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SITE TESTING AT SAN PEDRO MÁRTIR

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RESUMEN

El Observatorio Astronómico Nacional está localizado en la Sierra San Pedro Mártir, en la península de Baja California, México, a una elevación de 2800 m sobre el nivel del mar. Sus coordenadas son 31°02′40″ N y 115°28′00″ W. Aquí se presentan los resultados resumidos de más de tres décadas de recabar información sobre la caracterización astronómica del sitio. Se cubren los siguientes aspectos: estabilidad atmosférica, calidad de imagen, opacidad atmosférica en el visible, infrarrojo y milimétrico, brillo del cielo nocturno y nubosidad. La Universidad Nacional Autónoma de México y otras instituciones internacionales están llevando a cabo estudios de muy largo plazo para establecer mejor los resultados.

ABSTRACT

The Observatorio Astronómico Nacional at San Pedro Mártir is located at 31°02′40″ N and 115°28′00″ W on the summit of the Sierra San Pedro Mártir on the Baja California peninsula, Mexico, at 2800 m above sea level. The results of more than three decades of site characterization work are summarized. These cover the following aspects: weather, cloud coverage, atmospheric optical extinction, night sky brightness, millimetric and infrared opacity and seeing. Overall, San Pedro Mártir is one the most favorable accessible sites in the Northern Hemisphere for astronomical observations. The number of cloudless nights, minimal turbulence and favorable local wind conditions, to mention but a few of its characteristics, make it well-suited for large telescopes. Long-term monitoring of the site is being undertaken by the Universidad Nacional Autónoma de México and other international institutions.

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

1. INTRODUCTION

Mexico's National Astronomical Observatory (OAN) was formally inaugurated almost 130 years ago on top of a hill where the Castillo de Chapultepec is located, at the time, in the outskirts of Mexico City (Figure 1). In 1929, the Federal Government transferred custody and operation of the OAN to the Universidad Nacional Autónoma de México (UNAM). Since the end of the 19th Century, the OAN has been moved to other parts of central Mexico: Tacubaya, close to Chapultepec, and Tonantzintla, not far from the city of Puebla, always trying to escape the influence of big cities and their associated light and atmospheric pollution. Of course, the nearby cities soon grew considerably and by the early 1960s a new site had to be found for the OAN complying with the conditions recognized for the new generation of large observatories around the world.

A search was made to find the best site for (optical) astronomical observations in Mexico. This was done by analyzing two years (1969 - 1971) of meteorological satellite photographs (Mendoza et al. 1972) and several *in situ* tests on the most prominent candidate sites. The summit of the Sierra of San Pedro Mártir in Baja California, in northwestern Mexico, was chosen to locate the Observatorio Astronómico Nacional. Construction of wooden cabins began in 1969 and the first two research telescopes were installed in 1971 and 1972. The Observatorio Astronómico Nacional de México at San Pedro Mártir (OAN-SPM) was formally inaugurated in 1979.

In the "early days" of the observatory, several studies of the climatological properties of this site were made by a number of Mexican and NorthAmerican astronomers, mainly based on data that covered short periods during the first years of operation of the observatory. These were reported by Mendoza (1971, 1973) Mendoza et al. (1972), Walker (1971, 1983), Westphal (1974), Alvarez (1982) and Alvarez & Maisterrena (1977).

The OAN-SPM is located at 31°02′40″ N and 115°28′00″ W, some 100 km east of the West Coast of Baja California, Mexico. At present, it operates three Ritchey-Chrétien telescopes of diameters 0.84-, 1.5- and 2.1-m. The latter started continu-

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Fig. 1. Anonymous watercolor of the Castillo de Chapultepec, ca. 1880, housing the recently founded Observatorio Astronómico Nacional.

ous science operation in 1981. Figure 2 presents a panoramic view of the hill where the these telescopes are located. It is expected that in the near future, the Mexican astronomical community engages in the construction and operation of larger telescopes to be located at San Pedro Mártir. This site is also being evaluated as a candidate for locating other future international large telescopes.

This contribution summarizes the most important results of the characterization work done at San Pedro Mártir from 1982 to the present. Several aspects are discussed: sky transparency in the optical and infrared, meteorology, night sky brightness, seeing. A preliminary survey of specific sites for installing future large telescopes within San Pedro Mártir is also described. Progress reports on the site testing studies at SPM have been put together in a dedicated volume of the Serie de Conferencias of Revista Mexicana de Astronomía y Astrofísica (Cruz-González, Avila, & Tapia 2003), summarized in Cruz-González, Avila, & Tapia (2004) and Tapia, Cruz-González, & Avila (2007).

2. CLOUDS, WEATHER AND SKY TRANSPARENCY

Compilations of one and two continuous decades of weather and observing statistics of OAN-SPM have been reported by Tapia (1992, 2003). The fractional number of nights with totally clear, partially clear and mostly cloudy skies were determined from the nightly 2.1-m telescope observing log. The definitions and details of the method of compilation are described by Tapia (1992). Table 1 shows the results of this homogeneous long-term monitoring from July 1982 to December 2006. Table 2 gives the mean monthly percentage of photometric and spectroscopic nights compiled for all months of the January 1984 to December 2006 period. The yearly fractions are given in Table 3. Previous to January 1984, no report of the percentage of clouds is available, only the fraction of nights lost due to bad weather. The data of both tables are plotted in Figures 3 and 4. In the latter, the fraction of nights actually used for observation (from July 1982 to December 2006) is also shown.

The satellite-based method developed by Erasmus & van Staden (2002) for determining the transparency of the atmosphere (cloud cover and also water vapor content) above existing and potential observatory sites was applied by these authors to San Pedro Mártir and other existing and potential observatories in North America as part of the site survey work for the California Extremely Large Telescope (CELT) project. The method consists of combin-

Fig. 2. Aerial photograph of the telescopes of the Observatorio Astronómico Nacional at San Pedro Mártir. The 1.5-m,0.84-m and 2.1-m telescopes are aligned from right to left. The leftmost white structure is close to the site where most of the seeing tests have been performed (TIM-01).

ing two infrared band satellite imaging (6.7 μm and 10.7 μm), with a spatial resolution of 4 to 8 km and a time resolution of a fraction of a day, for determining the opacity and water content of the atmosphere over preselected sites. One of its main advantages, especially when applied in a simultaneous manner, is that it provides an "objective" direct comparison between sites irrespective of their geographical conditions. In the case of SPM, Erasmus and van Staden's monthly results for the period of their study, June, 1997 to May, 1998, agreed to within 5% with the statistics presented here for the same period (see Figure 4).

