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ADDITIONAL ATMOSPHERIC OPACITY MEASUREMENTS AT MILLIMETER WAVELENGTHS FROM SAN PEDRO MÁRTIR SIERRA IN BAJA CALIFORNIA

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RESUMEN

Se presentan mediciones de la opacidad atmosférica en la dirección del cenit a una longitud de onda de 1.4 mm (210 GHz) sobre el Observatorio Astronómico Nacional en la Sierra de San Pedro Mártir, Baja California, México (San Pedro Mártir Observatory). Los datos cubren 251 días durante el año de 1999. Las mediciones fueron hechas continuamente cada ocho minutos utilizando un radiómetro heterodino. Para este periodo, la opacidad media total obtenida fue de 0.13 nepers a esta frecuencia; la opacidad media total diurna fue de 0.14 nepers y la nocturna de 0.12 nepers. Estas mediciones complementan las hechas anteriormente en 1992, y que cubrieron 210 días (Hiriart et al. 1997). En 1992 se encontró una opacidad media total del cielo de 0.24 nepers a la frecuencia de 215 GHz. Los resultados que se presentan confirman que las mediciones hechas durante 1992 fueron afectadas por el fenómeno de El Niño. Al comparar las mediciones de la opacidad durante 1999 con mediciones similares hechas en Kitt Peak y Mount Graham en ese mismo año, se encontró que la actividad del monzón, que incrementa la opacidad del cielo a longitudes de onda milimétricas, duró aproximadamente dos meses menos en la Sierra de San Pedro Mártir que en el suroeste de EUA.

ABSTRACT

Measurements of the atmospheric zenith opacity at a wavelength of 1.4 mm (210 GHz) carried out at the Observatorio Astronómico Nacional in the Sierra San Pedro Mártir, Baja California, México are presented. The data cover 251 days in 1999. Measurements were made on a continuous basis every eight minutes using a heterodyne radiometer. For this period, the total mean zenith opacity was 0.13 nepers; with mean values of total opacity for night time and day time of 0.14 and 0.12 nepers. The data presented here supplement those covering 210 days in 1992 (Hiriart et al. 1997). That year, a total mean sky opacity of 0.24 nepers at a frequency of 215 GHz was found. The present results confirm that measurements in 1992 were affected by El Niño activity. By comparing the results of 1999 with similar measurements made at Kitt Peak and Mount Graham observatories in the same year, it is found that the North American monsoon that increases the sky opacity at millimeter wavelength lasted two months less in Baja than in southwestern USA.

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

1. INTRODUCTION

Hiriart et al. (1997) presented atmospheric opacity measurements at a frequency of 215 GHz over the Observatorio Astronómico Nacional at the Sierra San Pedro Mártir covering 210 days in 1992. This is the only recorded or published data set of sky opacity at millimeter wavelengths for any length of time over the Sierra San Pedro Mártir in Baja California, México. The reported measurements were part of a campaign for the site survey to install the Large Millimeter Telescope (Kaercher & Baars 2000), a joint project of the Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE), México, and the University of Massachusetts at Amherst, USA. After finishing the survey at this site, more radiometers were built with some changes to improve the original system. Among such modifications was the change of observing frequency to 210 GHz. From 1995 to 1998, one of these the radiometers was installed at La Botella Azul Mountain, 6 miles away from the Observatory in the south-east direction. In 1998 the radiometer was installed back in the facilities of the Observatorio Astronómico Nacional. Since then, the radiometer has been measuring continuously the sky opacities, except for malfunction of the equipment and shutdown of the Observatory operation during holidays or snow storm periods. Thus, a constant record of the sky opacities at millimeter wavelengths at the site is kept. Also, because the sky opacity at this wavelength is proportional to the precipitable water vapor (PWV) plus a dry opacity offset, measurements taken by the radiometer help to monitor the sky conditions during near- and mid-infrared observing runs at the Observatory.

