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# Giant Magellan Telescope Site Testing: PWV Statistics and Calibration*

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## ABSTRACT

Cerro Las Campanas located at Las Campanas Observatory (LCO) in Chile has been selected as the site for the Giant Magellan Telescope. We report results obtained since the commencement, in 2005, of a systematic site testing survey of potential GMT sites at LCO. Atmospheric precipitable water vapor (PWV) adversely impacts mid-IR astronomy through reduced transparency and increased background. Prior to the GMT site testing effort, little was known regarding the PWV characteristics at LCO and therefore, a multi-pronged approach was used to ensure the determination of the fraction of the time suitable for mid-IR observations. High time resolution monitoring was achieved with an Infrared Radiometer for Millimeter Astronomy (IRMA) from the University of Lethbridge deployed at LCO since September of 2007. Absolute calibrations via the robust Brault method (described in Thomas-Osip et *al.*[1]) are provided by the Magellan Inamori Kyocera Echelle (MIKE), mounted on the Clay 6.5-m telescope on a timescale of several per month. We find that conditions suitable for mid-IR astronomy (PWV < 1.5 mm) are concentrated in the southern winter and spring months. Nearly 40% of clear time during these seasons have PWV < 1.5mm. Approximately 10% of these nights meet our PWV requirement for the entire night.

**Keywords:** precipitable water vapor, site testing

## 1. INTRODUCTION

High columns of water vapor in the atmosphere above the telescope can significantly impact sensitivity, particularly in the mid-IR. $H_20$ is not only a source of opacity. In the thermal IR, reductions in transmission due to $H_20$ are accompanied by increased emissivity and, hence, higher backgrounds. Water vapor, ozone and $CO_2$ lines define the atmospheric transmission windows for wavelengths longer than 0.9 µm and the impact of water is particularly severe in the 25 µm window. In addition to defining the atmospheric windows, water lines impact significant portions of the in-band spectrum. At high elevations the equivalent widths of the water lines scale roughly linearly with the PWV column; at low elevations and high columns, pressure broadening extends the wings of the lines, affecting a larger range of wavelengths than one would expect from a simple scaling by PWV column. The PWV properties of most Chilean sites are poorly or incompletely characterized. The only information for LCO comes from our current site testing effort starting in 2005, and there are only modest amounts of data for Cerros Paranal, La Silla, and Pachón. Due to their proximity and similar elevations, La Silla, Tololo, and Pachón are the most relevant for comparison with LCO.

### 1.1 La Silla

Ground-based absorption measurements were carried out with a mid-IR sky radiance monitor[2] at La Silla during the 1983-1989 period as part of the VLT site survey. The absolute scale of these data was calibrated via simultaneous coudé spectroscopy of a water vapor line at 694.38 nm. A strong seasonal difference is observed in these measurements, which

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are plotted in Figure 1. The summer-time median PWV value for La Silla is roughly 6 mm; the winter data, though sparse, are consistent with a median value of ~2 mm.

PWV estimates derived from GOES-8 data for La Silla are available on the ESO website[‡], and also display a strong seasonal variation. These data show a substantial difference between Paranal and La Silla over all seasons. The absolute calibration of these data for Paranal is on a fairly solid footing; the calibration for La Silla is less certain (Sarazin, private communication). Indeed, the data show many nights with PWV well over 10-15 mm and most of the summer nights are over 5 mm, in contrast to the data from the more-reliably calibrated VLT site survey.

