Remote Sensing of Water Vapour above the Las Campanas Observatory*

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ABSTRACT

We present simultaneous precipitable water vapour (PWV) measurements made at the Las Campanas Observatory, Chile, in Fall of 2007 and May 2009 using an Infrared Radiometer for Millimetre Astronomy (IRMA), the Magellan Inamori Kyocera Echelle (MIKE) optical spectrograph, and radiosondes. Opacity due to water vapour is the primary concern for ground based infrared astronomy. IRMA has been developed to measure the emission of rotational transitions of water vapour across a narrow spectral region centred around 20 microns, using a 0.1 m off-axis parabolic mirror and a sophisticated atmospheric model to retrieve PWV. In contrast, the MIKE instrument is used in conjunction with the 6.5 m Magellan Clay telescope, and determines PWV through absorption measurements of water vapour lines in the spectra of telluric standard stars. With its high spectral resolution, MIKE is able to measure absorption from optically thin water vapour lines and can derive PWV values using a simple, single layer atmospheric model. In an attempt to better understand the PWV above the Observatory, we explore the potential of fitting a series of MIKE water vapour line measurements to the simulated manifold output from our multi-layer, line-by-line, site-specific radiative transfer model, BTRAM. These fits were performed in the near-infrared absorption bands located around 700, 800 and 900 nm.

Keywords: Radiative transfer, atmospheric modeling, echelle, infrared, radiometer, water vapour

1 INTRODUCTION

The 6.5 m Magellan Clay telescope, located at the Las Campanas Observatory in the Chilean Andes, houses several facility instruments. One of these instruments, the Magellan Inamori Kyocera Echelle (MIKE) , is a double echelle optical spectrograph, which, with its high dispersion and wide spectral range, is used to measure stellar photospheric spectra.

Water vapour is the principle source of opacity at infrared wavelengths. For this reason infrared telescopes are placed on high and dry mountain peaks. Several methods exist for measuring the amount of water vapour in the atmosphere, whose vertical column abundance is expressed as precipitable water vapour (PWV) . These instruments have been used in a variety of roles, including site evaluation, phase correction of radio interferometry signals, and optimising the scheduling of infrared observations.

Extracting meaningful results from a remote sounding instrument involves the use of a sophisticated atmospheric model. Moreover, the uncertainty in the retrieved PWV depends in part on the accuracy of the model. The simplest model consists of a plane-parallel, single layer atmosphere defined by a limited set of parameters. More complex models involve many layers in which the full radiative transfer from the top of the atmosphere to the observer is computed on a layer-by-layer basis . The multi-layer approach allows one not only to account for the distribution of individual constituent profiles, but also variations in the physical characteristics of the atmosphere, such as temperature, pressure, adiabatic lapse rate and scale height. Although several modeling programs exist, they use as

*This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile.

inputs a limited set of atmospheric profiles. Unfortunately few of these profiles are well-suited to the sites of astronomical interest. This provided the impetus for the development of a site-specific atmospheric radiative transfer model called BTRAM . While BTRAM uses the standard HITRAN database , it allows the user to fine tune the model to a specific geographical location using whatever meteorological data are available (e.g. radiosondes, atmospheric sounders, LIDAR).

The infrared radiometer used in this study, IRMA , operates in the thermal infrared, therefore careful attention must be given to the systematic errors that can arise through the calibration process, since any stray light from ambient sources will be detectable by the radiometer. During a recent field deployment of an IRMA unit in support of the site evaluation campaign for the Giant Magellan Telescope (GMT) at Las Campanas, it was proposed to validate the retrieved IRMA PWV values with those derived from the MIKE data by launching a series of radiosondes. These radiosondes were launched from the nearby, La Silla Paranal Observatory, situated ~30 km south of Las Campanas Observatory. A serendipitous bi-product of MIKE spectra is a measure of the many absorption lines of atmospheric water vapour. Since these transitions have high excitation energies, the derived column abundances are less sensitive to the atmospheric model used in the retrieval process.

