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SAN PEDRO MÁRTIR: CHARACTERISTICS OF THE SITE FOR OPTICAL AND INFRARED OBSERVATIONS

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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 casi tres décadas de recabar información sobre la caracterización astronómica del sitio. Se cubren los siguientes aspectos: tiempo, nubosidad, meteorolgía local, opacidad atmosférica en el óptico y milimétrico, calidad de imagen, perfiles de turbulencia y de viento, y simulaciones 3D de turbulencia atmosférica. Se concluye que San Pedro Mártir es uno de los sitios accesibles del planeta con mejores condiciones para las observaciones astronómicas y en particular para instalar grandes telescopios. La UNAM y otras instituciones internacionales están llevando a cabo estudios de muy largo plazo para establecer mejor estos resultados.

ABSTRACT

The Observatorio Astronómico Nacional at San Pedro Mártir is located 31°02′40″ N and 115°28′00″ W on the summit of the Sierra San Pedro Mártir in the Baja California peninsula, Mexico, at 2800 m above sea level. The results of nearly three decades of site characterization work are summarized. These cover the following aspects: weather, cloud coverage, local meteorology, atmospheric optical extinction, millimetric opacity, seeing, optical turbulence profiles, wind profiles and 3D simulations of atmospheric turbulence. Overall, San Pedro Mártir is one the most favorable sites in the world for astronomical observations. Its excellent turbulence and local wind conditions, to mention but two characteristics, make it particularly well suited for large telescopes. Long-term monitoring of the site is being undertaken by the National Autonomous University of Mexico and other international institutions.

Key Words: **SITE TESTING**

1. INTRODUCTION

Mexico's National Astronomical Observatory (OAN) was formally inaugurated 128 years ago on top of a hill where the Castillo de Chapultepec is located in the, then, outskirts of Mexico City. In 1929, the federal government gave OAN to the National Autonomous University of Mexico (UNAM) for custody and operation. Since the end of the 19th century, the OAN has been moved to other parts of central Mexico (Tacubaya and Tonantzintla), always trying to escape from the influence of big cities and their associated light and atmospheric pollution. In the late 1960s, a site at the Sierra San Pedro Mártir National Park in northwest Mexico was chosen based on limited meteorological satellite surveys. Construction 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.

The OAN-SPM is located 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 Ritchie-Chrétien telescopes of diameters 0.84-m, 1.5-m and 2.1-m. The latter started continuous science operation in 1981. Figure 1 presents a panoramic view of the site. It is expected that in the near future the Mexican astronomical community will engage 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 international large telescope projects.

This paper summarizes the most important results of the San Pedro Mártir site characterization work done previous to 2004. Four aspects are discussed: sky transparency, atmospheric turbulence,

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Fig. 1. Aerial photograph of the telescopes of the Observatorio Astronómico Nacional at San Pedro Mártir.

meteorology and sky brightness. The complete description of the site testing studies presented here has been put together in a dedicated volume of the Serie de Conferencias of Revista Mexicana de Astronomía y Astrofísica (Cruz-González, Avila, & Tapia 2003) and in abbreviated form in Cruz-González, Avila, & Tapia (2004).

2. SKY TRANSPARENCY

Twenty years of weather and observing statistics of OAN-SPM have been reported by Tapia (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 2005. The monthly and yearly means are shown graphically in Figures 2 and 3.

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 4 and these are compared with data from other observatories (Parrao & Schuster 2003). It is seen 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 higher and less consistent. The rest of the year the extinction is intermediate.