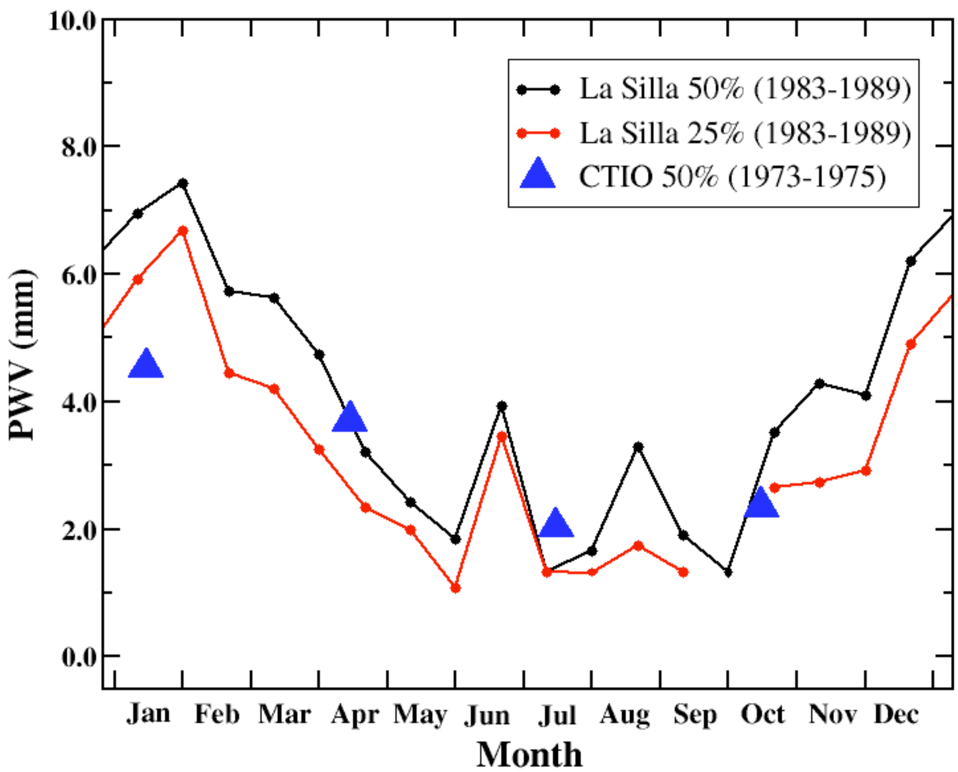


Figure 1. Lines show results from PWV measurements carried out at La Silla from 1983-1989 as part of the ESO VLT site survey. Points show PWV measurements from Cerro Tololo for 10/73-5/75 from Hansen and Ciamanque.

A brief campaign was carried out at La Silla in 1981 by Sherwood and Greve[3]. They measured the PWV level 24 hours a day for 10 days using an IR hygrometer. A four-day period with PWV <2 mm followed a 2 day wet period (PWV ~ 5-6 mm). During the driest period they observed with a 350 μm filter and measured PWV levels of 0.6-0.7 mm, well below the sensitivity limit of the broad-band 1 mm system. They note that the water column is higher during the day and that the Hansen and Caimanque[4] data for Tololo (see below) are biased to high columns. The Sherwood and Greve data show two important results at La Silla that are likely to be applicable to Las Campanas: 1) there are multi-day periods of very dry weather, and 2) there are periods in which PWV levels drop below 1 mm and most surveys to date have been insensitive to these very dry conditions.

### 1.2 Cerros Tololo and Pachón

Data in Figure 1, taken from Ref [4], shows daytime measurements from Cerro Tololo, a site further south and slightly lower than La Silla and LCO. These data show that summer days are characterized by PWV levels from ~3-6 mm while clear winter days are in the 1.5-3 mm range. Figure 3 in Ref [4] shows that in June and July 45-50% of clear days have PWV below 2 mm. The clear fraction in the winter is typically ~50%, so one can expect a total of roughly 20-25 nights of dry (PWV < 2 mm) weather in a Chilean winter if the 1973-1975 period is representative.

[‡] See http://www.eso.org/gen-fac/pubs/astclim/lasilla/h2o/

In summary, all of the available data for La Silla, Tololo, and Pachón point to there being strong seasonal variations in the PWV at Las Campanas. There is good reason to believe that in the winter the PWV on Campanas Peak is comparable to median conditions at high elevation sites. Nevertheless, some uncertainties remain in reconciling the various data sets. In this work we aim to resolve the discrepancies with measurements and calibration work done on site at LCO. This study is part of the larger site testing effort to evaluate potential Giant Magellan Telescope sites at LCO[5].

## 2. OVERVIEW OF PWV MEASUREMENTS AND INSTRUMENTATION

Due to the importance of ascertaining the PWV characteristics of the site, the project has taken a multi-pronged approach to this problem consisting of monitoring PWV with high time resolution (with an IRMA since September of 2007 and a Tipper in the winter of 2005) and absolute calibrations provided by MIKE on a timescale of several per month (discussed in the next section).

A 225 GHz tipping radiometer (Tipper) belonging to the Arizona Radio Observatory was loaned to LCO during the Southern winter months of 2005. This instrument measures the opacity in the wing of a strong water vapor absorption line at 183 GHz. The resulting opacity at 1.2 cm can be directly related to the PWV using MIKE optical echelle spectra for calibration[1].

