Calibration of the Relationship between Precipitable Water Vapor and 225 GHz Atmospheric Opacity via Optical Echelle Spectroscopy at Las Campanas Observatory

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ABSTRACT. We report precipitable water vapor (PWV) measurements made at Las Campanas Observatory using optical spectra of H$_2$O lines obtained with the Magellan echelle spectrograph, and calculated using a robust technique that is accurate to 5%–10%. Calibration of the relationship between our PWV measurements and opacity values at 225 GHz was made possible by simultaneous observations with a tipping radiometer. Based on this calibration, we present Las Campanas Observatory wintertime precipitable water vapor statistics, measured using the tipping radiometer, during a 1.5 month campaign. The median value of 2.8 $\pm$ 0.3 mm is consistent with that measured at the nearby La Silla Observatory during the VLT site survey. We conclude that in the Southern hemisphere winter months, we can expect good conditions for infrared observing ($\approx$1.5 mm) approximately 10% of the time at Las Campanas Observatory.

1. INTRODUCTION

As part of the Giant Magellan Telescope site-testing program at Las Campanas Observatory, we are interested in characterizing precipitable water vapor, due to its impact on mid-IR observations through decreased transparency, increased thermal-IR background, and the introduction of extraneous spectral features. In this study, we report on our efforts to absolutely calibrate the relationship between 225 GHz opacity and precipitable water vapor (PWV).

The opacity at 225 GHz has been shown to be directly related to the column of precipitable water vapor in the atmosphere (e.g., Plambeck 1978; Chamberlin & Bally 1995; Davis et al. 1997). However, the relationship is also a function of pressure (and therefore altitude) and temperature, due to the fact that the 225 GHz opacity derives from the wing of a strong water vapor absorption line at 183 GHz arising from the 3–2 rotational transition (Waters 1976), where the wings are mostly due to pressure broadening. Efforts to calibrate this relationship have taken several different forms, including deducing the column of PWV from a model of the atmospheric transmission at mm wavelengths and measuring the PWV using radiosonde-type devices. Comparison between methods can be complicated by the effects of other atmospheric constituents (e.g., O$_3$, O$_2$, and N$_2$) on the dry air opacity.

Swings et al. (1990) combined high-resolution echelle spectroscopy of a water vapor line at 6943.79 Å with a technique devised by Brault et al. (1975, henceforth B75) to calibrate mid-IR sky radiance measurements obtained at La Silla Observatory during the VLT site survey. Through the use of modern partition functions and the addition of 13 new optical lines for PWV measurement, we have substantially improved on the B75 method when used in conjunction with high-resolution echelle spectroscopy. Section 2 describes the method in detail, and our results using it. Section 3 presents our campaign to measure the 225 GHz opacity using a tipping radiometer, the resulting calibration, and the PWV statistics for Las Campanas Observatory.

2. OPTICAL ECHELLE SPECTROSCOPY

The MIKE (Magellan Inamori Kyocera Echelle) spectrograph was used to acquire spectra of rapidly rotating A and B stars in the visual magnitude range 4.0 to 6.0. Due to the high
continuous opacity, these hot stars show very few absorption lines, particularly in the red optical region. Furthermore, their high rotational velocities ensure that any extant stellar lines are rotationally broadened, to widths much larger than lines arising from absorption through the Earth’s atmosphere.

The Las Campanas Observatory site-monitoring program includes a list of 16 telluric standard stars that pass close to the zenith, such that at any time, one or more stars are within 2 hr of the meridian. Observers were instructed not to submit echelle spectra taken through cirrus clouds as a precaution against spurious PWV measurements arising from clumpy clouds.

Typically, spectra were acquired when the hot stars were close to the zenith. The spectral resolving power was normally ~40,000, with a signal-to-noise ratio (S/N) in excess of 100:1. The echelle spectral format offers the advantage that light of a given wavelength occurs in two consecutive orders. This permits independent measurement of each line in two orders, providing that the lines fall on the echelle CCD array and that there is sufficient signal.

Reductions of the raw spectra were performed using the MIKE pipeline reduction software written by D. Kelson, using algorithms outlined in Kelson et al. (2000), Kelson (2003), and Kelson (2007).