In this paper, additional atmospheric opacity measurements at millimeter wavelengths over San Pedro Mártir Sierra are presented for 251 days in 1999. The data are reported here in terms of zenith opacity at 210 GHz measured in nepers. The data are directly compared to similar radiometric measurements made at millimeter wavelengths at Kitt Peak and Mount Graham observatories. These sites have geographical location and elevation similar to San Pedro Mártir.

This paper is organized as follows way: § 2 presents the equipment and procedure to measure the sky opacity. § 3 shows the outcome of the measurements. § 4 presents a discussion of the results obtained, and § 5 summarizes the main conclusions of this work.

2. MEASUREMENTS

The detailed description of the measuring instrument, the data reduction technique, and the method used to measure the sky opacity were given in an earlier paper (Hiriart et al. 1997). Here, only a brief description of these and the new radiometer system are presented.

After the first year of measurements in 1992 over San Pedro Mártir, new radiometers based on the first prototype were built, in order to improve their behavior and make them more reliable. Among the few modifications to the system was the change of operation frequency from 215 GHz to 210 GHz due to the availability of a mixer and local oscillator that, combined, yield the lower noise temperature at 210 GHz (2041 K). With this noise temperature, a passband frequency of 300 MHz, and an integration time of 1 second, the minimum sky temperature difference that can be measured is 0.12 K.

The new systems are a copy of the original simple heterodyne radiometer. They are coupled to the sky through a conical feed horn that provides a 9 degree field of view. A 105 GHz Gunn diode oscillator produces a signal which yields an equivalent 210 GHz local oscillator in the harmonic mixer. The second harmonic mixer combines the local oscillator signal with the signal emitted by the sky. The result is sent through a 1–2 GHz amplifier followed by a 300 MHz bandwidth passband filter centered at the frequency of 1.3 GHz. This is followed by a second 1–2 GHz amplifier. An attenuation of 6 dB between the two amplifiers maintains a linear output response at the detector, which generates a voltage signal proportional to the sum of the system noise temperature and the temperature of an object which fills the receiver beam. The signal is then sent to a 12-bit analog-to-digital converter, and finally saved in a host computer.

On May 1998, the 210 GHz radiometer was installed at the Observatory close to the 84 cm telescope building near the summit of the telescope ridge. Observations were made on a continuous basis, with emission measurements made every four minutes for eight zenith angles: 26.4, 44.4, 53.4, 58.8, 64.2, 66.0, 69.6, and 71.4 degrees in the north-south direction by positioning a scanning mirror. Unfortunately, no measurements were made toward the zenith itself that might be used as an extra check of the results. Measurements of the sky at the indicated zenith angles alternate with measurements of an ambient temperature reference load located on the back of the scanning mirror. A complete scan of the sky takes four minutes. The idle time between scans is also four minutes. Therefore, the period of the measurements is eight minutes.

The relation between zenith opacity τ_0 and the measured signal from the sky is given by (cf. eq. [7] from Hiriart et al. 1997)

$$\ln\bigl(V_{\mathrm{REF}} - V_{\mathrm{SKY}}(z)\bigr) = -\tau_0 \sec z + \ln a; \qquad (1)$$

where V_{REF} is the voltage measured from the reference load signal at the back of the mirror; $V_{\mathrm{SKY}}(z)$ is the voltage measure from the sky signal at zenith angle z; and a is a constant related to the radiometer gain and coupling factor, as well as to the physical atmosphere temperature. For data reduction, only