MIKE spectra have previously been used to determine water vapour abundance using carefully selected weak lines from which PWV can be derived using a simple, single layer atmospheric model . In this paper we present a more comprehensive analysis of over 1100 water vapour lines in the MIKE spectra to determine more precisely the column abundance of water vapour. Finally, we compare the retrieved PWV amounts from IRMA and MIKE when both were operating simultaneously. The comparison employs the same atmospheric model (BTRAM). In May 2009, a series of high-cadence (~1 spectra collected every 30 seconds) measurements were made with MIKE in an attempt to measure PWV fluctuations observed on the time-scale of the IRMA measurements (~1 second). A time-series of MIKE-derived PWV, IRMA PWV and radiosonde PWV from May 10th, 2009 are presented here.

2 EQUIVALENT-WIDTH DERIVED PWV

The MIKE echelle spectrograph operates across the visible and near-infrared by making simultaneous spectroscopic measurements defined by the wavelength ranges 320–480 nm (blue) and 440–1000 nm (red) respectively . In this study we restrict ourselves to data from the long wavelength channel. When MIKE is used to determine PWV, the resolving power must be greater than ~31 000, which is sufficient to clearly identify many atmospheric water vapour lines when observing the photospheric continuum of standard stars.

Thomas-Osip *et al.* (2007) describes a method of using MIKE spectra to determine PWV following the weak line method of Brault *et al.* (1975) . In this method, the integrated area under a weak and isolated absorption line is computed, and using the line strength and lower energy transition from a molecular database such as HITRAN, the PWV can be determined.

When spectral lines are weak, and therefore optically thin, PWV can be computed directly from an absorption feature using the equivalent width of the line:

$$W = \int \left(1 - \frac{I(\lambda)}{I_0} \right) d\lambda \rightarrow N \int \sigma_\lambda d\lambda = N \sigma_0 \Delta\lambda \quad \text{[nm]} \tag{1}$$

where W is equivalent width [nm], $I(\lambda)/I_0$ is the transmission, N is the column density of atoms [molecules cm^{-2}], σ_λ is the amount of absorption per atom [cm^2], and σ_0 is the mean cross-section [cm^2] averaged over the bandwidth $\Delta\lambda$ [nm]. Thus, given σ_0 and a measurement of the equivalent width of the line it is possible to retrieve the column density N.

The column abundance of H_2O in 1 mm PWV is $N_{H2O} = 3.346\times10^{21}$ [molecules cm^{-2}], resulting in the following relationship for PWV:

$$PWV = \frac{W}{S \times N_{H_2O}} \quad \text{[mm]} \tag{2}$$

where S is the line strength [cm^{-1}/ (molecule cm^{-2})], and the equivalent width must be expressed in frequency units [cm^{-1}].