While the site survey program, including the measurement of PWV, is ongoing, this paper is based on measurements of 15 spectra taken on 15 nights from 2005 July 21 to November 21. Table 1 lists the details of these observations. The tipping radiometer (Tipper) was not operational on every night that echelle spectra were taken; thus, our Tipper calibration is based on 11 of the 15 spectra.

Figures 1 and 2 show the spectrum near the H$_2$O line used by B75 at 6943.79 Å, in consecutive orders on our driest and wettest nights. The equivalent widths of the line in these spectra range from 5 to 52 mA.

2.1. Analysis of the Spectra

Following B75, we analyze our spectra using a robust and computationally simple method, but we employ improved partition functions that result in a slightly different choice of line excitation potentials than are used in B75. We have also added five new weak optical lines that can be used for reliable PWV estimates.

B75 pointed out that for a given temperature, there is a certain unique energy level that corresponds to a temperature-insensitive absorption coefficient. This follows from the Boltzmann equation (eq. [1]) describing the population of the energy levels of atoms and molecules: at any given temperature $T$, the population of levels with a unique excitation potential (EP) matches the sensitivity of the partition function to temperature;

\[ \frac{n_j}{N_{tot}} = \frac{g_j e^{-EP_{j}/kT}}{Q(T)}, \]

where the partition function $Q(T)$ is given by

\[ Q(T) = \sum g_j e^{-EP_{j}/kT}. \]

In Figure 3, we show a plot of $(n_j/N_{tot})$ versus temperature for three different energy levels over a range of temperatures expected in the Earth’s atmosphere; the plots were calculated using equation (1) and are normalized to a temperature of $T = 270$ K. Figure 3 is similar to Figure 1 in B75, but here we have used the partition function taken from the Kurucz3 Web site, which we believe is more appropriate than the simple approximation for the H$_2$O partition function employed by B75. Figure 3 indicates that for levels with excitation energy in the range of $225–300$ cm$^{-1}$, the ratio $n_j/N_{tot}$ varies by less than ~5% over the temperature range from 220 to 300 K. The excitation energy range that is least sensitive to atmospheric temperature, around 270–280 cm$^{-1}$, is slightly higher than the value of $225$ cm$^{-1}$ indicated by B75, and probably results from our use of modern partition functions. We note that even the ~5% uncertainty could be reduced by using a weighted average of the results from lines spanning the critical range of excitation energies.

Figure 4 shows an MSIS-E-904 model atmosphere for Las Campanas Observatory on one of the nights for which we have

\[ \text{See } \text{http://www.lco.cl/lco/operations-inf/gmt-site-testing-1/stars-for-measuring-pwv-with-mike/stars-for-measuring-pwv.} \]

\[ \text{See } \text{http://kurucz.harvard.edu.} \]

\[ \text{See } \text{http://modelweb.gsfc.nasa.gov/models/msis.html.} \]
a PWV spectrum. It can be seen that the temperature range of the model is covered by the range in Figure 3. The largest deviation from 270 K in the model is 210 K and occurs at the tropopause between a height of 10 and 20 km, encompassing approximately 20% of the mass of the atmosphere. We note that the water vapor pressure above ice (or water) at 220 K is approximately 0.6% of the vapor pressure at 270 K (e.g., Mason 1971). Thus, if the H$_2$O is uniformly distributed through the atmosphere, we estimate that approximately 0.1% of the mass of the atmospheric water vapor lies in the 10–20 km region, where the temperature differs most from 270 K. In other words, the coolest region of the atmosphere contains a negligible fraction of the total water vapor, and thus even the small systematic deviation of $n_i/N_{tot}$ from this region will be insignificant compared to the whole atmosphere. We conclude that lines with excitation levels near 270–280 cm$^{-1}$ can provide very robust estimates of the atmospheric PWV.

Under the assumption of pure-absorption radiative transfer and a constant line profile function through the Earth’s atmosphere, B75 pointed out that the PWV is given (in cm) by

$$PWV = \frac{L}{SX}, \quad (2)$$

where $L$ is the logarithmic flux, $S$ is the line strength parameter, and $X$ is the air mass. B75 referred to $L$ as the “log equivalent width” and defined it as the integral of the natural logarithm of the flux removed from the continuum by the line

$$L = \int_{-\infty}^{\infty} - \ln \left( \frac{l(v)}{I_c} \right) \, dv.$$  

The line strength parameter $S$ depends on atomic parameters, as follows:

$$S = g_f \left( \frac{\pi e^2}{mc} \right) e^{-E_{\text{rot}}/kT} \left( \frac{N_i}{N_{H_2O}} \right). \quad (3)$$

Note that the $g_f$-value can be calculated from the Einstein
spontaneous emission coefficient \( A_{ul} \) by the relation

\[
gf = 1.4992 \lambda^2 g_{up} A_{ul},
\]

where \( \lambda \) is in cm and \( A_{ul} \) is in Hertz.

