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ATMOSPHERIC OPACITY AT 215 GHz OVER SAN PEDRO MARTIR SIERRA IN BAJA CALIFORNIA

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RESUMEN

Presentamos mediciones de profundidad óptica de la atmósfera en 215 GHz (1.4 mm) sobre el Observatorio Astronómico Nacional en la sierra de San Pedro Mártir, Baja California, México. Para llevar a cabo las mediciones en forma contínua, hemos desarrollado un radiómetro computarizado que opera autónomamente por períodos extensos. De esta forma, se observó durante 210 días en 1992. Los valores medianos obtenidos para la profundidad óptica durante el día y la noche fueron de 0.24 y 0.20 respectivamente. La mediana total para profundidad óptica resultó en 0.22 en esta frecuencia. Para comparar estos valores con los de otros observatorios, convertimos la profundidad óptica a valores de columna de agua precipitable (PWV, por sus siglas en inglés), y encontramos que los resultados son similares a los reportados para Mauna Kea, Hawaii y Pico Veleta, España, lo cual confirma a San Pedro Mártir como un sitio promisorio para observaciones astronómicas en longitudes de onda que van desde infrarrojas hasta milimétricas.

ABSTRACT

We present radiometric measurements of the zenith optical depth at 215 GHz (1.4 mm) over the Observatorio Astronómico Nacional in the Sierra San Pedro Mártir, Baja California, México. In order to perform the measurements in a continuous way, we have developed a computerized radiometer that allows unattended operation for long periods of time. Observations were carried out during 210 days in 1992. The median values of day-time and night-time zenith sky optical depth of 0.24 and 0.20 respectively were found; the total median sky optical depth at this frequency was 0.22. To compare with other observatories, we have converted the sky optical depth to the Precipitable Water Vapor; in that case the results are similar to those reported for Mauna Kea, Hawaii, and Pico Veleta, Spain, thus placing San Pedro Mártir as a promising site for astronomical observations from the infrared through the millimetric region.

Key words: **ATMOSPHERIC EFFECTS — SITE TESTING**

1. INTRODUCTION

Several parameters must be considered in the selection of a location for new astronomical facilities. Among the most important is the optical depth of the sky at the frequency of observation. From millimeter through infrared wavelengths, sky opacity is dominated by the amount of oxygen and precipitable water vapor (PWV) present in the atmosphere. The amount of oxygen is roughly constant in time, while the content of PWV depends on weather and climatic patterns and can change on a relatively short time scale. A useful determination of the PWV must be obtained from measurements carried out over a long period.

The amount of precipitable water vapor can be measured by different methods: e.g., radiosonde probes, infrared hygrometer, detection of emission from astronomical objects, and emission from the atmosphere. Surface humidity measurements are not considered to be accurate indicators of the PWV (Reber & Swope 1972). In general, the emission from the atmosphere is the most feasible mean to measure this quantity in a continuous and automatic mode.

For measurements near 1 mm wavelength a numerical relation between the zenith optical depth and the column density of precipitable water vapor can be found (Zammit & Ade 1981); thus, the measurement of zenith optical depth at this wavelengths directly yields the PWV of the site.

This paper presents the results of the measurements of the zenith optical depth over the Observatorio Astronómico Nacional (OAN) in the Sierra San Pedro Mártir (SPM), Baja California, México in the 1 mm region. The observatory is located at latitude +31 N and longitude +115 W, and is at 2950 m above sea level. At this place, the Observatorio Astronómico Nacional, of the Universidad Nacional Autónoma de México (UNAM), is located. Among the facilities is the optical 2-m telescope that has been used for the past 10 years for photometric infrared observations with very good results. The data from the survey will help to establish the quality of the site and to decide the location of new thermal infrared, sub-millimeter and millimeter facilities, such as the Large Millimeter Telescope (LMT) planned to be constructed by the Five College Radio Astronomy Observatory (FCRAO) and the Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE); and for the Telescopio Optico-Infrarrojo Mexicano (TIM), a 6.5-m class telescope that will operate in the thermal infrared, under design by UNAM.

Measurements regarding PWV content, cloud cover and humidity for San Pedro Mártir, have been reported in the past. Westphal (1974) obtained low precision measurements of sky emission at 10 μm for San Pedro Mártir, during a 10 month survey in 1971–1972, indicating a considerable fraction of time (36%) with low sky noise emission ($< 5 \times 10^{-7}$ watts cm^{-2} str^{-2}). For the same period, Alvarez & Maisterrena (1977) measured the amount of PWV by means of the atmospheric opacity to solar radiation in two adjacent filters at 1.65 μm and 1.87 μm, obtaining a median value close to 2.5 mm of PWV (mean = 3.3 mm). Tapia (1992) has compiled 10 years of weather statistics and found an average of 80.4% of spectroscopic quality nights and 56.7% of photometric quality.

