SNFSL and SNASL, respectively. The power has been normalized to the power in the DC component, thus the height of the diurnal sidelobes represents their relative strength compared to any solar amplitude. The sidelobes are very prominent, with the first sidelobe having a log normalized power of around −0.3, representing a 50% amplitude relative to any solar spectral line. The background noise is at a level of about 1E-04. A similar power spectrum may be obtained for the six-site GONG network, as in Hill *et al.* (1988). It is seen that the prominent diurnal sidelobes appearing in the case of a single site are considerably attenuated. The noise background in the window power spectrum reduces by a factor of 50, first sidelobe by a factor of 400 and a set of five sidelobes by a factor of 200 as compared to a single site. Thus, a six-site network promises to produce solar oscillations nearly free of contamination by diurnal sidelobes. Preliminary results on network performances of various combinations of 6 sites have been published elsewhere (Hill *et al.* 1988). The Udaipur site constitutes an important link in these network calculations for achieving reported duty cycle of over 93%, more than adequate to accomplish the science goals of helioseismology (figure 10).

5. Conclusions

In all, there were 192 reasonably distributed 6-site networks possible from the 15 candidate sites participating in the GONG site evaluation program. A statistical comparison of the duty cycles for all these networks has shown that networks containing Udaipur Solar Observatory are superior to networks with an alternative site (Hill *et al.* 1991 a, b). As a result of this, the Udaipur Solar Observatory has been selected as one of the six sites that will comprise the GONG network. The other five sites, underlined in Figure 1, will be at Big Bear Solar Observatory (USA), Learmonth Solar Observatory (Australia), Observatorio del Tiede, Izana (Spain), Cerro Tololo Inter-American Observatory (Chile), and either Mees Solar Observatory, Haleakala or the High Altitude Observatory, Mauna Loa (Hawaii, USA). Figures 4 and 5 indicate clearly the severity of monsoon at the Udaipur site and the resulting sharp drop in the duty cycle during the months of July-August. During the monsoon season at Udaipur, the six-site GONG network effectively becomes a five-site network, hence to provide additional coverage during the monsoon season at Udaipur, an additional seventh site at Urumqi, China is under further study. Analysis of gap-filling techniques is currently underway to determine