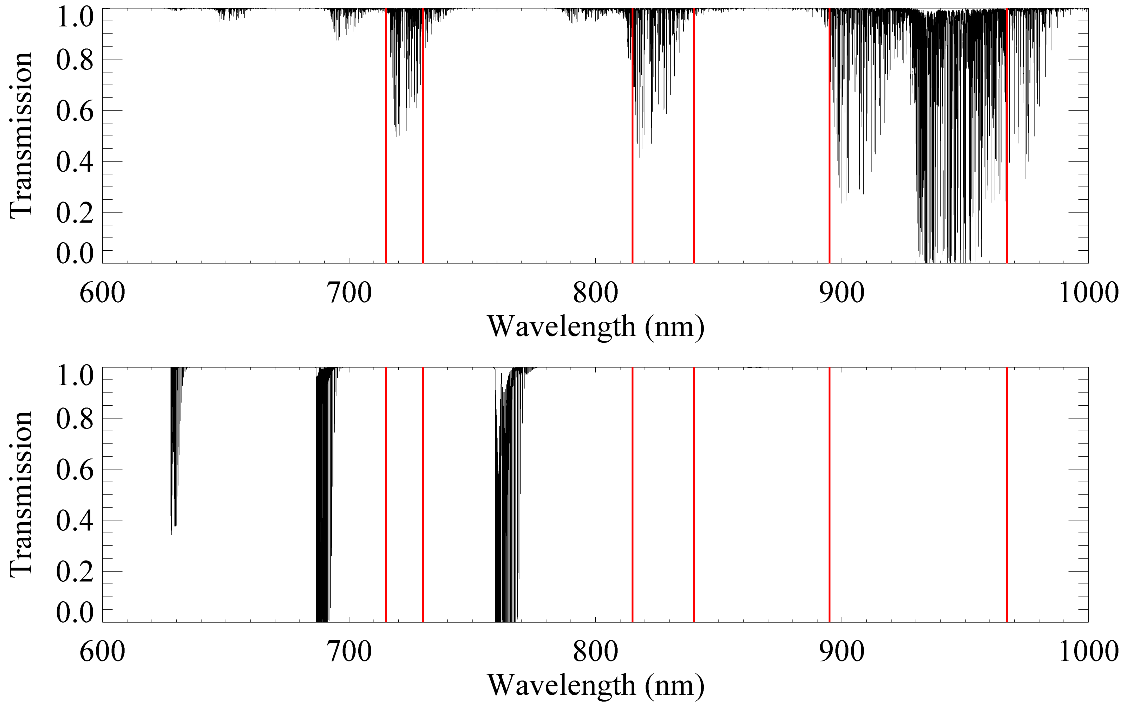

Figure 1. Theoretical transmission spectra produced by BTRAM for the Las Campanas Observatory Site. The upper plot shows the transmission spectrum for water vapour alone (PWV = 1 mm). The lower plot shows the transmission due to all other significant atmospheric constituents, which for this wavelength region are CO_2 and O_2, and no water vapour. The red vertical bars delineate the three regions that were used for fitting to MIKE data.

The advantage of this technique is that it is a simple computation using a limited number of molecular parameters. The principle disadvantage of the method is that it requires weak and isolated lines to correctly identify correctly the continuum (I_0 in Equation (1)) from which the equivalent width is derived. Moreover, the signal-to-noise ratio of weak lines is inferior to that of stronger lines, resulting in higher uncertainties in derived PWV.

The Astronomical Instrumentation Group (AIG) at the University of Lethbridge developed a sophisticated, line-by-line, layer-by-layer, radiative transfer model to support the variety of projects conducted by the group ; this code is commercially available . While this model has been validated at many different wavelengths its primary use has been at mid- and far-infrared spectral ranges (longer than 10 μm).

In this paper we have applied BTRAM to the wavelength range accessible to MIKE. A comprehensive fitting of the complex manifold of water vapour lines has been used to determine more accurately the column abundance of water vapour. These results have been compared to the simple, single line technique used by Thomas-Osip et al. (2007) , and are presented in the next section.

3 BTRAM DERIVED PWV USING ECHELLE DATA

The BTRAM radiative transfer and atmospheric modeling program has been used to generate a theoretical transmission spectrum of the atmosphere above the Las Campanas Observatory. The results are shown in Figure 1 for the wavelength range 600–1000 nm, which is part of the red channel of MIKE. The upper plot shows the absorption due to atmospheric water vapour alone for a column abundance of 1 mm PWV. The lower plot shows the equivalent spectrum containing the principle constituents responsible for absorption in this range (mostly CO_2 and O_2), but no water vapour. Examination of these plots shows that there are several regions where water vapour can be isolated for analysis. In this study we have selected the regions delineated by the vertical lines.