An IRMA (Infrared Radiometer for Millimeter Astronomy) from the University of Lethbridge Astronomical Instrumentation Group has been deployed at LCO since September of 2007. IRMA monitors a spectral emission line of water vapor at a wavelength of ~20 μm[6]. The advantage of working at this wavelength is that the water lines are very strong and uncontaminated allowing good signal-to-noise measurements to be achieved on very short time scales. IRMA has also been adopted by the TMT project for measuring PWV and one of their units has visited LCO for cross-calibration purposes.

Figure 2. Photo of IRMA near the Alcaino Seeing Tower at LCO, looking towards the Magellan telescopes.

As a check on the consistency of the IRMA internal calibration method and data we operated a second IRMA (borrowed from the TMT project, called IRMA 11) next to our IRMA for a period of 10 months. The results show very good qualitative and temporal agreement (see Figure 3) but there is a clear gain and offset in their absolute calibration (see Figure 4).

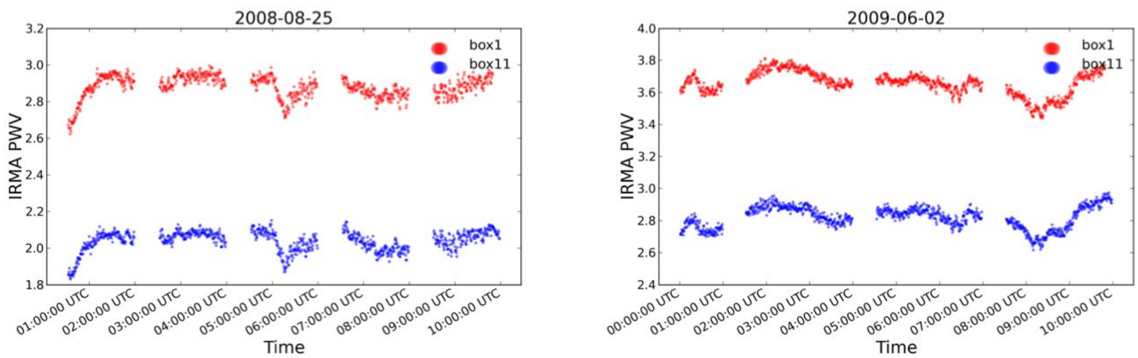


Figure 3. Two examples of the variation of pwv over the course of a night as measured by both IRMA units. These have not been calibrated via the MIKE calibration to show the offset in absolute calibration. The two instruments clearly see the same temporal variation.

