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# STATISTICAL CHARACTERIZATION OF PRECIPITABLE WATER VAPOR AT SAN PEDRO MARTIR SIERRA IN BAJA CALIFORNIA

A. Otárola,[1] D. Hiriart,[2] and J. E. Pérez-León[2]

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RESUMEN

Presentamos datos del vapor de agua precipitable durante 2006 para la Sierra de San Pedro Mártir obtenidos de mediciones de la emisión atmosférica como función del ángulo de elevación por un radiómetro operando a la frecuencia de 210 GHz. Las mediciones de este radiómetro se combinan con valores de temperatura y presión atmosférica a nivel del suelo en el sitio para determinar una relación matemática para la conversión de la opacidad atmosférica al cenit a 210 GHz y la columna de vapor de agua precipitable para San Pedro Mártir. Los datos del vapor de agua precipitable se analizan estadísticamente para conocer su función de densidad de probabilidad y su distribución acumulativa, así como para determinar el número de horas continuas al año en que el vapor de agua precipitable permanece por debajo de los umbrales de 1 mm, 2 mm y 3 mm. Esta información es de interés para evaluar el desempeño de telescopios operando desde la región del óptico hasta longitudes de onda milimétricas en este sitio.

ABSTRACT

We present time series of precipitable water vapor (PWV) for San Pedro Martir Sierra in 2006, obtained from measurements of atmospheric emission as a function of elevation angle from a 210 GHz tipping radiometer. These radiometric measurements are employed together with collocated surface temperature and pressure data to determine a mathematical relationship for the conversion of 210 GHz zenith optical depth to PWV in the atmospheric column for San Pedro Martir. The PWV time series are statistically analyzed to gain insights on its probability density function and cumulative distributions, as well as to learn the number of continuous hours over a year that the PWV remains below given thresholds, namely 1 mm, 2 mm, and 3 mm. This information is of interest to evaluate the expected performance of telescopes operating from optical to millimeter wavelengths at this site.

*Key Words:* atmospheric effects — site testing



## 1. INTRODUCTION

The amount of integrated water vapor in the atmospheric column is one of many relevant parameters in the determination of the suitability of a site for the deployment and operation of an astronomical observatory. The transparency of the atmosphere to the propagation of electromagnetic signals of cosmic origin, for a given level of Precipitable Water Vapor (PWV) in the atmosphere depends strongly on the wavelength of the propagating signals. Figures 1 and 2 show the atmospheric transmission in the near infrared (NIR) spectrum as a function of wavelength, and in the radio spectrum as a function of frequency, respectively. Figure 1 is a high-resolution spectrum created from transmission data available for the Kitt Peak observatory and described in Hinkle, Wallace, & Livingston (2003). Figure 2 was produced with transmission data generated by the program *am* using a multi-layer, line-by-line, atmospheric model (Paine 2004) for 1 mm of PWV in the atmospheric column, and using typical parameters (surface temperature, surface pressure, and temperature lapse rate) for the San Pedro Martir location.

[1]TMT Observatory Corporation, Pasadena, CA, USA.
[2]Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, B. C., Mexico.

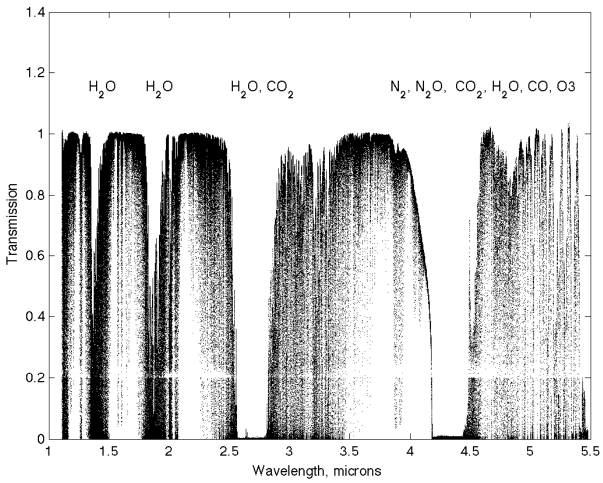


Fig. 1. Example of the measured atmospheric transmission at Kitt Peak (at standard atmospheric conditions) for the near infrared.