In equation (3), \( N_A \) is Avogadro's number, \( 6.022 \times 10^{23} \), and \( A_{H_2O} \) is the atomic mass of H\(_2\)O, at 18.0. Note that use of equation (3) will give PWV in cm if the logarithmic flux integration \( L \) is performed over the frequency spectrum of the line in Hertz units. For an assumed temperature of 270 K, which is our single model atmosphere parameter, equation (3) reduces to

\[
S_{270} = \frac{2.917335 \times 10^8}{\sigma_{vac}^2} A_{ul} g_{up} e^{-\frac{\nu P}{187.6524}}
\]

(4)

In equation (4), we have applied the additional factor \(-c\sigma_{vac}^2\) (where \( \sigma_{vac} \) is the vacuum wavenumber) in the calculation of the strength factor \( S \) to account for the line flux measured in kaysers (cm\(^{-1}\)), consistent with the \( S \)-factors given in B75.

In practice, the line profile depends most strongly on the atmospheric pressure, which is a function of height, so a constant line profile condition, mentioned by B75, does not apply. However, in the case of unsaturated lines, the line profile does not affect the total absorbed flux, and equation (2) becomes valid, even with large variations in the line profile through the atmosphere. In this study, we computed PWV values from our measured H\(_2\)O line logarithmic fluxes, with wavelengths in cm\(^{-1}\) units, using equations (2) and (4); this is correct for unsaturated lines. For saturated lines, the variability of the line profile with height signals the breakdown of equation (2). In this case, to properly measure PWV would require a model atmosphere that accounts for the relation between line profile and column mass of H\(_2\)O.
Fig. 3.—Plot of the fractional population of levels \((n_l/N_{tot})\) in H\(_2\)O as a function of temperature in the range 220–300 K for energy levels of 225, 275, and 300 cm\(^{-1}\). Over the range of temperatures seen in the Earth’s atmosphere, the fractional population of levels in this energy level range changes very little and allows for robust measurement of PWV, without a detailed model atmosphere.

B75 measured the line strength parameter \(S\) using the McMath Solar Telescope for numerous lines with excitation near 225 cm\(^{-1}\), mostly for lines in the near-IR region of the spectrum. However, B75’s list did include one line in the optical, at 6943.79 Å. As a check of the B75 value of \(S\) for this line, we computed \(S\) from the Kurucz\(^5\) \(gf\)-value using equation (4). The Kurucz \(gf\)-value, which was taken from theoretical predictions by Partridge & Schwenke (1997), leads to a value of \(S\) that is \(\sim\)60% higher than the B75 measurement, although there is reason to suspect the veracity of this result, since the relative Kurucz \(gf\)-values appear to be inconsistent with the appearance of lines in our telluric spectra.

Given this disagreement, we decided to check the result from the 6943.79 Å line by identifying additional optical H\(_2\)O lines with excitation energies near 270–280 cm\(^{-1}\) and reliable measured \(gf\)-values. Our criteria for selecting the additional lines also stipulated that they be strong enough to be measured in our spectra, but not so strong that they might be saturated, and that the lines be clear of blends, including H\(_2\)O lines and other lines present in our telluric spectra (e.g., from the O\(_2\) molecule). We searched the HITRAN\(^6\) database of H\(_2\)O line parameters for suitable lines and visually inspected our telluric spectra to check for non-H\(_2\)O blends.

In Table 2, we show line parameters for the 6943.79 Å line of B75 and five new weak lines identified in this work. The HITRAN database included optical H\(_2\)O-line \(gf\)-values from a variety of sources. The \(gf\)-values for our lines in Table 2 came from Coheur et al. (2002), measured using a high-resolution spectrograph and a controlled, fixed water vapor path. For the

\(^5\) See footnote 3.

