Determination of Telluric Water Vapour using Absorption Measurements of Lunar Irradiance

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ABSTRACT

A novel instrument has been designed to measure the atmospheric water vapour column abundance by near-infrared absorption spectrophotometry of the moon. The instrument provides a simple, inexpensive, portable, effective means of rapidly measuring the water vapour content along the lunar line-of-sight. Moreover, the instrument is relatively insensitive to the atmospheric model used and has the potential to provide an effective, independent calibration for other measures of precipitable water vapour from both ground and space-based platforms.

Keywords: Radiometer, Precipitable Water Vapour, Infrared, Astronomy

1 INTRODUCTION

Determination of atmospheric water vapour content is important to ground-based astronomy on account of its strong absorption and emission characteristics in the infrared spectral region. In addition, the distribution of water vapour can be highly dynamic, varying dramatically, both spatially and temporally. Thus, any practical method for measuring and monitoring the water vapour abundance in real-time has direct applications in ground-based infrared astronomy and by extension in space-based terrestrial remote sensing.

The impetus behind the development of the lunar spectrophotometer was to provide an independent measurement of precipitable water vapour (PWV) in order to validate the calibration of an infrared radiometer, IRMA, which was developed by our group to measure PWV through the emission of water vapour at 20 μm. This is particularly important at remote sites where alternate measures of PWV are not available. The lunar spectrophotometer, is a simple, compact and lightweight device, which measures the atmospheric water vapour content by absorption spectroscopy of the moon using four bands centred around 0.95 μm. Two of these bands are carefully chosen to include transitions from atmospheric water vapour (on-band), while the other two bands measure the continuum at adjacent regions of the spectrum (off-band). The ratio of on-band to off-band radiance measurements can be used with an atmospheric model, BTRAM , to derive the PWV. Results from the prototype instrument are presented and their values compared with other available simultaneous PWV measurements, including radiosondes launched at the observing site.

2 BACKGROUND

Studies have shown that water vapour is the largest source of opacity in the infrared and severely limits ground-based infrared astronomy. Water vapour has a multitude of transitions from the visible into the far-infrared. While in the far-infrared, water vapour is the dominant source of opacity, a lesser but still significant amount of absorption occurs in the near-infrared region, around 0.95 μm. The lunar spectrophotometer is designed to measure this absorption band.

Several methods exist for estimating water vapour column abundance, including heterodyne receivers (183 and 225 GHz) , emission measuring radiometers (IRMA) , solar reflectance-based satellite measurements, absorption-based estimates using high-resolution echelle spectrographs , through to direct measurements with radiosonde instrumentation . Calibration is a challenging problem for all radiometers and particularly for those operating in the thermal infrared. The lunar photometer, by virtue of the fact that it operates at a wavelength at which the atmosphere emits virtually no radiation, provide a robust calibration point, since the derived PWV values are relatively insensitive to the atmospheric profile used in the model.
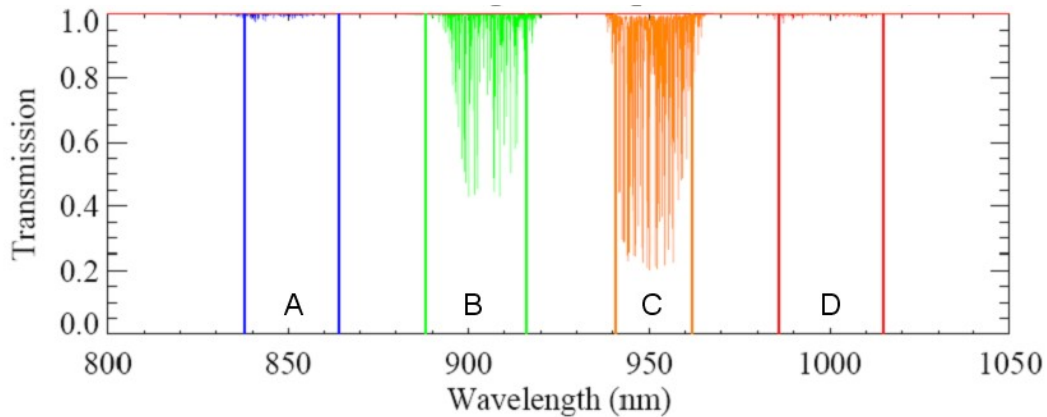
Figure 1. A simulated water vapour transmission spectrum for the atmosphere above the La Silla Paranal Observatory in Chile situated at an elevation of ~2400 m. The model was calculated for a PWV of 1 mm at a resolution of 0.001 nm. Regions A and D have negligible absorption, whereas regions B and C are regions of weak and strong absorption, respectively.