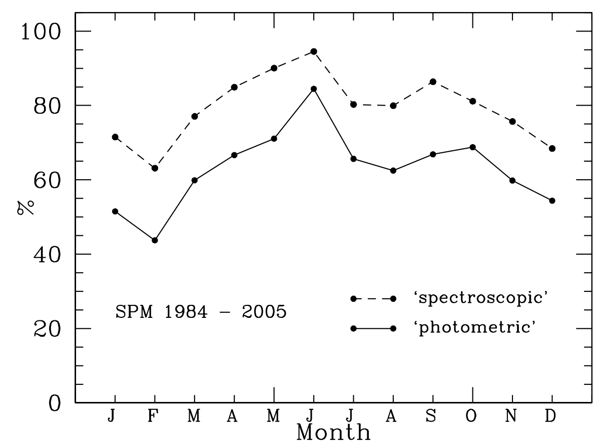

Fig. 2. Monthly fraction of nights of photometric and spectroscopic quality in San Pedro Mártir during the period January 1984 to December 2005.

3. SKY BRIGHTNESS

The following are the mean sky brightness (expressed in magnitudes per square arcsec) measurements over the Observatorio Astronómico Nacional at San Pedro Mártir in the photometric broad-bands *UBVRIJHK* as obtained during several moonless nights in 2005 August by Dr. Michael Richer (http://haro.astrossp.unam.mx/indexspm.html):

TABLE 1

SPM 2.1-M TELESCOPE OBSERVING STATISTICS: JULY 1982 TO DECEMBER 2005

	Number of nights	% over total number of calendar nights	% over number of scheduled nights
Total calendar	8585	100.0	–
Engineering	637	7.4	–
Scheduled for observation	6541	76.2	100.0
Observed	4643	54.1	71.0
Lost due to weather	1401	–	21.4
Lost due to telescope/dome/guider failure	139	–	2.1
Lost due to instrument failure	212	–	3.3
Lost due to other circumstances	92	–	1.4
Not scheduled	1410	16.4	–

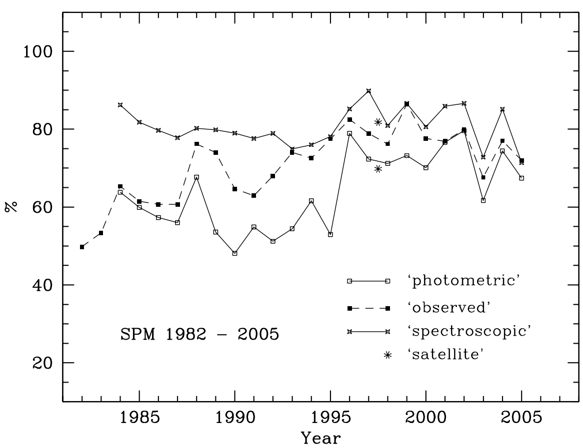

Fig. 3. Yearly fraction of nights of photometric and spectroscopic quality in San Pedro Mártir during the period January 1984 - December 2005. Also shown is the actual use of the 2.1-m telescope from July 1982 to December 2005. The asterisks refer to the mean satellite June 1997 - May 1998 measurements by Erasmus and van Staden (2002).

$U = 21.5$, $B = 22.3$, $V = 21.4$, $R = 20.7$, $I = 19.2$, $J = 16.5$, $H = 14.1$ and $K = 14.9$.

Figure 5 shows the calibrated night sky spectrum taken by M. Richer the night of 5 June 2005 (new moon) with a low dispersion spectrograph on the 2.1-m telescope.

4. ATMOSPHERIC WATER CONTENT

Eight years (1995-2002) of radiometric measurements of the zenith atmospheric opacity at 210 GHz (1.4 mm) over SPM have been carried out by Hiriart et al. (2003) using a differential heterodyne radiometer. They obtained the following results: 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 6 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 sensitive 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.