\(^6\) See http://cfa-www.harvard.edu/HITRAN.

| \(\alpha_{esc}\) (cm\(^{-1}\)) | \(\lambda_{obs}\) (Å) | EP (cm\(^{-1}\)) | \(S_{275}\) (cm\(^{-2}\)) | \(S_{225}\) (cm\(^{-2}\)) | \(S_{285}\) (cm\(^{-2}\)) | \(EW_{dry}\) (mA˚) | \(EW_{wet}\) (mA˚) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 13,717.1744     | 7288.10         | 275.50          | 3.233 \(\times\) 10\(^{-9}\) | 0.2387          | 6               | 88              |
| 13,718.5755     | 7287.36         | 300.36          | 1.251 \(\times\) 10\(^{-9}\) | 0.4912          | 21              | 134             |
| 13,823.1810     | 7232.21         | 300.36          | 5.602 \(\times\) 10\(^{-9}\) | 0.2200          | 9               | 75              |
| 13,894.6253     | 7195.02         | 285.42          | 6.159 \(\times\) 10\(^{-9}\) | 0.2619          | 12              | 84              |
| 14,397.3641     | 6943.79         | 224.84          | 3.059 \(\times\) 10\(^{-9}\) | 0.1795          | 5               | 52              |
| 16,788.1104     | 5954.94         | 300.36          | 8.942 \(\times\) 10\(^{-10}\) | 0.03511         | ...             | 6               |

\(S\) and \(gf\)-values calculated from Coheur et al. (2002) \(A\)-values.

\(a\) Compares well with Brault et al. (1975) \(S\) value of 0.180.
eight strong H$_2$O lines listed in Table 4 that were used for the saturation investigation (see § 2.3), the $gf$-values were taken from Coheur et al. (2002) and similar laboratory measurements of Brown et al. (2002). For the 6943.79 Å line, the empirical Coheur et al. (2002) $gf$-value indicated a line strength parameter $S$ that agreed with the B75 value to within 1%. Given the good agreement between the experimentally determined $S$ factors, and the difficulty in making theoretical $gf$-predictions for weak lines (due to the small overlap of the level wave functions), we chose not to use the Kurucz H$_2$O $gf$-values.

### 2.2. Results of Optical PWV Measurements

The range of line equivalent widths (in mÅ) for our list of temperature-insensitive H$_2$O lines is indicated in Table 2. Table 3 shows the logarithmic line fluxes and the resulting PWV values computed using equations (2) and (4) (multiplied by 10 to get PWV in mm). The PWV values range from 1 to 7 mm for the 15 nights, and there is good agreement, typically $\sim 10\%$, between the results for each line. This dispersion is consistent with the accuracy of the measured line $gf$-values: good $gf$-values are usually accurate to 5% to 10%. The weakest line in Table 2 is at 5954.9 Å and is most reliable on nights with more than $\sim 5$ mm PWV. The strongest line in Table 2, at 7287.4 Å, is useful for measuring PWV on very dry nights; on wet nights, it will be the first line to become saturated.

In Figure 5, we compare the individual PWV results for each line with the average for each spectrum. The figure shows no clear systematic differences between the PWV values for the individual lines. The rms scatter of the individual line PWV measurements about the mean for each spectrum is 0.3 mm H$_2$O on average, corresponding to $\sim 10\%$.

In Figure 5, the 7287.4 Å point for the wettest night appears below the main correlation, slightly more than might be expected from the general scatter of the points. In addition, for the next two wettest nights, the 7287.4 Å PWV points are also the lowest of the six lines used. Although these differences are extremely subtle and could easily be random, they may indicate the beginning of saturation in the 7287.4 Å line; indeed, the expected effect of saturation is to reduce the computed PWV from equations (2) and (4). If that is the case, then the strength of our 7287.4 Å line on the wettest night, at 134 mÅ, represents the useful upper limit for PWV measured using unsaturated H$_2$O lines under the assumption of no saturation.

The method used to measure PWV here could be applied to...
Fig. 5.—Plot of the individual PWV results from all lines, compared to the average PWV of each spectrum. The straight line corresponds to a 1 : 1 relation. Symbols for different line wavelengths are indicated at top left. There are no unambiguous systematic trends of individual lines deviating from the mean.