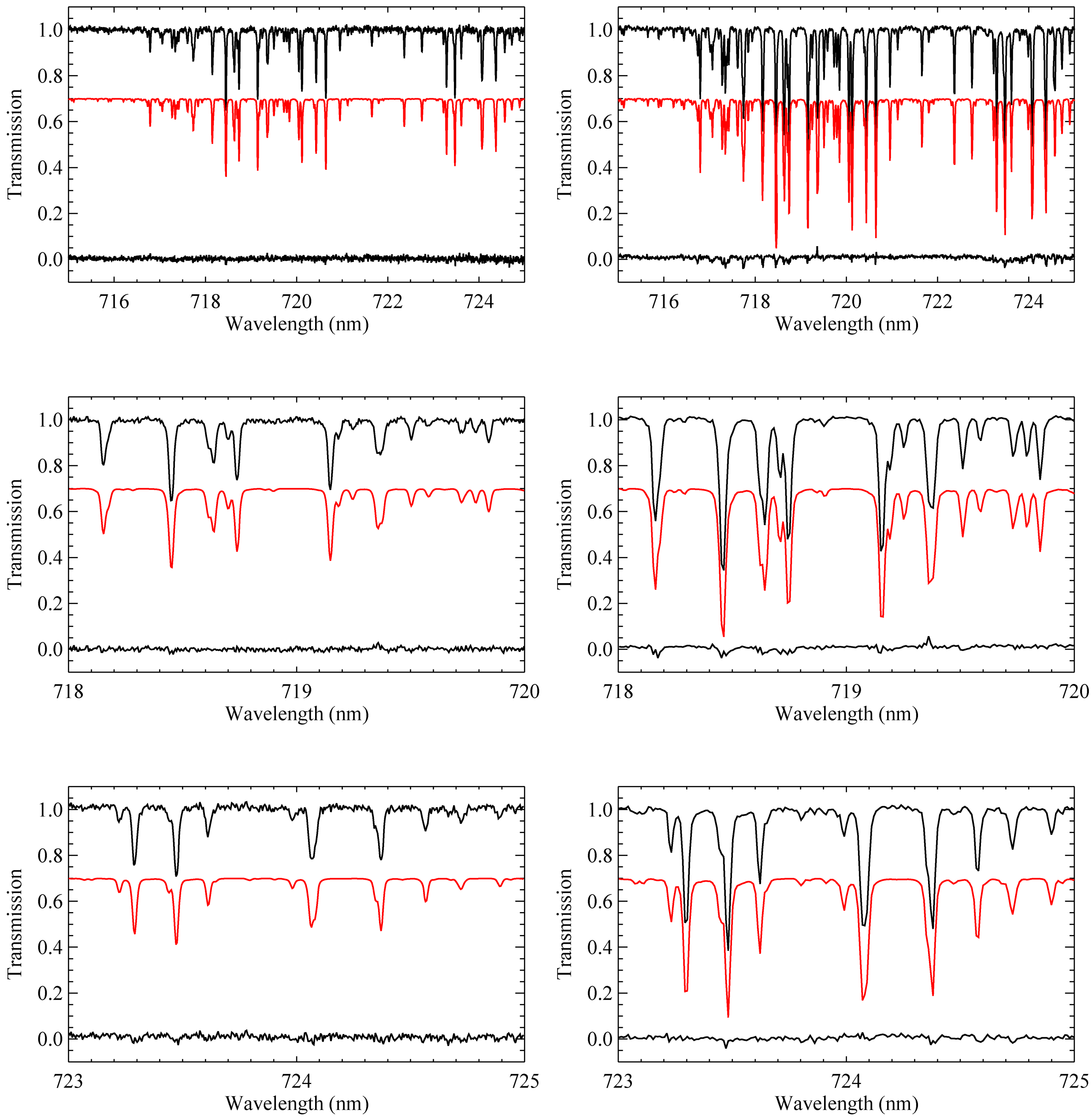

Figure 2. Transmission plots of MIKE data and the corresponding fitted BTRAM data over the 700 nm region for a dry night (PWV ~1.6 mm), left column, and a wet night (PWV ~5.2 mm), right column. The upper trace is the MIKE data, the middle trace is the fitted BTRAM data displaced by 0.3 for clarity, and the bottom trace shows the residual difference between the MIKE and BTRAM data.

