Support for site testing of the European Extremely Large Telescope: precipitable water vapour over La Silla[†]

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ABSTRACT

The European Southern Observatory (ESO), the Institute for Space Imaging Science (ISIS) and the AstroMeteorology group at the Universidad de Valparaiso collaborated on a project to understand the precipitable water vapour (PWV) over the La Silla Paranal Observatory. Both La Silla and Paranal were studied with the goal of using them as reference sites to evaluate potential E-ELT sites. As ground-based infrared astronomy matures, our understanding of the atmospheric conditions over the observatories becomes paramount, specifically water vapour since it is the principle source of atmospheric opacity at infrared wavelengths. Several years of archival optical spectra (FEROS) have been analysed to reconstruct the PWV history above La Silla using an atmospheric radiative transfer model (BTRAM) developed by ISIS. In order to better understand the systematics involved, a dedicated atmospheric water vapour measurement campaign was conducted in May 2009 in close collaboration with Las Campanas observatory and the GMT site testing team. Several methods of determining the water column were employed, including radiosonde launches, continuous measurements by infrared radiometers (IRMA), a compact echelle spectrograph (BACHES) and several high-resolution optical echelle spectrographs (FEROS, HARPS and MIKE). All available observations were compared to concurrent satellite estimates of water vapour in an attempt to ground-truth the satellite data. We present a comparison of the methods used, and results from the archival study and measurement campaign. A mean PWV of 3.4 ± 2.4 mm is found for La Silla using FEROS data covering the period 2005–2009. Important lessons on the strengths and limitations of satellite data are presented. The value of a stand-alone high time resolution PWV monitor has been demonstrated in the context of parallel observations from Las Campanas and La Silla.

Keywords: precipitable water vapour, PWV, site testing, atmosphere, radiative transfer model, infrared radiometer, echelle, radiosonde, La Silla, Las Campanas, E-ELT, BTRAM, FEROS, HARPS, IRMA, MIKE

1. INTRODUCTION

Water vapour is the principle source of opacity at infrared wavelengths in the Earth's atmosphere. Measurements of atmospheric water vapour serve two primary purposes when considering operation of an astronomical observatory: long-term monitoring of precipitable water vapour (PWV), whose vertical column abundance is expressed in mm,[1] is useful for the characterization of potential observatory sites, while real-time monitoring of PWV is useful for optimizing their use, in particular with regards to mid-infrared observations.

In support of site testing for the European Extremely Large Telescope (E-ELT), we have used La Silla and Paranal as calibration sites to ground-truth satellite measurements of PWV. To this end, dedicated measurement campaigns have been conducted at both sites and also at Las Campanas Observatory (LCO) through a collaboration between the Institute for Space Imaging Science (ISIS), scientists from the European Southern Observatory (ESO), and the Giant Magellan Telescope (GMT) site test team at LCO.

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

Several independent measurement techniques were used in this study. Continuous measurements were provided by IRMA[1–3] infrared radiometers operating at 20 μm. PWV was also retrieved from measured spectra covering the wavelength range from the visible to the near-infrared using facility instruments (FEROS,[4] HARPS[5] and MIKE[6]) through fitting their data to simulated atmospheric spectra. In addition, a compact light-weight echelle spectrograph, BACHES,[7] was used with the ESO 1-m telescope to allow for greater flexibility in timing observations to coincide with radiosonde launches. And finally, we evaluated the potential utility of a simple stand-alone 4-band lunar spectrophotometer, operating at ∼0.94 μm, which employed a 100 mm diameter telescope.

Local meteorological data were provided by a series of radiosonde launches timed to coincide with satellite overpasses. The radiosondes provided *in situ* measurements of PWV, and time and location specific atmospheric profiles. Together, this multi-faceted approach has resulted in a unique data set. Integral to this analysis is a site-specific atmospheric radiative transfer model (BTRAM[8,9]), common to all echelle fitting and radiometer retrieval schemes used in this study.

The PWV history over La Silla has been reconstructed by analysing >1700 high-resolution echelle spectra of standard stars using archival FEROS data. The retrieved PWV values have been compared to estimates derived from a GOES satellite[10] and the MERIS[11] spectrometer aboard the Envisat spacecraft. Together, these unique data spanning several years, can be used to investigate the seasonal variations in the water column above the Chilean site.

Our three PWV measurement campaigns in 2009, described below, have resulted in a unique data set both in terms of quality and quantity of measurements. An unprecedented number of independent instruments and methods has been used which allows for a meaningful comparison of results. In most cases, there is found to be good agreement between the methods used. Comparison with satellite data shows excellent agreement for Paranal while for La Silla the topography combined with the limited spatial resolution of the GOES data introduces a wet bias. The PWV retrieval algorithm used with the GOES images employs a profile derived using data from radiosondes launched at Antofagasta (∼110 km from Paranal, while ∼625 km from La Silla). This may also explain why the GOES PWV agreement is better for Paranal than for La Silla. The wet-bias observed in the GOES derived PWV is less pronounced in the higher resolution MERIS data set. It is reasonable that Paranal can be used as a reference for sites in northern Chile, while La Silla, still requires further detailed analysis, but can still provide important lessons for other sites. The long-term mean PWV for Paranal is 2.3 ± 1.8 mm while La Silla is wetter at 3.4 ± 2.4 mm. The relatively large uncertainties in these values are due to pronounced seasonal variations that exist on both sites. A dedicated campaign to better understand the systematics of PWV analysis has been successfully conducted on La Silla (May 2009) in high to moderate PWV conditions; two additional campaigns on Paranal (Jul/Aug 2009 and Nov 2009) enjoyed much lower PWV. We report on the results of all campaigns in this paper and a parallel submission. Based on the experience gained in this study it will be possible to select the best-suited methods and suggest optimised strategies for supporting PWV monitoring at current and future observatory sites.