Fig. 6.—Plot of the results from PWV calculations for strong and weak lines on the wettest night (2005 August 2; filled circles) and a moderately dry night (2005 August 20; open boxes). For the wettest night, there is a clear downturn in the PWV estimates above a reduced equivalent width around \( \lambda = 4.6 \) to \( \lambda = 4.7 \), indicating that lines above that width suffer from saturation. On the drier night, only one line was saturated; the excellent agreement between the unsaturated lines shows that the downturn of the PWV points for the wettest night was not due to systematic error in line \( gf \)-values.

TABLE 4

| \( \sigma_{\text{sys}} \) (cm\(^{-1}\)) | \( \lambda_{\text{sys}} \) (\( \overline{\text{Å}} \)) | EP (cm\(^{-1}\)) | \( gf \) | \( S_{270} \) (cm\(^{-1}\)) | EW\(_{\text{wet}}\) (mA\(_{\text{Å}}\)) |
|----------------|----------------|----------------|------|----------------|----------------|
| 10,704.4205    | 9339.33        | 300.36         | 2.730 \times 10^{-7} | 10,7240\(^{1}\) | 1047.0          |
| 11,002.2178    | 9086.55        | 300.22         | 1.245 \times 10^{-8} | 0.5303\(^{2}\) | 186.0           |
| 11,124.6353    | 8986.56        | 300.36         | 3.017 \times 10^{-8} | 1.1852\(^{2}\) | 343.0           |
| 12,254.5139    | 8157.99        | 300.36         | 1.676 \times 10^{-8} | 0.6584\(^{3}\) | 208.0           |
| 11,096.9124    | 9009.01        | 300.36         | 4.443 \times 10^{-9} | 0.1892\(^{2}\) | 111.0           |
| 12,238.3078    | 8168.79        | 222.05         | 7.226 \times 10^{-9} | 0.4309\(^{2}\) | 180.0           |
| 12,062.4127    | 8287.91        | 224.84         | 1.770 \times 10^{-8} | 1.0397\(^{3}\) | 313.0           |
| 12,037.5135    | 8305.05        | 325.35         | 2.243 \times 10^{-8} | 0.7714\(^{4}\) | 241.0           |

\(^{1}\) \( S \) and \( gf \)-values calculated from Brown et al. (2002) \( A \)-values.

\(^{2}\) \( S \) and \( gf \)-values calculated from Coheur et al. (2002) \( A \)-values.

with the equivalent widths of each line on our wettest night (2005 August 2). It is interesting to note that the stronger \( \text{H}_2\text{O} \) lines tend to lie at redder wavelengths than those in Table 2.

In Figure 6, we show a plot of reduced equivalent width (REW = ln EW/\( \overline{\text{Å}} \)) for all 14 \( \text{H}_2\text{O} \) lines (from Tables 2 and 4) versus PWV for the nights of 2005 August 2 and 20, calculated using equation (2). It is clear that the stronger lines on August 2 give systematically lower PWV values, decreasing roughly linearly with increasing strength; for lines weaker than REW ∼ −4.6 to −4.7, the PWV values are approximately constant. This satu-

2.3. Saturation Investigation

As mentioned above, the Brault et al. method used to compute PWV in this paper is quite robust, provided that the lines are not saturated. To use saturated lines for reliable PWV measurement would require a detailed model atmosphere treatment in which the run of temperature with PWV, or fractional PWV, would be specified through the atmosphere. Given the small scatter in our results, it seems likely that all of the lines measured in Table 2 are unsaturated, although the line at 7287.36 \( \overline{\text{Å}} \) may be low on our wettest night, indicating the onset of saturation. The use of saturated lines will result in lower computed PWV values, with the error becoming more pronounced with increasing line strength.

It would be useful to know the approximate saturation limit in terms of line strength so that we do not use overly strong lines in the PWV calculations; this is particularly important for the wettest nights. In order to do this, we have conducted a search for strong \( \text{H}_2\text{O} \) lines in the HITRAN database that have lower level excitation energies, in the range 225–300 cm\(^{-1}\) (the range in which PWV measurements are insensitive to atmospheric temperature). We have calculated the parameters for this list of eight strong \( \text{H}_2\text{O} \) lines, as shown in Table 4, along
ration limit corresponds to ~160 mÅ at 7300 Å; this is larger than the 134 mÅ value for the line at 7287.36 Å on the wettest night, which we had previously suspected could be affected by saturation. Therefore, future PWV measurements that use the Brault et al. method should disregard lines above REW ~ −4.65. The August 20 points in Figure 6 show that when the lines are below the saturation limit, they give results that are in good agreement; this eliminates the possibility that the decreasing PWV values for strongest lines on the wettest night are due to a systematic error in the line gf-values. The unsaturated August 20 points have a standard deviation of 11% in PWV, giving an error on the mean PWV of only 3.3%.