2. EQUIPMENT

2.2. Selection of the Frequency of Operation

For wavelengths smaller than 1 cm, sky emission is dominated by radiation coming from the atmosphere. For frequencies between 10 GHz and 300 GHz, the flux of radiation from the atmosphere increases monotonically with frequency and presents strong emission lines from oxygen and water vapor. For frequencies over 200 GHz the emission is dominated by the water content.

Measurements made at the center of emission lines have higher signal to noise ratio. However, the peak of the emission line is very sensitive to temperature and pressure changes that produce broadening of the line, and can be mistaken as changes in the amount of emitting material. This effect can be minimized by selecting a frequency displaced from the line center (Hogg et al. 1983). Indeed, atmospheric optical depth in the wing of these lines is optically thin, so in this case we can get an estimate of the total amount of water vapor through the atmosphere.

Although measurements at lower frequencies could simplify the electronics of the receiver, extrapolation of the measured opacities from the microwave to the millimeter region can carry large uncertainties. Therefore, since we are interested in sky opacities at millimetric wavelengths and shorter, we decided to observe at the upper wing of the resonant line of water vapor located at 183.3 GHz.

2.2. Equipment Description

Figure 1 illustrates the basic radiometer system block diagram. A 35.8 GHz Gunn oscillator produces a signal which is subsequently tripled and after the second harmonic mixer yields a 215 GHz local oscillator frequency (LO). The second harmonic mixer combines this LO with the signal emitted by the sky. The result is sent through a 1–2 GHz amplifier followed by a 350 MHz bandwidth 1.2 GHz filter, which is then followed by a second amplifier. An attenuation of 6 dB between the two system amplifiers maintains a linear output response at the detector, which generates a DC signal proportional to the sum of the system noise temperature and the temperature of an object which fills the receiver beam. We have found that, when followed by an instrumentation amplifier with a gain of 1 000, the detector produces a signal of 1.1 V, for an ambient temperature load (297 K). The signal drops by 0.4 V in response to a microwave absorber at liquid nitrogen temperature (77 K) which fills the beam. The system noise temperature is approximately 6 400 K. The system is coupled to the sky through a feed horn that provides a 10 degrees field of view.

A single board computer inside the radiometer reads the signal and various other housekeeping in-

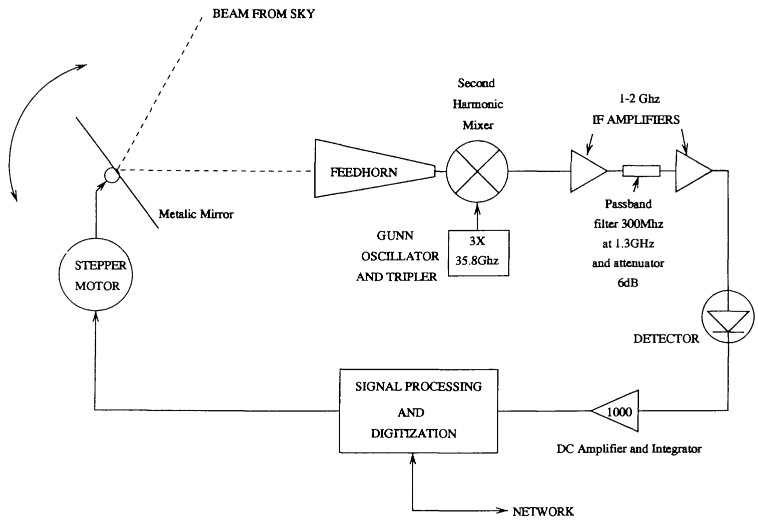

Fig. 1. Basic radiometer system block diagram.

formation, through a 12 bit analog to digital (A/D) converter, spanning the range from 0 to 4.5 V. A multiplexor at the input of the A/D converter, allows to read one of the 8 input channels. At present seven channels are used to read the following: detector output, computer expansion board temperature, outside ambient temperature, Gunn oscillator temperature, first amplifier temperature, system power supply, Gunn oscillator power supply.

This computer also controls the position of the beam-reflecting mirror via a stepper motor. The stepper motor completes one full revolution in 400 steps (0.9 degrees/step). An infrared sensor provides a consistent optical reference for the home mirror position.

The microprocessor that resides on the computer, has its own restricted subset of BASIC language stored in on-chip read-only memory (ROM). The control program for the radiometer resides in a separate erasable programmable ROM (EPROM); the principal duties of this program are to read the A/D converter, to control the stepper motor, and to communicate the radiometer through a serial port. After setting the date and time, the program scans the sky from near zenith to near horizon once every few minutes.