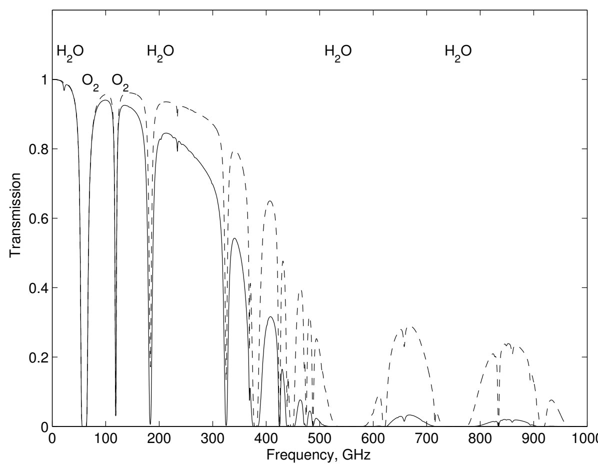


Fig. 2. Modeled atmospheric transmission at San Pedro Martir for 3 mm (solid line) and 1 mm (dashed line) of PWV, surface temperature of 280 K, surface pressure of 730 hPa, temperature lapse rate of −6.5 K/km, and water vapor scale height of 1.8 km.

Some of the opaque bands in the spectra shown in Figures 1 and 2 are due to absorption of electromagnetic signal energy by molecules of water vapor ($H_2O$) in the atmosphere. Additional absorption bands are attributed to absorption by $CO_2$, $O_2$, $O_3$, $N_2O$, and other active constituents in the earth's atmosphere.

For the performance of an astronomical observatory for conducting research in the infrared and millimeter bands not only the absolute amount of PWV in the atmospheric column is important, its temporal variability within the span of a given astronomical research program and over the course of the observing night are equally important.

This study focuses on the statistical characterization of PWV time series estimated for the San Pedro Martir site through 2006. However, it also includes the evaluation of statistical results from previous studies available in the scientific literature covering the period 1995–2002. § 1 describes the basic observables given by the atmospheric thermal emission detected by a 210 GHz tipper radiometer as function of elevation angle (airmass), and its conversion to optical depth at zenith using the Langley plot approach. § 2 explains the strategy developed to take optical depth time series and collocated surface weather parameters to derive an empirical model useful to estimate PWV from optical depth measurements. § 3 provides the results of the statistic characterization of the PWV time series. § 4 provides the conclusions from the analysis of the PWV data for the San Pedro Martir Sierra site and some recommendations for future work.

## 2. BASIC OBSERVABLES AND DETERMINATION OF OPTICAL DEPTH TIME SERIES

Time series of atmospheric thermal emission at the San Pedro Martir site have been generated with the help of a tipping radiometer operating at 215 GHz in the period 1992 until 1994. A technical description of the instrument, logic of the data reduction process to obtain zenith optical depths time series and results of the observations through 1992 were presented by Hiriart et al. (1997). The first generation 215 GHz tippers were modified to make them more reliable, capitalizing on the availability of mixers and and Gunn oscillators that yield lower overall instrumental noise temperature working at 210 GHz. A description of the changes introduced in the tipper radiometers and time series of optical depths at 210 GHz observed in 1999 is included in Hiriart (2003a).

In a succinct way, optical depth can be obtained from measurements of atmospheric emission at different elevation angles through (Hiriart et al. 1997)

$$\ln(V_{\mathrm{REF}} - V_{\mathrm{SKY}}(z)) = -\tau_o \sec(z) + \ln(g\eta T_{\mathrm{ATM}}) , \quad (1)$$

where the basic observables $V_{\mathrm{REF}}$ and $V_{\mathrm{SKY}}(z)$ are the voltage measured by feeding the tipper radiometer with the signal from a reference load at room temperature, and the voltage measured from the sky signal at a zenith angle $z$, respectively.

Figure 3, known to atmospheric scientists as the Langley plot, shows an example of a full *skydip* ob-

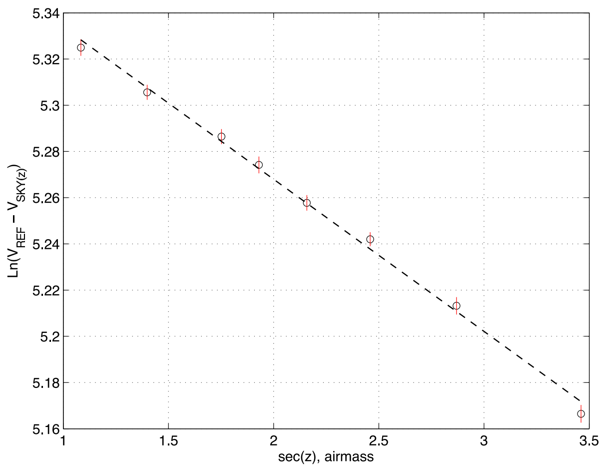


Fig. 3. Langley plot to show $\ln(V_{\mathrm{REF}} - V_{\mathrm{SKY}}(z))$ as a function of airmass $z$ for a full skydip.

