Support for site testing of the European Extremely Large Telescope: precipitable water vapour over Paranal

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ABSTRACT

In support of characterization of potential sites for the European Extremely Large Telescope (E-ELT) the European Southern Observatory (ESO), the Institute for Space Imaging Science (ISIS) and the astrometeorology group of the Universidad Valparaiso have jointly established an improved understanding of atmospheric precipitable water vapour (PWV) above ESO's La Silla Paranal Observatory. In a first step, 8 years worth of high resolution near-IR spectra taken with VLT-UVES have been statistically analysed to reconstruct the PWV history above Paranal. To this end a radiative transfer model of Earth's atmosphere (BTRAM) developed by ISIS has been used. A median PWV of 2.1 mm is found for Paranal based on UVES data covering the period 2001-2008. Furthermore we conclude that Paranal can serve as a reference site for Northern Chile due to the stable atmospheric conditions in the region. The median offset between Paranal and Armazones is derived to be 0.3 mm, but local arbitrary variations of a few tenths of a mm between the sites have been found by measurement. In order to better understand the systematics involved two dedicated campaigns were conducted in August and November 2009. Several methods for determining the water column were employed, including radiosonde launches, continuous measurements by infrared radiometer, and VLT instruments operating at various wavelengths: CRIRES, UVES, VISIR and X-shooter. In a first for astronomical instruments all methods have been evaluated with respect to the radiosondes, the established standard in atmospheric research. Agreement between the radiosondes and the IR radiometer (IRMA) is excellent while all other astronomical methods covering a wavelength range from 700 – 20000 nm have also been successfully validated in a quantitative manner. All available observations were compared to satellite estimates of water vapour above the observatory in an attempt to ground-truth the satellite data. GOES can successfully be used for site evaluation in a purely statistical approach since agreement with the radiosondes is very good on average. For use as an operational tool at an observatory GOES data are much less suited because of significant deviations depending on atmospheric conditions. We propose to routinely monitor PWV at the VLT and to use it as an operational constraint to guide scheduling of IR observations at Paranal. For the E-ELT we find that a stand-alone high time resolution PWV monitor will be essential for optimizing the scientific output.

Keywords: precipitable water vapour, PWV, site testing, atmosphere, radiative transfer model, infrared radiometer, radiosonde, Paranal, ELT

1. INTRODUCTION

Precipitable water vapour (PWV) is the major contributor to the opacity of Earth's atmosphere in the infrared domain. In the context of astronomical observations the amount of PWV above an observatory is of fundamental importance for successful scientific operations: on long time scales PWV determines how well a site is suited for IR astronomy, while in an operational sense reliable knowledge of the content of PWV throughout a given night is critical for the success and quality of science observations. As part of site testing and evaluation for the European Extremely Large Telescope (E-ELT) we address primarily the first point. In the process of comparing various methods to determine atmospheric PWV though we have learned what methods will be suited to support IR science at the E-ELT in an operational sense.

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1.1 Water vapour and atmospheric models

Several methods exist for measuring the amount of water vapour in the atmosphere, whose vertical column abundance is expressed as precipitable water vapour (PWV) in mm[1]. So far an accurate and reliable means of determining PWV has remained elusive. For the ALMA project monitoring of water vapour levels is crucial also because this information is needed for phase correction. Radiometers operating at 183 GHz are used for this purpose[2]. Conditions at the site of the ALMA pathfinder experiment APEX are described in more detail at: http://www.apex-telescope.org/sites/weather.

So far the most successful approach using ground based optical spectroscopy[3] is the so-called weak-line method[4], which uses lines intrinsically insensitive to temperature variations. Thus a simplified description of the atmosphere with a limited number of molecular parameters can be used. The principle disadvantage of the method is that it requires weak lines. Hence spectra with good S/N ratio are required, and the result is sensitive to the placement of the continuum from which the equivalent width is derived. On Paranal PWV is now routinely derived from CRIRES, UVES, VISIR and X-shooter observations[5, 6, 7].

Recent developments by ISIS at the University of Lethbridge (Canada) using their multi-layer atmospheric radiative transfer model (BTRAM)[8] has greatly improved our ability to obtain precise PWV measurements from absorption line spectroscopy in the wavelength range 580 - 980 nm. That model uses input data from HITRAN[9] and employs a profile of the distribution of water vapour in the atmosphere. As a consequence a large number of weak and strong lines can be used for the analysis resulting in more accurate and more robust PWV values than for the weak-line method. Querel et al.[10] provide a comprehensive analysis of spectra taken with the MIKE echelle spectrometer at Las Campanas observatory in the context of field testing of an IR radiometer (IRMA). They use a total of more than 1000 water vapour lines to derive the column abundance of PWV, with excellent results.