5. 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 ($\sim$ 20m) on San Pedro Mártir. One of the instruments was the 31-cm Site Testing Telescope (STT), twin of the one 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

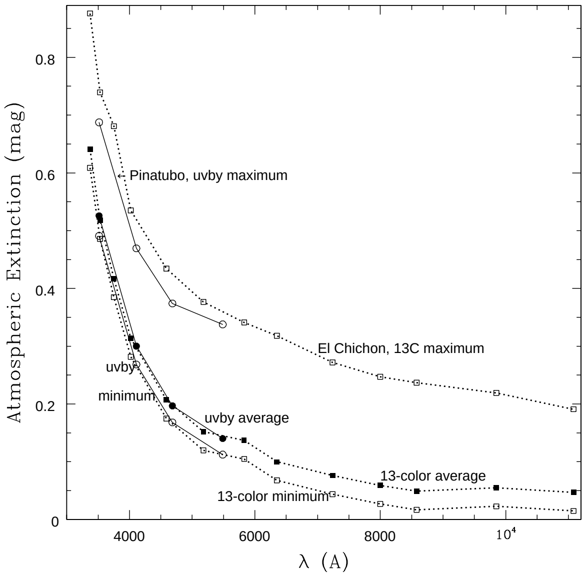

Fig. 4. Maximum, minimum and average atmospheric extinction curves for the 13C (dotted curves) and *uvby* (solid curves).

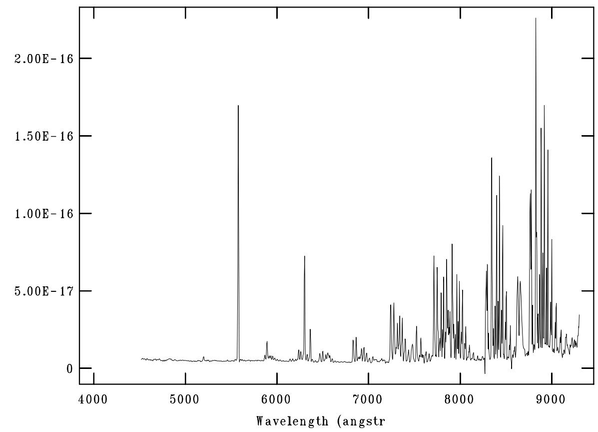

Fig. 5. The sky brightness (1 square arcsecond) in intensity units (erg s^{-1} cm^{-2} A^{-1}) as a function of wavelength.

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 other instrument was a 20-cm seeing monitor telescope equipped with guiding drives (Persson, Carr, & Jacobs 1990) mounted on an 8-m high tower with a semi-open dome. This instrument measures changes in the position of any stellar image in one dimension with a single detector. A few bright stars were measured each night for one year from 1992 September to 1993 August. The median size of the seeing over the whole duration of the surveys was 0.61 arcsec with the STT and 0.63 arcsec with the Carnegie monitor with first quartile values of $0\farcs50$ and $0\farcs48$, respectively. Echevarría et al. (1998) also reported that the wind direction and speed distributions were homogeneous and uncorrelated with seeing values. Note that during very strong winds, no seeing measurements were taken.

Subsequently, Michel et al. (2003a) reported almost three year monitoring of the integrated seeing at SPM using a Differential Image Motion Monitor (DIMM). 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 $0\farcs48$ 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, 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 reliable determination of seasonal variations requires longer 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 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 employed were different.

Avila et al. (2003) presented results of optical–turbulence profiles and 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 $0\farcs31$. 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 al-

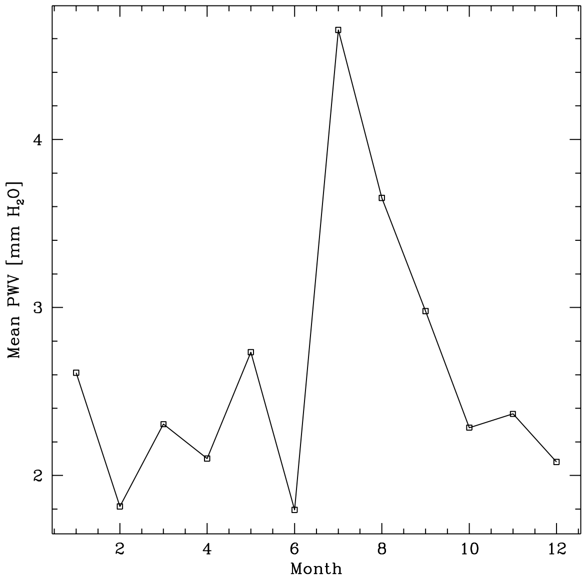

Fig. 6. Weighted monthly mean amount of precipitable water vapor over San Pedro Mártir for the period 1995 - 2002 during observable days/nights.

titudes 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 median speed 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 $\mathbf{V}$ profiles are extremely important for choosing a site for a large telescope or any optical telescope with adaptive optics.