servation. Circles show the natural log of the difference between the mean values of $V_{\mathrm{REF}}$ and $V_{\mathrm{SKY}}(z)$, the vertical bars correspond to the $\pm 1\sigma_{\mathrm{obs}}$ in the $\ln(V_{\mathrm{REF}} - V_{\mathrm{SKY}}(z))$ quantity. At each airmass, the radiometer measures 30 times the values of the sky and the reference load signals, and delivers the mean value of the observable $V_{\mathrm{REF}}$ and $V_{\mathrm{SKY}}(z)$ and its standard deviation $\sigma_{\mathrm{REF}}$ and $\sigma_{\mathrm{SKY}(z)}$, respectively. Following the propagation of the errors on the basic observables, we obtain

$$\sigma_{\mathrm{obs}} = \frac{1}{V_{\mathrm{REF}} - V_{\mathrm{SKY}(z)}} (\sigma^2_{V_{\mathrm{REF}}} + \sigma^2_{V_{\mathrm{SKY}}(z)})^{1/2} \,. \quad (2)$$

The dashed line in Figure 3 corresponds to the linear polynomial function that best fits the observations, in a weighted least-squares sense. The solution of this fit is given by

$$X = (G^T W_{\mathrm{obs}} G)^{-1} G^T W_{\mathrm{obs}} Y \,, \quad (3)$$

where $X$ is a column matrix of size 2 with the first element being the solution for $\tau_o$ (slope) and $\ln(g\eta T_{\mathrm{ATM}})$ (intercept), respectively. The intercept is a measure of a quantity that relates to the gain of the radiometer system (Hiriart et al. 1997). The $G$ matrix array has two columns, the first column is 1 and the second column corresponds to the magnitude of $\sec(z)$ with a total of eight rows, one for each airmass observed. The $W_{\mathrm{obs}}$ correspond to the statistical weights for the observable quantity $\ln(V_{\mathrm{REF}} - V_{\mathrm{SKY}}(z))$ and are defined as $W_{\mathrm{obs}} = 1/\sigma^2_{\mathrm{obs}}$ In this way, the less disperse measurements have higher relevant weights.

The covariance matrix of the model parameters, $Cov_x$, is given by

$$Cov_x = (G^T G)^{-1} G^T Cov_{\mathrm{obs}}((G^T G)^{-1} G^T)^T \,, \quad (4)$$

where $Cov_{\mathrm{obs}}$ is the covariance matrix of the observables. The main diagonal of the covariance matrix, $Cov_x$, includes the variance for the model parameters $\tau_o$ and $\ln(g\eta T_{\mathrm{ATM}})$.

The 210 GHz radiometer data at San Pedro Martir can be used to produce a determination of zenith optical depth with a time resolution of about six minutes.

## 3. OPTICAL DEPTH AND PRECIPITABLE WATER VAPOR

At radio wavelengths, the atmospheric transparency is dominated by absorption of water vapor –because of its permanent electric dipole– and molecular oxygen –because of its permanent magnetic dipole– as shown in Figure 2. A line-by-line, multi-layer radiative transfer model, such as *am* (Paine 2004), ATM (Pardo, Cernicharo, & Serabyn 2001), MODTRAN (Berk, Bernstein, & Robertson 1989), or any other equivalent model, together with known vertical profiles of temperature ($T$), atmospheric pressure ($P$), and water vapor density ($\rho_W$), can be used to compute the atmospheric optical depth ($\tau_o$) at a given frequency. An accurate determination of $\tau_o$ implies a corresponding accurate knowledge of the state of the atmosphere along the vertical axis at the site of interest; this is possible when data from vertical atmospheric soundings are available. Similarly, if the total optical depth is known the integrated water vapor (IWV) in the atmospheric column can be obtained through an inversion process. However, this process is rather time-consuming since the radiative transfer model has to be run iteratively by varying the IWV until the modeled and observed optical depths match within acceptable tolerances.

For this study, we obtain time series of basic observables in the period of time 2004 to 2006 from the SPM radiometer. Unfortunately, the time series show gaps of varying length in time (see Figure 4) and this prevents us from having a good coverage of all seasons through these years. The year with the most data is 2006 and an approach was developed in this study to use the data from years 2004 and 2005 to fill some of the gaps in the data series for 2006. This approach is valid under the assumption of stable climatology in the period 2004-2006, supported by a quick analysis of the *El Niño 3 index*[3] time series available from the NOAA Climate Prediction Center at `http://www.cdc.noaa.gov/ClimateIndices/List/`.