IRMA, the Infrared Radiometer for Millimetre Astronomy, is based around a cryocooled, photoconductive HgCdTe detector. The detector sensitivity peaks at a wavelength of ~20 μm, which is near the peak of the Planck curve for typical atmospheric temperatures (~260 K), and in a region that contains many strong transitions from atmospheric water vapour . IRMA observes atmospheric emission in a spectral band on the order of 2 μm centred at a wavelength of ~20 μm. The detected flux is converted to PWV by use of a sophisticated atmospheric radiative transfer model. Studies have shown that temperature and scale height of water vapour are dominant factors affecting the retrieved PWV in the atmospheric model. Pressure and adiabatic lapse rate being less important parameters. However, since it operates in the thermal-infrared region, IRMA is sensitive to any source of stray radiation from ambient temperature sources which may be in the field of view and thus requires careful calibration.

3 LUNAR SPECTROPHOTOMETER

In contrast to the thermal-infrared, the atmosphere is mostly transparent in the visible. However, in the near-infrared (i.e. 700-1000 nm) there are several relatively strong absorption bands due to oxygen and water vapour. The absorption across these bands is directly proportional to the amount of water vapour in the simulated atmosphere. By measuring the drop in transmission across bands selected to contain transitions from atmospheric water vapour, and by use of an atmospheric model, it is be possible to derive the PWV. The concept is illustrated in Figure 1. Bands A and D are the so-called off-bands, while B spans a region of weaker water vapour transitions and could be used to probe high PWV amounts, whereas region C has strong transitions and would thus be limited to probing lower PWV amounts due to the early onset of line saturation.

As seen in Figure 1, the principal water vapour absorption region that is employed in this scheme is centred near 950 nm, while the continuum measures are determined in bands centred at 850 nm and 1000 nm, respectively. The technique to derive water vapour from the absorption measurement is shown in Figure 2. This technique has been used extensively by instruments making day-time measurements of ozone, aerosols and water vapour abundance by using the sun as a source . In principle, the technique could be extended to use the light emitted from the photosphere from a star, but this would require a telescope with a large collecting area. An intermediate solution, and the one we have adopted, is to use the moon as a source and a small (100 mm) telescope aperture. Since the moon is not a source of near-infrared photons, but merely acts as a diffuse reflector of solar irradiance, it has a well defined spectrum. The continuum level corresponding to the zero absorption case, L'_C is determined from the off-band measurements. The ratio of the measured radiance, L_C, to L'_C, in combination with the atmospheric model, is used to yield PWV.
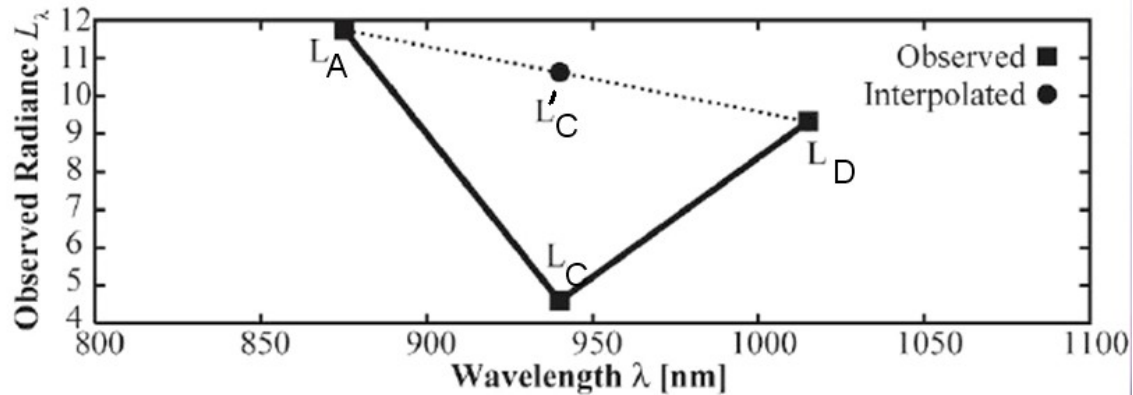
Figure 2. Illustration of the technique used to determine absorber abundance through a sequence of on- and off-band measurements. L_A and L_D are the observed radiance within bands A and D (Figure 1). These two measurements serve to establish the continuum radiance, L'_C. The ratio of the measured radiance, L_C to L'_C, yields a band transmission which is used to derive PWV .

Since there is minimal emission in this wavelength range from atmospheric water vapour, due to the low temperatures encountered in the atmosphere, the radiative transfer is greatly simplified and the uncertainties associated with the model are reduced. The lunar spectrophotometer thus provides a powerful, independent validation of the measurements made by the IRMA radiometer.