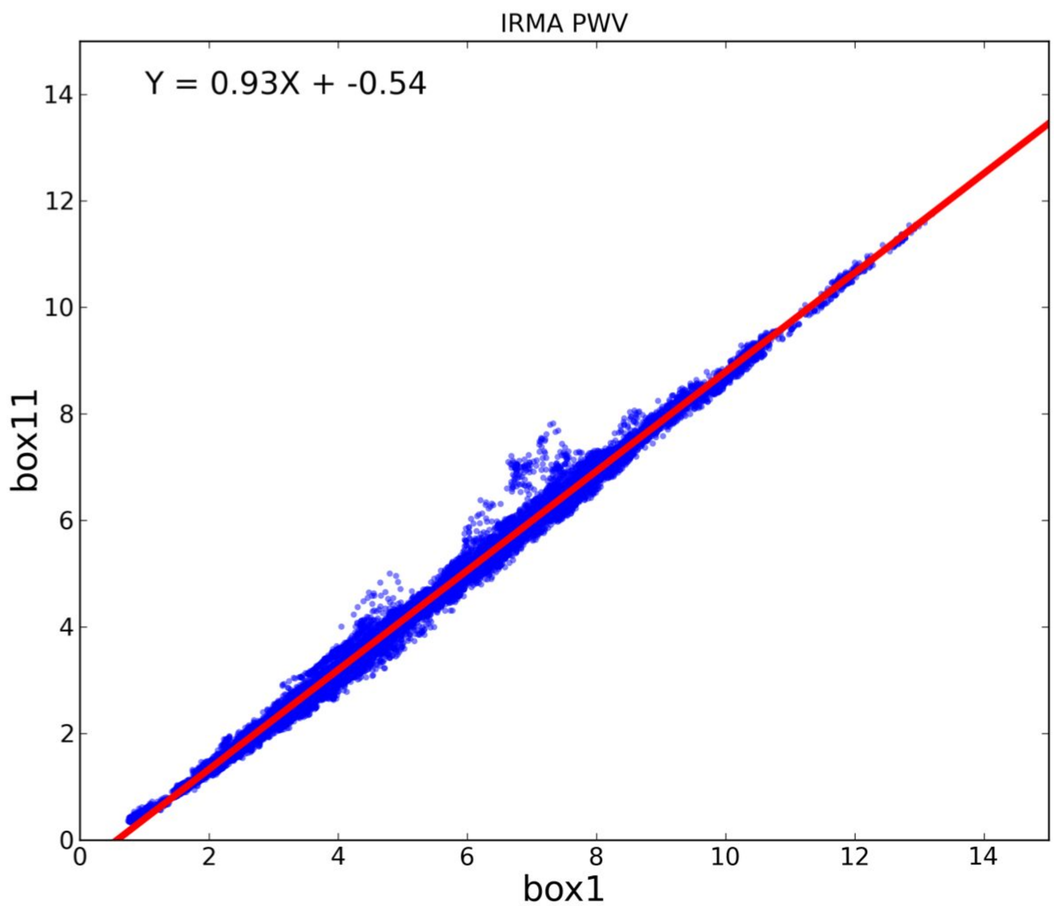


Figure 4. Correlation between the PWV as measured by the two different IRMA units. The relative rms error between these data sets is 5% indicating reasonable precision between the units.

## 3. CALIBRATION

Absolute calibration, an important part of relating the column of precipitable water vapor to its various effects such as increased thermal-IR background, decreased transparency, and the introduction of extraneous spectral features, is achieved through high-dispersion spectroscopy of certain weak $H_2O$ absorption lines in the optical and near-IR wavelength regions. The fractional populations in the energy levels for lines with low excitation potentials around 225-300 $cm^{-1}$ are temperature insensitive over temperatures found in Earth's atmosphere. This allows a robust measurement of PWV without a detailed model atmosphere as long as the lines are unsaturated. Swings et. *al.*[7] combined high resolution echelle spectroscopy of a water vapor line at 694.38 nm with a technique devised by Brault et. *al.*[8] to calibrate mid-infrared sky radiance measurements obtained at the La Silla Observatory during the VLT site survey. Brault et *al.* also suggested use of a quick method for computing PWV, using the natural log of the line flux (log-Flux) and claimed that good results were obtained for lines with central depths less than 50%.

Thomas-Osip et *al.*[1] extended this method with improved partition functions and additional temperature-insensitive $H_2O$ lines. Rapidly rotating A and B type stars with magnitudes between 4 and 6 are readily observed with the Magellan Inamori Kyocera Echelle (MIKE) mounted on the Clay Magellan 6.5-m telescope. MIKE is used occasionally (approximately once per night when MIKE is in use on a clear night) to measure the precipitable water vapor. The method is not practical for constant monitoring of the PWV, but provides an excellent tool for verifying the absolute calibration.

### 3.1 BTRAM/Brault method discrepancy

Querel et *al.*[9] compared the PWV values reported in Ref [1] with detailed atmosphere calculations, using the BTRAM radiative transfer and atmospheric modeling program, and found those in Ref [1] to be 10 to 25 % systematically low. To investigate this disagreement we have computed PWV values from measured equivalent widths (EWs) of the temperature-insensitive $H_2O$ lines listed in Ref [1], using a single slab model atmosphere at T=270K and P=0.4 bars. Our simple code assumed Lorentzian line profiles with a central Gaussian sigma=0.6 km/s, appropriate for T=270K, and the pressure broadened half-widths due to atmospheric gases listed in the HITRAN database. Also included in our model is a wavelength range parameter over which the EW measurements were made; this is especially important for strong lines, for which a large fraction of the EW is located in the wings.

We note that in our simple calculations we did not include $H_2O$ self-broadening, but this is very small compared to broadening from other atmospheric gases. A key point is that in our single slab model we do not employ Brault's log-Flux line measurements, but instead we integrate over our computed line profile for synthetic EWs.

### 3.2 Resolution

In Figure 5a we show our single-slab PWVs, computed using 5 temperature-insensitive lines on 13 nights in 2007, compared to the BTRAM results for the same nights, kindly supplied by Richard Querel (2010, private communication). Figure 5b shows the comparison with the average of our 5 temperature-insensitive lines. The agreement between the BTRAM and our single-slab PWV results is remarkable, with apparently near-perfect agreement, to within the uncertainties, for PWV in the range 1 to 8 mm. This excellent agreement immediately tells us two things: first, that a single-slab model with temperature-insensitive lines can produce the same results as the more complex BTRAM model atmosphere method (BTRAM requires highly tailored model atmospheres); secondly, the Brault log-Flux approximation is the likely source of the previously under-estimated PWV values in Ref [1].