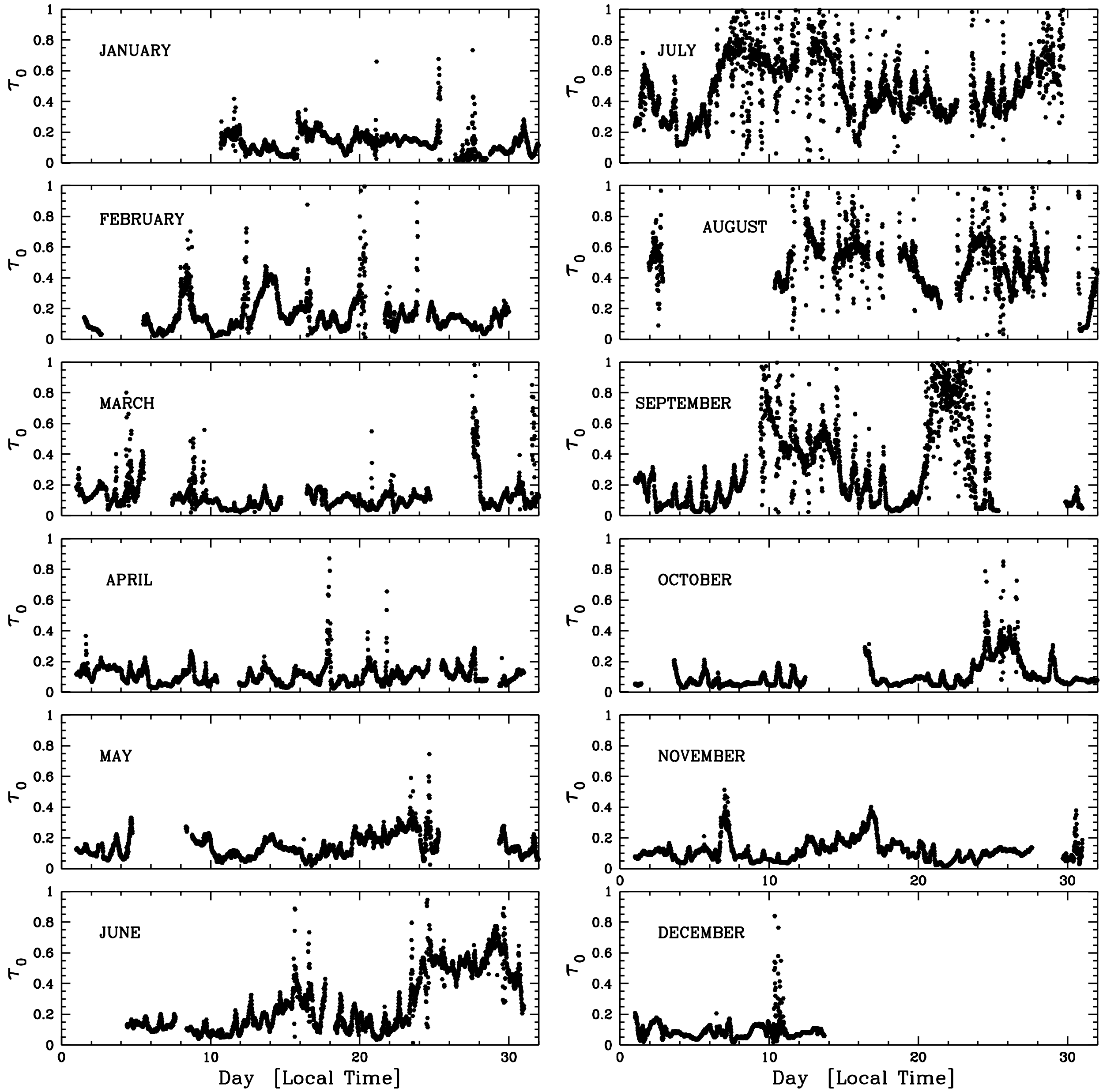

Fig. 1. Time evolution of the 210 GHz zenith atmospheric opacity τ_0, in nepers, for each month in 1999 over San Pedro Mártir, México. See Table 1 for the percentage of data coverage in each month, the day-time and night-time mean opacities, and the total mean opacity.

measurements between 26.4 and 64 degrees of zenith angle have been taken into account. Larger zenith angles have been rejected because the plane-parallel geometry is no longer a good approximation.

The present zenith sky opacity, and a graph with the last three days of available measurements, are shown at the web page http://haro.astrossp.unam.mx/~hiriart/radiometro. The page also contains the data and statistics archives in monthly and yearly format from September 1995 to May 1998 for La Botella Azul, and from May 1998 to the present for San Pedro Mártir Observatory.