Data from the radiometer is sent through a serial communication port to a host computer, installed in a more favorable environment, where they are displayed on the screen and stored on hard disk. If the host computer is on a network, the acquisition program is able to transmit the results once a day to any other computer connected to the network.

3. MEASUREMENTS

The radiometer was installed close to the 84 cm telescope building, near to the summit of the OAN mountain. It was tilted to 30 degrees from the horizontal and the mirror scanned the sky from near the zenith to the North. Although some low-level azimuthal anisotropies might be present, the sky was scanned only in the North-South direction to simplify data reduction and interpretation. We took precautions to protect the radiometer from direct exposure to sunlight, in order to avoid gain changes of the amplifiers produced by changes in temperature.

The observations were made on a continuous basis, with emission measurements made every four minutes for eight zenith distances: 26.4, 44.4, 53.4, 58.8, 64.2, 66.0, 69.6, and 71.4 degrees. Unfortunately, no measurements were made at the zenith that will allow us an extra check up of our results. These zenith distances were selected so they cover the sky uniformly and also to adjust the size of the step at the stepper motor of the receiver. By using the 6 zenith distances we minimize the effect of the curvature of the atmosphere and the finite beamwidth of the antenna. Corrections for spillover effects were made for large zenith distances; this is specially important since the spillover introduces in the tilt radiometer the signal from the ground.

Measurements of the sky at the indicated zenith distances are alternated with reference measurements of an ambient temperature load, located on the back of the scanning mirror. A complete scan takes one minute. The time, date, temperatures and system voltages, are recorded with each set of data.

The radiometer operated continuously from January 22 to December 16, 1992. However, some data were lost through the year due to various problems, mainly associated with the operation of the radiometer. Additional data were lost because of an intermittent failure of a power supply, during late May and early June. Even so, we do not believe that the lost data are representative of any weather conditions in particular.

4. RESULTS

4.1. Reduction Theory

Ignoring the cosmic background radiation, the measured antenna temperature at the input of the radiometer is given by

$$T_{ANT} = \eta T_{ATM}(1 - e^{-\tau}) \ , \qquad (1)$$

where T_{ATM} is the atmosphere temperature, η is the coupling factor between the antenna and the radiometer, and τ is the optical depth, which we wish to measure.

Including the noise temperature of the receiver T_{RX}, the expressions for the antenna temperature for the sky and the load reference are given, respectively, by

$$T_{SKY} = \eta T_{ATM}(1 - e^{-\tau}) + T_{RX}, \qquad (2)$$

and

$$T_{REF} = \eta T_{LOAD} + T_{RX}. \qquad (3)$$

The voltage at the output of the amplifier is related to the antenna temperature by a factor g, and the comparison of voltages for a sky measurement to the reference yields

$$V_{REF} - V_{SKY} = g\eta(T_{LOAD} - T_{ATM}(1 - e^{-\tau})). \quad (4)$$

If we assume an isothermal atmosphere, the ambient temperature surrounding the receiver T_{LOAD} would be approximately the same everywhere (i.e., $T_{LOAD} \approx T_{ATM}$); thus we have

$$V_{REF} - V_{SKY} = g\eta T_{ATM} e^{-\tau}. \qquad (5)$$

The optical depth τ at a given direction in the sky, can be expressed in terms of the optical depth at the zenith τ_0 by

$$\tau = \tau_0 sec(z), \qquad (6)$$

z being the zenith angle.

Thus equation (6) can be written as

$$ln(V_{REF} - V_{SKY}) = -\tau_0 sec(z) + ln(g\eta T_{ATM}). \quad (7)$$

In the case of an isothermal atmosphere, there is a linear relation between the logarithm of the differences of the voltages, which are measured, and the zenith distance, which is known. We can then solve for the slope, which is the zenith optical depth. Also the last term in equation (7) contains, among other things, the gain of the radiometer and can be used to estimate the stability of the system.

If we assume a difference in temperature between the atmosphere and the ambient temperature $\Delta T = T_{LOAD} - T_{ATM}$, then

$$V_{REF} - V_{SKY} = g\eta(\Delta T - T_{LOAD} + \Delta T e^{-\tau}). \quad (8)$$

We assumed that temperature differences between the load T_{LOAD} and the weighted value of T_{ATM} is constant ($\Delta T = 20K$). Then another method to determine τ_0 is to obtain a non-linear fit of this equation to the measured values. Again the returned value of the fit for $g\eta\Delta T$ can be used to estimate the stability of the radiometer.

We fit the data to the linear and the non-linear model. Comparing the χ^2 merit of value, the non-linear model does a better job in deriving the value of τ_0 only for values bigger than 0.5, which represent a small portion of the data. We have thus decided to use a linear model.