Because line saturation in red giant stars begins around REW ~ −5.1, it is clear that the telluric H2O lines must be more strongly broadened than lines in red giants. Atmospheres of red giant stars are much hotter and have much larger turbulent velocities than the Earth’s atmosphere; therefore, the main source of broadening for the telluric H2O lines cannot be due to temperature or turbulence. The only possibility is that the larger broadening of the telluric lines is due to the much denser Earth atmosphere (i.e., pressure broadening), for which one would expect the collision frequency and Van der Waals forces to be greater than for lines formed in the low-density atmospheres of stars.

Given the larger saturation point for telluric lines than for stellar lines, the pressure broadening must be overwhelmingly dominant. Thus, it may be the case that the saturation point changes with atmospheric pressure; for example, due to the change in the collision frequency experienced by the H2O molecules. It is also possible that the saturation point is affected by humidity, both because of the presumably larger H2O collision cross section av, and also as a result of different Van der Waals forces for H2O compared to other atmospheric gases.

Future PWV measurements can utilize the stronger H2O lines listed in Table 4, provided that the saturation limit is not exceeded.

2.4. Temperature Diagnostic

We have attempted to estimate the mean temperature for the wettest night, 2005 August 2, using H2O lines covering a range of excitation energies. Iterative calculations were performed to find the temperature where the line PWVs matched the temperature-independent PWV value. This mean temperature is actually weighted by the water vapor mass, so it should reflect the temperature closer to the ground, where most of the water vapor lies.

We identified and measured nine lines from the HITRAN database with energies ranging from 0 to 756 cm⁻¹. The derived temperatures ranged from 268 to 290 K, with a mean of 279 K and an rms scatter of 9.5 K. Some of the scatter may have resulted from blending of weak high-excitation lines. We note that the mean temperature verifies our use of a temperature of 270 K for the PWV calculations.

Apart from verifying our initial assumption, it is not clear how useful the mean temperature diagnostic would be; perhaps it may be used to compare with mass-weighted temperatures calculated from tailored atmosphere models. A better way to compare with theoretical models would be to use profiles of strongly saturated lines to derive the run of temperature with H2O opacity; but this would require accurate estimates of the line broadening in the theoretical models.

3. 225 GHz TIPPING RADIOMETER OPACITY

Opacity at 225 GHz was studied through the use of the University of Arizona Radio Observatory (ARO) 225 GHz tipping radiometer, on loan to Las Campanas Observatory for the 2005 Southern hemisphere winter season. This radiometer is one of four originally constructed for millimeter array site-testing purposes by the NRAO and has been in regular use at ARO for sky quality assessment since 1995. These systems have been used to characterize many other sites, including Mauna Kea (one of the units has been in operation since 1989 at the Caltech Submillimeter Observatory [CSO]), Antarctica, Cerro Chajnantor (Chile), South Baldy, and the VLA site in New Mexico (Owen & Hogg 1990; Schwab et al. 1990; Chamberlin 2004).

The characteristics of this radiometer have been extensively described elsewhere (Liu 1987; McKinnon 1987; Chamberlin & Bally 1994); therefore, only a short description is provided here. The radiometer is illuminated via a mirror (with a beamwidth of 3.4°) that rotates through 11 elevation angles between an air mass of 1 and 3, thus providing a “tip” (measurement of the sky brightness as a function of zenith angle). The beam enters a temperature-controlled box in which a chopper wheel allows the receiver to alternately view in repeatable sequences the sky, a cold (45°C) load, the sky, and finally a hot (65°C) load. The use of two different temperature reference loads allows the gain to be measured. The opacity and an estimate of its uncertainty are then derived according to a slab model of the atmosphere from a linear fit to the natural logarithm of the sky brightness temperature as a function of air mass.

Opacities were obtained approximately every 5 minutes continuously between 2005 July 17 and August 30, with some exceptions due to storm activity. Of these data, 2999 measurements were selected from the 29 full and partial nights when the conditions were judged to be photometric. The requirement of photometric conditions was imposed not only because of concerns that nonphotometric conditions would lead to incorrect fluxes and opacity measurements from the Tipper, but also because of the desire to characterize the PWV on nights that were suitable for mid-IR astronomy.