4 DESIGN

The detailed design of the lunar spectrophotometer will be presented elsewhere, but is summarised here. The instrument consists of a small, off-axis parabolic telescope, which directs light to a filter wheel containing four filters (shown as the coloured bands in Figure 1), which is mounted immediately in front of a Silicon (Si) photodiode. Since atmospheric water vapour varies on timescales of <1s and that measurements of all 4 bands must occur in within this time, a relatively fast detector was required; the photodiode easily met this requirement. The fast time response also removed the requirement for lunar tracking. Si photodiodes, which are sensitive over the range of interest, provide a simple and inexpensive detector solution. Moreover, they operate at room temperature, eliminating the need for complex cooling systems, such as those required for IRMA HgCdTe detectors.

5 CALIBRATION AND OPERATION

The purpose of calibration is to create a set of comparison points for projecting measurements made with the instrument onto a known reference scale. Once measurements are presented relative to a recognised reference, they are then able to be intercompared with all other measurements that have been similarly translated.

To calibrate the detector and filter assembly, an Ocean Optics USB spectrometer was used in conjunction with an ASD Inc. integrating sphere. The combination of integrating sphere and its collimated light source were used to provide diffuse, uniform illumination. A fiber optic cable was mounted into the integrating sphere, and attached to the high resolution USB spectrometer. This allowed us to measure the apparent spectrum of the halogen bulb/integrating sphere system. The detector, complete with filter wheel assembly was positioned at an open port of the integrating sphere. Detector signal voltages were measured on a digital multimeter while the filter wheel was manually rotated between the four filters.

Once the relative sensitivity between adjacent channels was determined the detector and filter wheel were mounted into the enclosure along with the OAP mirror. On May 10th, 2009, when the moon was nearly full (to maximise the potential signal) several measurements, over all of the bands were recorded, a representative data set is shown in Figure 3. Using the relative channel response determined with the integrating sphere it was possible to process the moon-based measurements.
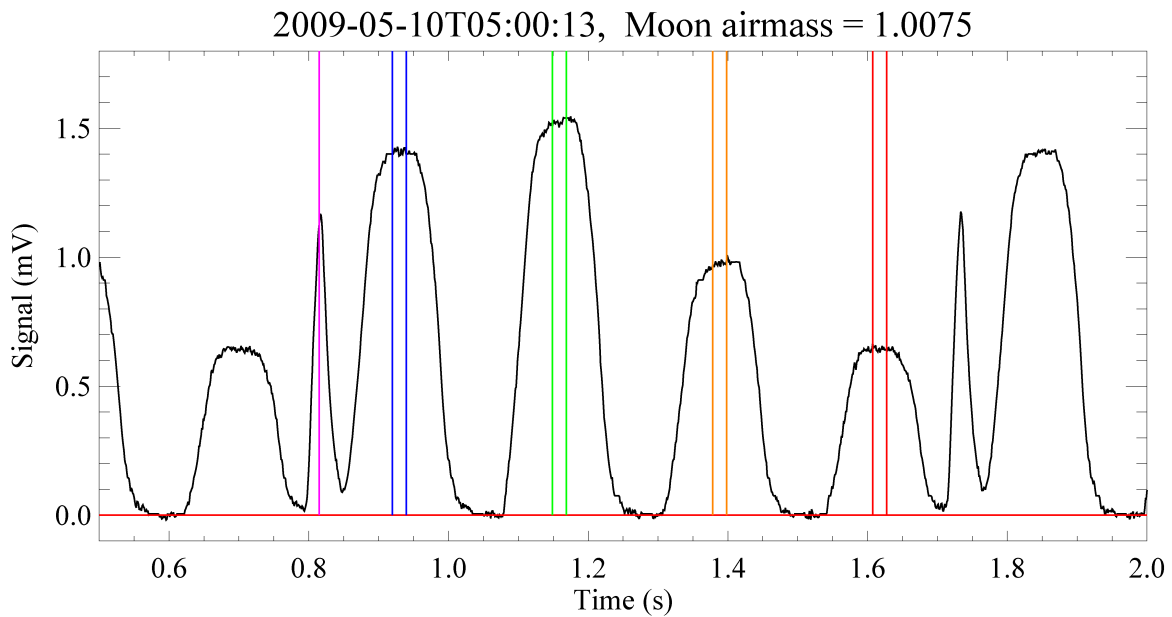
2009-05-10T05:00:13, Moon airmass = 1.0075