The PWV project has the following goals in order to directly support E-ELT site testing:

1. Reconstruct the record of precipitable water vapour (PWV) over La Silla and Paranal from archival data;
2. Correlate the ground-based PWV values with satellite data to establish La Silla and Paranal as reference sites for E-ELT site evaluation; and,
3. Evaluate the merit of various method to determine PWV for operational use at an observatory.

1.1 Water vapour and atmospheric models

Several methods exist for measuring the amount of water vapour in the atmosphere. To date, an accurate and practical means of determining PWV has remained elusive. One approach that uses ground based optical spectroscopy is the so-called weak-line method,[12,13] which uses isolated spectral lines that are intrinsically insensitive to temperature variations. This allows for a simple, single-layer atmospheric model with a limited number of molecular parameters. The principle disadvantage of this method is the requirement of weak lines which makes identifying the spectral continuum from which the equivalent width is derived of critical importance.

Recent developments by the ISIS using their multi-layer atmospheric radiative transfer model (BTRAM) has greatly improved our ability to obtain precise PWV measurements from absorption line spectroscopy in the wavelength range 580–980 nm. This model uses input data from HITRAN2008[14] and employs a customizable profile of the distribution of water vapour in the atmosphere. As a consequence an entire manifold of weak and strong blended spectral lines can be fitted simultaneously to retrieve more accurate and robust PWV values. A study was performed to assess the validity of this method by fitting spectra taken with the MIKE echelle spectrometer at Las Campanas observatory in the context of field testing an IR radiometer (IRMA).[15] The fit used a total of 1100 water vapour lines to derive the column abundance of PWV, with excellent results (∼5% precision). Although some systematics effects remain, there is generally good agreement between the weak-line method and BTRAM derived values.[16]

2. HISTORY OF PWV OVER LA SILLA PARANAL OBSERVATORY FROM ESO ARCHIVAL DATA

Using the new spectral modelling approach pioneered at ISIS[15] many lines covering several atmospheric bands can be used simultaneously to achieve a global fit between a measured high-resolution spectrum and a simulated manifold of water vapour lines. To study the seasonal variations of PWV over the La Silla site, we analysed ∼1700 FEROS flux standard calibration observations covering the period from 2005 to 2009, stored in the ESO data archive. Figure 1 shows examples of these fitting results. These flux standard spectra of white dwarfs have nearly flat and featureless stellar continuum making them particularly well suited for this study. These were reprocessed to provide the PWV fitting algorithm with a homogeneous data set. The approach used for the FEROS data reduction is similar to the UVES reprocessing project using validated master calibration files.[17] The standard star observations are performed at a relatively high spectral resolution (R∼40000). Similarly, standard star observations taken with UVES (∼1500 spectra) have been used to make an equivalent analysis for Paranal, see parallel submission by Kerber *et al.*[18] For both instruments the number of useable spectra could be increased by including science observations as well, however, stellar features represent a significant complication to the extraction of PWV values. Analysis of science data would require the careful selection of targets, for example only stars with temperatures >10,000 K, to minimize the number of photospheric lines; thus we limited our sample to standard star observations.

For the analysis with BTRAM, a mid-latitude profile modified with site-specific archival radiosonde data from Antofagasta has been employed. Since the distribution of water vapour is highly time dependent this profile represents a median distribution. It is expected that the median is more applicable to Paranal, which is located ∼110 km from Antofagasta, while less representative for La Silla, since it is ∼625 km from Antofagasta. In all cases the distribution of water vapour, usually expressed in terms of a scale height, is the dominant source of uncertainty.

2.1 Satellite data and ground truth

The archive value of the FEROS standard stars data sets are essential in establishing a statistical relationship between the ground-based data and the satellite data taken with the geostationary GOES satellite and the MERIS spectrometer onboard the sun-synchronous ENVISAT, situated in a low Earth orbit. Calibration and validation of space-borne instruments is usually achieved using ground based observations: the goal being to render the satellite data more accurate by characterising systematic effects between instruments and techniques.

For example, GOES provides good temporal resolution – one full Earth disk observation every 3 hours – but offers only limited spatial resolution (12 × 12 km). Moreover, the GOES radiometer cannot measure water vapour directly but instead derives it based on an empirical relationship between brightness measurements at 6.5 and 10.7 µm (a water vapour emission band and an IR window, respectively). This approach is sensitive to temperature effects. On the other hand, the MERIS spectrometer directly measures water vapour lines between 890 and 900 nm with a spatial resolution of 1.2 × 1.2 km, however, due to its polar orbit it passes over sites in Chile only every 2–3 days; always around 14:30 UTC, thus providing only day time measurements.