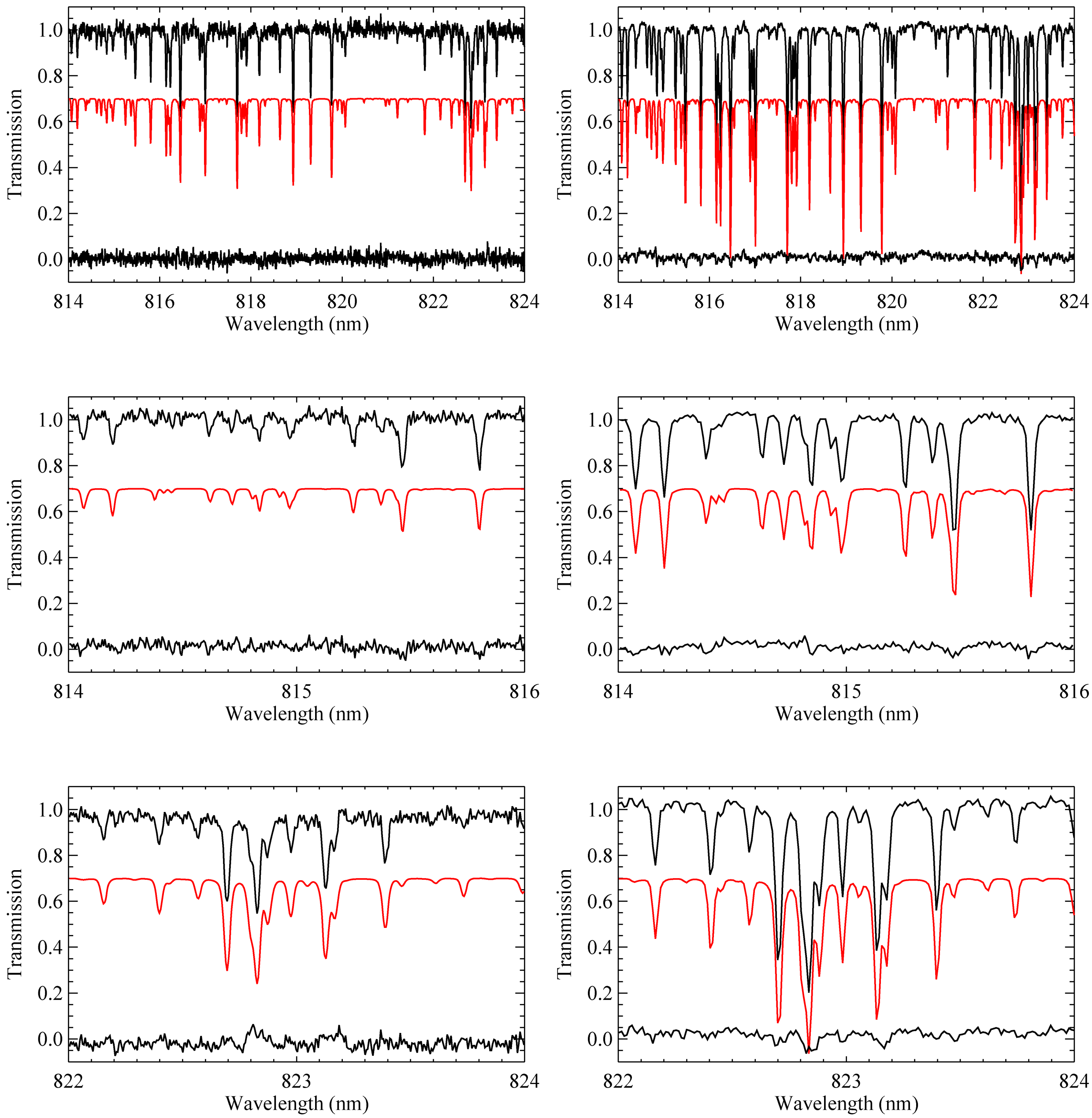

Figure 3. Transmission plots of MIKE data and the corresponding fitted BTRAM data over the 800 nm region for a dry night (PWV ~1.6 mm), left column, and a wet night (PWV ~5.2 mm), right column. The upper trace is the MIKE data, the middle trace is the fitted BTRAM data displaced by 0.3 for clarity, and the bottom trace shows the residual difference between the MIKE and BTRAM data.