In 1999, the radiometer measured the sky opacity continuously from January to December. However, some data were lost throughout the year due to various problems, mainly associated with operation of the radiometer. Data at the beginning of January and at the end of December were lost due to shutdown of the Observatory. Even so, the lost data are not representative of any peculiar weather condition

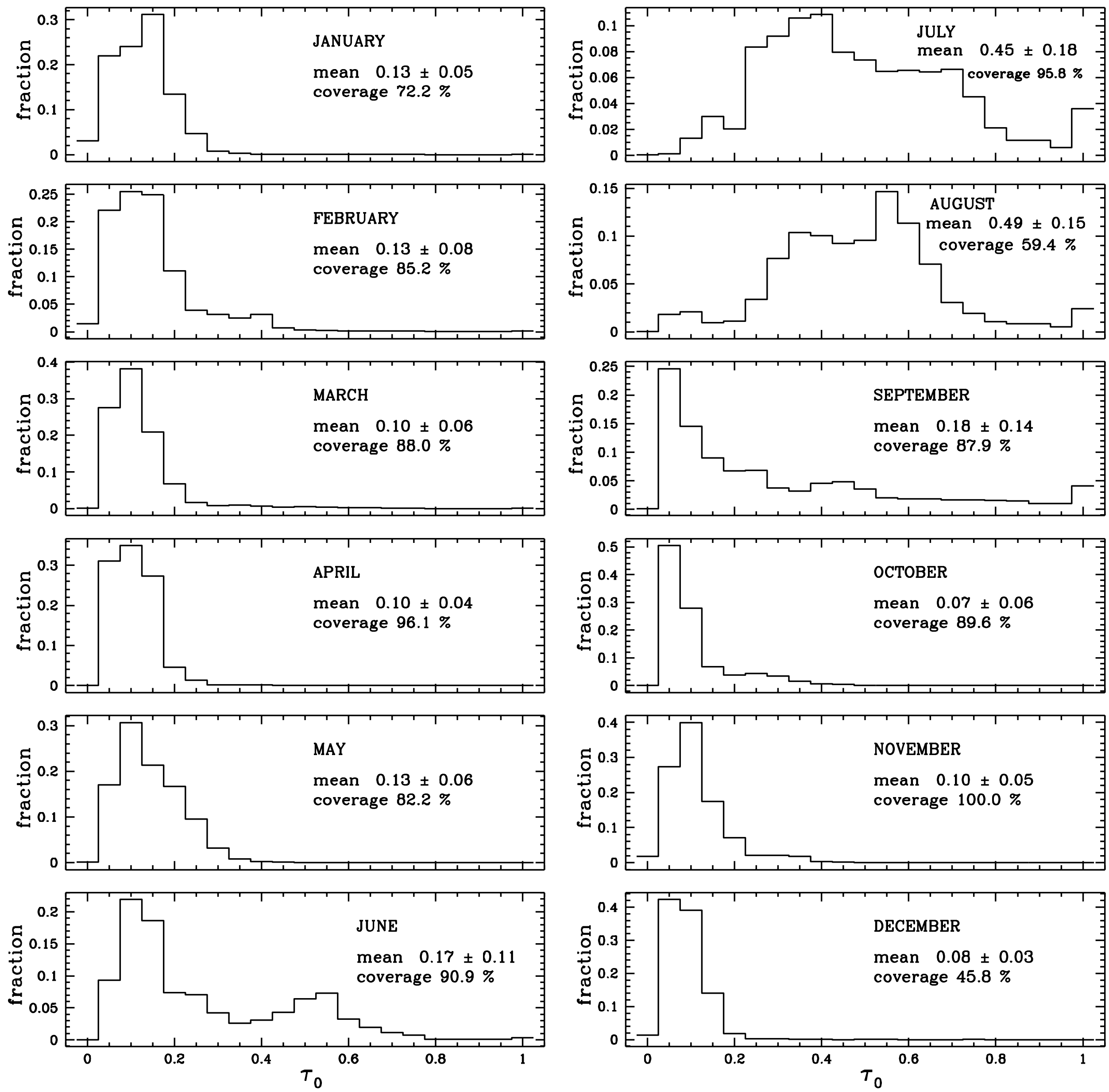

Fig. 2. Differential distributions of the 210 GHz zenith atmospheric opacity τ_0 from data on Fig. 1. The values for the mean and dispersion are quoted here, as well as the percentage of data coverage for the month.