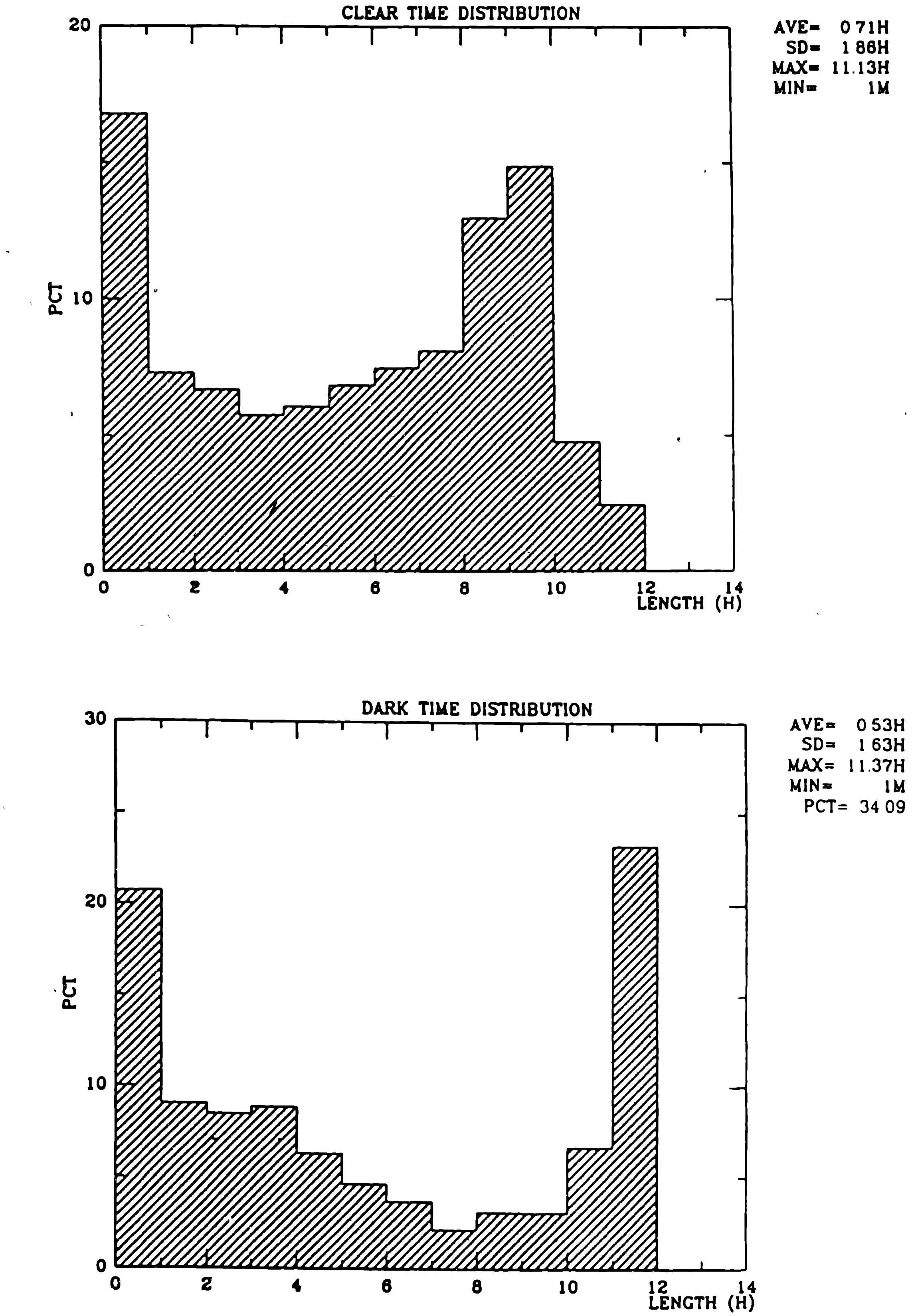