The region of southwestern California and northwestern Mexico is suffering from a drought that started in 1995, with the only winters of heavy rain in 1995–1996 and 2003–2004. Normally, the rain season in the coastal regions occurs in winter (mid-October to early-May) and is primarily caused by the southern tails of North Pacific winter storms reaching Southern California and Northern Baja California. This also explains the relatively low percentage of clear and useable nights in winter. Figure 5 shows the total annual (July to June) amount of precipitation recorded in San Diego, California, from 1976 to 2007. The mean of that distribution coincides with the mean of the 150 year period of the climatic archive (dashed line in Figure 5). Nine of the last eleven years have had an amount of precipitation for the region well below the mean value. In fact, the total precipitation during the 2001–2002 winter was the lowest recorded since 1884–1885.

Unfortunately, we had to wait until about a year ago to have a sturdy and reliable weather station (Davis Instruments, model Vantage-Pro) installed at SPM as previously we were unable to build a complete on-site weather data base. The basic data recorded by this instrument is currently available on-line at `http://www.astrossp.unam.mx/weather15/`. Examples of the plots of the basic climatic parameters recorded at the site of the 1.5-m telescope for nearly one year are shown in Figures 6 to 8. These are the daily averages of the temperature (Figure 6), relative humidity (Figure 7) and wind speed (Figure 8). Typical night to day temperature differences are up to 5°C in winter and up to 3°C in summer. As pointed out by other authors (e.g. Echevarría et al. 1998), there is no dominant or preferential wind direction and the wind is generally

TABLE 1

SPM 2.1-m TELESCOPE OBSERVING STATISTICS: JULY 1982 TO DECEMBER 2006

	Number of nights	% Over total number of calendar nights	% over number of scheduled nights
Total calendar	8950	100.0	–
Engineering	676	7.6	–
Scheduled for observation	6847	76.5	100.0
Observed	4875	54.5	71.2
Lost due to weather	1465	–	21.4
Lost due to telescope/dome/guider failure	146	–	2.1
Lost due to instrument failure	219	–	3.2
Lost due to other circumstances	92	–	1.3
Not scheduled	1430	16.0	–

weak (see Figure 9). Note that the gap in the data (all plots) for the end of December corresponds to the staff holiday period between Christmas and New Year, the only dates when most years the observatory remains closed for observations and the weather station is switched off.

The characteristics of previous non-continuous weather measurements can be summarized as follows:

Temperature measurements inside the dome of the 2.1-m telescope for 1998–2006 show a winter minimum of $-14°$C, a summer maximum of 25°C, and an annual night to day gradient of 7°C. The relative humidity shows a seasonal dependence, large variations on short timescales specially occur during the summer. Measured atmospheric pressure values are in the range of 550 to 565 mm Hg during 1998–2002.

Wind measurements from Echevarría et al. (1998) on 386 nights (1992–1994) with a propeller anemometer, supplemented by 150 days of measurements in 2002–2003 by Michel, Hiriart, & Chapala (2003) with an ultrasonic anemometer show that winds have steady night-time speeds that rarely exceed 11 m s^{-1}. The strongest winds come from the SSW and the wind rarely comes from the E and WNW. The wind speed distribution appears almost uniform.

The wind power spectrum at the TIM-01 site (cf. Figure 19) has been measured by Hirart, Ochoa, & García (2001) with a wind sampling frequency of 40 Hz. For the high frequency part of the spectrum, they found that the power law ($f^{-\gamma}$) of the spectrum has a spectral index, γ, in the range 0.625 to 0.969, depending on the wind direction.

The photometric extinction coefficients in the optical have been studied since 1973 by Schuster et al. (2002). The most recent results of the mean extinction curve for SPM (1973-1999) are shown in Figure 10 and are compared with data from other observatories (Parrao & Schuster 2003). It is shown that San Pedro Mártir is a high quality site for accurate photometry with a mean visual (549 nm) atmospheric extinction coefficient, k_y, of 0.14 mag/air mass. Nearly two-thirds of the photometric nights have k_y values equal or below this mean, with a median and a minimum of about 0.13 and 0.11 mag/air mass, respectively. The extinction is low and very stable in autumn while in spring it is

TABLE 2

PERCENTAGE OF PHOTOMETRIC AND SPECTROSCOPIC NIGHTS: JANUARY 1984 TO DECEMBER 2006

Month	% Over scheduled nights	
	photometric	spectroscopic
January	53.2	72.7
February	44.6	63.7
March	59.1	76.0
April	66.6	84.3
May	72.2	90.2
June	83.8	94.0
July	65.6	79.9
August	63.2	80.3
September	65.9	85.9
October	68.0	80.9
November	60.5	76.4
December	55.3	69.5
Total	64.1	80.3

TABLE 3

PERCENTAGE OF PHOTOMETRIC AND SPECTROSCOPIC NIGHTS: JANUARY 1984 TO DECEMBER 2006

Year	% Over scheduled nights	
	photometric	spectroscopic
1984	63.8	86.2
1985	59.9	81.8
1986	57.3	79.7
1987	56.0	77.8
1988	67.7	80.2
1989	53.6	79.8
1990	48.1	79.0
1991	54.9	77.6
1992	51.2	78.9
1993	54.4	74.9
1994	61.6	76.0
1995	52.9	78.1
1996	78.9	85.2
1997	72.3	89.8
1998	71.2	80.9
1999	73.2	86.6
2000	70.1	80.6
2001	76.9	85.9
2002	79.6	86.6
2003	61.7	72.8
2004	74.4	85.1
2005	67.4	74.4
2006	68.1	77.0

higher and less consistent. The rest of the year the extinction is intermediate.

3. BROAD-BAND BRIGHTNESS

Table 4 presents the sky brightness measured in optical broadband Johnson-Cousins filters for SPM. The individual measurements were made at modest zenith distances, usually within 30° of the zenith. The measurements were made during the period 26 August 2004 to 22 February 2006. Images were obtained of known blank fields (usually). Typical exposure times are shown. The image reduction followed standard procedures. The overscan was subtracted from all images. The overscan-subtracted bias images were averaged and the resulting bias images was subtracted from all other images. The blank sky images were then divided by flat field images obtained during twilight. The sky brightness (in counts) was determined from the mode of a large section of the image. Observations of photometric standard stars

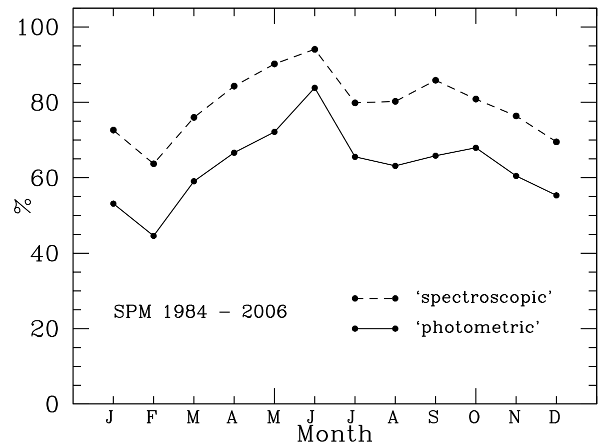

Fig. 3. Monthly fraction of nights of photometric and spectroscopic quality in San Pedro Mártir during the period January 1983 to December 2006.