in particular. The time evolution of the optical depth is presented in Figure 1 for each month of the year 1999. Westphal (1974) presents a graph with the time behavior of the PWV on time in Baja California similar to the one shown in Fig. 1. The differential and cumulative distributions for each month are presented in Figure 2 and Figure 3, respectively. The values for the median and dispersion are quoted there (see also Table 1), as well as the amount of data sampled each month. A typical daily variation of the zenith sky opacity, under stable weather conditions, shows a maximum at about 15:00 hours and a minimum at about 2:00 hours local time.

3. DISCUSSION

Compared to the year of 1992, the data for 1999 present higher sky opacities during summer. This effect appears at the end of June and disappears by early September. In both years, the summer conditions of high opacities appear suddenly, last for about three and a half months, and rapidly disap-

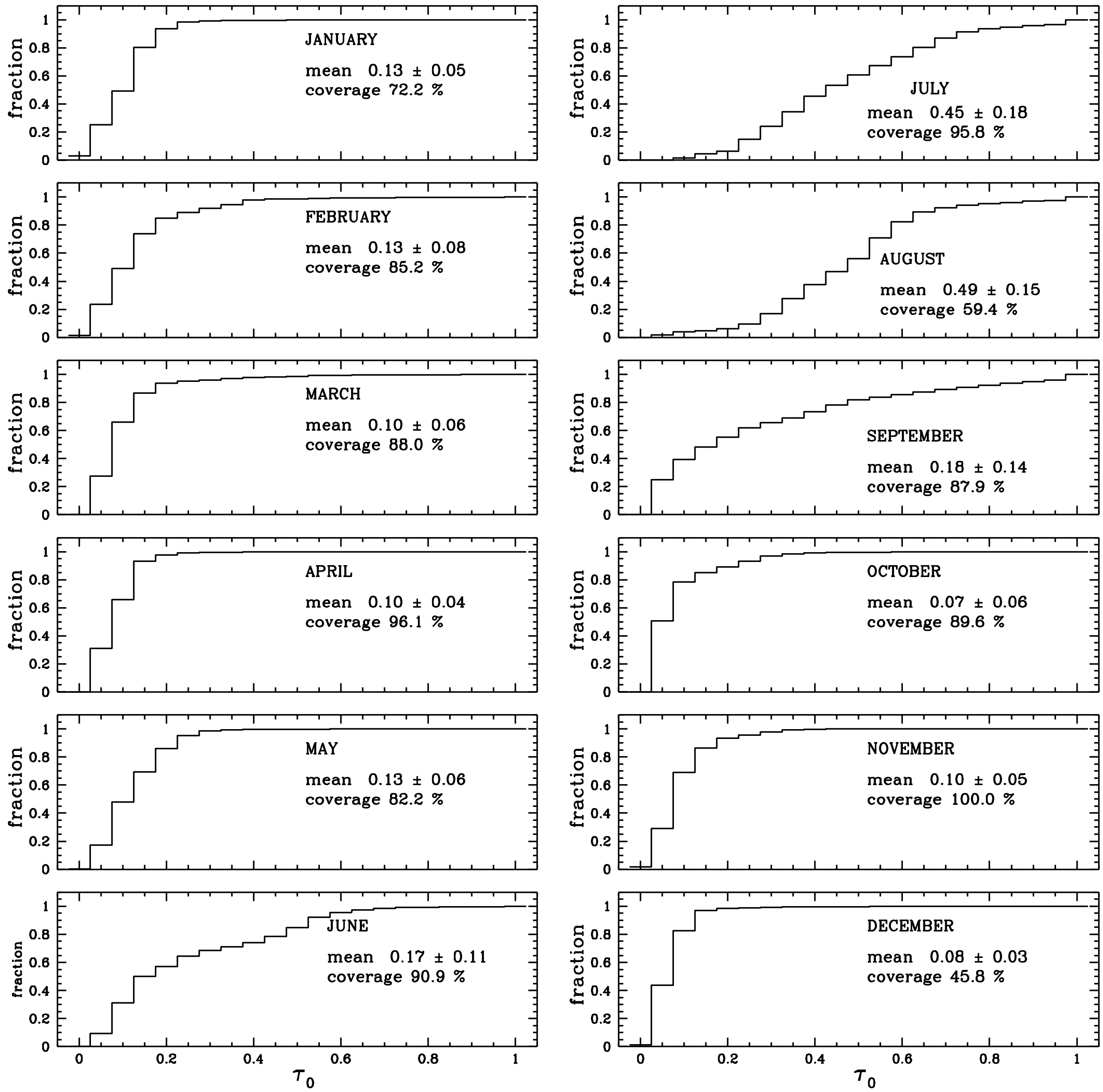

Fig. 3. Cumulative distributions of the 210 GHz zenith atmospheric opacity τ_0 from data on Fig. 1. Same quotations as in Fig. 2. See Table 1 for the monthly values of the first and third quartile.

pear. High opacities during these months are produced by the North American monsoon activity that carries high amounts of moisture to the top of the mountain. Typical weather during this period is characterized by strong midday showers and lightning storms followed by clear skies. These storms leave high amounts of humidity near the ground. On the other hand, the winter season at the Observatory is characterized by occasional heavy snow storms, followed by quite dry atmospheres. The presence of a snow storm front translates into a rapidly rising sky opacity at 210 GHz, followed by a random variation during the storm. In both years the fall and beginning of winter are characterized by a very stable sky opacity.