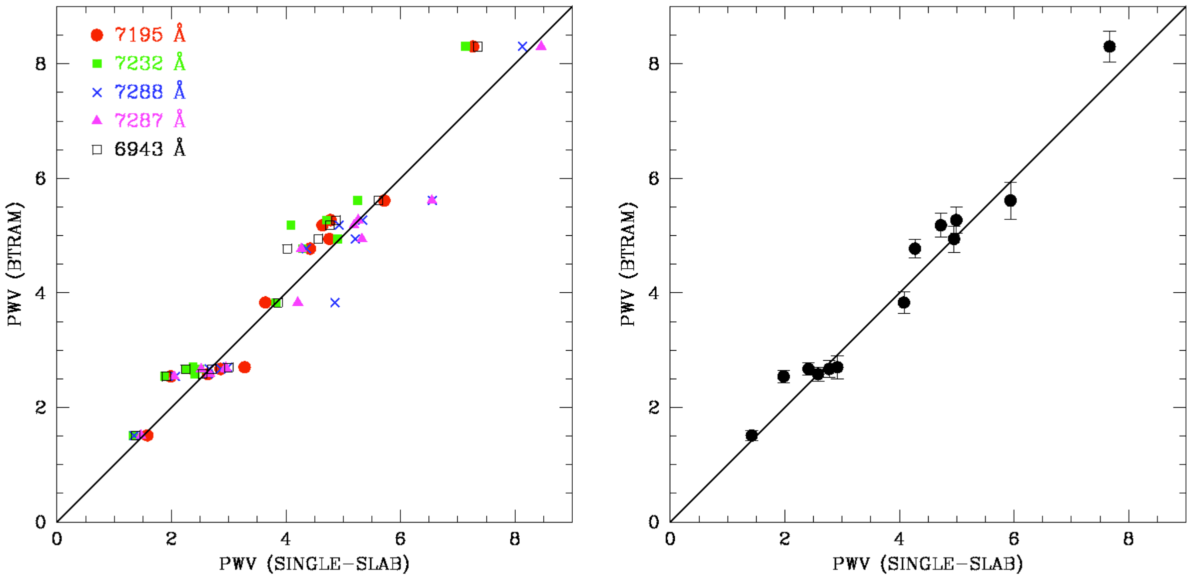


Figure 5. LEFT: BTRAM PWV values compared to those from the single-slab model for 5 temperature-insensitive lines. RIGHT: Same as on left but for the average of the 5 temperature-insensitive lines.

We further investigated the log-Flux approximation in our single-slab model by producing synthetic $H_2O$ line profiles with 0.003Å steps and then measuring log-Flux for the line, in order to compute PWV values exactly as suggested by Brault et *al.* and performed in Ref [1]. We found that this produced nearly the same PWV as the computed EW from the single-slab model. However, when we convolved the synthetic profile with a Gaussian instrumental profile, for R=40,000 spectral resolution, the log-Flux PWV results were reduced by 18% from the input value. This numerical experiment showed that the use of log-Flux does not provide acceptable PWV values at R=40,000; indeed, if the wavelength steps are increased to 0.01Å for un-convolved spectra there is an unacceptable systematic reduction in the derived PWV values with the log-Flux method, even for lines near 15mÅ (fully resolved depths less than 20%). Thus, we find that the suggestion of Brault et *al.* to employ line log-Flux values for computational convenience introduces unacceptable errors, so we do not recommend it; however, their idea to use temperature-insensitive lines is very effective.

In Figure 5a the range in PWV values seem smallest for the driest nights; however, careful inspection shows that the error on the mean PWV, although slightly smaller for the drier nights, is roughly constant, at 5 to 7% over the entire range from 1 to 8 mm. There may be a small tendency for the strongest of the temperature-insensitive lines, at 7287 and 7288Å, to give higher PWV values on the wettest nights. For a single-slab model we expect that weaker lines would be better modeled than more saturated lines. We note that a 5% change in EW for a 50mÅ line gives a 6.5% change in PWV, but for a 130mÅ line a 5% change in EW results in a 10% change in derived PWV; the stronger $H_2O$ lines also have an increased sensitivity to atmospheric pressure. For these reasons, weak $H_2O$ lines, less than about 75mÅ are preferred for PWV measurement. In this regard, a list of temperature-insensitive $H_2O$ lines with EWs in the range 20-70mÅ for PWV greater than 8mm would be helpful in future studies.