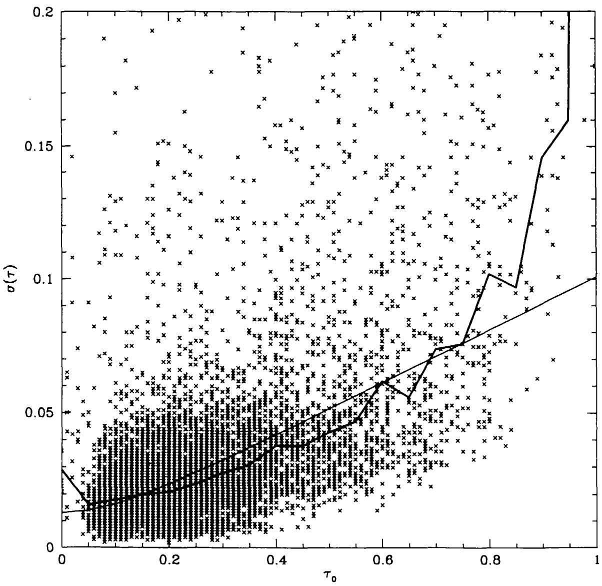

Fig. 2. Dispersion σ_τ in the measurements of τ_0. Individual measurements are marked with crosses and the median is indicated with a thick solid line. A consistent (1σ) model is indicated with a thin line and is described in the text.

4.2. Data Reduction

We calculated zenith optical depths as outlined above, by fitting a straight line to the first 6 zenith angles of each individual observation (taken every 4 minutes). We then grouped the 4 minute values in 30 minute bins, using the median as an indicator of the central tendency. The dispersion σ_τ in bins, can be taken as an indication of the intrinsic noise and the stability of the system. In Figure 2 we present this dispersion as a function of τ_0. Individual measurements are marked with crosses and the median is indicated with a thick solid line. A consistent (1σ) model is indicated with a thin line and is described as follows: Three regimes can be identified

1) For very small the optical depths ($\tau \rightarrow 0$) the dispersion takes a constant value $\sigma_\tau = 0.013$, which is to be identified with the intrinsic precision of the measurements.

2) A roughly proportional region of $\sigma_\tau = 0.10\tau_0$, for $\tau_0 < 0.6$, which can be due to real variations in τ_0 in short intervals, or variations of τ for different directions in the atmosphere.

3) For $\tau_0 > 0.6$ the variations are consistently random and can be large, implying that the approximations and assumptions used in various steps are no longer valid, and the measurements may be in error. Fortunately, this occurs at large values of τ (0.6 $\approx$ 11 mm of PWV, see below) and is of no concern to us. Measurements of τ_0 below this limit are thus good to better than 10% or 0.013 (0.24 mm of PWV), whichever is larger. However, there are points that deviate largely from the median all over. From the raw data it is apparent that large variations are obtained under clouds or rain, with the probable exception of some data taken during May, when a power supply of the radiometer failed. However, we will count all points with $\sigma_\tau > 0.15$ as cloudy conditions and we will not use them for calculations of the median τ.

The time evolution of the optical depth is presented in Figure 3 for each month of the year 1992. The thin lines in the bottom of the graphs represent data lost in the operation of the acquisition program, and are not due to bad weather. Data taken under cloudy conditions identified with a thick line on the top of the figures. In Figures 4 and 5 we present differential and cumulative distributions for each month. The values for the median and dispersion are quoted there (see also Table 1), as well as the amount of data sampled each month (i.e., not lost), and the fraction lost due to cloudy conditions, which amounts to 16% through the year.

5. DISCUSSION

In Figure 6 we present the differences in the mean opacities corresponding to day-time and night-time, for each day of the year. The conditions are somewhat better during night-time, but the dispersion is larger than the mean, preventing to derive general conclusions on this issue. However, for days between 100 and 140 the dispersion is lower, so better night conditions can be emphasized there. These data correspond to the months of April and early May. During these months there was a fast increment of the optical depth in the morning, probably due to the ascent of a convective moist cell up to the top of OAN-SPM. A corresponding decrease was observed during the afternoon.

Since there is little variation between day and night conditions, we can further address the question of the duration of certain observing conditions, or how long the good time lasts. In Figure 6 we show the frequency (fraction of the year) with observing conditions better than a given τ, that last for a certain period of time. We can see, for example, that 45% of the time there are continuous periods of 8 hours with $\tau < 0.24$ ($\approx$ 4.4 mm of PWV); 39% of the time for periods of 4 hours with $\tau < 0.2$. Periods of $\tau < 0.12$ occur 23% of the time, but last only for one hour, while those that last for 4 hours occur 10% of the time. It is not unusual that fair conditions last for continuous periods of up to 40 hours. This detailed analysis is usually not made or published for other observatories.