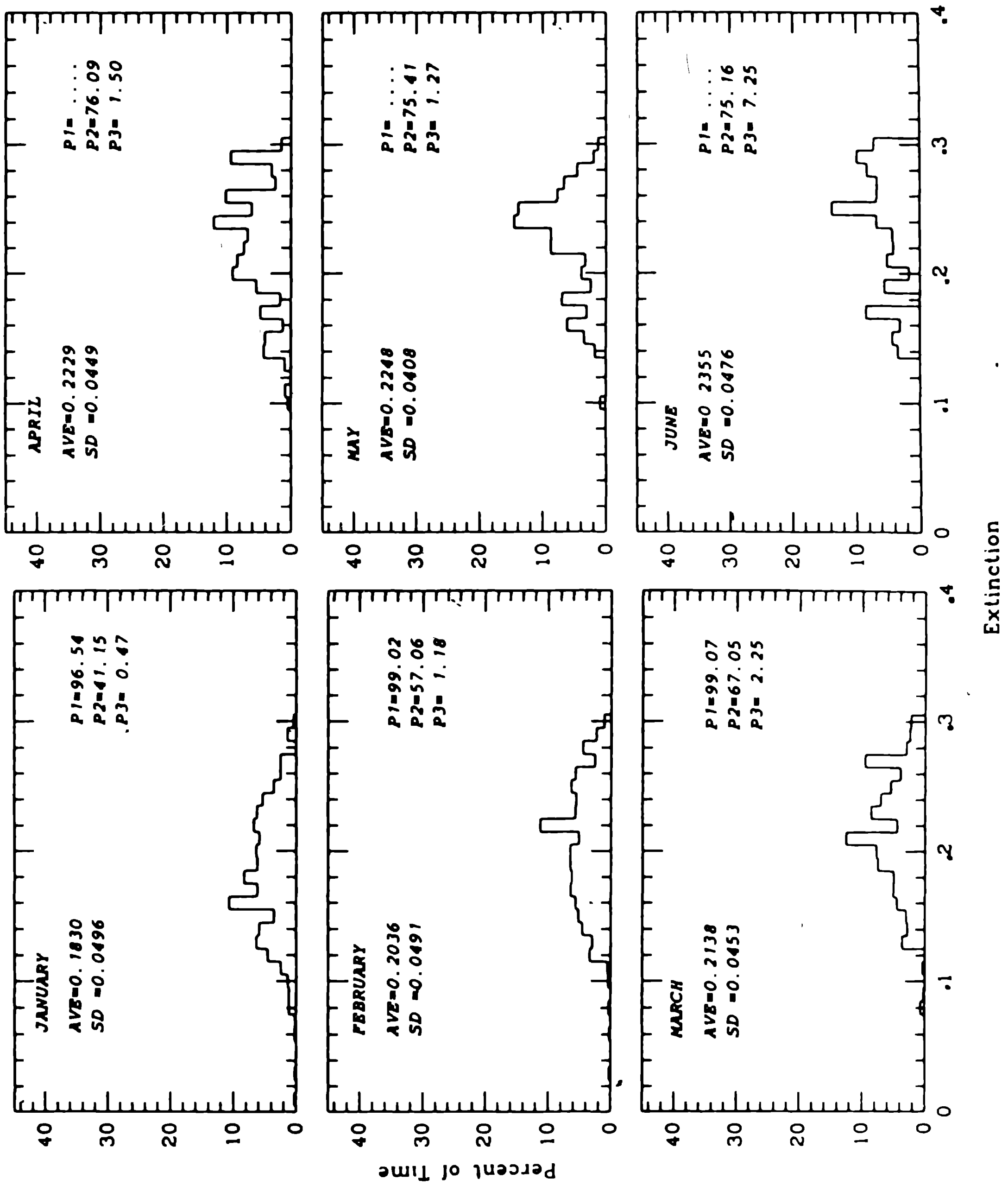