## 4. RESULTS

As discussed in Ref [1], an excellent correlation was obtained between MIKE PWV measurements and 225 GHz Tipper opacities. The calibrated tipper PWV data for 29 clear nights in Southern winter 2005 give a median of 2.8±0.3 mm, in agreement with VLT Site Testing measurements at La Silla. To determine how much useful time is available for mid-infrared work we characterized periods of low PWV that are longer than 2 hours. Furthermore, in the Southern hemisphere winter months, we can expect good conditions for infrared observing (<~1.5 mm) at the tenth percentile level. During the Tipper campaign it was found that 14±7 % of the clear night time occurs in blocks longer than two hours during which the PWV is less than 1.5 mm. That percentage rises to 25±10 % when considering PWV less than

2.0 mm. Extrapolating this to all of wintertime, 15-25 % or up to 270 hours spread over periods ranging from 2 hours to more than 3 contiguous days could be useful for mid-infrared work. Further details of both the calibration method and the results from the 2005 Tipper campaign can be found in Ref [1].

It is important to note, however, that the MIKE PWV measurements used in the above study suffered from a systematic underestimation due to the log-Flux approximation as described in the previous section. The underestimation is most severe at large PWV. Since we use the same method to calibrate the IRMA data, it was necessary to develop a transformation to correct the underestimation. Synthetic line profiles were produced with the single slab model (T=270 and P=0.4) for each of the 5 lines at PWV=1.0, 2.0, 4.0, 8.0, and 12.0 mm. These were then convolved with a Gaussian slit profile function for R=40,000 and re-binned to 0.10 Å/pixel, in order to mimic the observed spectra after which the log flux was measured as in Ref [1]. Finally an average was taken for all five lines. These transformation values are shown in **Table 1** and are interpolated to provide a correction to all the measured PWV from the MIKE spectra. This correction depends on the line strength and is thus specific to the 5 lines used here.

Table 1. The transformation used to correct the underestimation of the Brault et al. log flux approximation.

| **Input PWV** | **log-F PWV (average)** |
|---|---|
| 1.0 | 0.937 |
| 2.0 | 1.817 |
| 4.0 | 3.424 |
| 8.0 | 6.164 |
| 12.0 | 8.422 |

The transformation above is applied to the MIKE PWV measurements and then these are used to calibrate the IRMA PWV observations as shown in **Figure 6**. This calibration includes two full years worth of data and 86 points in common between IRMA and MIKE.

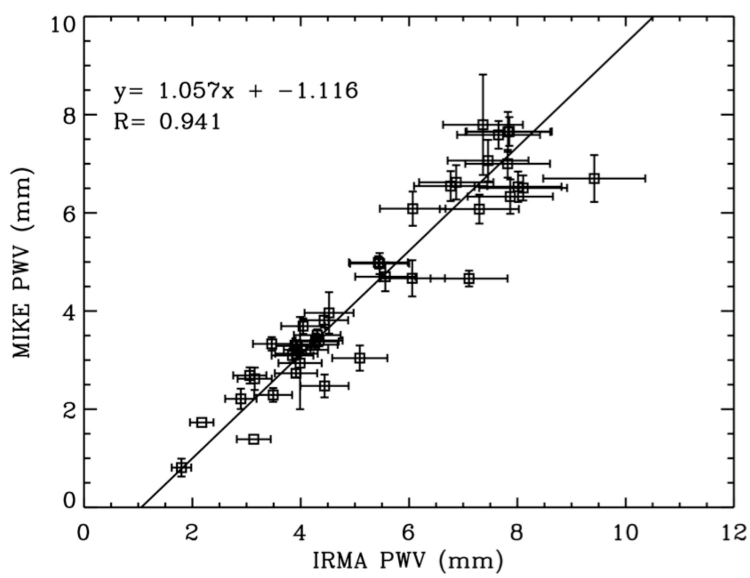


Figure 6. The correlation between MIKE PWV and IRMA PWV. Linear fit and correlation coefficients displayed in upper left. MIKE error bars are standard deviations for the means of the 5 different optical pwv lines measured. IRMA error bars are set to 10% in the absence of a true uncertainty calculation based on a reduced chi-squared near one in the above fit. The uncertainties on the coefficients are 0.050 and 0.282.