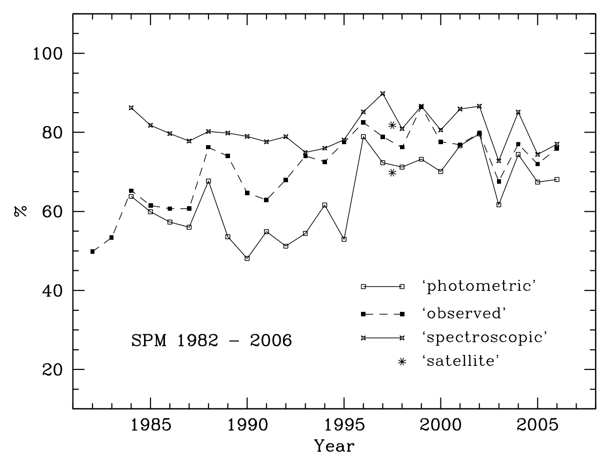

Fig. 4. Yearly fraction of nights of photometric and spectroscopic quality in San Pedro Mártir during the period January 1984 - December 2006. Also shown is the actual use of the 2.1-m telescope from July 1982 to December 2006. The asterisks refer to the mean satellite June 1997 – May 1998 measurements by Erasmus & van Staden (2002).

(Landolt 1992) were used to convert the sky brightness from counts to fluxes per square arcsecond. The mean values for dark sky conditions are tabulated in Table 4, including the number of measurements in each average. No measurements have been made exactly at full Moon, but the measurements available indicate that the sky brightness increases by at least 2.8 mag, 2.9 mag, 2.1 mag, 1.4 mag, and 1.0 mag in the U, B, V, R, and I bandpasses, respectively.

Table 4 also includes zenith values for the sky brightness in the near infrared J, H, and K′ pass-

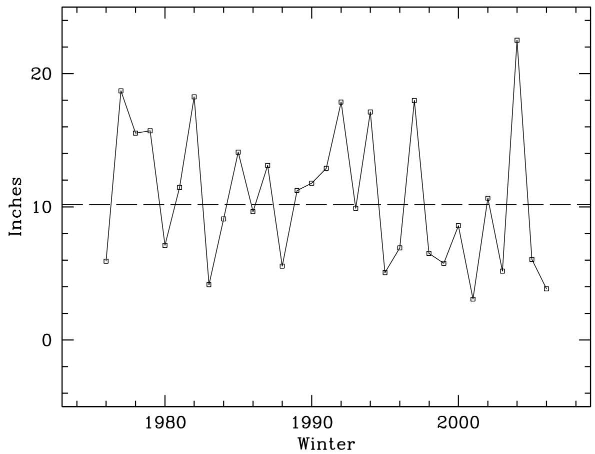

Fig. 5. Total annual (July to June) precipitation recorded in the city of San Diego, California, USA from 1996–1997 to 2006–2007. The dashed line indicates the mean of all years since the records began in 1850. This rain behavior is practically identical to that observed for the city of Ensenada, Baja California, Mexico and should be representative of that of coastal regions at the latitude of SPM.

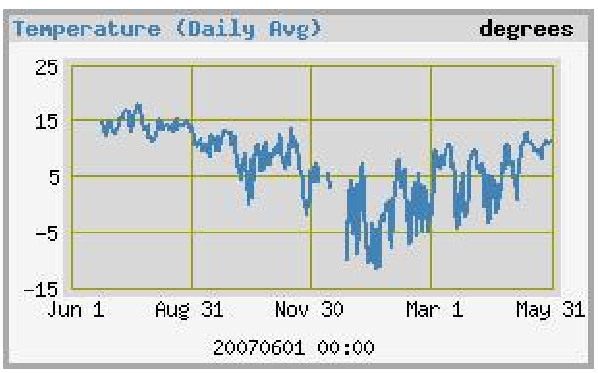

Fig. 6. Plot of the daily average temperature (^{o}C) recorded at SPM (1.5-m telescope) for the period June 2006 to May 2007.

bands obtained in March and April 2005 and in May 2006. All of these measurements were made before morning twilight. Since the camera used for these measurements contributes significantly to the background in K′ (Cruz-González et al. 1994), the sky brightness was determined by measuring the total counts in a fixed area of images (fixed image coordinates) taken at different airmasses. By fitting a line to the sky brightness as a function of airmass, the intercept provides an estimate of the instrumental background while the slope provides an estimate of the sky brightness at an airmass of unity (the

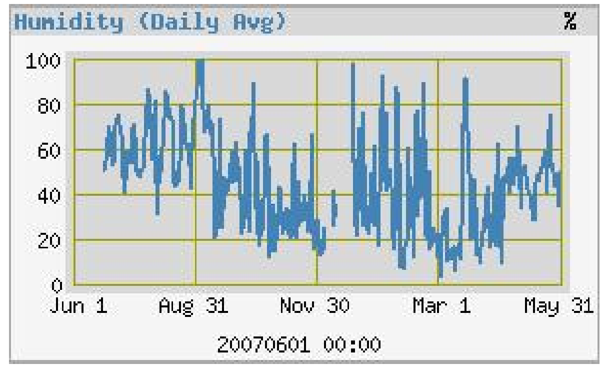

Fig. 7. Plot of the daily average relative humidity recorded at SPM (1.5-m telescope) for the period June 2006 to May 2007.

zenith). Consequently, the sky brightness is that expected at the zenith. The same procedure was used for the J and H passbands, but, since the instrument has no thermal contribution at these wavelengths, the fit was forced to go through the origin. Figure 11 illustrates this procedure using the data from 25 April 2005. When multiple measurements are available, a range of sky brightness is presented, since the sky brightness can vary substantially.

Figure 12 presents spectra of the sky in San Pedro Mártir for the 4000–9300Å wavelength interval obtained on 16 and 18 March, 2006. Again, the position is that of a known blank sky area. A routine data reduction was used. The overscan bias was subtracted from all images. An average bias image was constructed from the overscan-subtracted bias images and this was subtracted from all other images. The blank sky and standard star spectra were divided by a twilight flat field. Spectra of a CuHeNeAr lamp were used for wavelength calibration. The blank sky spectrum was median-filtered in the spatial direction, and a portion of this was extracted and calibrated in flux. The flux-calibrated spectrum was then normalized to a slit area of 1 square arcsecond and converted to an AB magnitude scale (Oke et al. 1983).