Figure 6. Clear and dark time distributions


JANUARY
AVE=0.1830
SD =0.0496
P1=96.54
P2=41.15
P3= 0.47
FEBRUARY
AVE=0.2036
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P1=99.02
P2=57.06
P3= 1.18
MARCH
AVE=0.2138
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P1=99.07
P2=67.05
P3= 2.25
APRIL
AVE=0.2229
SD =0.0449
P1= ....
P2=76.09
P3= 1.50
MAY
AVE=0.2248
SD =0.0408
P1= ....
P2=75.41
P3= 1.27
JUNE
AVE=0.2355
SD =0.0476
P1= ....
P2=75.16
P3= 7.25
Percent of Time
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30
20
10
0
Extinction
0
.1
.2
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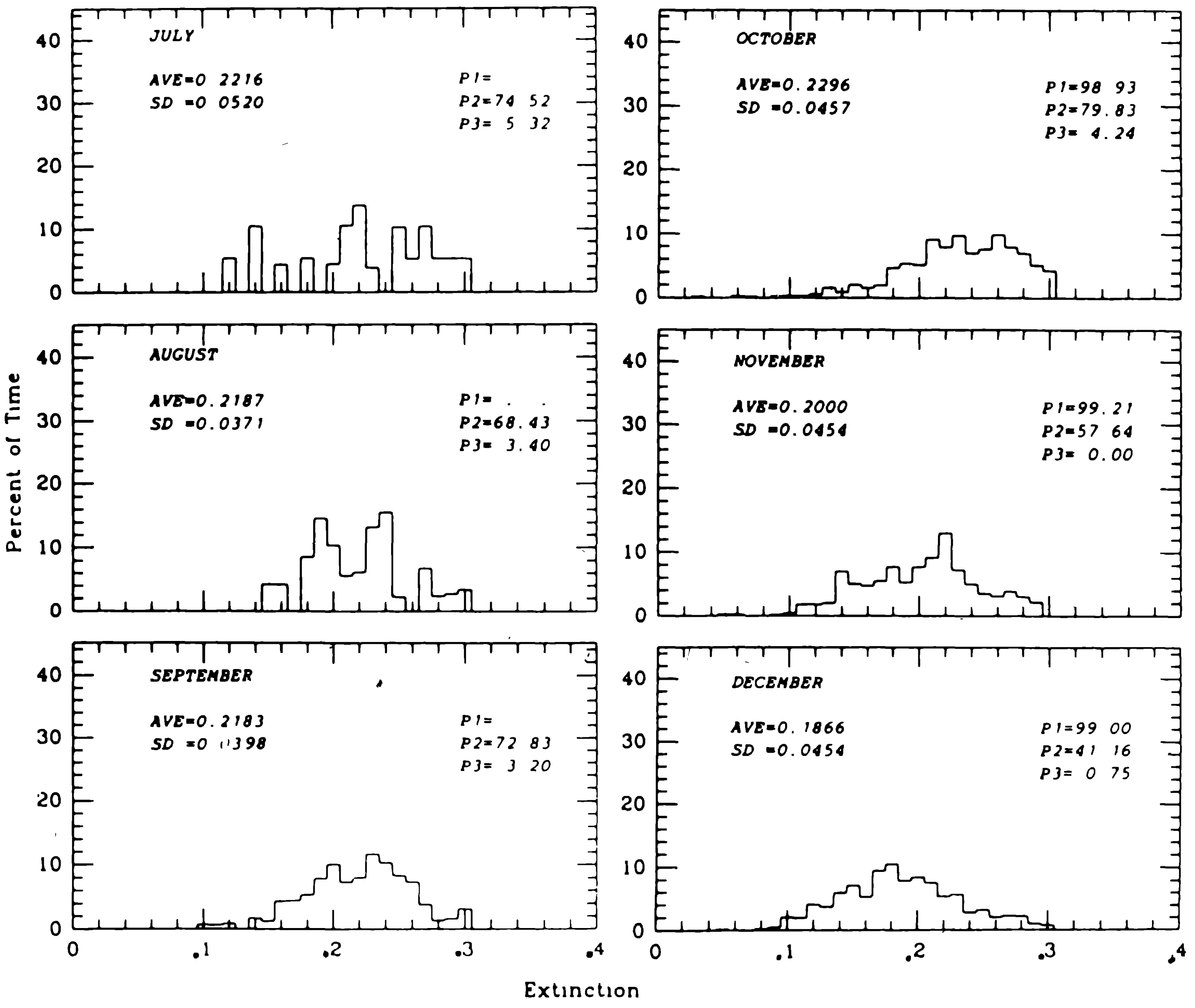
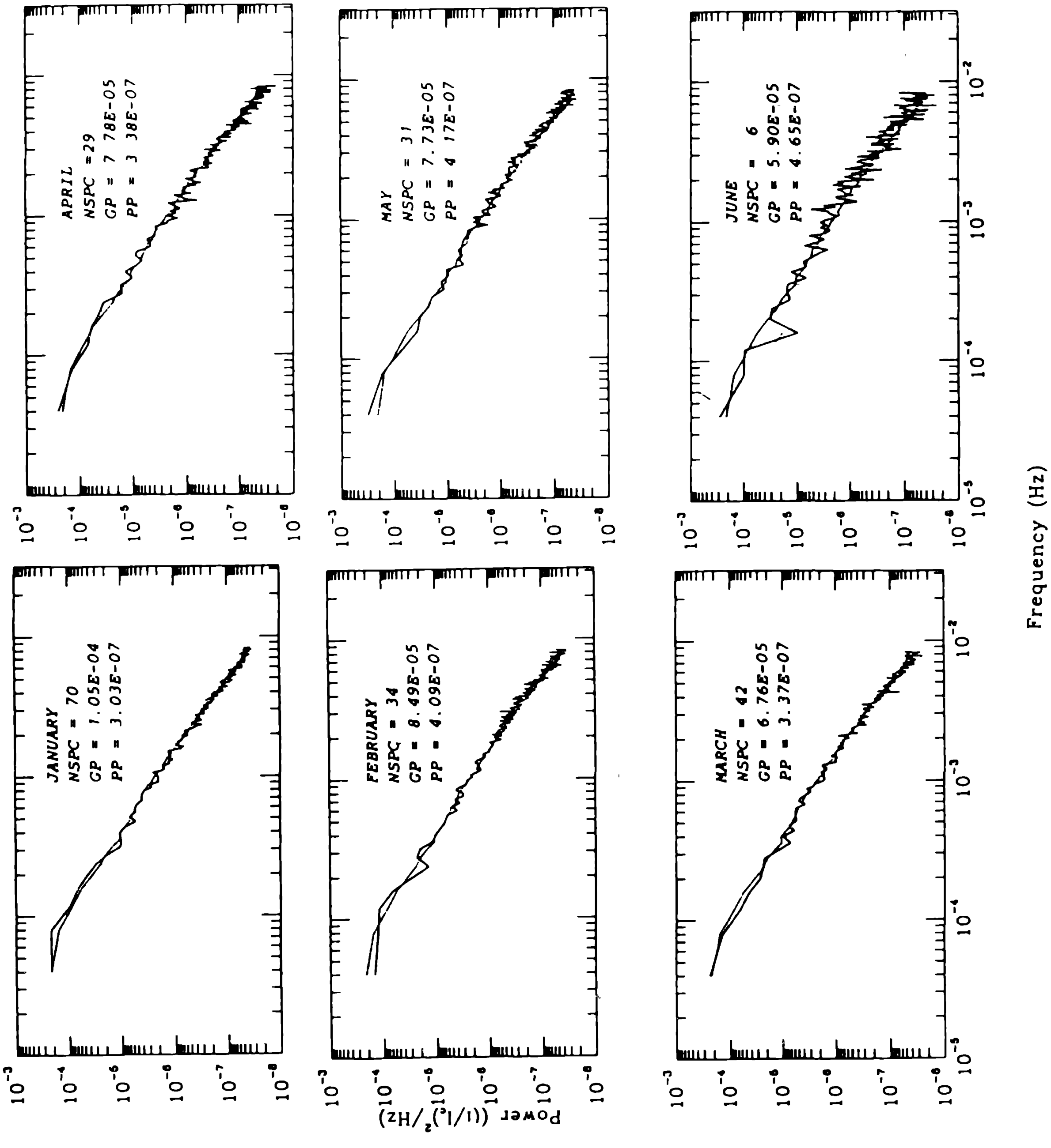