3.1. Relationship of 225 GHz Opacity to Precipitable Water Vapor

The relationship between 225 GHz opacity τ and the column of precipitable water vapor (PWV, in mm) can be represented
where the opacities and the coefficient $B$ are reported in nepers per air mass and nepers per air mass per mm H$_2$O, respectively. As used here, a neper is a measurement of attenuation similar to a decibel but based on the natural logarithm, as opposed to a decibel.

Plambeck (1978) reports the first estimate of the relationship between $\tau$ and PWV. The opacity measurements made at the University of California Hat Creek Observatory (with an altitude of 1050 m) were correlated with PWV as measured by a radiosonde in Medford, Oregon (210 km to the northwest). Although no values below 4 mm PWV were measured, the coefficient $B$ was found to be 0.06. In the development of the NRAO tipping radiometers, one of which was used in our study, McKinnon (1987) used a similar relationship but included a constant opacity offset of 0.005 nepers per air mass, due to absorption by oxygen. They also mention that the relationship is weakly dependent on elevation.

Chamberlin & Bally (1995) report on their calibration efforts in Antarctica using another NRAO tipping radiometer to measure 225 GHz opacities and radiosonde upper air soundings to measure PWV. Their coefficients can be found in Table 5. A reanalysis of this data is presented by Chamberlin (2004) but does not change the finding of a significant nonzero dry air opacity. The cause of the dry air opacity is not well understood, as many atmospheric transmission models (e.g., Pardo et al. 2001; E. Grossman 1989, unpublished$^7$; Liebe 1989) have failed to reproduce it. A new model that accounts theoretically for the collision-induced absorption by N$_2$N$_2$ molecular partners may be able to resolve this discrepancy (Paine 2004). Further work in understanding and characterizing this parameter is especially important to the characterization of the low precipitable water vapor sites at mm wavelengths.

At Mauna Kea, this relationship was established in a different way (Davis et al. 1997), and the coefficients can also be found in Table 5. The 225 GHz opacities were measured with the CSO tipping radiometer, also one of the original NRAO tipping radiometers. The PWV values were obtained through the use of an atmospheric spectral synthesis model called FASCOD2. As the PWV has not been independently measured, it is unclear whether this model might also underestimate the dry air opacity. Given that this calibration is now canonically used to produce PWV values from 225 GHz opacities for Mauna Kea, and also to draw comparisons to other sites, it is important to measure the dry air opacity there.

At Las Campanas Observatory, the precipitable water vapor values that were determined with the MIKE spectrograph in § 2.2 and shown in Table 3 were correlated with the 225 GHz opacity measurements as shown in Figure 7. The opacities at the times nearest those in Table 3 were selected. There was never more than 5 minutes difference, and a total of 11 points with times in common were found. A linear relationship was determined using a linear least-squares regression with errors in both the independent and dependent variables. Our coefficients are also listed in Table 5. More points would be needed to better constrain the dry air opacity there.

A meaningful comparison of the available calibration coefficients at different sites is made difficult by the lack of uncertainties reported for the calibrations cited in Table 5. Chamberlin & Bally (1995) reported very small uncertainties for their

\begin{equation}
\tau = \tau_{\text{dry-air}} + B \text{ PWV}
\end{equation}

$^7$ Atmospheric Transmission (AT) Program, Ver. 1.5, distributed by Air Head Software, Boulder, CO.

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**TABLE 5**

**Comparison of Calibration at LCO and Other Sites**

| Site                      | Altitude (km) | $\tau_{\text{dry-air}}$ | B       | Reference               |
|---------------------------|---------------|--------------------------|---------|-------------------------|
| LCO Alcaino               | 2410          | 0.015 ± 0.013            | 0.076 ± 0.005 | This work              |
| South Pole                | 2835          | 0.026 ± 0.001            | 0.083 ± 0.002 | Chamberlin (2004)      |
| Mauna Kea                 | 4100          | 0.016                    | 0.05    | Davis et al. (1997)    |
| Llano de Chajnantor       | 5104          | 0.0068                   | 0.0407  | Delgado et al. (1999)  |