[3]This corresponds to the sea surface temperature on the Eastern Tropical Pacific (5S-5N;150W-90W).

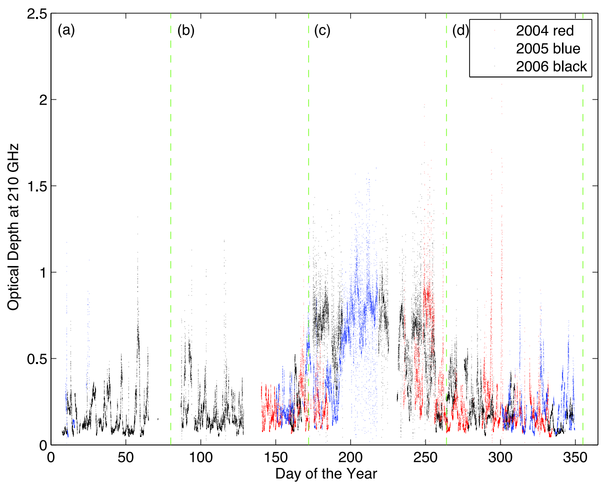


Fig. 4. 210 GHz optical depth time series in 2004 (red), 2005 (blue), and 2006 (black). See the electronic version version of this paper for the color codings.

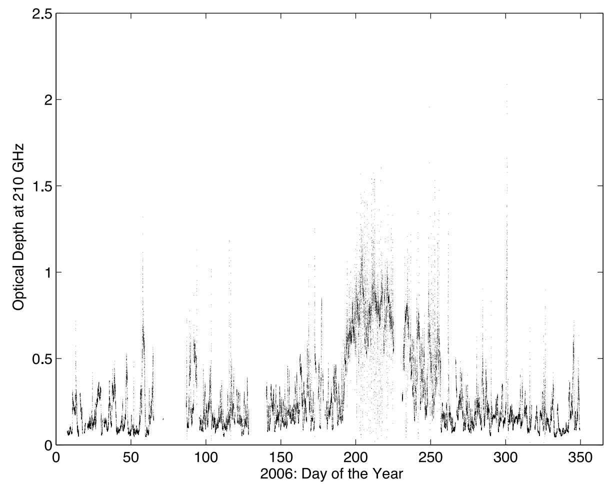


Fig. 5. SY2006, 210 GHz optical depth time series. The time resolution of the tipper measurements is 6 minutes.

In those few cases when data overlapped (noticeable after day 150 in Figure 4) the criterion was to pick the drier of the time series since this is perfectly possible within the normal inter-annual variability of the atmosphere at the site. This approach produced a synthetic year 2006 time series (SY2006 herein, Figure 5) that represents the best case for the data available for the study. The overlapping seasonal data series are not large enough to have a significant effect in the overall statistical characterization of the atmospheric conditions at SPM.

### 3.1. *A simple model to convert 210 GHz optical depths to PWV in the atmospheric column at San Pedro Martir Sierra*

The SY2006 data series includes a total of 72,580 data points with a time resolution of 6 minutes. Running a radiative transfer model iteratively for each of these data points until the modeled and observed optical depths match within a given tolerance is definitely a very time consuming task. Consequently, a subset of data points were used to derive an empirical model between the zenith optical depth at 210 GHz and PWV faster and without sacrificing accuracy. A relation like this is derived by Hiriart & Salas (2007) with the help of the ATM atmospheric model using fixed values for surface temperature and pressure, a temperature lapse rate of $-5.6$ K/km, and a water vapor scale height of 2.0 km. In this study we used a subset of 172 observations of optical depth and calculations from the *am* atmospheric model to estimate the amount of precipitable water vapor in the atmospheric column. These data correspond to those at noon time from the SY2006 and with collocated measurements of surface pressure and temperature from the site survey weather station of the Thirty Meter Telescope (TMT) Project.

Our analysis considers the following assumptions: (a) the temperature profile falls with a lapse rate of $-6.5$ K/km; (b) the water vapor decreases exponential with altitude with a scale height of 1.8 km, and; (c) we ignore the existence of a temperature inversion layer and its role in the mixing process of the atmosphere in the boundary layer. The lapse rate of $-6.5$ K/km corresponds to a mixed (dry and water vapor) atmosphere falling between the dry and moist adiabats, and the water vapor scale height is a good compromise between a well-mixed (high scale height) and low-mixed (low scale height) humidity profile. Of the assumptions made in this study the most unrealistic one is to ignore the existence of a temperature inversion layer to cap the boundary layer. This last assumption introduces a wet bias in our solution since low-level water vapor contributes to a larger optical depth at 210 GHz due to collisional broadening of the 183 GHz water line. A quick evaluation of the error that might be introduced in this case was conducted by running a limited number of cases. Assuming that 30% of the PWV is trapped in the lowest 500 meters close to the surface, with the rest distributed exponentially with a scale height of 1.8 km, it was found that the PWV needed to explain the observed optical depth at 210 GHz is about 5% lower than when the temperature inversion layer is neglected and the water vapor is distributed exponentially with altitude all the way from the surface.