In order to compare the San Pedro Mártir results to other sites, we separated the data into day and night time, and transformed the zenith optical depth at 215 GHz to millimeters of PWV. For this purpose we have used the numerical relation where τ=1 corresponds to 18.4 mm of PWV. This is the conversion value found by Danese & Partridge (1991) for Kitt Peak for zenith optical depth at 225 GHz. This value is also close to the one found by Zammit & Ade (1981) for a frequency of 212.4 GHz. Table 1 gives the monthly median values of PWV measured during the year of 1992, separated into day and night time values. Also shown in this table are the fraction of data available for the statistics, the fraction of cloudy time, and the median, first and third quartile for each month.

Mauna Kea is known to be an excellent astronomical location, especially for infrared observations, and Quesada (1989) has found that Pico Veleta in Spain has similar conditions, as far as water vapor content is concerned. Merril & Forbes (1987) have found an annual average of PWV $\approx$ 3 mm above Mauna Kea. Quesada (1989) found an annual average of PWV $\approx$ 2.97 mm for Pico Veleta. At Kitt Peak, Cota & Sramek (1984) have measured for the months of June and July optical depths at 225 GHz between 0.211 and 0.799 with an average of 0.449; i.e., PWV from 3.6 to 14 mm with an average of 8 mm . For San Pedro Mártir we found an annual average of PWV $\approx$ 4.05 mm.