As is shown in the next section, despite the large difference in spatial and temporal resolution, there is general agreement between the water wapour derived by the two satellites.[11] However, it should be noted that there is an approximate factor of 100 reduction between the GOES footprint and the MERIS footprint, and another

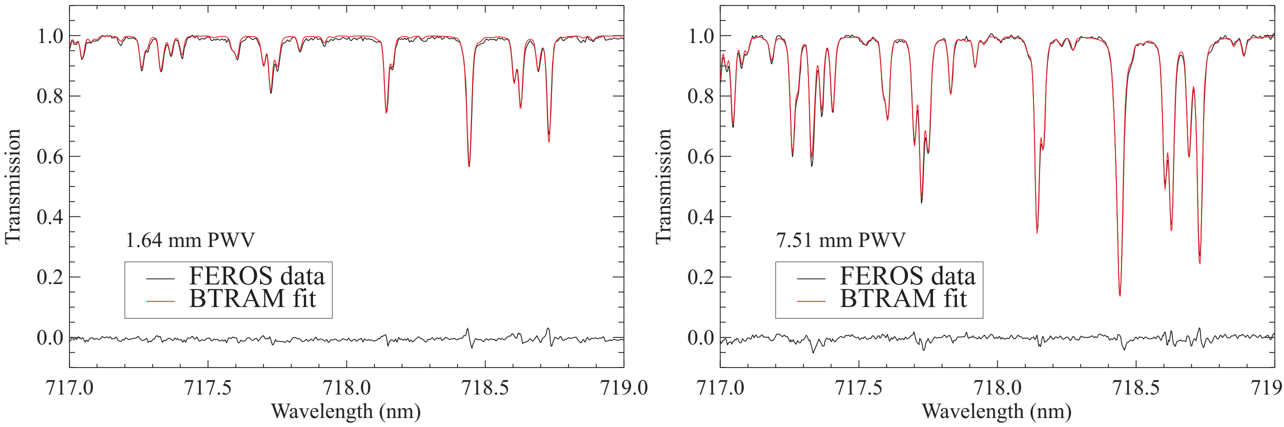

Figure 1. Example of deriving PWV from fitting a simulated atmosphere to FEROS archival data. Each plot shows the measured spectra, simulated spectra and a residual. Both spectra were measured in October 2005. The left panel represents dry conditions, whereas the right panel is a relatively wetter night.

factor of 18,000 reduction between the MERIS footprint and the collection area of typical 10 m telescope. This overall factor of 1.8 million between the area sampled by GOES and the area observed by a telescope illustrates the challenge in directly comparing their retrieved PWV values. The larger areas will necessarily include regions around the observatories. Since these regions are low-lying and wetter their retrievals will tend be biased. Notwithstanding this limilation, the FEROS archival provides an ideal data set to compare ground and space-based measurements.

2.2 Results from the archive

When comparing the PWV values derived from the FEROS archival spectra and the satellite data one has to keep in mind that these approaches are different in a number of important aspects. In the ground-based case, the observations sample a very small volume of the atmosphere – a single line-of-sight towards a star. The satellite-borne instrument is nadir-viewing, recording an average of PWV over its field-of-view representing many square kilometres which may contain lakes, fields, roads, etc. Also, the ground-based telescopes benefit from using a well-defined stellar continuum as a background source, while the satellites rely on sunlight reflected by the Earth (MERIS) or emission from the atmosphere (GOES). FEROS and MERIS determine PWV from absorption lines in the near-IR (700–1000 nm), while GOES measures brightnesses in the thermal IR (water vapour emission at 6.5 μm and an IR window at 10.7 μm). Regardless of the methodology used, in all cases a model of the Earth's atmosphere (which include pressure, temperature and density profiles) is required to derive PWV.

Given the significant differences between ground and space-based measurement techniques, particularly in spatial and temporal coverage, the degree of agreement found in our study is quite remarkable. In all cases, except for those rare times for which simultaneous radiosonde launches exist, all retrieval methods are based upon a mean atmospheric profile. Since the scale height and distribution of water vapour is time dependent, all results based on archival data can be affected by systematic errors of up to 20% as a consequence of having used a median profile in their retrieval. Even with this caveat it is important to note that when comparing the results presented in this paper, no zero-point offsets or scaling factors have been applied to the individual data sets.

An example of the agreement between FEROS, GOES and MERIS in the form of a time series diagram is given in Figure 2. A mean PWV value of 3.4 ± 2.4 mm has been derived for La Silla from the FEROS data. These values are similar to those reported by Thomas-Osip *et al.* at nearby Las Campanas observatory.[16] It can be seen from Figure 2 that the GOES retrieved PWV are consistently higher than those derived from the MERIS instrument. The primary reason for this difference most likely arises from the larger, 12 × 12 km, spatial resolution of the GOES measurement which must include lower altitude and therefore wetter regions in the vicinity of the observatory site. This is reflected in the higher derived GOES estimates given in Table 1. The