The PWV project in support of E-ELT site characterization had the following goals:

- Reconstruct the record of PWV over Paranal & La Silla from archival data (see Querel et al[11] for the work on La Silla)
- Correlate the ground-based PWV values with satellite data to establish Paranal and La Silla as reference sites for E-ELT site evaluation
- Evaluate the merit of various methods to determine PWV for operational use at an observatory

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

With the BTRAM modeling approach many lines can be used simultaneously to achieve a global fit of the spectrum. For reconstructing the history of PWV over the La Silla Paranal Observatory we extracted from the archive about 1500 UVES flux standard calibration observations covering the period 2001 to 2008. With their almost flat and featureless stellar continuum these white dwarfs are particularly well suited for this study. The approach for data reduction is similar to the UVES reprocessing project[12] using validated master calibration files. Since the standard star observations are done with a wide slit (5 or 10 arsec) they provide essentially seeing-limited spectral resolution (R~40000), at which the model is capable of correctly treating line blending and deriving accurate PWV values. Similarly standard star observations (~1700 spectra) taken with FEROS have been used to make an equivalent analysis for La Silla which is described in detail by Querel et al.[11]. For both instruments the number of spectra useable for the purpose could be increased by including science observations as well. Since stellar features are a significant complication to the extraction of PWV values one would have to select the suitable targets individually; hence we limited our sample to standard stars.

For the analysis with BTRAM a mid-latitude profile modified with site-specific archival radiosonde data from Antofagasta – a median profile from more then 3000 individual radiosonde ascents covering about a decade (1998 to 2007) - has been used. Since the actual distribution of water vapour is highly time dependent this profile represents a median distribution. In the case of Paranal the Antofagasta profile certainly is a good match while for La Silla it will be much less accurate because of the much larger distance. The scale height of the water vapour distribution remains the largest uncertainty in all of the analysis.

2.1 Satellite data and ground truth

The UVES standard stars data set is essential in providing the ground truth for the calibration of satellite data taken with the geostationary GOES satellite and ENVISAT in sun-synchronous, low Earth orbit. Calibration using additional observations from the ground is a standard approach with remote sensing and atmospheric sounding techniques. Its main goal is to make satellite data more accurate in an absolute sense by characterising systematic effects.

GOES provides good temporal resolution - one full Earth disk observation every 3 hours - but offers only limited spatial resolution (12 by 12 km). Moreover, the GOES radiometer does not measure water vapour directly but obtains a brightness measurement at 6.5 (centered on an H_2O band) and 10.7 µm (background, see http://www.atm.ox.ac.uk/group/mpias/atlas); this approach is sensitive to temperature effects. ENVISAT on the other hand carries a spectrometer MERIS that directly measures water vapour lines between 890 and 900 nm with a spatial resolution of 1.2 by 1.2 km but only provides day time measurements; due to its sun-synchronous orbit it passes over sites in Chile only every 2-3 days; always around 14:30 UTC. Agreement between both satellite data sets is very satisfactory[13] but systematic effects exist. Since both sets suffer from some limitations they need to be complemented by night time observations taken at the observatory for validation. The UVES archival data serve this purpose perfectly.

2.2 Results from archival data

When comparing the PWV values derived from the UVES 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 looks down recording an average of PWV over its field of view a few square kilometers in size. The ground-based telescopes use a stellar continuum as a background source while the satellites rely on sun light reflected by the Earth (MERIS) or emission from the Earth's atmosphere (GOES). UVES and MERIS determine PWV from absorption lines in the near-IR (700-1000 nm) while GOES measures a brightness in the thermal IR (6.5 & 10.7 µm). In all cases a model of the Earth's atmosphere including a profile of the spatial distribution of water vapour is required to derive PWV from the measurements.

Given these significant differences the degree of quantitative agreement found is quite remarkable (Fig. 1). It is important to note that the actual distribution of water vapour in the atmosphere is unknown for all archival data regardless of the source, since this can only be provided by contemporaneous radiosonde launches. The scale height of water vapour is time dependent, therefore all results based on archival data are affected by systematic errors of up to 20% as a consequence of using a median profile.

Table 1: Median PWV for Paranal derived from ground-based spectroscopy and remote-sensing by satellite instruments and fraction of nights with PWV less than a given value. For comparison the median PWV for Mauna Kea is about 1.5 mm.