Convective cells of moisture must have an effect on the atmospheric opacity at 210 GHz, especially in April and early May. It is typical then for a convective cell to rise to the top of the mountain around midday, with the corresponding rise in the sky opacity. A decrease follows in the afternoon. Figure 4 presents the differences in day-time and night-time

TABLE 1

MONTHLY MEAN ZENITH OPACITY AT 210 GHZ OVER SAN PEDRO MÁRTIR, MÉXICO

Month	Coverage %	Day-time (nepers)	Night-time (nepers)	Median (nepers)	1st Quartile (nepers)	3rd Quartile (nepers)
January	72.2	0.13	0.12	0.13	0.07	0.16
February	48.3	0.12	0.13	0.06	0.04	0.14
March	24.7	0.11	0.10	0.06	0.04	0.10
April	33.4	0.11	0.09	0.10	0.06	0.14
May	75.3	0.14	0.12	0.13	0.09	0.18
June	90.9	0.20	0.12	0.17	0.11	0.44
July	95.8	0.47	0.44	0.45	0.33	0.63
August	61.5	0.51	0.47	0.31	0.10	0.50
September	87.9	0.24	0.14	0.18	0.08	0.44
October	89.6	0.08	0.06	0.07	0.05	0.11
November	100.0	0.11	0.10	0.10	0.07	0.13
December	45.8	0.08	0.08	0.08	0.06	0.11
TOTAL	68.8	0.14	0.12	0.08	0.13	0.29

TABLE 2

SITES IN BAJA CALIFORNIA, MÉXICO AND SOUTH-WESTERN USA WITH RADIOMETERS AT MILLIMETER WAVELENGTHS

Site	Longitude (°W)	Latitude (°)	Elevation (m)	Radiometer Frequency (GHz)
San Pedro Mártir	115	32	2800	210
Kitt Peak	111	32	2058	225
Mount Graham	109	32	3185	225

mean opacities for each day of the year. As in 1992, day-time conditions have larger opacities than night-time conditions, especially between days 180 and 300; i.e., end of June to early September. Better conditions occur at night-time for days 40 to 140 when the dispersion is also lower. This period corresponds to the months of February to early May in 1999 data. The 1999 data show that the time of better night conditions peaks toward the months of late winter, while in 1992 this happened between the months of April and early May. Also, for 1992 the differences during day-time and night-time were larger.