1 Uncertainties from Chamberlin & Bally (1995).

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**Fig. 7.—**Correlation between MIKE spectrograph PWV measurements and 225 GHz tipper opacities at LCO during the period between mid-July and mid-September of 2005. Where no error bars are visible, the errors are within the size of the symbol. The line represents a linear least-squares fit, with characteristics denoted in the legend.
calibration efforts at the South Pole. However, their results were superseded by a reanalysis of the tipping radiometer measurements in which the opacities were adjusted systematically upward by 15% (Chamberlin 2004). No mention of the relative uncertainties was made in Chamberlin (2004), and since adjustments were systematic in nature, we quote the original uncertainty values from Chamberlin & Bally (1995) in Table 5. Regardless of the lack of uncertainties in the reported calibrations, it appears that the dry air opacity decreases with altitude, and as expected due to the pressure broadening seen in the wing of the 183 GHz line, the coefficient $B$ also decreases with altitude. In other words, at lower altitudes (higher pressure),
less PWV is required to produce the same opacity at 225 GHz as seen at higher altitudes.

3.2. Calibrated Precipitable Water Vapor at Las Campanas Observatory

Given the calibration determined in the previous section, millimeters of precipitable water vapor and its uncertainty estimate are calculated from the Tipper opacities and errors, in the following manner:

\[
PWV = \frac{\tau - \tau_{\text{dry-air}}}{B},
\]

\[
\sigma_{\text{PWV}} = \sqrt{\sigma_{\tau_{\text{dry-air}}}^2 + (\tau B)^2 + B\sigma_{\tau}^2}.
\]

Figure 8 shows the resulting precipitable water vapor values at night under photometric conditions as a function of time during our campaign. The fraction of the measurements for which PWV was found to be below a given value is displayed in Figure 9. Uncertainties in our PWV estimates are on the order of 10%.

Over the 1.5 month period covered by our measurements, we find a median PWV of 2.8 ± 0.3 mm. Assuming that this time period is representative of the winter PWV characteristics at Las Campanas Observatory, we can expect good conditions for mid-IR observing (<1.5 mm PWV) 10% of the time in winter (e.g., Giovannelli et al. 2001). These results agree well with measurements made at the nearby La Silla Observatory during the VLT site survey (Swings et al. 1990). La Silla is located 24 km south of Las Campanas and has nearly exactly the same altitude. The VLT site survey measurements were obtained using a mid-IR sky radiance monitor (Morse & Gillette 1982). The absolute scale of these data was calibrated using the B75 method on coudé spectra of the 6943.79 Å line obtained simultaneously with mid-IR sky radiance measurements on several nights.

4. CONCLUSIONS

We report on the calibration of the relationship between the column of precipitable water vapor (PWV) and opacity at 225 GHz at Las Campanas Observatory as measured by an NRAO tipping radiometer on loan from the University of Arizona Radio Observatory, and from the high-resolution echelle spectrograph MIKE on the Magellan Clay Telescope. We have expanded the absolutely calibrated method for measuring PWV using temperature-insensitive lines in high-resolution stellar spectra presented by Brault et al. (1975) with improved partition functions and 13 additional lines. We found that optical H2O lines with reduced equivalent widths weaker than \( \sim 4.7 \) to \( \sim 4.6 \) are unsaturated and suitable for measuring PWV using the Brault method. This saturation level indicates that the lines are strongly pressure broadened. A calculation of the mass-weighted mean temperature validates the use of a single slab model atmosphere with \( T = 270 \) K to compute PWV values. The linear relationship we found between the MIKE PWV and the 225 GHz opacities is consistent with opacities formed from a pressure-broadened wing of the strong water vapor line at 183 GHz, including a dry air opacity component. The effect of altitude (due to atmospheric pressure changes) is demonstrated by comparing our calibration at Las Campanas Observatory with those few available in the literature. We note the paucity of such absolute PWV calibration efforts and encourage further work, especially at sites like Mauna Kea and Paranal, where the capability for high-resolution echelle spectra already exists.

Based on the relationship determined between the measured PWV and 225 GHz opacities, we find a median PWV of 2.8 ± 0.3 mm and a range between 0.5 and 7.5 mm for our 2 month Southern hemisphere wintertime campaign. This is consistent with that measured at the nearby La Silla Observatory during the VLT site survey (Swings et al. 1990). Finally, if our campaign is representative of the Southern hemisphere winter months, we can expect good conditions for infrared observing (≤1.5 mm) at the tenth percentile level.

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