Applying this calibration to the IRMA data taken on clear nights between September 2007 and October 2009, gives the percentiles found in **Table 2**. Also shown are the percentiles split into season as well as the percentage of time during which the PWV is below the site requirement goal of 1.5 mm. From this table we can see that although the PWV can go below 1.5 mm at any time of the year it is much more likely during the Winter and Spring seasons. Furthermore, LCO exceeds the science requirement defined for GMT of at least 10% of the clear time with PWV less than 1.5 mm.

These statistics imply that there are approximately 320 hours of clear nighttime with PWV < 1.5 mm during the winter. Approximately, 40% this time during which the 1.5 mm criterion is met occurs in periods of an entire night. This level of stability would allow for IR observations on approximately 17 full nights per year with about half of these occurring in the winter.

Table 2. Clear nighttime calibrated IRMA PWV (mm) percentiles.

| **Season** | **10%** | **25%** | **50%** | **75%** | **90%** | **% < 1.5 mm** | **Samples** |
|---|---|---|---|---|---|---|---|
| **All** | 1.2 | 2.1 | 3.7 | 6.1 | 8.2 | 15 | 186300 |
| **Winter** | 0.5 | 0.9 | 1.4 | 2.0 | 2.7 | 55 | 13312 |
| **Spring** | 1.0 | 1.4 | 2.1 | 3.2 | 4.2 | 28 | 58594 |
| **Summer** | 2.0 | 3.0 | 5.1 | 7.1 | 10.0 | 4 | 48633 |
| **Fall** | 2.9 | 3.7 | 4.8 | 6.6 | 8.2 | 3 | 65761 |

In addition to its use in absolute calibration, we have accumulated enough MIKE data (133 measurements between 2005 and 2009) to examine the overall statistics and rough seasonal variation as shown in **Table 3**. Due to a calibration campaign (discussed below) that occurred in the fall, it was necessary to average multiple measurements on certain nights so that the number of samples per season is roughly equivalent. Thus, only one point per night has been used to calculate the statistics bringing the total sample to 86. The percentiles for both IRMA and MIKE data (along with the means and standard deviations) are displayed in Figure 7 and show similarities with the PWV statistics found at nearby La Silla and Cerro Tololo shown in Figure 1.

Table 3. PWV percentiles and the percent less than 1.5 mm as measured with MIKE. The data are separated into seasons and the number of samples in each season is found in the last column.

| **Season** | **10%** | **25%** | **50%** | **75%** | **90%** | **% < 1.5 mm** | **Samples** |
|---|---|---|---|---|---|---|---|
| **All** | 1.6 | 2.3 | 3.1 | 4.7 | 6.5 | 9 | 87 |
| **Winter** | 1.1 | 1.9 | 2.9 | 4.0 | 5.4 | 15 | 26 |
| **Spring** | 1.4 | 1.7 | 2.4 | 2.7 | 3.8 | 16 | 19 |
| **Summer** | 2.2 | 2.8 | 3.7 | 5.5 | 17.0 | 0 | 24 |
| **Fall** | 3.0 | 3.5 | 4.3 | 6.5 | 7.8 | 0 | 18 |

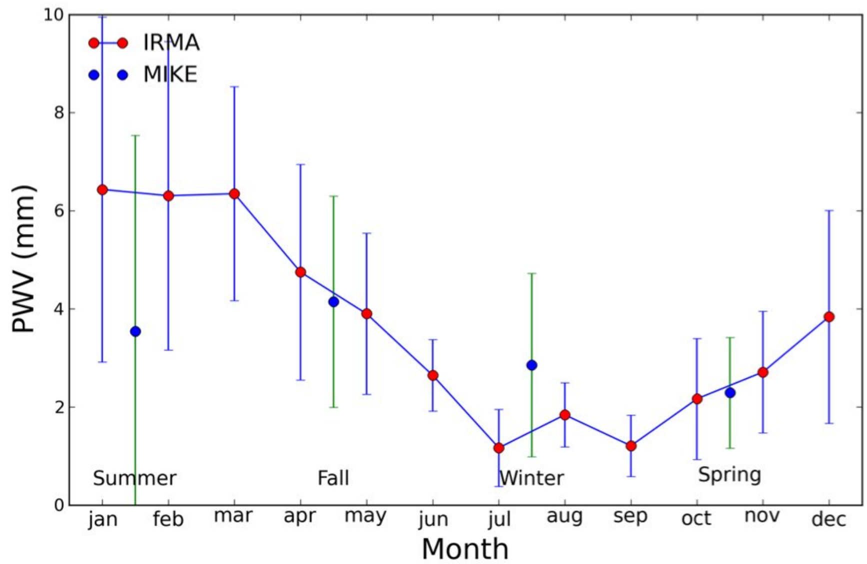


Figure 7. Monthly variation in calibrated IRMA PWV and seasonal variation in MIKE PWV. Points are monthly or seasonal medians with standard deviation within that time period shown as error bars.