Since little variation between day and night conditions are observed in 1999, the question of the duration of certain observing conditions, or how long the good weather lasts, has to be further addressed. Figure 5 shows the frequency (fraction of the year) with observing conditions better than a given value of the sky zenith opacity, τ_0, that last for a certain period of time; for example, in 20% of the time during the year there are continuous periods of 8 hours with $\tau_0 < 0.08$. During 1999, lower opacities were present and they lasted for longer continuous periods of time compared to opacities measured during 1992.

It is interesting to compare the results of 1992 with the record presented here, since the former data were recorded well into the strong "El Niño" cycle from 1991–1992 which perturbed normal weather conditions throughout the Pacific basin with heavy winter rains on the California coast. In northwestern Mexico, summer rainfall increased during the presence of these conditions (Reyes & Mejia-Trejo

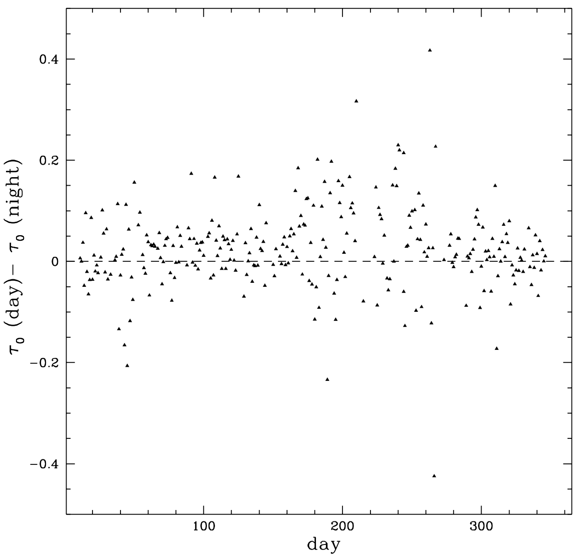

Fig. 4. Differences in the mean opacities corresponding to a day-time and night-time, for each day of the year 1999.

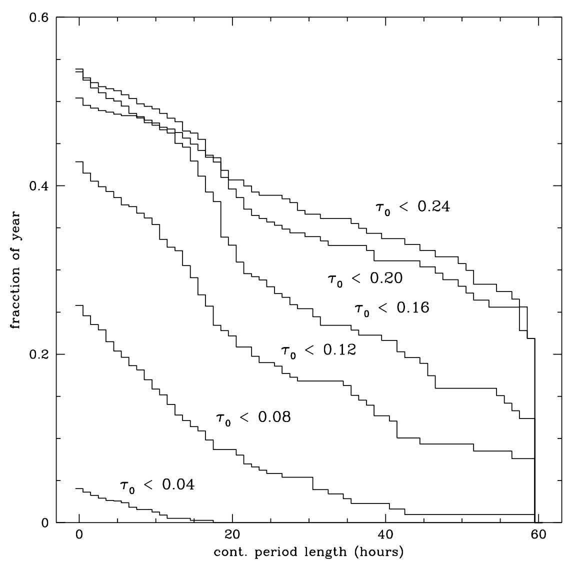

Fig. 5. The frequency (fraction of the year) with observed conditions better than a given zenith sky opacity τ_0, that last for a certain period of time (see text for explanation).

1991). In 1992, the mean values of the night-time and day-time millimeter wavelength sky opacities were 0.24 and 0.20 nepers respectively; total mean sky optical depth was 0.22 nepers. Values found for 1999 are 0.14 and 0.12 nepers for night-time and day-time respectively; total mean sky optical depth is