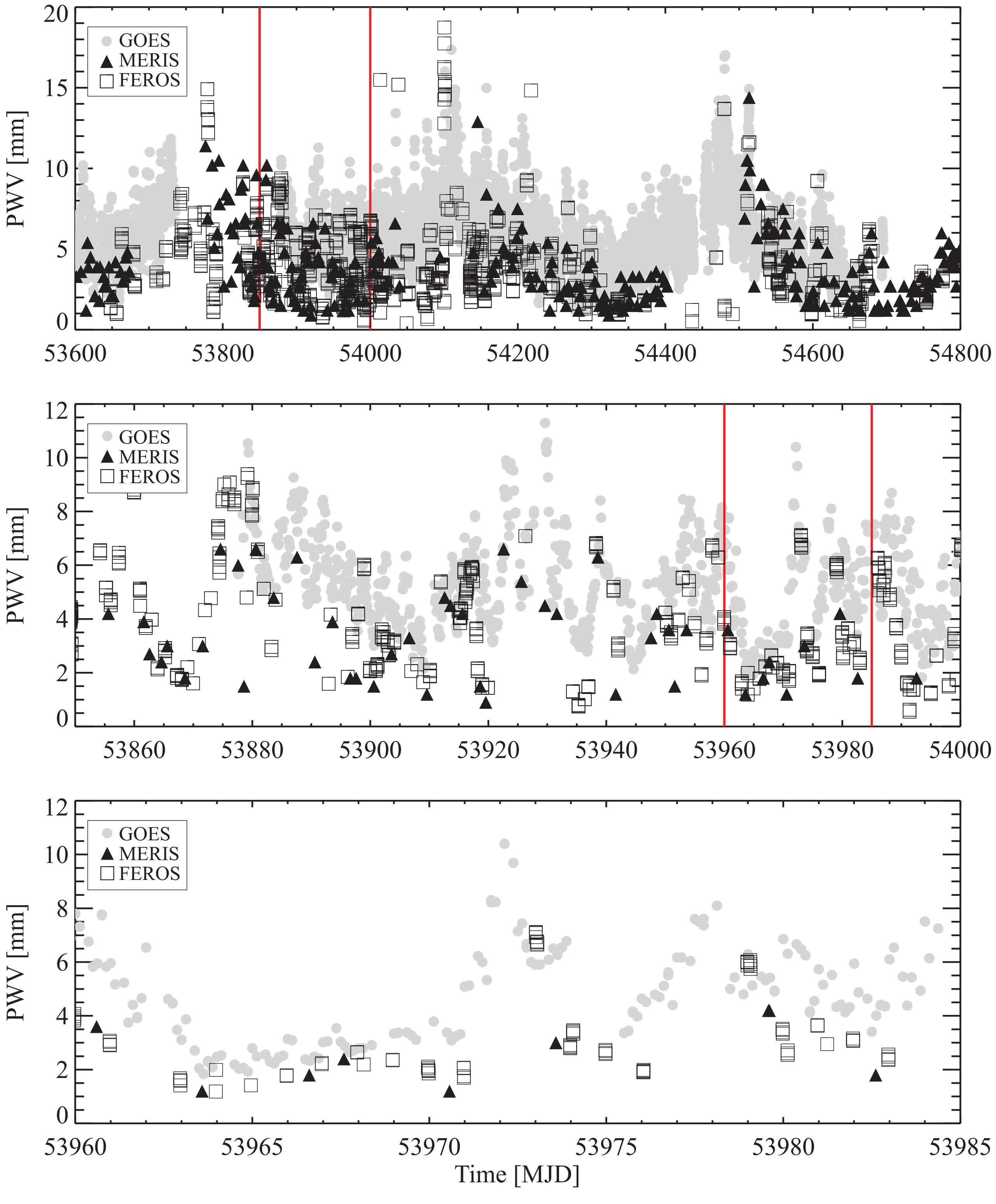

Figure 2. Comparison of PWV data derived from FEROS archival data and satellite data for the period 2005–2009. Pronounced seasonal variations are evident as is the more qualitative agreement when compared to the archival analysis for Paranal.[18] Middle and bottom plots show zoomed in subsets of the time series (delineated by the vertical bars). Agreement between the data sets is excellent. In terms of absolute PWV, GOES values are consistently higher than FEROS results. The dampening effect of its limited spatial resolution is evident.

Table 1. Mean PWV over La Silla derived from different methods and fraction of nights with a PWV less than a given value. For comparison, the mean PWV for Mauna Kea is 1.5 mm.

La Silla	Mean PWV ± Std.Dev. [mm]	<1 mm [%]	<1.5 mm [%]	<2 mm [%]
FEROS	3.4 ± 2.4	3.3	9.2	18.4
GOES	5.9 ± 2.5	0.02	0.4	1.8
MERIS	4.0 ± 2.3	0.8	11.2	17.2

superior agreement between the MERIS and FEROS derived PWV is most likely due to the smaller footprint of the MERIS observations.

The results of the archival analysis have highlighted a number of potential sources of systematic error which can be traced directly to temporal and spatial variations of the atmospheric path under study. This provided the impetus for a series of dedicated campaigns to measure PWV over La Silla and Paranal.