The method employed to fit the theoretical BTRAM spectrum to the MIKE data involved the following steps. The MIKE data were reduced using the standard pipeline . The final data product of the pipeline is a multispec .FITS file containing spectra for the sky, the object, calibration lamp data, flattened-flat or blaze, and the spectra divided by the flattened flat, or relative fluxing. Each of these is present for every diffraction order of the MIKE observation. In the analysis we ingest the relative flux MIKE data, from which a continuum must be removed. The continuum is determined by first examining the regions of the BTRAM spectrum that have absorption less than 0.2%. These corresponding regions are then mapped onto the MIKE data and assumed to fairly represent the continuum. A second order polynomial is fitted to the continuum and subsequently removed, resulting in a normalised transmission spectrum.

The theoretical atmospheric transmission spectrum is iteratively fitted to the normalised MIKE data using the non-linear least-squares Levenberg-Marquardt algorithm . Fit parameters include PWV, Gaussian half-width, and a wavelength-dependent shift. The desired output parameter from the fit is PWV. The theoretical transmission spectrum has a higher resolution than the MIKE data (0.001 nm as compared to ~0.005–0.015 nm). The resulting spectrum is convolved with a Gaussian profile to represent the instrumental lineshape of the echelle spectrograph. The Gaussian half-width is one of the fitting parameters in the minimization routine. In order to account for the varying dispersion across the echelle spectrograph, and the difference between air and vacuum wavelength, a wavelength-dependent shift is fitted in the narrow regions under study.

A comparison of the MIKE data and the best-fit BTRAM data for two spectral ranges, 715–730 and 813-838 nm, are shown in Figures 2 and 3 for both a dry night (left column) and wet night (right column). The top graphs in each figure show a 10 nm range of the 700 and 800 nm windows respectively. The middle and bottom plots show two different zoomed regions of the upper plots, each 2 nm wide. In each plot the upper trace is the MIKE data, the middle trace is the fitted BTRAM data displaced for clarity, and the bottom trace shows the residual difference between the MIKE and BTRAM data. There is seen to be excellent agreement across the complex manifold of water vapour lines observed by MIKE. It can also be seen that the signal to noise in the 700 nm band is superior to that observed in the 800 nm band. Instrumental artifacts in the MIKE data become apparent in the 900 nm band, which when included along with the near-saturation levels that quickly occur, make removal of the continuum more challenging. For this reason derivation of water vapour using the 900 nm band has not been included in the current analysis.

4 IRMA

Developed as a collaboration between the University of Lethbridge and the Herzberg Institute of Astrophysics, the Infrared Radiometer for Millimetre Astronomy (IRMA) determines the column abundance of atmospheric water vapour by measuring the integrated emission in the 20 µm region. The precise spectral region around 20 µm region, set by band defining filters, is carefully chosen so that no other atmospheric molecules contribute to emission in this band . Moreover, this wavelength region lies at the peak of the Planck curve for typical atmospheric temperatures and thus results in increased flux and relatively high signal-to-noise. As part of the GMT site testing campaign, IRMA was deployed at the Las Campanas Observatory. A photograph of the field deployment is shown in Figure 4.

While IRMA was designed to operate on a nightly basis, MIKE is a facility instrument that operates on a scheduled basis. Furthermore it is only MIKE data from standard calibration stars that can be used in this analysis since spectra from other stars may contain features which would invalidate the fitting procedure. When it was realised that the MIKE data could be used to validate the calibration of IRMA, data from evenings when the two instruments were simultaneously operating were collected. These data form the basis for the comparison presented in this study.

5 COMPARISON OF WATER VAPOUR MEASUREMENT METHODS

The echelle spectra derived PWV measurements shown in Figures 2 and 3 were from 14 nights of MIKE measurements from February to December 2007. IRMA was deployed at LCO in September 2007, and was operating for 6 of the 14 nights for which MIKE observations were performed. Although the PWV from IRMA were derived using a calibration method that is still being refined , it is possible to compare directly the PWV values derived from each instrument while they were operating simultaneously by using a common atmospheric model. The results are shown in Figure 5. While encouraging, the limited number of data points made a direct comparison between IRMA and echelle-derived PWV challenging.