On the other hand, Bely (1987) gives night-time

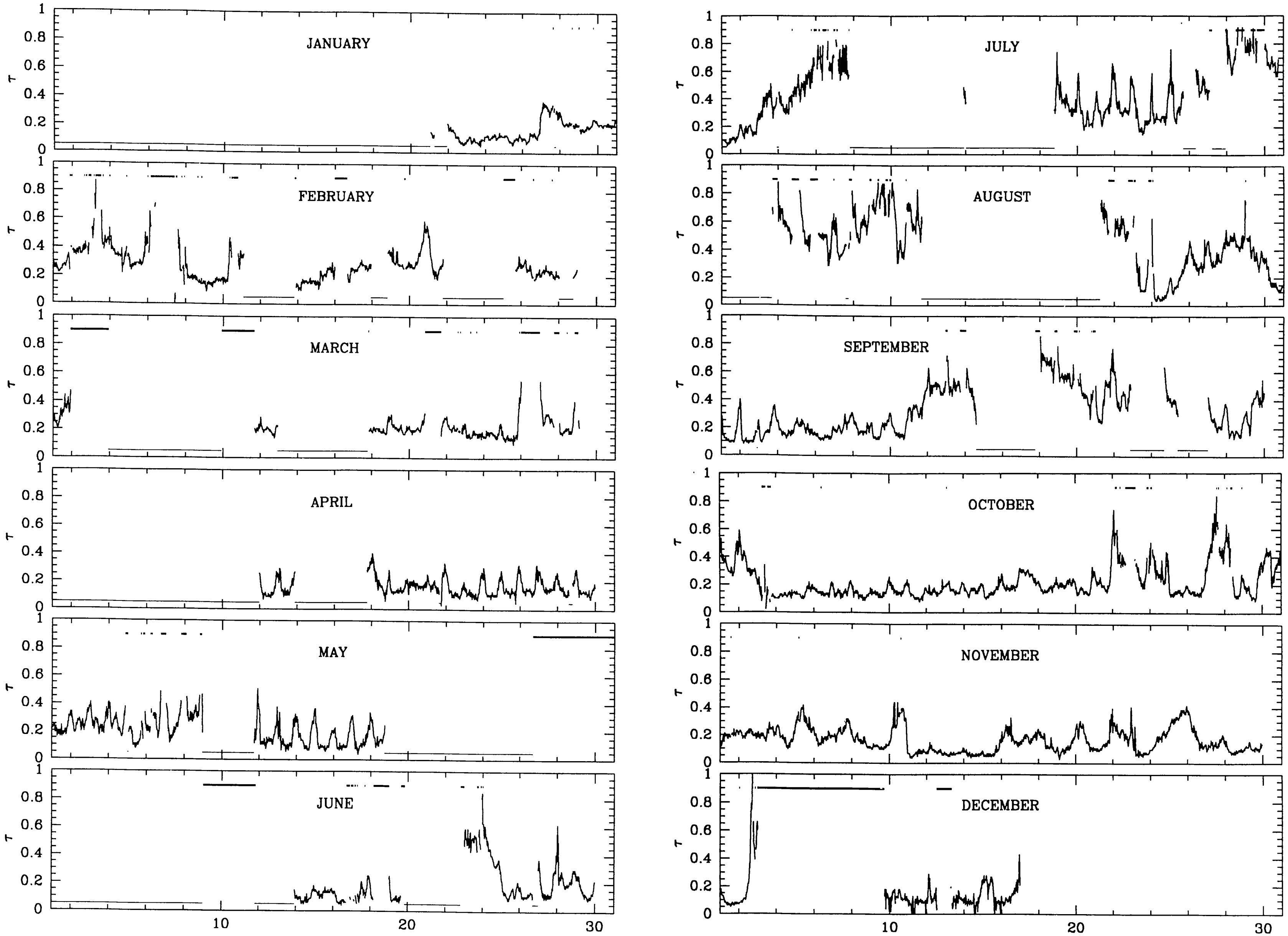

Fig. 3. Time evolution of the optical depth for each month of the year 1992. The thin lines in the bottom of the graphs represent data lost in the operation of the acquisition program. Data taken under cloudy conditions is identified with a thick line on the top of the figures.

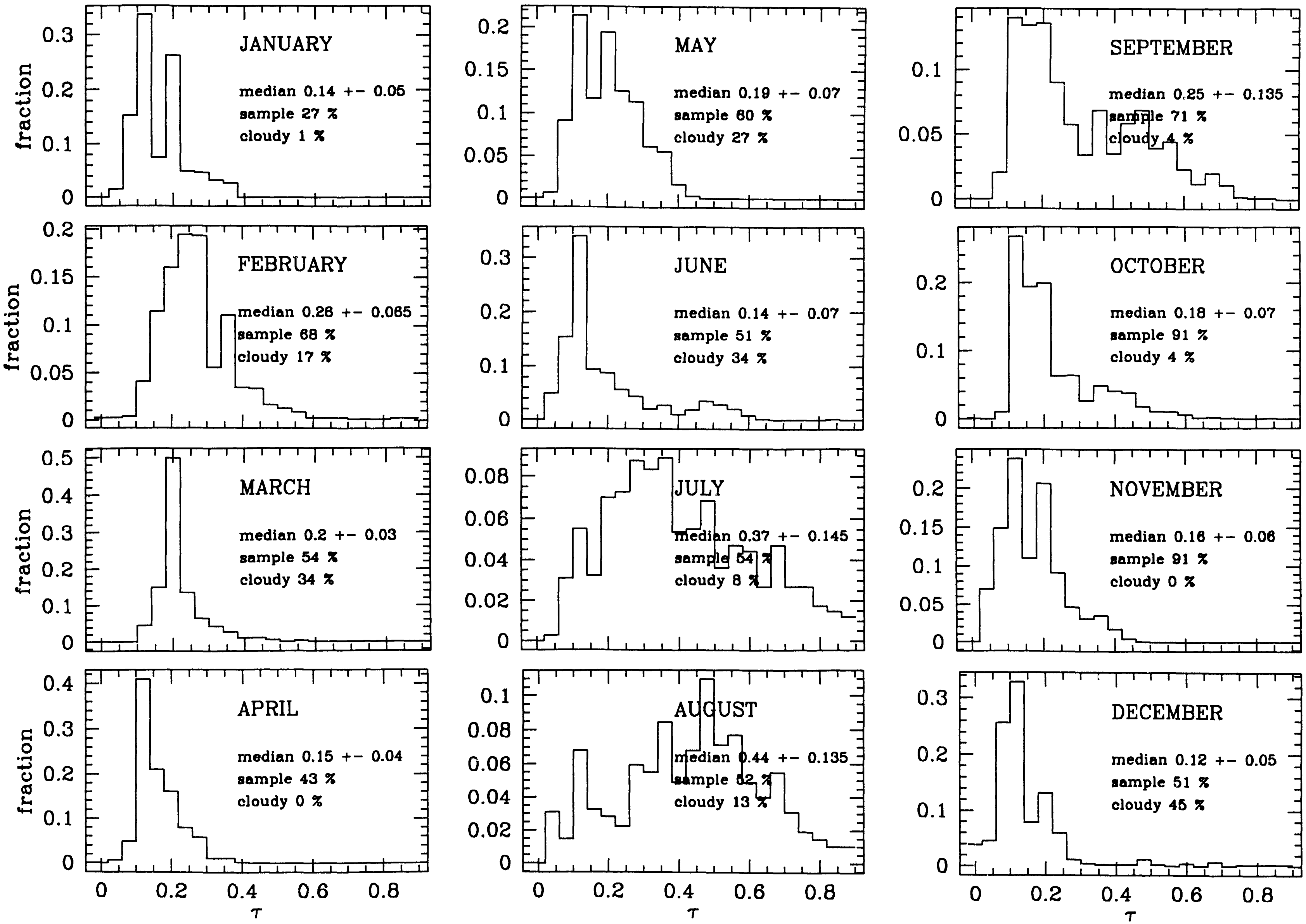

Fig. 4. Differential distributions of optical depth for each month of the year 1992. The values for the median and dispersion are quoted there (see also Table 1), as well as the amount of data sampled each month (i.e., not lost), and the fraction lost due to cloudy conditions.