3. DEDICATED PWV CAMPAIGNS

The objectives of these campaigns were to:

1. Assess variation of PWV with air mass through optical spectroscopy;
2. Measure temporal variability of PWV over extended periods (>4 h) and at high cadence (<5 min) with optical spectroscopy and IR radiometers in parallel;
3. Obtain contemporaneous profiles of water vapour distribution using radiosondes;
4. Assess spatial variations by means of parallel observations from two adjacent sites (La Silla and LCO) with optical spectroscopy and IR radiometers;
5. Collect data over a period of at least 1 week; and,
6. Compare and contrast the results from the different ground-based measurements with satellite data.

The first of three water vapour measurement campaigns was conducted at the La Silla site of the ESO La Silla Paranal Observatory during the period May 3–15, 2009. The details of the instruments used in this campaign and the data available for analysis are given in Table 2. Figure 3 presents the time-series data from the La Silla measurement campaign. Expanded regions corresponding to the vertical bands of the upper plot are shown in middle and lower plots. To address point 4 above, some measurements were made in unison with those performed by the Las Campanas Observatory, located ∼30 km to the north of the La Silla site.

Despite some bad weather all campaign goals have been completed. The PWV values encountered during the period were always moderate to high (2–12 mm) in an astronomical sense, as was to be expected for the sites at this time of the year. The data set presented in Table 2 is unique both in terms of quality and quantity because it allows one to compare and contrast nine independent instruments and four different techniques. Given the diversity of the instruments and techniques employed, it is perhaps somewhat surprising that there exists a high degree of correlation between them, which suggests that the determination of PWV could benefit from a multimodal approach.

3.1 Comparison of methods and validation with respect to Radiosondes

Radiosondes are the gold standard method for atmospheric sounding, providing contemporaneous, *in situ* measurements above the launch site and are frequently used to validate other remote sensing techniques. Thus, in our campaign we arranged for a series of radiosonde launches while we were acquiring data in order to validate our instruments/methods. Radiosondes are not without their own limitations, however, once launched they rise at a rate of a few m/s, travelling through the lower atmosphere, containing the majority of the water vapour,

Instrument	Type	Wavelength	Location	Time	Actual/Planned	Data collected	Cadence
La Silla (Lat: -29.261167, Long: -70.731333, Alt: 2400 m)							
Vaisala RS92	Radiosonde	n/a	launched near the Schmidt telescope	May 5–15	17/20 launches	Profile measured to 20–25 km in $\sim$1.5 h	0/6/12UT
BACHES	Optical cross-dispersed Echelle spectrometer	400–900 nm	ESO-1m telescope	May 4–15	9.5/12 nights (due to weather)	$\sim$450 spectra	$\sim$12 min
FEROS	Optical cross-dispersed Echelle spectrometer	350–920 nm	MPG/ESO-2.2m telescope	May 6, 7	0.9/2 nights	$\sim$300 spectra	$\sim$minutes
HARPS	Optical cross-dispersed Echelle spectrometer	378–691 nm	ESO-3.6m telescope	May 8, 9	2/2 nights	$\sim$1100 spectra	$<$30 s
IRMA 11	IR radiometer	20 μm	near the Schmidt telescope	May 3–15	Nightly coverage achieved	$\sim$168 h	seconds
IRMA 12	IR radiometer	20 μm	near the Schmidt telescope	May 3–15	Nightly coverage achieved	$\sim$179 h	seconds
Prototype 4-band lunar absorbtion spectrophotometer		850,900,950, 1000 nm	ESO-1m telescope observing platform	May 5–15	Nightly measurements	$\sim$1500 scans	seconds
Las Campanas (Lat: -29.015, Long: -70.692222, Alt: 2380 m)							
IRMA 1	IR radiometer	20 μm	Alcaino peak	Continuous	Nightly coverage achieved	$\sim$124 hours	seconds
MIKE	Optical cross-dispersed Echelle spectrometer	320–1000 nm	Magellan Clay telescope	May 9/10, 14	2.5/3 nights	$\sim$1380 spectra	$<$30 s

Table 2. Summary of the instrumentation used and the data collected during the dedicated PWV campaign conducted at the La Silla site and Las Campanas Observatory during May 3–15, 2009.