Figure 4. An IRMA unit installed at the Las Campanas Observatory.

A high degree of correlation is seen between the two independent measures of water vapour, which is very encouraging. However, when compared to the radiosondes and echelle-derived measures, the amounts recorded by IRMA are systematically higher. The errors shown in Figure 5 for the echelle-derived PWV are the standard deviations of the fitted PWV values computed using 5 spectral windows (715-725, 725-730, 813-821, 822-824 and 830-838 nm); the errors for the IRMA PWV represent the random noise in the IRMA measurement.

In an attempt to better understand the PWV characteristics above LCO a series of high-cadence measurements were made on May 10th, 2009 with MIKE, while IRMA was collecting data, and two radiosondes were launched from nearby La Silla Paranal Observatory at 00UT and 06UT. The time-series data is shown in Figure 6. Again, there is a visible offset within the IRMA data. However, as expected, both MIKE and IRMA were able to measure PWV variations on a short time-scale. The radiosondes were launched ~30 km from the observing site, and thus do not represent the identical line-of-sight, but, they do offer an *in situ* measurement with which we can gauge the validity of the remote measurements.

It is clear from the 2007 and 2009 measurement campaigns that both instruments are detecting water vapour. Two possible causes for the overestimation of IRMA PWV are being explored. While the derived MIKE results are less sensitive to the choice of atmospheric model, and particularly the scale height of water vapour, the IRMA results have been shown to be sensitive to the assumed scale height . A second concern is that since IRMA observes near the peak of the Planck curve for typical ambient temperatures, the possibility of signal contamination due to stray light from components within the IRMA subsystem exists. An investigation of the impact of stray light is currently being conducted. It is anticipated that with better baffling and a refined atmospheric model that the systematic differences between the two independent measurement techniques can be further reduced.

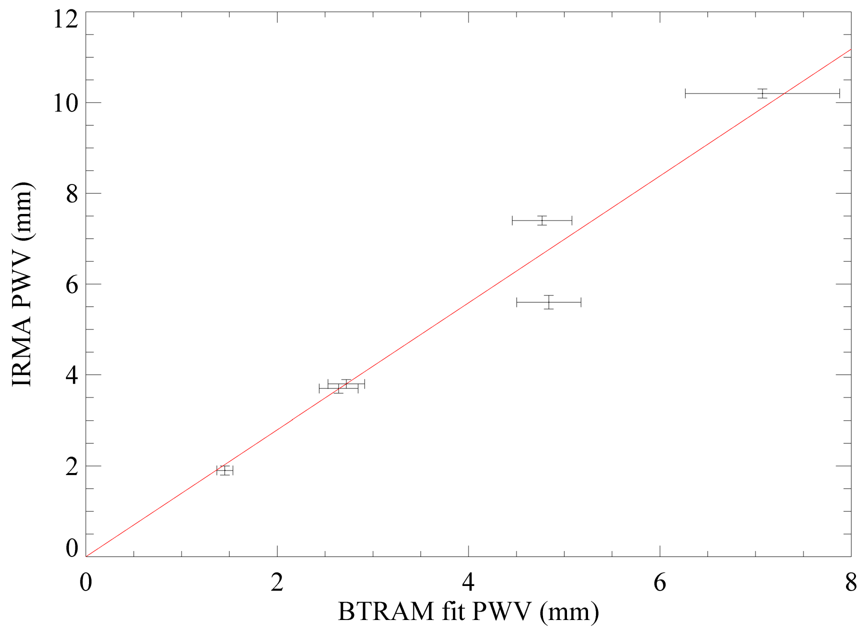

Figure 5. IRMA derived PWV versus the PWV derived from the MIKE data using BTRAM. Using the 6 nights of simultaneous data from 2007 to make the comparison, the best-fit slope to these data is 1.397. The errors plotted on the BTRAM-derived PWV are the standard deviation of PWV values computed from 5 spectral windows for each of the 6 observations. The errors plotted on the IRMA PWV represent the random noise in the IRMA measurement. Systematic errors in the IRMA system are not plotted.