4. ATMOSPHERIC TURBULENCE

Medium-term atmospheric turbulence monitoring has been carried out in SPM for over a decade. Echevarría et al. (1998) reported the results of two independent but nearly simultaneous campaigns carried out at visible wavelengths with two totally different seeing monitors located close together (∼20m) on San Pedro Mártir. One of the instruments was a 31-cm Site Testing Telescope (STT), twin of the one

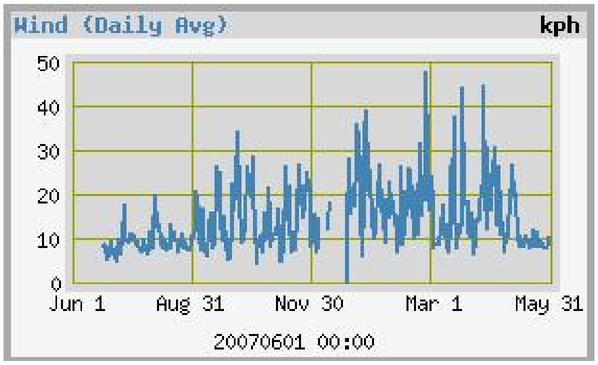

Fig. 8. Plot of the daily average wind speed recorded at SPM (1.5-m telescope) for the period June 2006 to May 2007.

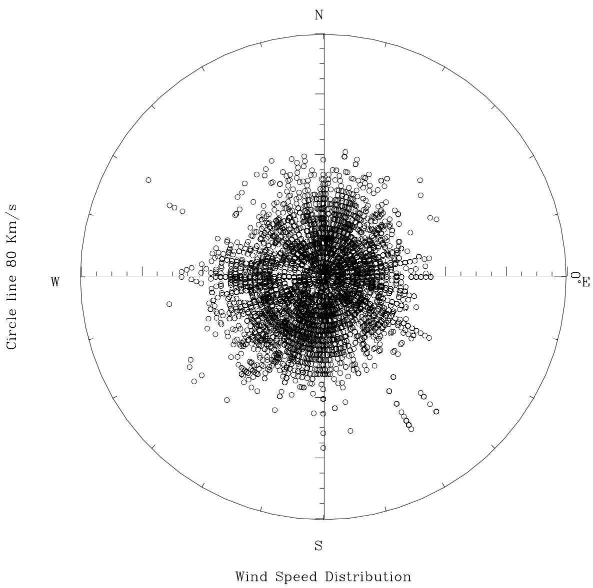

Fig. 9. Night-time wind spatial distribution. Nearly 6150 observations covering 386 nights are plotted. From Echevarría et al. (1998).

used for testing Mount Graham (Cromwell, Haemmerle, & Woolf 1998). This telescope points permanently at Polaris. The size of the stellar image was obtained by measuring the 2-D variations of the motion of the star in all frames every 90 s on the digitized video recordings taken from 1993 March to 1994 August. The observed distribution of the size of the seeing disk for all trusted measurements is shown in Figure 13, yielding a median value of 0.61 arcsec and a first quartile value of 0.″5.

The other instrument was a 20-cm seeing monitor telescope equipped with guiding drives (Persson, Carr, & Jacobs 1990) named "Carnegie monitor" mounted on an 8m-high concrete tower with an

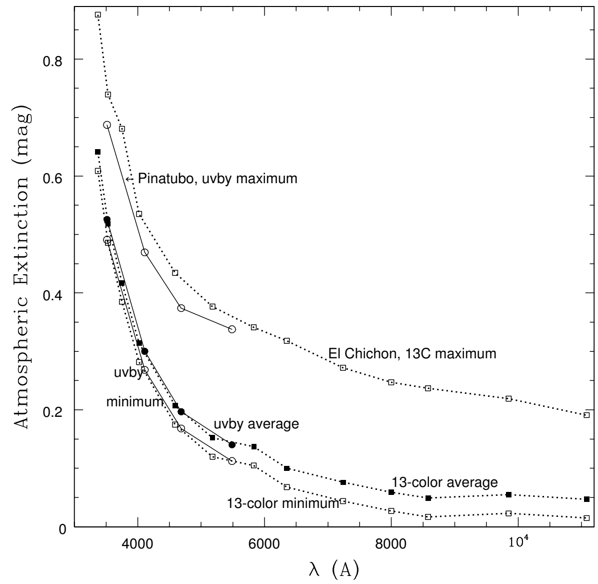

Fig. 10. Maximum, minimum and average atmospheric extinction curves for the 13-color (dotted curves) and *uvby* (solid curves) photometric systems.

TABLE 4

SKY BRIGHTNESS IN SAN PEDRO MÁRTIR

Filter	dark sky (mag□′′$^{-1}$)	N[a]	exp. time (s)	
U	21.7	3	1800	
B	22.4	3	1200	
V	21.5	3	900	
R	20.7	4	600	
I	19.2	4	600	
	Mar-Apr 2005		May 2006	
Filter	brightness (mag □′′$^{-1}$)	N[a]	brightness (mag□′′$^{-1}$)	N[a]
J	16.0–16.9	2		
H	14.1	1		
K′	14.4–15.1	8	13.6–14.0	3

[a]Number of measurements.

isolated semi-open dome. This instrument measures changes in the effective position of any stellar image in one dimension with a single detector. A few bright stars were measured throughout each night for one year from 1992 September to 1993 August. The median size of the seeing over the whole duration of the survey was 0.″63 with first quartile values of 0.″48. The distribution is shown in Figure 14.

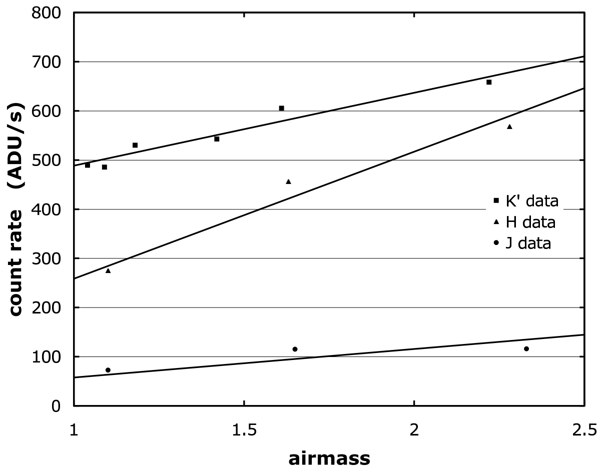

Fig. 11. Method used to derive the sky brightness at the zenith. The data were obtained on 25 April 2005 using the CAMILA infrared camera.