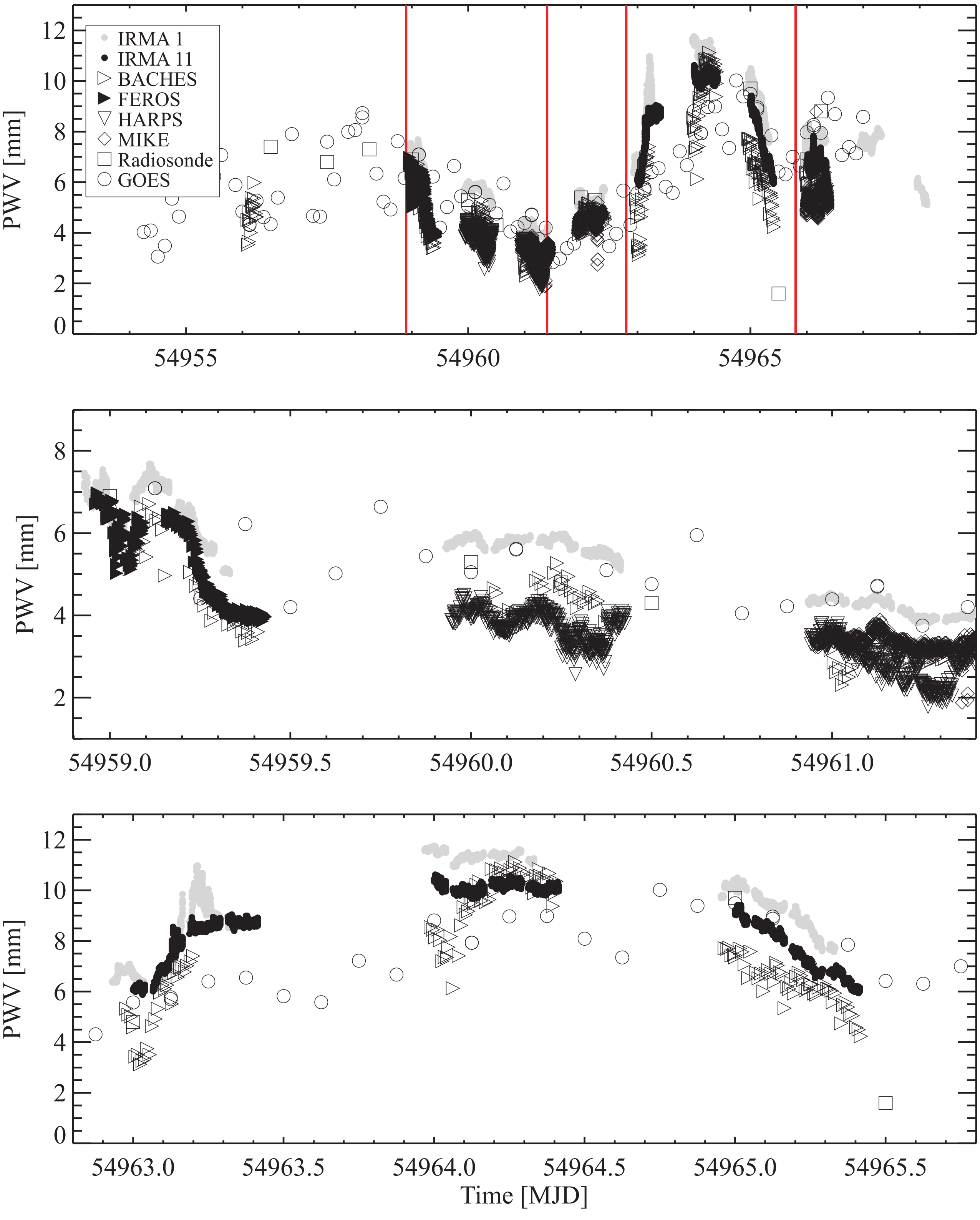

Figure 3. Upper window is a comparison of PWV data derived from the various methods during the PWV campaign on La Silla and Las Campanas in May 3–15, 2009. IRMA 1 and MIKE are located at Las Campanas, all other instruments are at La Silla. GOES satellite data has been overplotted for comparison. The middle and lower plots are expanded subsets of the time-series, denoted by the vertical bars in the upper plot.