Figure 7. Monthly average extinction coefficients obtained from the sunshine data from November 8, 1986–March 14, 1991.


JANUARY
NSPC = 70
GP = 1.05E-04
PP = 3.03E-07
FEBRUARY
NSPC = 34
GP = 8.49E-05
PP = 4.09E-07
MARCH
NSPC = 42
GP = 6.76E-05
PP = 3.37E-07
APRIL
NSPC =29
GP = 7 78E-05
PP = 3 38E-07
MAY
NSPC = 31
GP = 7.73E-05
PP = 4 17E-07
JUNE
NSPC = 6
GP = 5.90E-05
PP = 4.65E-07
Power ((I/I$_c$)^2/Hz)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Frequency (Hz)
10^{-5}
10^{-4}
10^{-3}
10^{-2}

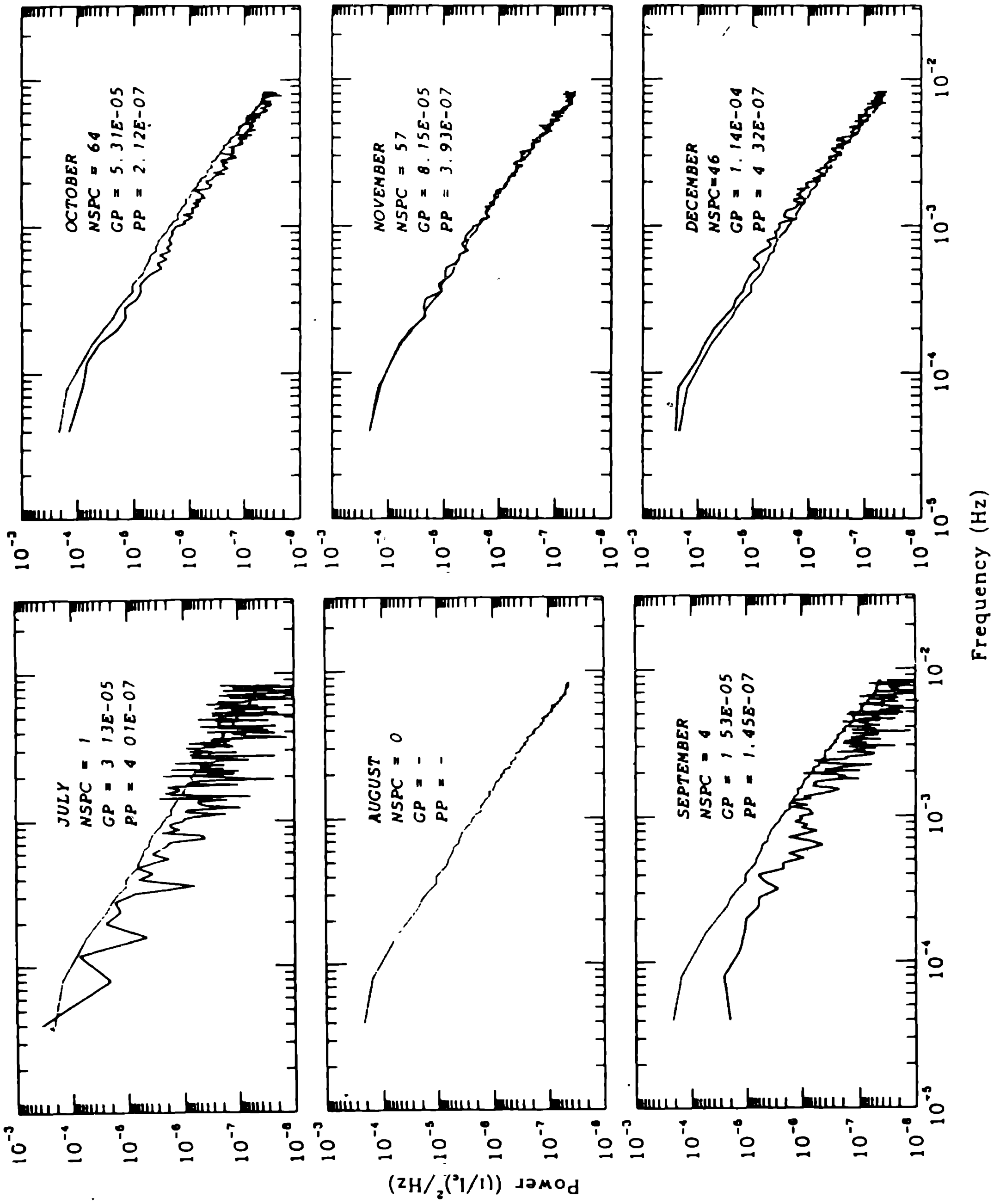


Figure 8. Monthly average transparency power spectra. The dotted curve in the monthly panels represents overall averge transparency spectrum obtained using 384 spectra during November 1986-March 1991.