Paranal	Median PWV [mm]	PWV <1 mm [%]	PWV < 1.5 mm [%]	PWV < 2 mm [%]
UVES	2.1 ± 0.3	13.5	32	47.3
GOES	2.4 ± 0.5	4.8	18.9	38
MERIS	2.7 ± 0.3	1.5	7.9	29

For Paranal very good quantitative agreement between UVES and the satellite data is found. A few examples of the excellent agreement between UVES and GOES/MERIS in the form of time series diagrams are given in figures 2 to 4. No zero-point offsets or scaling factors have been applied when comparing the data sets. A median PWV of 2.1 mm is found for Paranal (table 1) based on UVES data covering the period 2001-2008. The standard deviation given describes the scatter seen over the years. This value is in excellent agreement with the previous PWV results reported for site testing for VLT. Some dry-bias can be expected for UVES data since standard stars observations are only done under clear sky conditions. For GOES data a value of 2.4 mm is reported. The geostationary GOES satellite undergoes eclipse periods of 48 days each twice a year. The maximum loss of observing time is 3 hours hence good temporal coverage is maintained. Given the significant differences in the measuring techniques the observed agreement is very re-assuring, also see section 3.1. For MERIS the median PWV is higher at 2.7 mm. A detailed analysis shows that MERIS systematically overestimates PWV under very dry conditions, leading to a wet bias in the median.

It is important to note that PWV over Paranal shows pronounced seasonal variations (Fig. 1). As a result conditions will be encountered during the course of a year that are significantly better as well as worse than what one would expect from the median. Table 1 therefore also lists the percentage of nights with PWV conditions well suited for IR observations (PWV < 2 mm). These seasonal variations are stable over the years, with periods of high PWV occurring during the Southern summer months when the site is partially affected by the *invierno altiplánico*.

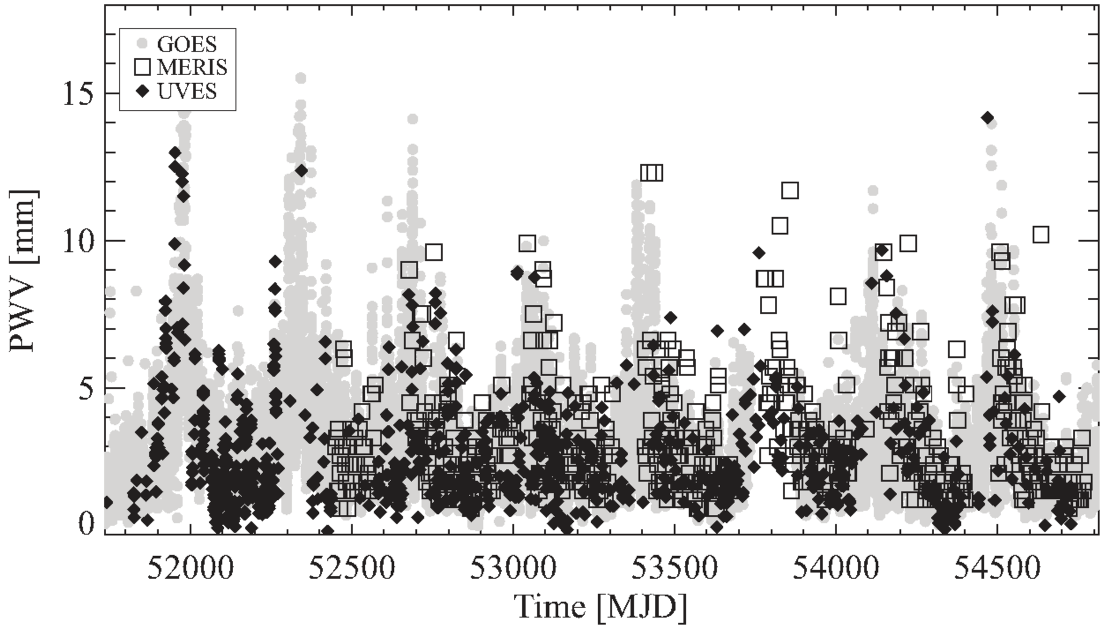

Figure 1: Record of precipitable water vapour over Paranal. Comparison of PWV data derived from UVES archival data and satellite data for the period 2000-2008. Pronounced seasonal variations are evident as is the quantitative agreement between the different data sets.