Figure 3. Time-series data from the lunar spectrophotometer detector as recorded by a Data Translation DT9822 USB Data Acquisition Board. One period of the filter bands (from Figure 1) are delineated with the colour bars. A notch in the filter wheel used as a position check is marked by the violet bar at ~0.8 s in this plot.
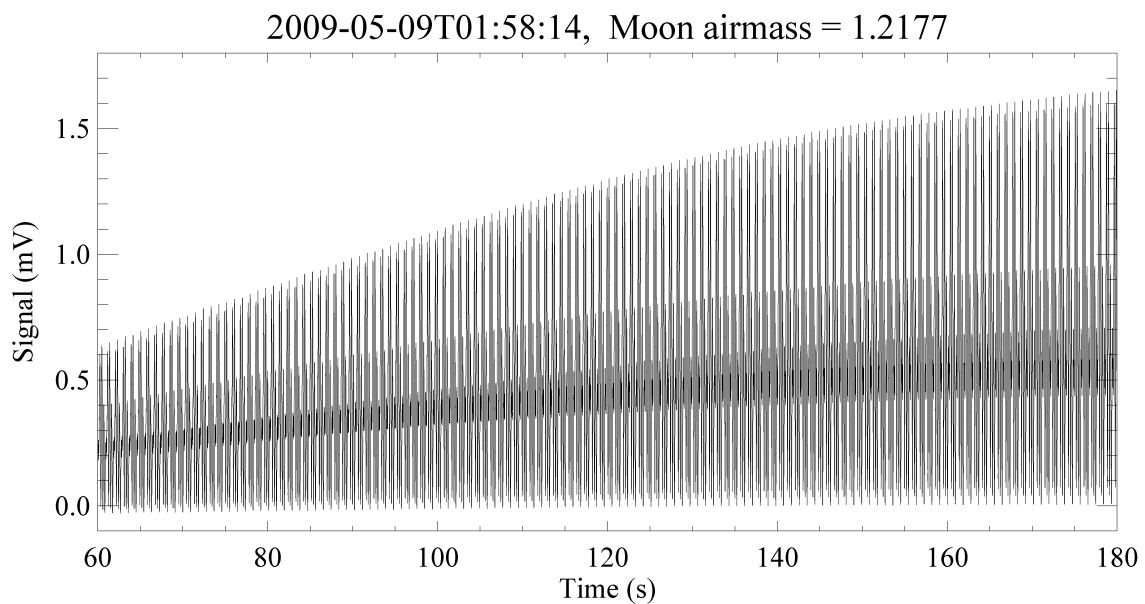
2009-05-09T01:58:14, Moon airmass = 1.2177

Figure 4. Two minutes of signal from the detector clearly shows that a lunar tracking system would be beneficial.
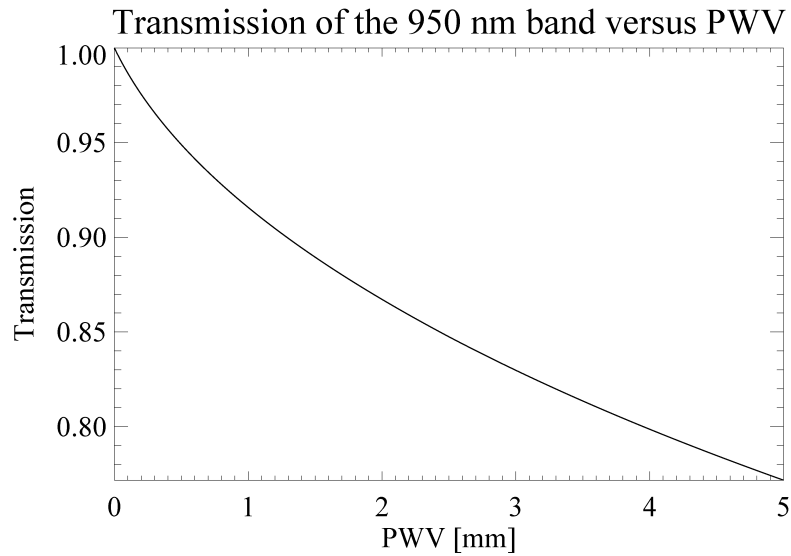
Figure 5. Transmission of the 950 nm spectral region resulting from a given water vapour column abundance for the simulated atmosphere above the La Silla Paranal Observatory computed using BTRAM.