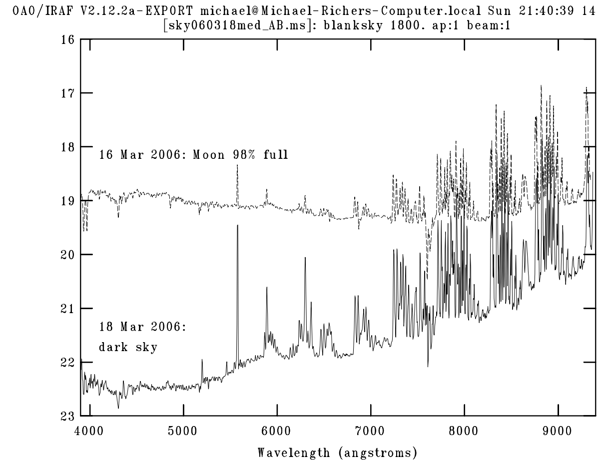

Fig. 12. Sky brightness on an AB magnitude scales as a function of wavelength. The data were obtained using the Boller & Chivens spectrograph. The spectral resolution is about 9Å.

Subsequently, Michel et al. (2003) reported sparse monitoring of the integrated seeing over a period of almost three years at SPM using a Differential Image Motion Monitor (SPM-DIMM). This instrument is a replica of the DA/IAC DIMM described by Vernin & Muñoz-Tuñón (1995). Measurements were made at a height of 8.3 m above the ground and with exposure times of 6 ms. Seeing was recorded for a total of 123 nights between August 2000 and June 2003. They reported a median seeing of $0\farcs60$ and a first quartile of $0\farcs48$ (see Figure 15) and concluded that the seeing can be excellent and very stable for whole nights, with the best measurements yielding a median of $0\farcs37$ and a first quartile of $0\farcs32$ during more than eight hours of continuous observations. A substantial seasonal variation of seeing was found (Figure 16), in general accordance with previous results (Echevarría et al. 1998): Summer, with a median of $0\farcs55$, is excellent; Spring and Autumn, with median values around $0\farcs62$, are very good; Winter, with a median of $0\farcs78$, was not as good. They noted that establishing reliable seasonal variations would require longer-term observations. The expected value of the median seeing 15 m above the ground and extrapolated to null integration time is $0\farcs61$.

It is interesting and important to note that the three totally independent medium-term but non-simultaneous seeing monitoring campaigns described above yielded amazingly similar results for the median and first quartile values of the seeing above the summit of San Pedro Mártir, although the instruments, methods and algorithms used were different. Note also that the wind direction and speed distributions were homogeneous and uncorrelated with seeing values, as shown in Figure 17. Note that during very strong winds, no seeing measurements were taken. Echevarría et al. (1998) reported that the wind direction and speed distributions were homogeneous.

Avila et al. (2003) presented the results of optical-turbulence profiles and the velocity of the turbulence layers at SPM using the Generalized Scidar (GS) of Nice University installed on the 1.5-m and 2.1-m telescopes. Their data were collected during 27 nights (11 in April–May 1997 and 16 in May 2000). The statistical analysis of the 6414 turbulence profiles obtained shows that the seeing produced by the turbulence in the first 1.2 km, not including dome seeing, at the 1.5-m and the 2.1-m telescopes has median values of $0\farcs63$ and $0\farcs44$, respectively. The dome seeing at those telescopes has median values of $0\farcs64$ and $0\farcs31$, respectively. The turbulence above 1.2 km and in the whole atmosphere produces seeing with median values of $0\farcs38$ and $0\farcs71$. The temporal correlation of the turbulence strength drops to 50% in time lags of 2 and 0.5 hours, approximately, for altitudes below and above 16 km above sea level, respectively. The turbulence above ∼9 km remained notably calm during 9 consecutive nights, which is encouraging for adaptive optics observations at the site. The 3016 profiles of the turbulent-layer velocity that are analyzed show that the fastest layers are found between 10 and 17 km, where the tropopause and the jet stream are located, with a median speed

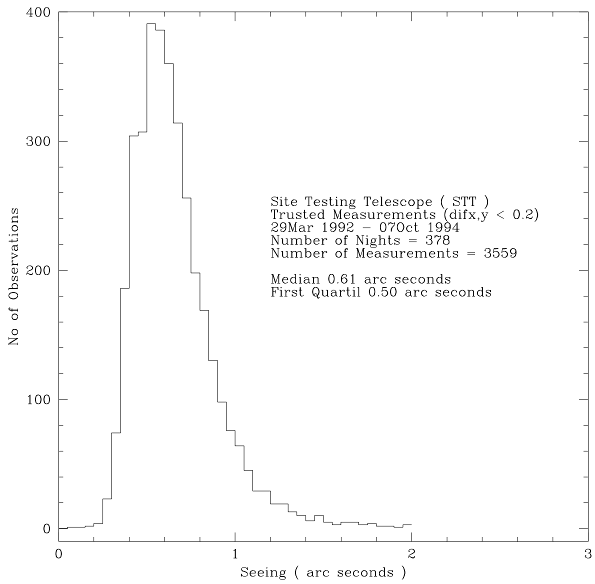

Fig. 13. Distribution of the seeing measured with the STT from 1992 March to 1994 October. From Echevarría et al. (1998).

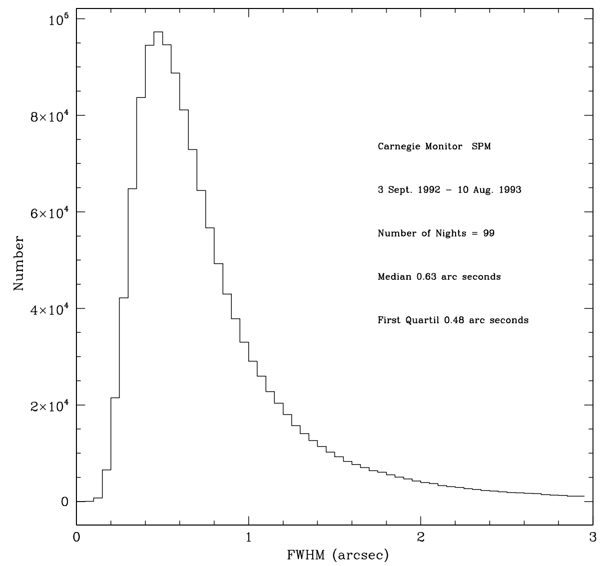

Fig. 14. Distribution of the seeing measured with the "Carnegie monitor" from 1992 September to 1993 August. From Echevarría et al. (1998).