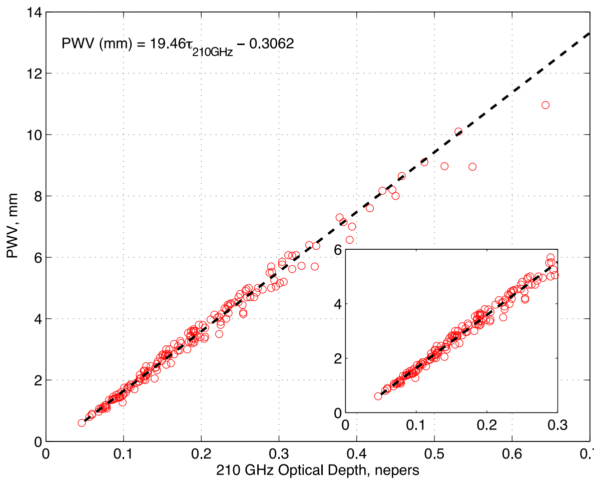


Fig. 6. Empirical relationship between 210 GHz optical depth and PWV for the San Pedro Martir Sierra.

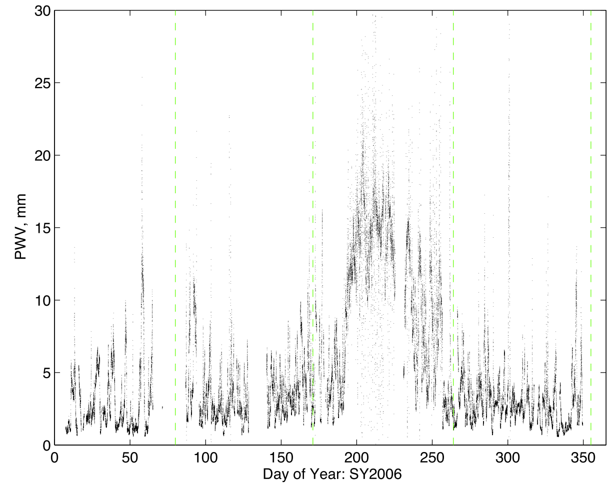


Fig. 7. PWV time series at San Pedro Martir Sierra from the SY2006 database. Green vertical dashed lines show the first day of each season. The SY2006 contains about 83% of the total number of data points that could have been possible based on the 6 minutes time resolution of the 210 GHz tipper sampling. See the electronic version of this paper for the color codings.

This uncertainty is well within the uncertainty of the determination of the optical depths (after error propagation of the basic observables) and consequently does not have much influence in the final results.

The relationship between the optical depth at 210 GHz and the integrated water vapor in the vertical column found in this study is given by

$$\mathrm{PWV(mm)} = 19.48\tau_{250\mathrm{GHz}} - 0.3062\,, \qquad (5)$$

where $\tau_{250\mathrm{GHz}}$ is the zenith opacity at that frequency. The sub-set of observations and the best fit are shown in Figure 6. This relationship predicts the 210 GHz optical depth at zenith in a dry atmosphere to be attributed only to the dry atmosphere opacity. Equation 5 represents the best fit to the observations in the range up to an optical depth of 0.31, since 87.5% of all data points fall below this limit. This approach was taken to minimize the possibility that the lapse rate of −6.5 K/km might not be the best assumption for the more humid atmosphere where the latent heat from condensation of water vapor helps to warm up the atmosphere and makes the absolute value of the lapse rate decrease. The dispersion of the data points in Figure 6 is explained by the varying temperature and pressure profiles of the atmosphere for the same value of optical depth through the year. This also explains the reduced scatter at the lower range in optical depth since this is achieved, most of the time, under very cold and clear winter nights with a low day-to-day variability.

Equation 5 was applied to the 210 GHz optical depth time series data of SY2006 to get the PWV time series for its statistical analysis. Figure 7 shows the result of this conversion. The absolute magnitude of PWV after the conversion using equation 5, derived in this study, is on average 5% (range 4.6% to 5.2%) lower than that obtained by using the equation derived by Hiriart & Salas (2007).