The GS studies performed at the OAN-SPM have revealed that the site has truly excellent 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 (Avila 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. 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 $0\overset{''}{.}11$.

The SPM2000 campaigns are part of an ongoing study of optical turbulence (OT) characterization. Masciadri et al. (2003) reported the results of an innovative technique that consists of the use of an atmospheric model (Meso-Nh model), conceived to simulate the classic meteorological parameters (V, T, p), to inclusively simulate the optical turbulence. Their aims were to validate the atmospheric model, that is, to calibrate the model on the SPM site and study its reliability, and to develop a climatological study, extended over one year, of the C_N^2 vertical profiles and all the integrated astroclimatic parameters above the SPM site.

6. METEOROLOGY

Temperature measurements in 1998-2002 show a Winter minimum of $-13°$ C, a Summer maximum of 25° C, and an annual night to day differential of 10° C. The relative humidity shows a seasonal dependence: large variations on short timescales especially occur during the summer. Measured atmospheric pressure values were in the range 550 to 565 mm Hg during 1998-2002.

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

7. SUMMARY

The relevant data that characterize the conditions for optical and infrared observations at San Pedro Mártir are summarized in Table 2

Many people of UNAM staff and collaborators have cooperated over the years in the site-survey campaigns described in this paper. They are: F. Angeles, E. Carrasco, R. Conan, R. Costero, D. X. Cruz, S. Cuevas, J. Echevarría, F. Garfias, S. I. González, L. Gutiérrez, O. Harris, D. Hiriart, F. Ibañez, L. A. Martínez, E. Masciadri, R. Michel, V. G. Orlov, L. Parrao, B. Sánchez, L. J. Sánchez, M. Sarazin, W. J. Schuster, V. V. Voitsekhovich, A. Cháidez, R. Flores, M. García, G. García, E. López, A. Lepe, J. López, F. Martínez, G. Mendoza, F. Montalvo, S. Monrroy, A. Paredes,

TABLE 2

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 2005	64.7%	81.3%
Integrated seeing[c]		
Annual (median)	$0\farcs62$	
Spring	$0\farcs58$	
Summer	$0\farcs58$	
Autumn	$0\farcs68$	
Winter	$0\farcs69$	
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
Sky brightness[f]	Dark	Bright
U	21.5	19.3
B	22.3	19.8
V	21.4	19.7
R	20.7	19.6
I	19.2	18.4
J	16.5	
H	14.1	
K'	14.9	
Optical turbulence[4]g	Altitude	Seeing
	2–4 km	$0\farcs44$
	4–9 km	$0\farcs17$
	9–16 km	$0\farcs24$
	16–21 km	$0\farcs08$
	21–25 km	$0\farcs02$
Surface layer seeing[5]h		$0\farcs11$
Mean wind velocity[6]i	27±3.6 m/s (GGUAS)	26.5±1.7 m/s (NCEP)

[a]Erasmus & van Staedel (2003).
[b]Tapia (2003).
[c]Echevarría et al. (1998), Michel et al. (2003a).
[d]Hiriart (2003).
[e]Parrao & Schuster (2003); k_y in mag/airmass.
[f]M. Richer in http://haro.astrossp.unam.mx/indexspm.html; in mag/arcsec.
[g]Avila et al. (2003).
[h]Sánchez et al. (2003).
[i]Carrasco & Sarazin (2003); GGUAS & NCEP data sets.

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