We can also compare the MIKE and IRMA data taken at LCO to some recent measurements taken by ESO at nearby La Silla. A calibration campaign in May 2009[10,11] combined results from many types of instruments and measurement methods. Two of the their datasets (GOES satellite data and FEROS optical echelle spectra fit with BTRAM) are presented for comparison purposes in Figure 8. The GOES data has been demonstrated to overestimate the PWV due to its poor resolution and therefore these data have been corrected in this plot by subtracting the median difference between the FEROS and GOES data. The seasonal variation and overall agreement between our data sets is evident.

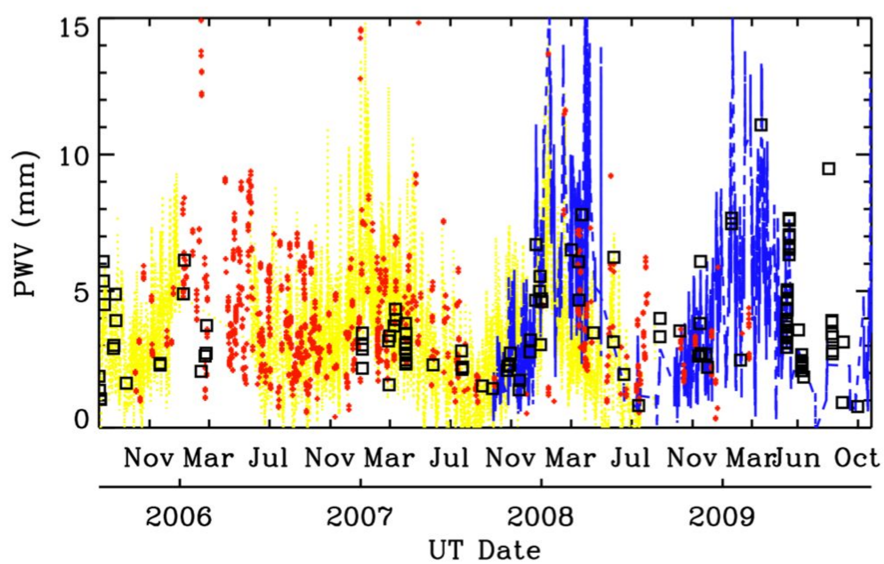


Figure 8. PWV as a function of time for a variety of sources at LCO and La Silla. The open boxes are MIKE spectra measured with the updated Brault method at LCO. The blue lines are IRMA data taken at LCO and calibrated with MIKE data. The red points are FEROS data from La Silla. The yellow lines are from the Erasmus model for the GOES-8 satellite (corrected by subtracting 2.5 mm as the median difference between the GOES and FEROS medians at La Silla as discussed in the text).

## 5. CONCLUSIONS

We set out to characterize the PWV at LCO. To do so required absolute calibration. Along the way we discovered that our previously reported calibration in Ref [1] contained an approximation causing a systematic underestimation of the PWV. A single-slab method was developed to resolve this discrepancy and it was found to work just as well a multi-layer model atmosphere like BTRAM. With this correction, the BTRAM and modified Brault results are now the same to within a few percent. This allows us an extra level of confidence in the calibrated PWV results for LCO.

We find that our data sets are consistent with both recent and historical data taken at nearby observatories (La Silla and Cerro Tololo). The PWV at LCO has a strong seasonal variation with the preponderance of the good PWV conditions occurring in the winter and spring. During the winter, the conditions are relatively stable with 10% of the clear nights meeting the 1.5 mm criterion for the entire night. Finally, LCO exceeds the science requirement defined for GMT of at least 10% of the clear time with PWV less than 1.5 mm. This fact along with many others described in Ref [5] contributed to the choice of Co. Las Campanas at LCO as the site of the future GMT.

## AKNOWLEDGEMENTS

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