## 4. STATISTICAL ANALYSIS OF THE PWV TIME SERIES

The precipitable water vapor probability distribution function and cumulative distribution function for night and day time conditions are shown in Figure 8. These statistics include all the data points in the SY2006 database that sample about the 83% of the year. Figure 7 shows the gaps in the winter and spring season. Therefore, the statistics are expected to show a wet bias. If the gaps in the data series were replaced by the median PWV of the winter season (∼2.2 mm), the overall median and third quartiles would decrease by about 20%, from 3.4 mm to 2.8 mm and from 6.7 mm to 5.6 mm, respectively.

Figure 9 shows the monthly PWV statistics calculated from optical depth statistics published by Hiriart (2003b) and using Equation 5 for the conversion from optical depth to PWV. The statistics were obtained from time series gathered through 1999. The mean value of the monthly medians is 2.7 mm.

Figures 10 and 11 show the PWV statistics from the conversion, using Equation 5, of the 210 GHz

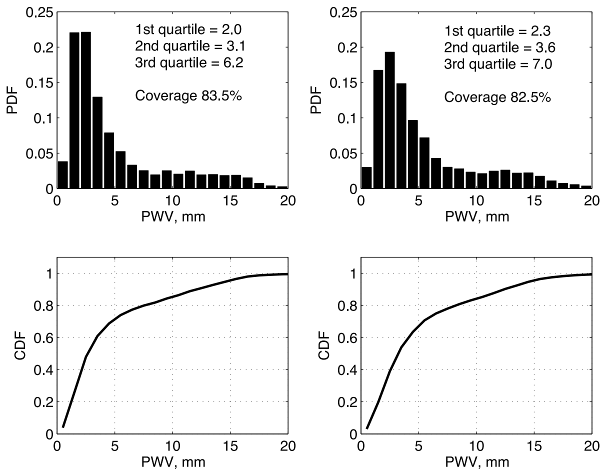


Fig. 8. PWV probability density function (PDF) and cumulative distribution function (CDF) for nighttime (left) and daytime (right) of the SY2006 database.

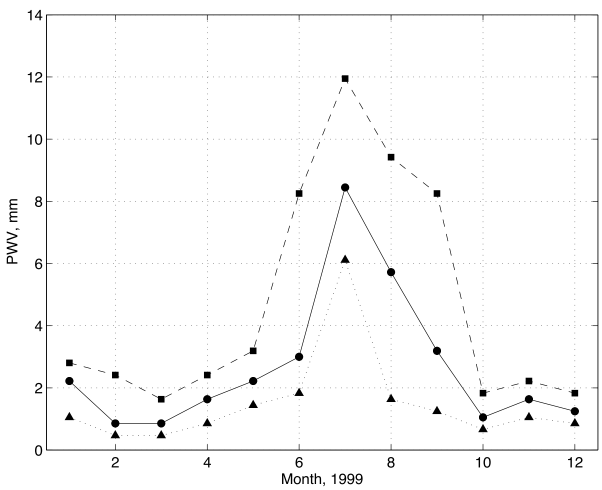


Fig. 9. PWV statistics at the San Pedro Martir Sierra, 1999. First quartile (triangles), monthly median values (ovals), and third quartile (squares).

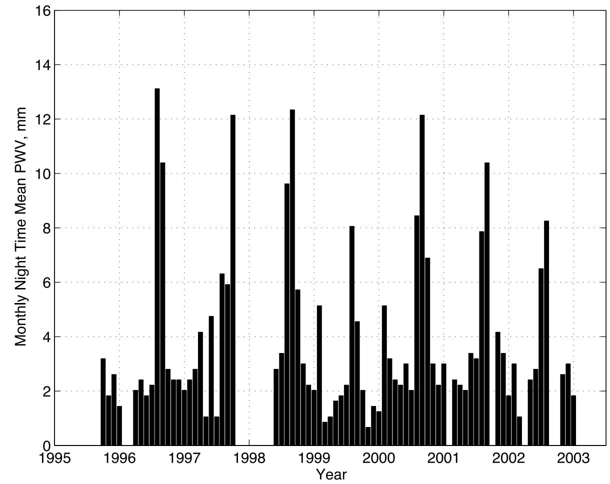


Fig. 10. Monthly nighttime mean PWV at the San Pedro Martir Sierra.