6 DATA PROCESSING

To convert the lunar measurements shown in Figure 3 into a PWV value, a model atmosphere is required. This is accomplished using a simulated atmospheric transmission spectrum created using BTRAM . The measurements were performed in central Chile, so a simulated spectrum was created using parameters applicable to that location, i.e., adiabatic lapse rate, elevation, local ambient temperature and pressure. This model was computed for 1 mm PWV. The transmission spectrum was convolved with each of the filter profiles to specifically select the bands of flux that would be incident on the detector, as seen in Figure 1. Once convolved, each band was integrated, resulting in an absorptance across the band. This process was repeated for PWV values from 1.1 to 20.0 mm. In each case the 1 mm PWV spectrum was converted to opacity, linearly scaled, and then converted back to transmission. The relationship between opacity and transmission, is given as $T = e^{-\tau}$, where τ is opacity. The resulting relationship between PWV and transmission is plotted in Figure 5.

7 RESULTS

Using the collection method and data processing described above, measurements were taken over the period from May 8 to May 13, 2009, at ESO La Silla Paranal Observatory in central Chile. As part of a PWV measurement campaign, the lunar spectrophotometer was included in the instrumentation suite. The instrument and installation are shown in Figure 6. In situ measurements of PWV were derived from radiosondes launched from the site at 00UT and 06UT. Two IRMA radiometers were on site to measure PWV, and high resolution echelle spectra (MIKE) were taken of calibration standard stars in order to derive PWV by fitting an atmospheric model to the reduced spectra. Comparison between these varying data sets, shown in Figure 7, suggests that, when properly calibrated, the lunar spectrophotometer could provide an effective, low-cost means of determining atmospheric water vapour columnar abundance.

Figure 6. The lunar spectrophotometer mounted on a tripod (left). The moon, as viewed through the open dome above the ESO, 1-meter telescope at La Silla Paranal Observatory, Chile (right).
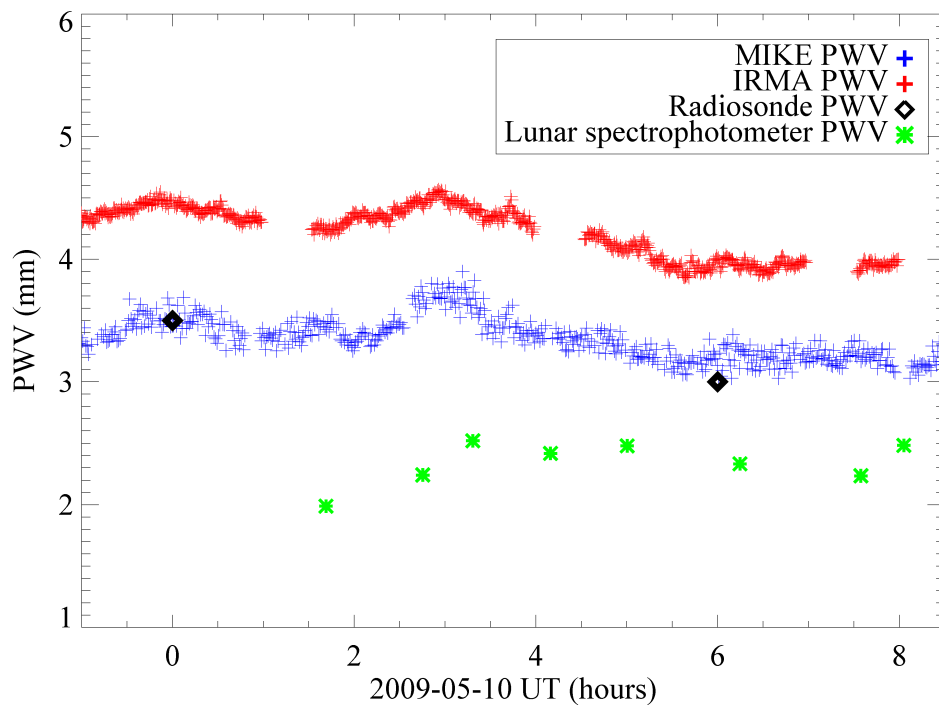

Figure 7. Time-series of water vapour measurements from using 4 different measurement techniques. IRMA is a radiometer measuring atmospheric water vapour emission around 20 μm. MIKE is a high resolution echelle spectrograph that was measuring atmospheric absorption due to water vapour, as seen in the continuum of photospheric lines from a known, source star. The radiosonde directly measures humidity versus altitude, from which partial pressure of water vapour can be calculated and PWV derived.

8 FURTHER WORK

The prototype lunar spectrophotometer and these proof-of-concept measurements have validated our main hypothesis and demonstrated the potential functionality of this instrument. Much can be gained by the addition of a lunar tracking system, which would facilitate long integration times. The preliminary results indicate that once calibration issues have been addressed, the lunar spectrophotometer will provide a simple and effective means of determining the PWV along the lunar line-of-sight.

ACKNOWLEDGEMENTS

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