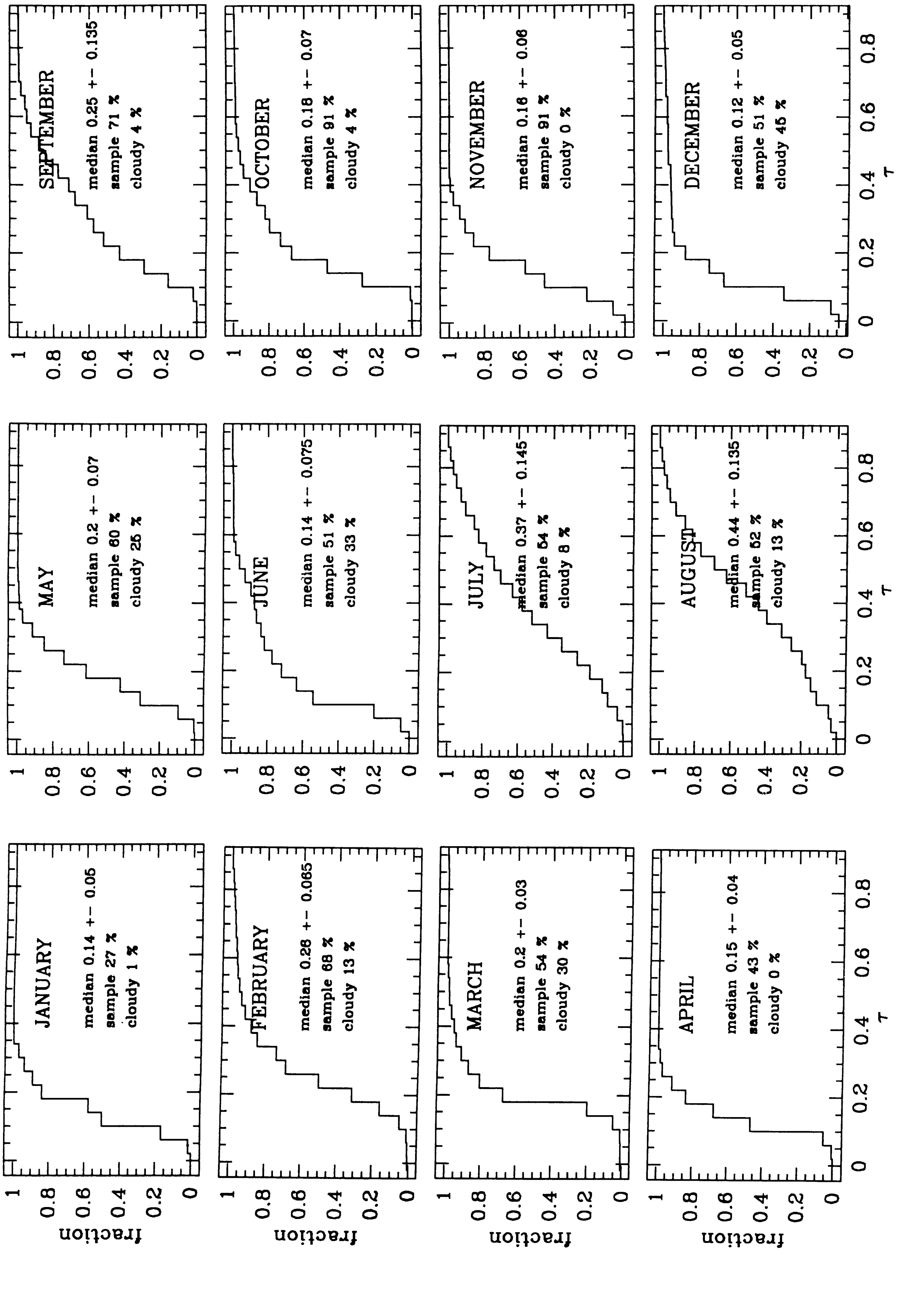

Fig. 5. Cumulative distributions of optical depth for each month of the year 1992. Same quotations as in Figure 4.