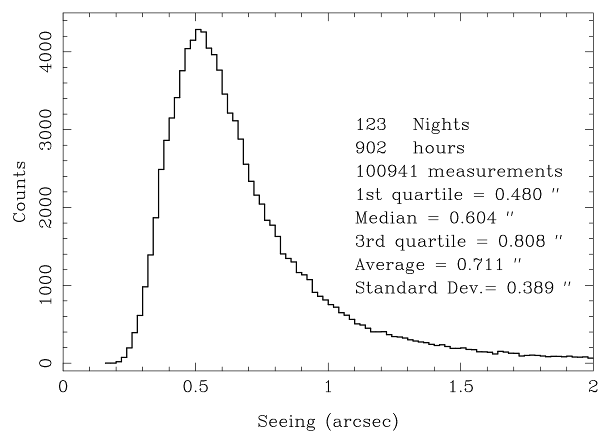

Fig. 15. Distribution of the seeing measured with the SPM-DIMM from 2000 August to 2003. From Michel et al. (2003).

of 24.4 m s^{-1}. In the first 2.2 km and above 17 km, the turbulent layers move relatively slowly, with median speeds of 2.3 and 9.2 m s^{-1}. The median of the wavefront coherence-time is 6.5 ms in the visible. The C_n^2 and **V** profiles are extremely important for choosing a site for a large telescope or any optical telescope with adaptive optics. The studies performed at the OAN-SPM have revealed that the site has vary favorable turbulence conditions. However, a longer-term monitoring is desirable, in order to confirm our results and identify seasonal behaviors, which is the motivation for developing a GS at UNAM (Cruz et al. 2003).

The turbulence in the surface layer was studied by Sánchez et al. (2003) using seven pairs of microthermal probes located at different levels of a 15-m-high mast. The measurements took place during 9 and 4 nights in May and August 2000, respectively. Incorporating DIMM data obtained simultaneously to the mast data, it was found that the optical turbulence located between 2.3 and 15 m represents 16% of that in the entire atmosphere (2.3 m – ∞). The mean value of the surface layer seeing obtained is $0''.16$ with a total contribution of 5.2% to the total C_n^2 (see Sánchez et al. 2007).

A two-element interferometer for monitoring atmospheric phase fluctuations operated in SPM for 28 days during June, 2001 (Hiriart et al. 2002). The system measured phase differences on the signal from a geostationary satellite received by two small antennas separated by 50 m. During that period, the rms phase fluctuation was $1^\circ.13$ at 11.715 GHz, that corresponds to a path length of 80 μm at that frequency.

5. RECENT SITE TESTING AT SPM

Astronomical site evaluation of a site has to be based on the most complete and long term data possible. The site survey group at SPM is making efforts in this direction: Since 1992, we have monitored the amount of water vapor through measurements of sky

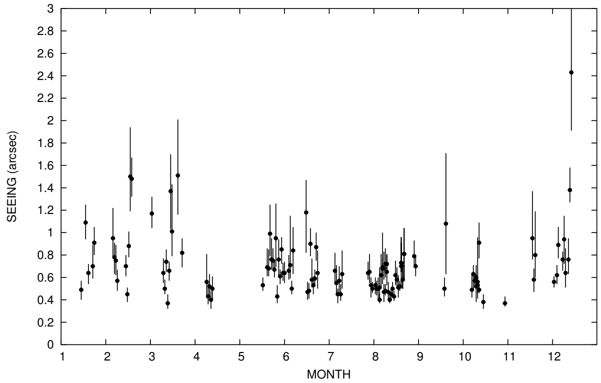

Fig. 16. Seasonal distribution of measured seeing with the SPM-DIMM from 2000 August to 2003 June. From Michel et al. (2003).

opacity at 210 GHz by using a tipper radiometer. We are also in the process of constructing a permanent seeing monitor using a robotic DIMM unit.

5.1. *Seeing Monitoring*

In 2005, we received on loan a CTIO Robo-DIMM unit (CTIO-DIMM). Thus, we had the possibility to have the SPM-DIMM, described in Section 4, and the CTIO-DIMM units side-by-side to get simultaneous seeing measurements. From a total of 1581 nearly synchronous measurements we found that the differences on the median seeing measurements of both instruments is less than 0.004 arcsec. The outcomes of the comparison between the SPM-DIMM and the CTIO-DIMM are presented in Núñez et al. (2007). The CTIO-DIMM has operational advantages over the old SPM-DIMM unit and these will be implemented in the permanent seeing monitor at SPM.

5.2. *Water Vapor Monitoring*

The San Pedro Mártir radiometer at 210 GHz (Hiriart et al. 1997) determines the sky opacity at that frequency by fitting a parallel atmosphere model to the skydips it obtains. A large archive of atmospheric opacity measurements at millimeter wavelength for Sierra San Pedro Mártir has been published for the years of 1992 (Hiriart et al. 1997) and 1999 (Hiriart 2003a). From the measurements of the sky opacity at 210 GHz it is possible to estimate the atmospheric water vapor content.

Recently, Hiriart & Salas (2007) have established a relationship between the atmosphere opacity at 210 GHz and the mid-infrared opacity measured with the CID (Double Infrared Camera), a mid-infrared camera system based on a BIB detector (Salas et al.

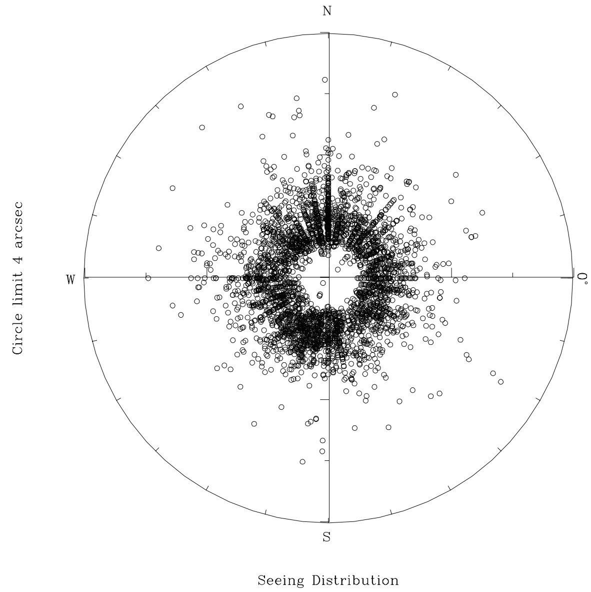

Fig. 17. Seeing as a function of wind direction, excluding measurements under high wind speeds (lower than around 30 km h^{-1}). From Echevarría et al. (1998).