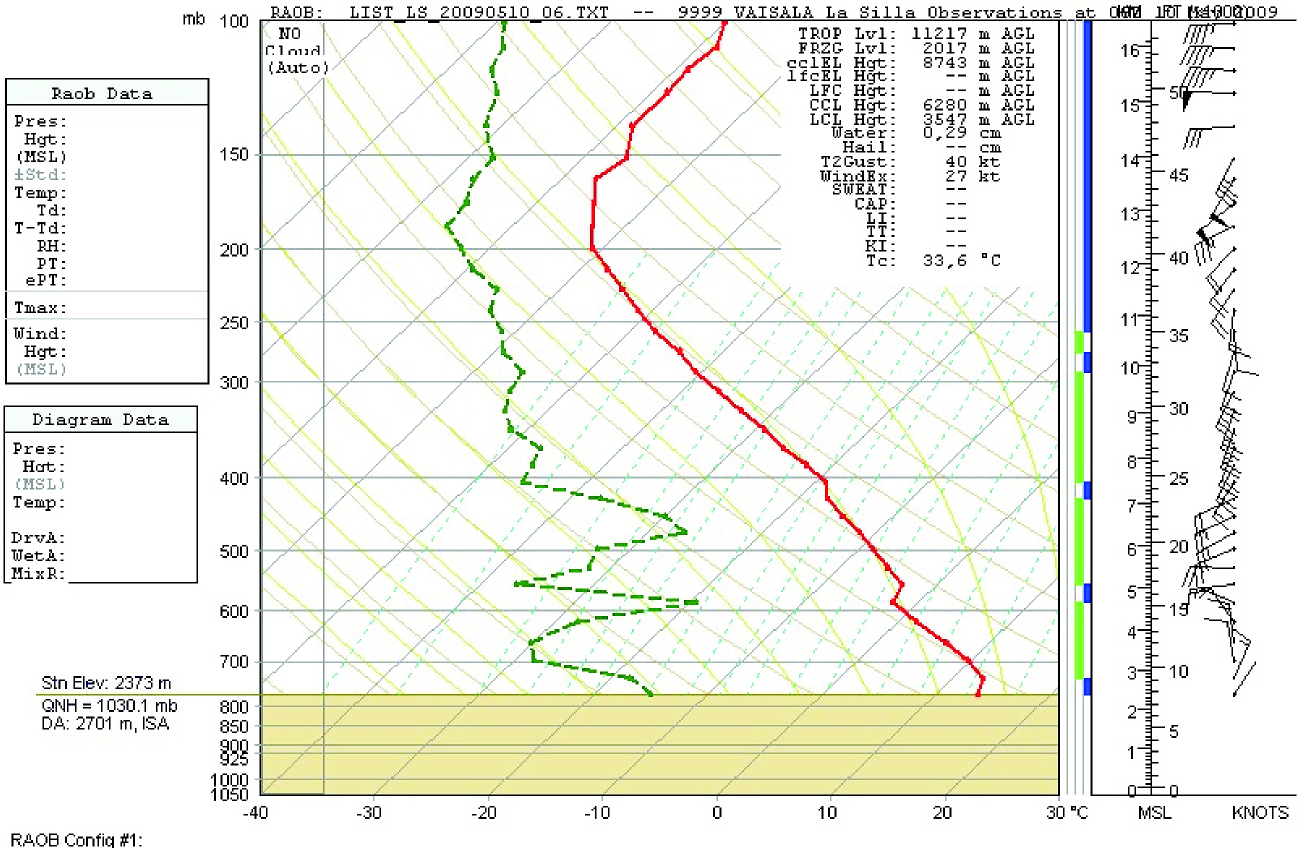

Figure 4. A standard method of plotting radiosonde data is through a SkewT-LogP Diagram.[19] The abscissa is temperature in degrees Celcius (°C) and the ordinate is altitude, given in both kilometres (km) and feet (FT). This coordinate system allows for the direct presentation of vertical profiles of atmospheric temperature (solid line) and dew point temperature (dashed line).

in <15 minutes. During their ascent to 20–25 km altitude, they are subject to the whims of the local weather patterns which will cause them to drift horizontally; we recorded eastward displacements between 80 and 150 km. Furthermore, radiosondes provide only a snapshot of the water vapour distribution along their complicated ascent vector. PWV is derived from radiosonde data by summing the amounts of water vapour determined by the local mixing ratio along the flight path expressed as a vertical column. An accuracy of 5% in derived PWV has been reported for radiosondes with that number increasing to 15% in dry conditions.[20, 21]

Figure 4 shows an example of the profile observed during a radiosonde ascent. These contemporaneous profiles can be used to optimize the analysis of the data taken with the various remote sensing methods. In the analysis present here, we have used a mean profile in the retrievals, it is our intention to use time-specific profiles to assess any systematic uncertainties introduced. It is hoped that this will lead to an improvement of the absolute accuracy for all remote sensing methods when compared to values retrieved using an Antofagasta-based profile.

While the radiosondes are ascending, only a small window of ∼1 hour is available to conduct meaningful parallel observations with other methods. For a stand-alone, high cadence monitor such as IRMA this is relatively easy to achieve, while for facility instruments careful planning and flexibility is essential.

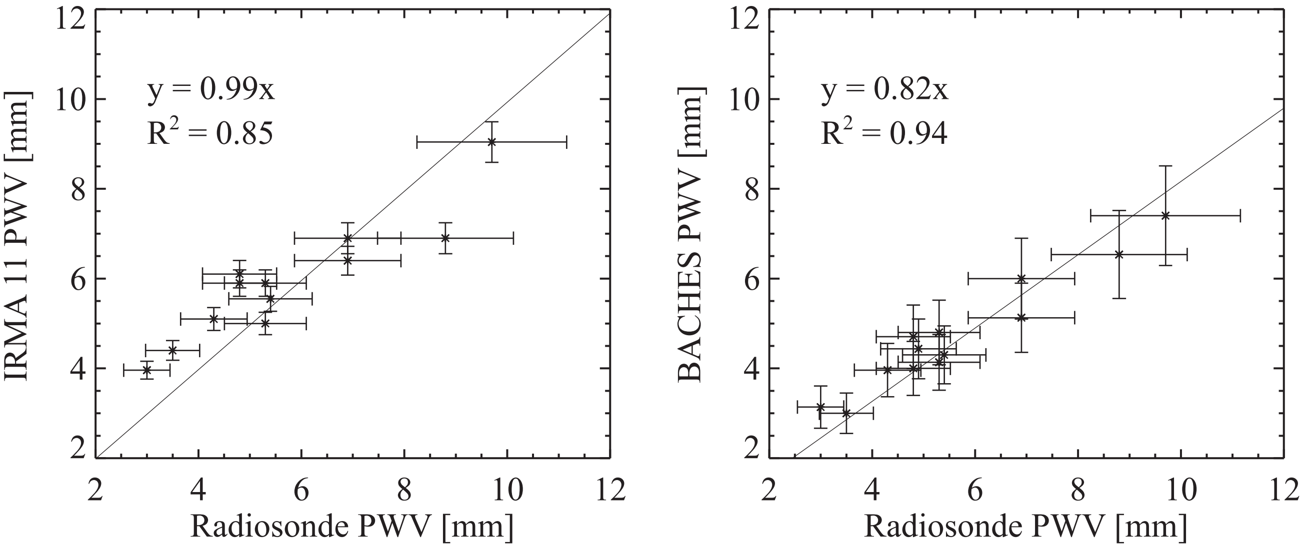

Figure 5. Left plot is a comparison of PWV data derived using an IR radiometer (IRMA) and the atmospheric profile recorded by radiosonde launches. The right plot is a comparison of PWV derived by fitting an atmospheric model to the BACHES optical spectrometer with PWV measured using radiosonde launches.