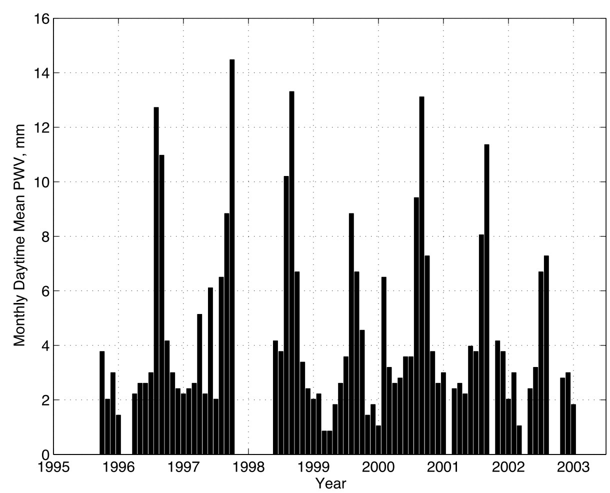


Fig. 11. Monthly daytime mean PWV at the San Pedro Martir Sierra.

optical depth statistics from the paper of Hiriart (2003b) for the nighttime and daytime at San Pedro Martir, respectively. The gaps in these figures correspond to times when measurements of 210 GHz optical depth were not available. The average of the mean values reaches 2.9 mm and 3.3 mm for the nighttime and daytime statistics in the 1995–2003 period, respectively.

The PWV time series in Figure 9 and the statistics shown in Figures 10 and 11 are useful to show that San Pedro Martir is characterized by a relatively dry period covering October through May and a wet period from June through September in the present data. The wet period might be attributed in part to the west reach of the North American Monsoon (NAM) and the effect of moisture advection as result of tropical storms and cyclonic activity originating on the east Pacific along the southern coast of Mexico.

In developing a site for astronomical research it is especially important to establish the relative stability of atmospheric conditions over time intervals representative of a typical observing sequence. In this regard, the SY2006 PWV data series were analyzed to look for the total number of hours that the PWV remains below a given threshold. The results of this analysis are shown in Table 1. Columns 2 & 3

TABLE 1

NUMBER OF HOURS THE PWV IS BELOW A GIVEN THRESHOLD AT SAN PEDRO MARTIR BASED ON THE SY2006 DATABASE

| PWV Threshold (mm) | Time with at at least 2 continuous hours below threshold (hours) | Percent of the 6 SY2006 database 7,276 total hours of available data (%) | Total Time with PWV below given threshold (hours) | Percent of the SY2006 database 7,276 total hours of available data (%) |
|---|---|---|---|---|
| 0.7 | 34.9 | 0.5 | 48.3 | 0.7 |
| 1.0 | 195.4 | 2.7 | 248.2 | 3.4 |
| 2.0 | 1529.4 | 21.0 | 1653.7 | 22.7 |
| 3.0 | 2966.0 | 40.8 | 3157.6 | 43.4 |
| 4.0 | 3987.4 | 54.8 | 4166.0 | 57.3 |
| 5.0 | 4671.4 | 64.2 | 4800.5 | 66.0 |
| 6.0 | 5095.6 | 70.0 | 5248.7 | 72.1 |
| 7.0 | 5394.7 | 74.1 | 5523.9 | 75.9 |
| 8.0 | 5595.1 | 76.9 | 5725.4 | 78.7 |
| 9.0 | 5770.6 | 79.3 | 5894.3 | 81.0 |
| 10.0 | 5919.8 | 81.4 | 6070.3 | 83.4 |



of Table 1 show the number of hours, and its percentage, of the data in SY2006 database that the PWV remains for at least two hours continuously below the threshold shown in the first column. Columns 4 & 5 show the total number of hours that the PWV remained below the given threshold with no restriction of a minimum of two consecutive hours.

The restriction of looking for at least two hours of PWV to remain below a given threshold has to do with the fact that, in a flexible scheduling operation of the telescope observing time, a reasonable time is necessary to set up the whole system (software and hardware) for a change in the observing program.

On average, in 2% of the time the PWV is not stable enough to remain at least two consecutive hours below the given threshold, as it can be inferred from the analysis of the information in Columns 3 and 5 in Table 1. Besides, from Table 1, it can be inferred that for about 20% of the time in the year the PWV values are larger than 10 mm, which amounts to about 2 months corresponding to the summer season.

Figure 12 shows the number of hours, with a minimum of 2 continuous hours, that the PWV at San Pedro Martir remains below the thresholds of 1 mm, 2 mm, and 3 mm through the year. The gaps centered around day of the year 80 and 140 are due to lack of data, but the gap from days 190 until 260 are due to the very wet conditions of the summer at San Pedro Martir and at no time the PWV goes below 3 mm for at least two continuous hours.