2005). They also established a link between the sky opacity at 210 GHz and the amount of atmospheric water vapor at SPM.

Eight years (1995–2002) of radiometric measurements of the zenith atmospheric opacity at 210 GHz (1.4 mm) over SPM have been compiled by Hiriart (2003b). The results can be summarized as follows: During all observable days and nights, the median total-sky opacity at 210 GHz was 0.143 nepers, equivalent to approximately 2.55 mm of precipitable water vapor (PWV). Figure 18 shows the weighted monthly mean PWV for the whole period of observations. Monthly comparisons show that during the summer, the opacity rises to a maximum in August due to the water vapor carried by the American monsoon. This effect is also sensible to global climatological effects. For example, results for 1998 reflect the presence of El Niño activity during that year. The eight-year mean value quoted above, though, is very similar to those obtained for shorter periods two decades ago with infrared solar hygrometers (median PWV of 2.5 mm; Westphal 1974, Alvarez & Meisterrena 1977) and, more recently, from satellite measurements (median PWV of 2.7 mm; Erasmus & van Staden 2002). The fraction of nights with PWV < 1 mm is around 15 to 20%, except during the two mid-summer months.

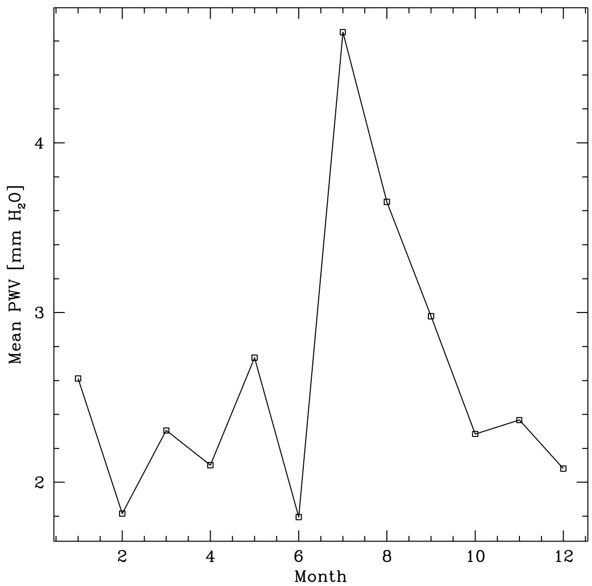

Fig. 18. Weighted monthly mean amount of precipitable water vapor over San Pedro Mártir for the period 1995 – 2002 during observable days/nights.

6. SITE SURVEY CAMPAIGNS IN SAN PEDRO MÁRTIR

During the last five years, San Pedro Mártir (SPM) has been selected by several projects as a potential site to install different astronomical facilities. In this section we give a review of the projects and the site survey studies that have been carried out at SPM. The results obtained have been quite useful in determining the astronomical quality of the site.

6.1. *Advanced Technology Solar Telescope (ATST)*

The ATST site survey began taking data on October, 2002 and concluded on November, 2003. This project afforded us with the opportunity to determine astronomical site quantities that are not usually measured at SPM.

The two main instruments used for the study were a seeing monitor and a sky brightness monitor. The seeing monitor contained two components: a solar differential seeing monitor (S-DIMM) and an array of six scintillometers known as the shadow band ranger (SHABAR). The seeing monitor was mounted on a 6-m tower designed in such way that the dominant motion of the platform was horizontal without tilting.

The sky brightness monitor (SBM) comprises a miniature coronagraph that compares the sky brightness in three wavelength bands (450, 530, and 890 nm) to the solar disk intensity. A dust counter instrument was installed to count particles in five size ranges (0.3, 0.5, 1, 2, and 3 μm). The dust counter was mounted on the 6-m tower close to the seeing monitor, while the SBM was located at ground level.

In addition to the seeing monitor and SBM, a weather station recorded wind speed, wind direction, atmospheric pressure, relative humidity, and temperature at two locations (top and bottom of the test tower).

The final report of the site survey for the ATST may be found at `http://atst.nso.edu/site/reports_final.shtml`.

6.2. *Large Synoptic Survey Telescope (LSST)*

As part of their site survey, the LSST Project installed an all-sky camera (MASCA) at SPM similar to the one at Cerro Tololo Inter-American Observatory (CTIO) (Smith, Walker, & Schwarz 2006). The camera started operating at SPM on July, 2005.

The all sky images allow monitoring of atmospheric effects of interest to astronomers, such as cirrus and contrails, otherwise invisible on moonless nights. It also allows to monitor air glow variations, light pollution in the Sodium and Mercury bands and aircraft lights. The Web address for the San Pedro Mártir all sky camera is `http://132.248.4.143`.

The LSST project also installed a 30 meter mast with 4 sonic anemometers at heights of 7, 12, 19, and 30 meters. It took wind data from December, 2005 to May, 2006. The data obtained during this period is being analyzed.

The LSST site evaluation results and analysis are presented in Sebag et al. (2006, 2007).

6.3. *Thirty Meter Telescope (TMT)*

The Thirty Meter Telescope (TMT) Project installed equipment that has been operating since October 2004 at SPM. Their equipment includes a MASS-DIMM monitor, a weather station, an ultrasonic anemometer, a dust monitor, and a Sonic Detection and Ranging System (SODAR).

To install their equipment they chose the western ridge of the telescope area, what is known colloquially as the "TIM hill" (on the extreme left of the photograph shown in Figure 2, TIM-01). This was also the area where the SPM-DIMM seeing monitor was installed. This allows us to compare their seeing data with our seeing monitor archive data. The survey is still in progress and a more detailed report of their instrumentation is found in the paper by Schöck et al. (2007).

7. SEARCHING FOR NEW TELESCOPE SITES IN SPM

In view of the possibility of installing new large telescopes at SPM, and the small space available at