4. RESULTS

The results of the La Silla campaign are shown in part in Figures 3 and 5. As described earlier, Figure 3 displays a time-series of all of the data measured during the campaign with the suite of instruments employed by our study listed in Table 2. Figure 3 illustrates the qualitative agreement and overall trends followed by the variety of instruments.

While making simultaneous measurements at the La Silla and Las Campanas observatories, some temporal and spatial differences were expected and observed. Each site had continuous PWV monitoring provided by an IRMA radiometer, this was supplemented with high cadence measurements by HARPS (La Silla) and MIKE (LCO). On one occasion a water vapour feature was seen to drift across both sites. The difference in elevation between LCO and La Silla is negligible (∼20 m) , however the PWV measured above each site was at times different. For example, in the lower plot of Figure 3 at 54963.2, a distinct peak is present in the IRMA 1 data (located at LCO; solid grey circles) while no such feature exists in the IRMA 11 data (solid black circles, located at La Silla).

A quantitative analysis of the data shown in Figure 3 allows for comparison of a specific instrument derived PWV with that obtained by a radiosonde. Figure 5 shows two examples of such correlations. The left pane shows the correlation between IRMA and the radiosonde retrievals. A near unity slope is found over a PWV range of 3–10 mm. Within the accuracies of the methods we find excellent agreement (R^2=0.85). This is despite the fact that IRMA samples a pencil-beam at the zenith, while the radiosonde samples along its arbitrary ascent vector.

The right panel of Figure 5 shows the relationship between the BACHES spectrometer derived PWV values and the simultaneous radiosonde retrievals of PWV. Again, a PWV range of 3–10 mm was sampled and a good correlation (R^2=0.94) is observed. Even with its lower spectral resolution and 1-m telescope, BACHES derived PWV values were comparable to the results derived from all of the high resolution facility spectrographs used in our study.

In general, a high degree of correlation is found between optical, IR and radiosonde derived PWV. Moreover, since all retrievals require an atmospheric model (BTRAM), our analysis brings an internal consistency by using the same model.

The La Silla campaign was the first of three PWV measurement campaigns. Some nights with poor weather conditions and difficulty scheduling observation times resulted in a limited set of high resolution spectra with which to correlate to concurrent radiosonde data. The reader is referred to the paper by Kerber et al.[18] which presents aggregates the La Silla data with the results from two later campaigns at Paranal. The two campaigns resulted in a larger data set and thus a better source of intercomparison of the spectrometer and radiosonde PWV estimates. Good agreement was also found between the GOES PWV retrievals and radiosonde estimates. This is fully consistent with the findings from the FEROS archival data. As described above the discrepancy between the FEROS archival PWV and GOES PWV values may be attributable to its limited spatial resolution. GOES is found to both over- and underestimate PWV depending on atmospheric conditions and the actual distribution of water vapour. For these and other figures see the parallel submission by Kerber *et al.*[18]

4.1 Conclusion

In this paper we have presented results from a campaign to measure atmospheric water vapour above Chilean sites using data from nine ground based instruments and two satellites together with contemporaneous launches of radiosondes from the sites.

All ground-based measurements, regardless of wavelength, used the same atmospheric model to retrieve PWV. A high degree of correlation between radiosonde data and the other methodologies has been found. When one considers the fact that the different techniques covers the wavelength range of 0.7–20 μm it is quite remarkable that such agreement exists.

The PWV measurement campaign was a multimodal approach to tackle the problem of determining PWV above the Chilean sites. Using the gold standard of radiosondes, given their limitations, we found there was a high degree of correlation between every approach. The use of ground-based instruments dedicated to monitoring the atmosphere is feasible and has the potential to add value to observatory scheduling operations. Real-time monitoring of PWV is useful as an operational tool (short-term) and for site characterisation and testing (long-term). FEROS and HARPS measurements of spectrophotometric standard stars have been demonstrated to be good tools for monitoring the PWV over La Silla. A continuous monitoring of PWV using this method (ideally once per day) would allow for the generation of a long-term data set which could help to characterise the site and serve as a baseline for understanding the climatology of other sites.

Analysis of the data from the three PWV campaigns at La Silla and Paranal have resulted in the following general conclusions. The internal precision of PWV data from optical spectroscopy is $\sim$7%. The internal precision of IR radiometer data is $\sim$3%. Relative agreement between all three IRMA units measuring at the same site is extremely good on time scales of a few seconds to several hours. Correlation between PWV values derived from radiosondes and IR radiometers is close to 1 with a small zero-point offset. From this we conclude that within the uncertainties of the methods the results in PWV are fully compatible.

This study also demonstrates the legacy value and utility of archival data. The historical comparison to satellite data would not have been possible without a well-maintained and accessible repository of measurements.

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