TABLE 1

MONTHLY AVERAGES OF PWV OVER OAN-SPM

Month	Samples %	Cloudy %	day-time (mm of PWV)	night-time (mm of PWV)	Median (mm of PWV)	1^{st} Quartile (mm of PWV)	3^{rd} Quartile (mm of PWV)
January	28	1	2.76	2.59	2.76	1.82	3.21
February	75	13	5.14	4.59	4.96	3.28	5.68
March	49	30	3.85	3.68	3.68	3.28	3.85
April	46	0	3.13	2.44	2.76	1.82	2.93
May	54	25	4.22	3.3	3.68	1.84	4.4
June	42	51	3.3	2.38	2.76	1.84	5.68
July	53	8	7.53	6.98	7.36	4.76	10.26
August	53	13	5.52	4.77	8.79	5.13	11.55
September	78	4	5.52	4.77	5.13	2.93	7.34
October	91	4	3.5	3.11	3.29	2.01	4.58
November	97	0	3.51	2.45	2.92	1.27	3.48
December	25	45	2.21	1.84	2.01	0.71	2.19
Total median	58	16	4.42	3.68	4.05	2.56	5.02

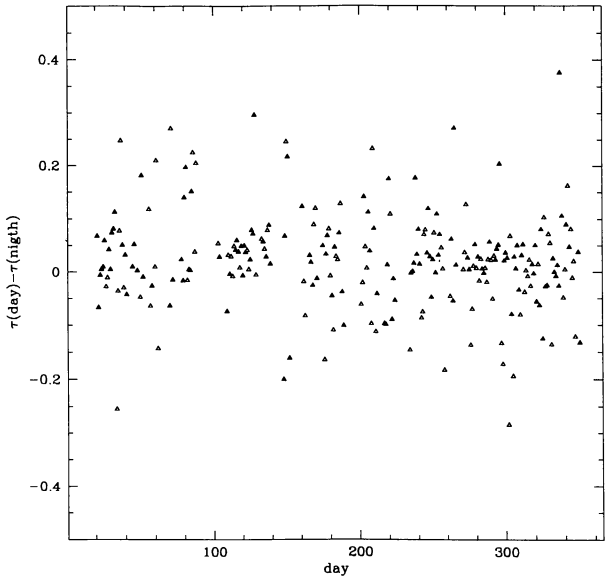

Fig. 6. Differences in the mean opacities corresponding to day-time and night-time, for each day of the year.

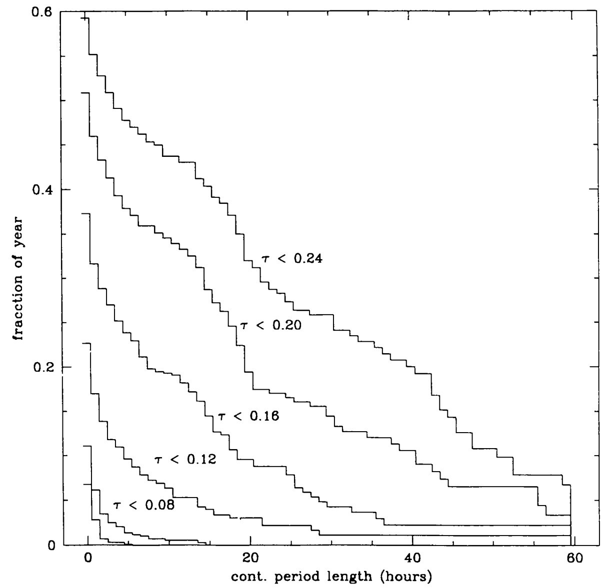

Fig. 7. The frequency (fraction of the year) with observing conditions better than a given τ, that last for a certain period of time.

values of 1.2 mm above the Hawaiian mountain, while in the case of Pico Veleta the value found is 2.1 mm. For San Pedro Mártir this value is 3.68 mm.

In addition, similar to Pico Veleta, a seasonal variation is observed at San Pedro Mártir. Compared with Mauna Kea, where PWV remains practically constant along the year, the values at San Pedro Mártir show larger variations in shorter time periods during the summer. During the fall and beginning of winter the optical depth stays very stable over large periods of time.

6. CONCLUSIONS

We have presented the results of a study of the atmospheric optical depth over the Observatorio Astronómico Nacional in San Pedro Mártir, Baja California, México. We found that the median of the PWV is 4.05 mm, for day-time the median PWV is 4.42 mm and for night-time the median PWV is 3.68 mm. These results are similar to Mauna Kea, Hawaii, and Pico Veleta, Spain. This qualifies San Pedro Mártir as an excellent astronomical site, as far as water vapor content is concerned. However, there is some concern from the authors that 1992 may had been affected by El Niño condition turning it into a particularly wet year. Provision has been taken to establish a permanent monitoring of the sky optical depth at 215 GHz at the OAN-SPM.

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