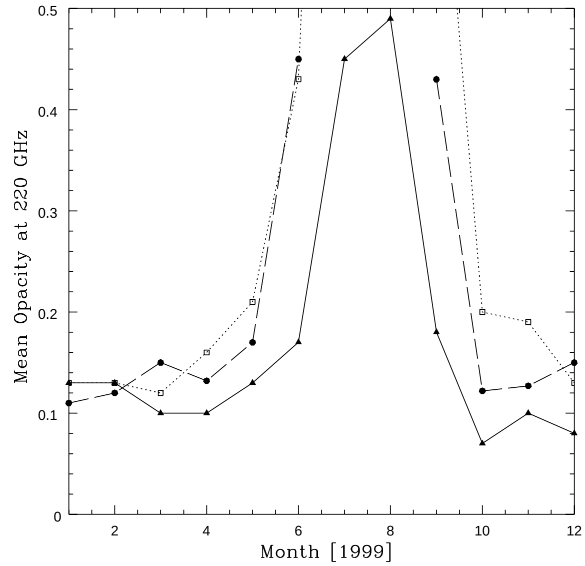

Fig. 6. Monthly mean values of the sky opacity for San Pedro Mártir Sierra (triangles), Kitt-Peak (squares), and Mount Graham (circles) for the year of 1999.

0.13 nepers. This fact confirms previous suspicions that the measurements of 1992 were affected by the presence of El Niño activity. However, sky opacities measured in January-May 1992 are still very good.

In 1997–1998 there was another "El Niño" period from which there are interesting Fourier Transform Spectroscopy data covering 300–1000 GHz from Mauna Kea, Hawaii (Pardo, Serabyn, & Cernicharo 2001). In the middle of the Pacific, the opacity statistics reveal much drier atmospheres during that event than during a normal year. This is opposite to what occurs in the Pacific Coast.

3.1. *Comparison with Nearby Observatories*

There are two sites with astronomical observatories in the southwestern USA with a location and elevation similar to San Pedro Mártir: Kitt Peak and Mount Graham. During 1999, these sites had radiometric measurements of the sky opacities at a frequency close to the one used in the radiometer of San Pedro Mártir. The radiometer at Kitt Peak is located near the 12 m millimeter radiotelescope operated at that time by the National Radio Astronomy Observatory; the one at Mount Graham is located at the Heinrich Hertz Sub-Millimeter Telescope Observatory (SMTO). The characteristics of the sites and the frequency of the observing radiometers are presented in Table 2. According to the Atmospheric Transmission at Microwaves (ATM) model (Pardo, Cernicharo, & Serabyn 2001) the difference in sky water vapor opacity between 210 and 215 GHz is only 3%, higher at 225 GHz.

Figure 6 presents the monthly mean values of the zenith sky opacity at ~ 1.4 mm for the San Pedro Mártir, Kitt Peak, and Mount Graham sites in 1999. For Kitt Peak, zenith opacity data at a frequency of 225 GHz are available at the web site http://www.tuc.nrao.edu/12meter/tipper.html. For Mount Graham, the equivalent data are found at the web site http://maisel.as.arizona.edu:8080/weather_stats.html. The data from the three sites clearly show the impact of the North American monsoon activity during the summer, especially during the months of July and August, Kitt Peak being the most affected by this phenomenon. In those months the opacity at Kitt Peak reaches the highest levels, while San Pedro Mártir and Mount Graham show lower opacities. During the months of winter and fall the three sites have approximately the same mean value of sky opacity at millimeter wavelengths.

The sky opacities from Kitt Peak and Mount Graham share a similar behavior as a function of time. This behavior is thus representative of that of southwestern USA. Since the three sites have the same latitude and similar elevation and only differ in longitude, seasonal differences in the sky opacities between San Pedro Mártir and the other two sites may be attributed to its geographical location close to the coast.

4. CONCLUSIONS

1. The results presented here may be of interest and utility in developing observing strategies for the facilities at the San Pedro Mártir Observatory, although this is not an attempt to answer the broader question of correlation between low water vapor and other area-wide meteorological patterns. However, there is a clear correlation between the months of monsoon activity and high sky opacities.

2. During fall and winter, the optical depth at millimeter wavelengths at San Pedro Mártir stays very stable over large periods of time.

3. The mean values of the sky opacity for 1999 were lower that those obtained in 1992, which proves that measurements made in San Pedro Mártir during 1992 were affected by "El Niño" activity.

4. In 1999, the monsoon activity lasted for two months less in the Baja Peninsula than in the inland South-West USA. Longer term measurements should be made to confirm this conclusion.

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