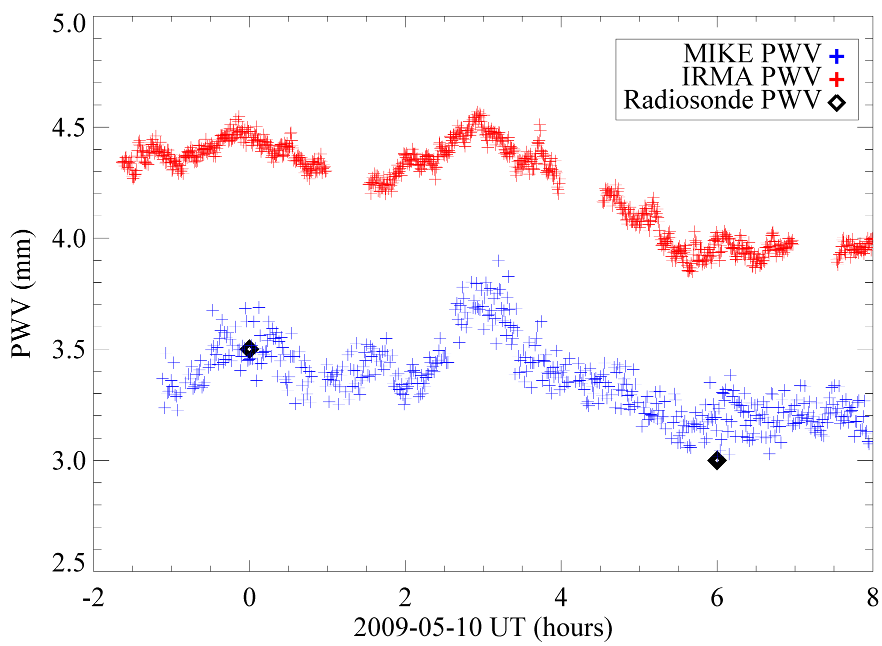

Figure 6. Time-series of IRMA PWV, echelle-derived PWV, and radiosonde estimates of PWV. The integration times for the IRMA and MIKE measurements were 1 and 30 seconds respectively. The radiosonde measurements fall within the overall uncertainty in the MIKE PWV. As seen in previous studies, IRMA is over-estimating the water vapour column abundance. However, both instruments clearly appear to be tracking similar, transient water vapour features occurring on a very short time-scale.

CONCLUSION

IRMA has to potential to be a powerful, real-time monitor of the atmospheric water vapour content. However, since it operates in the thermal infrared it is important to eliminate sources of stray radiation which will produce systematic errors. Independent calibration methods are therefore essential to understand any systematic sources of error in the IRMA data. Although MIKE has the advantage of the higher collecting area of a 6.5 meter telescope, we have shown that the MIKE-derived PWV values, which are less sensitive to the atmospheric model employed, provide an ideal calibration data set.

Having validated the utility of near-infrared echelle spectroscopic measurements as a method of deriving PWV, we are currently working with an international team of collaborators to extend the set of simultaneous IRMA observations with high-resolutions echelle instruments (BACHES, FEROS, HARPS, MIKE, UVES and VISIR) at several locations (LCO, La Silla and Paranal) to ultimately develop a better schema to validate IRMA measurements, and serve as ground-truth calibration for satellite estimates of PWV for on-going site evaluation efforts for the next generation of extremely large telescopes.

Moreover, since data from observatory facility instruments is archived we are currently re-analysing historical echelle spectra from decades worth of data to build up a statistical analysis of PWV above observatories that operate near-infrared echelle spectrographs. The atmospheric modeling application, BTRAM, with its ability to input site specific parameter data, is essential for this work.

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