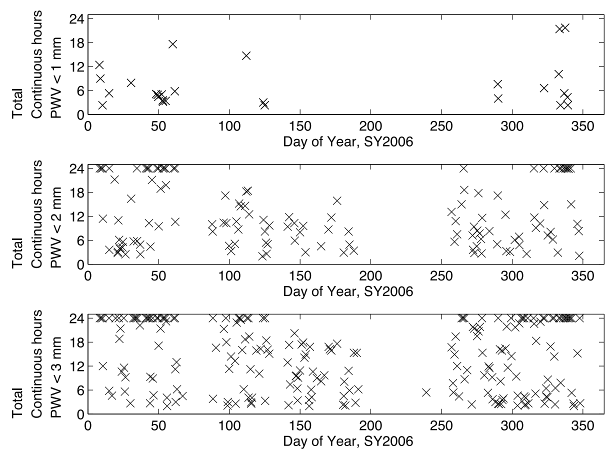


Fig. 12. Total number of continuous hours, with a minimum of 2 continuous hours, that the PWV at San Pedro Martir Sierra remains below the thresholds of 1 mm (top), 2 mm (middle), and 3 mm (bottom) as function of day of the year.

## 5. CONCLUSIONS AND FUTURE WORK

Time series of optical depth observed at the San Pedro Martir Sierra with the help of a 210 GHz tipping radiometer have been analyzed. The data include measurements performed in 2004, 2005, and 2006. The atmospheric conditions through this period of time are considered rather normal and representative of the climatology of the site. The data through these years show gaps, some of them quite large. The data from years 2004 and 2005 were used to fill up the gaps in the data series of 2006, in order to obtain a more representative vision of the recent time seasons at this site.

A small fraction of the optical depth data series in this synthetic database (SY2006) was used, together with collocated surface data (temperature and pressure) and with the help of the program *am* of a radiative transfer model, to derive a simple relationship to convert optical depths at 210 GHz to an equivalent amount of precipitable water vapor in the atmospheric column. This relationship, shown in Equation 5, produces PWV values which are about 5% smaller in magnitude than a similar relationship derived by Hiriart & Salas (2007). It is important to notice that the surface pressure of 625 mb listed by Hiriart & Salas (2007) in their Table 1 is too low a pressure for San Pedro Martir. In spite of this low pressure, the results in Hiriart & Salas (2007) are an indication that the pressure is affected by a typo error and the value used in that study was probably more like 725 mbar.

The PWV-optical-depth relationship found in this study was applied to the SY2006 database as well as statistical results known for the San Pedro Martir Sierra from other studies available in the scientific literature for the years 1999 (in a single study) and for the years 1995 to 2002 in another study. The results show that the overall mean value of PWV through the years at the San Pedro Martir Sierra is about 3 mm.

San Pedro Martir Sierra is characterized by a winter, spring and part of the fall season with relatively low values of PWV in the atmospheric column, with a median value of no more than 2.5 mm. However, it is also affected by a wet summer with at least two months of the year with PWV values larger than 10 mm. This wet period corresponds to that characterized by the reach of the North American Monsoon and the occasional incursion of tropical storms and cyclonic activity in general.

Regarding the persistence of the PWV series below given thresholds, of great importance for the development of astronomical observing programs, it was found that during about 20% and 40% of the time through the SY2006 database the PWV remains continuously below 2 mm and 3 mm for at least two uninterrupted hours, respectively. Concerning the very dry periods, the site remains below 1 mm of PWV for at least two continuous hours no more than 3% of the time. Hiriart (2003b), has found the persistence of PWV to stay below 1 mm (estimated from 210 GHz optical depth time series) to be 4% and 10% of the year for 1994 and 1999, respectively. The lower value of 3% found in this study from the analysis of the SY2006 database might be due to the fact there are gaps in the data series through winter time which correspond to the low PWV values season.

For future work it would be advisable to carry on a program for the vertical sounding of the atmosphere at San Pedro Martir by launching radioprobes. The information gathered in this way would help to better characterize the temperature lapse rate, water vapor scale height, and its variations through the seasons. It will also provide information on the existence and strength of temperature inversion layers and on the advection of water vapor into the different layers of the atmosphere. Ultimately, high vertical resolution soundings can provide useful information to gain insight on the atmospheric turbulence and wind profile which are also very relevant parameters affecting the performance of optical and infrared telescopes.

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Ángel Otárola: TMT Observatory Corporation, 2632 E Washington Blvd, Pasadena, CA, USA (aotarola@tmt.org).
David Hiriart and José Enrique Pérez-León: Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 877, 22830 Ensenada, B. C., Mexico (hiriart, eperez@astrosen.unam.mx).