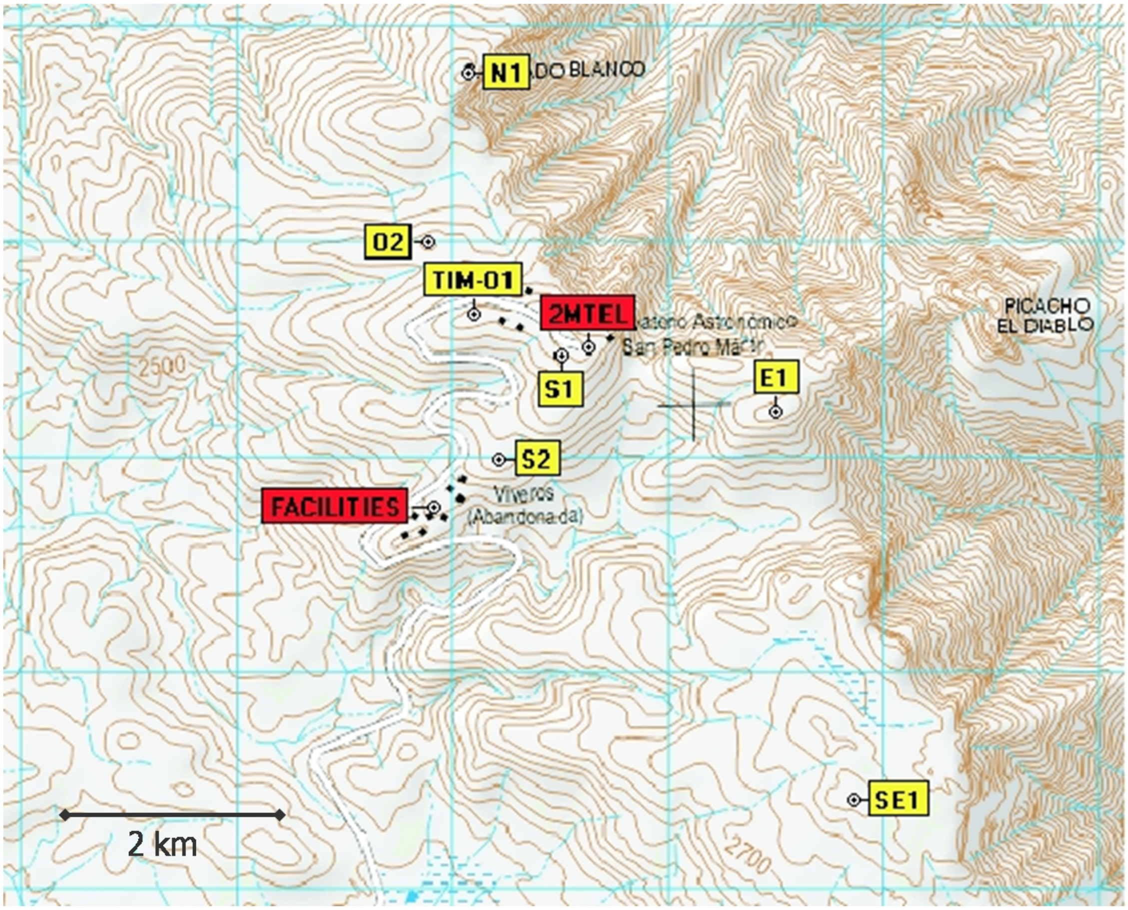

Fig. 19. Contour map indicating the location of the astronomical sites tested around SPM Observatory. Sites O2 and N1 were not tested. The map also shows the location of the 2-m telescope (2MTEL) and the observatory facilities (FACILITIES).

TABLE 5

ASTRONOMICAL SITES SURVEY AT SPM

Site	Latitude (N)	Longitude (W)	Height (m)
TIM-01	31° 2.′735	115° 28.′116	2770
S1	31° 2.′912	115° 28.′217	2695
S2	31° 3.′335	115° 28.′094	2710
E1	31° 2.′491	115° 27.′243	2800
SE1	31° 1.′512	115° 27.′063	2790

the present observatory area, a search for new astronomical sites was undertaken around the observatory.

To pinpoint promising sites, and to explore the topographically-induced turbulence, Vogiatzis & Hiriart (2004) modelled five prelected sites (see Sohn 2007) in San Pedro Mártir with 8 wind regimes. They used a 3-dimensional hydrodynamic code for a steady incompressible and isothermal fluid. The input data to the model were the topography, the wind speed, and wind direction. They found that "La Corona" is the best of these sites as far as turbulence of the wind is concerned. "Venado Blanco" is slightly better, and "Alamillos de Arriba" and "Botella Azul" are slightly worse than TIM-01. However, more reliable results would be obtained if higher resolution topography, thermal effects and more wind directions were considered.

From the listing of promising sites in Sierra San Pedro Mártir (see also Sohn 2007), we chose the ones with ease of access, low tree density and proximity to the present Observatory to share the infrastructure already in place at the Observatory area. Based on these criteria, we chose the four sites indicated in Table 5. TIM-01 site (see Figure 19) was chosen

TABLE 6

SAN PEDRO MÁRTIR SITE CHARACTERIZATION

Sky transparency	Clear nights	Usable nights
June 1997 – May 1998[a]	69.8%	81.6%
June 1997 – May 1998[b]	67.5%	83.7%
June 1996 – Dec 2002[b]	74.6%	85.0%
June 1984 – Dec 2006	64.1%	80.3%
Sky brightness	See Table 4	
Integrated seeing[c]		
Annual (median)	0.″62	
Spring	0.″58	
Summer	0.″58	
Autumm	0.″68	
Winter	0.″69	
Water vapor content		
Mean PWV satellite[a]	2.63 mm	
Mean PWV radiometer[d]	2.55 mm	
Mean extinction k_y[e]	0.14 @ 549 nm	0.055 @ 800 nm
Optical turbulence[g]	Altitude	Seeing
	2–4 km	0.″44
	4–9 km	0.″17
	9–16 km	0.″24
	16–21 km	0.″08
	21–25 km	0.″02
Surface layer seeing[h]		0.″16
Mean wind velocity[i]	27±3.6 m s^{-1} (GGUAS)	26.5±1.7 m s^{-1} (NCEP)

[a]Erasmus & van Staden (2003).
[b]Tapia (2003).
[c]Echevarría et al. (1998), Michel et al. (2003).
[d]Hiriart (2003).
[e]Parrao & Schuster (2003); k_y in mag airmass^{-1}.
[g]Avila et al. (2003).
[h]Sánchez et al. (2003).
[i]Carrasco & Sarazin (2003); GGUAS & NCEP data sets.

as the reference site, since most of the SPM seeing campaigns have been carried out on in that place.

A portable system had to be developed and constructed to carry out the study at the sites. The system consists of a portable DIMM, a weather station, an ultrasonic anemometer, a 6-meter tall foldable tower and living quarters. In doing the seeing measurements, we used the Robo-DIMM from Cerro Tololo Inter-American Observatory (CTIO; Walker et al. 2003).

Weather and seeing measurements were carried out at each location until 15 to 30 nights of data were obtained. The seeing data was compared to the seeing at the Observatory where simultaneous seeing measurements were being carried out. At the five places, we did not find significant differences on the values of measured seeing. Details of the site testing will be given by Bohigas et al. 2007 (in preparation).

8. SUMMARY

We have presented the results of almost three decades of astronomical site testing carried out at Sierra San Pedro Mártir. The relevant data that characterize the conditions for optical and infrared observations at this site are summarized in Table 6, while sky brightness is presented in Table 4.

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