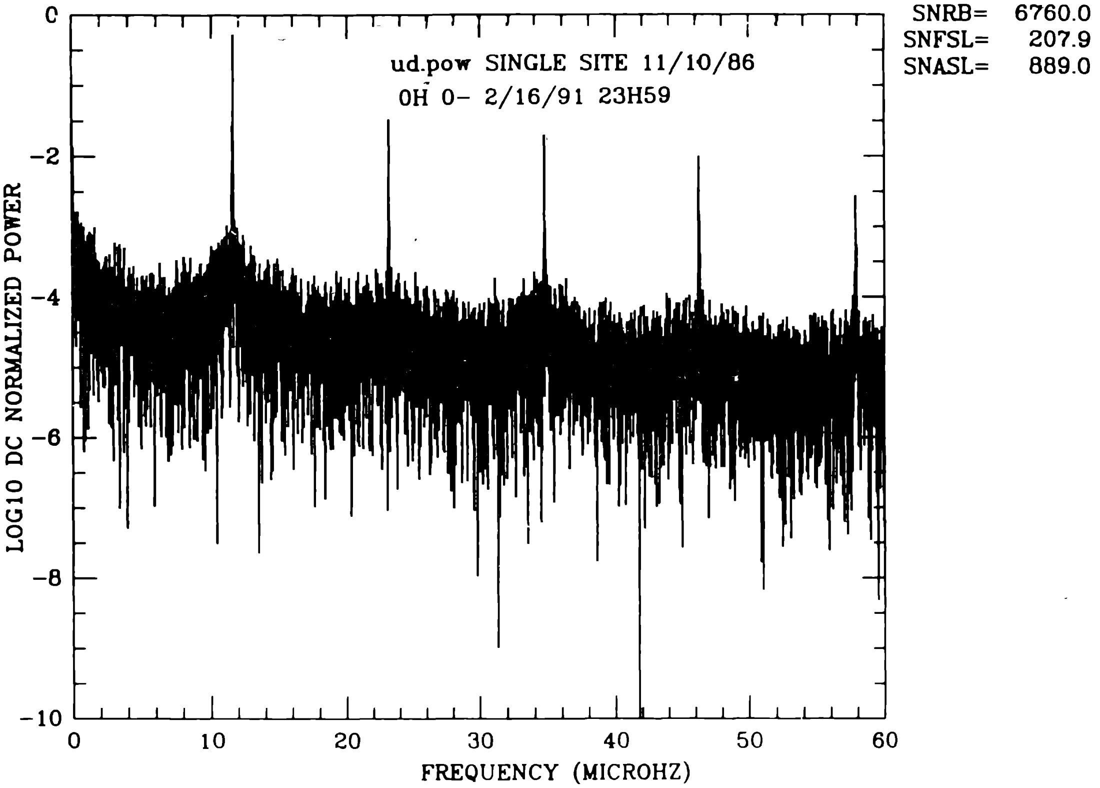


Figure 9. Single site sunshine window power spectrum obtained for Udaipur.

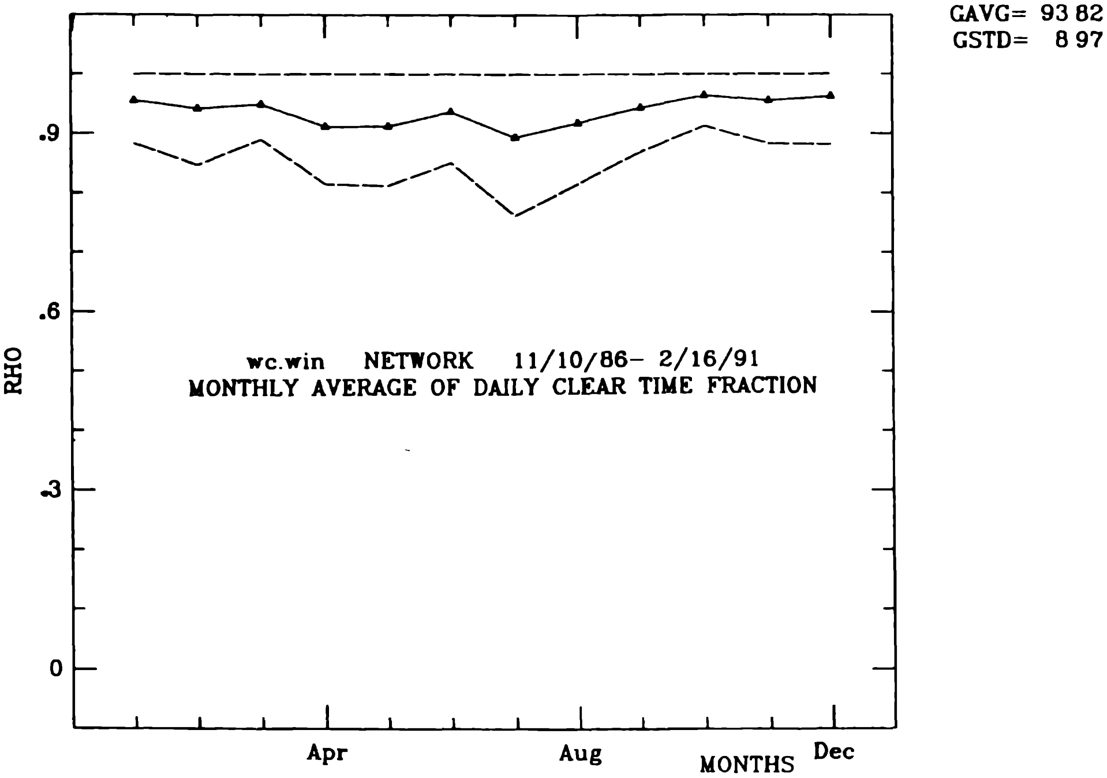


Figure 10. Monthly average of clear time fraction for the six site network consisting of Learmonth (Australia), Izana (Canary Islands), Udaipur (India), Hawaii (USA), Big Bear (USA), and Cerro Tololo (Chile).

if the improved network performance justifies the substantial additional cost of operating a seventh site in GONG network.

The deployment of the GONG network is currently scheduled for late 1993. It is anticipated that the network will observe for at least three, and perhaps six years to meet the goals of helioseismology. Indian scientists will have complete access to the data, which is expected to be useful for other non-helioseismic studies.

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