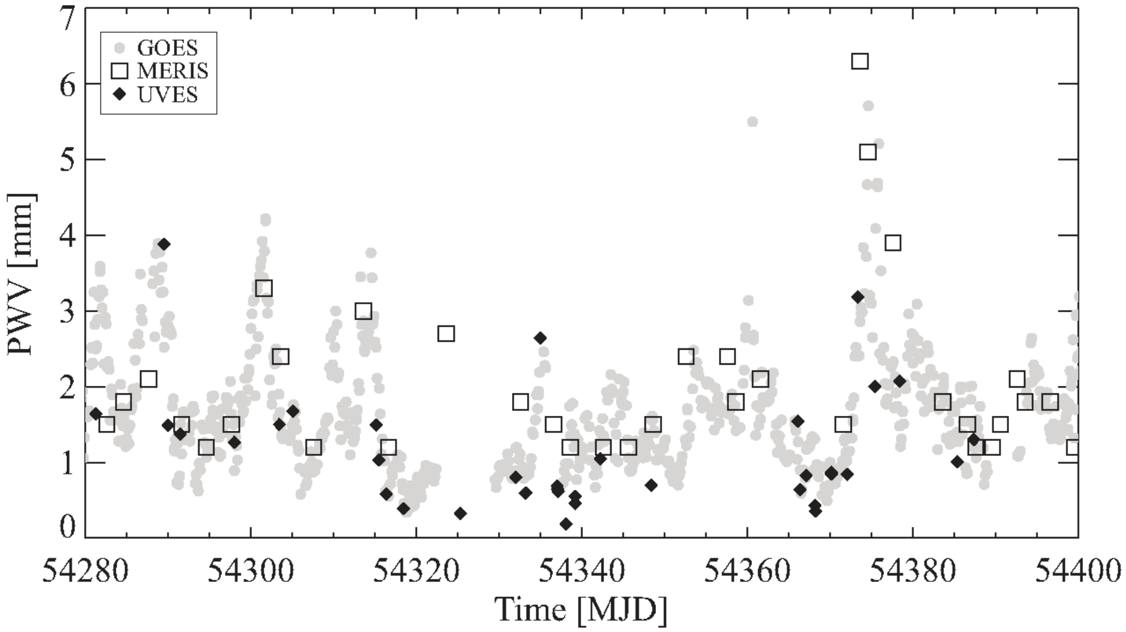

Figure 2: Comparison of PWV data derived from UVES archival data and satellite data June to December 2008.

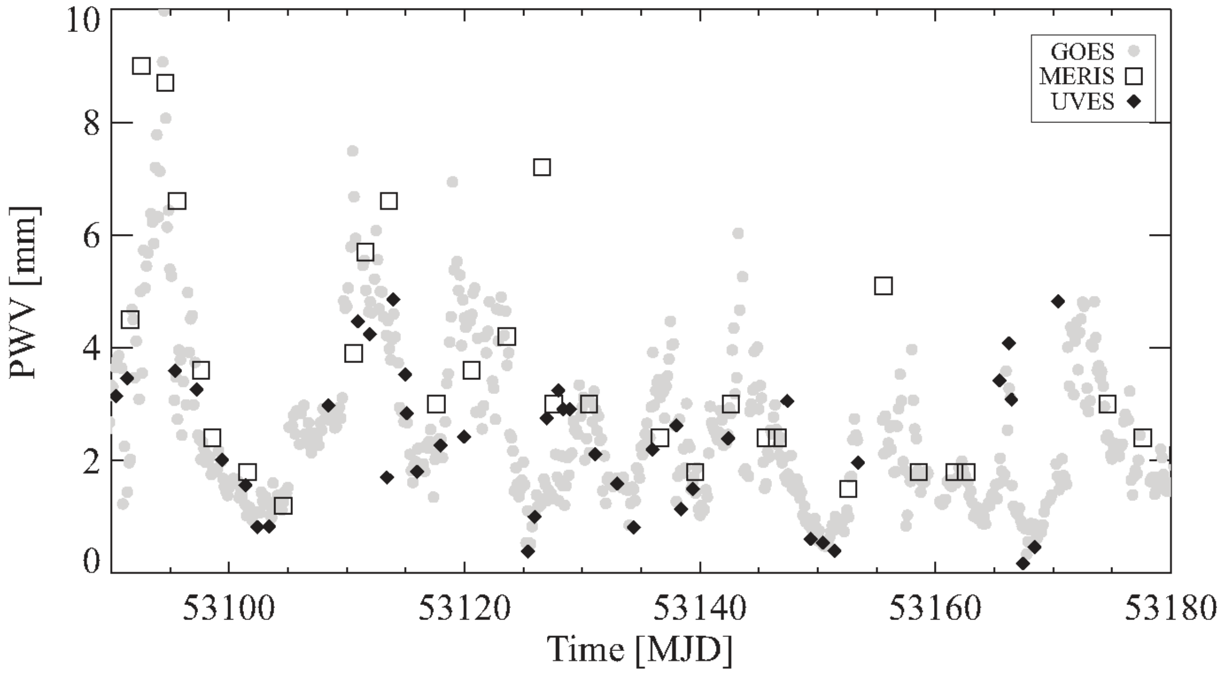

Figure 3: Comparison of PWV data derived from UVES archival data and satellite data for March to May 2004.

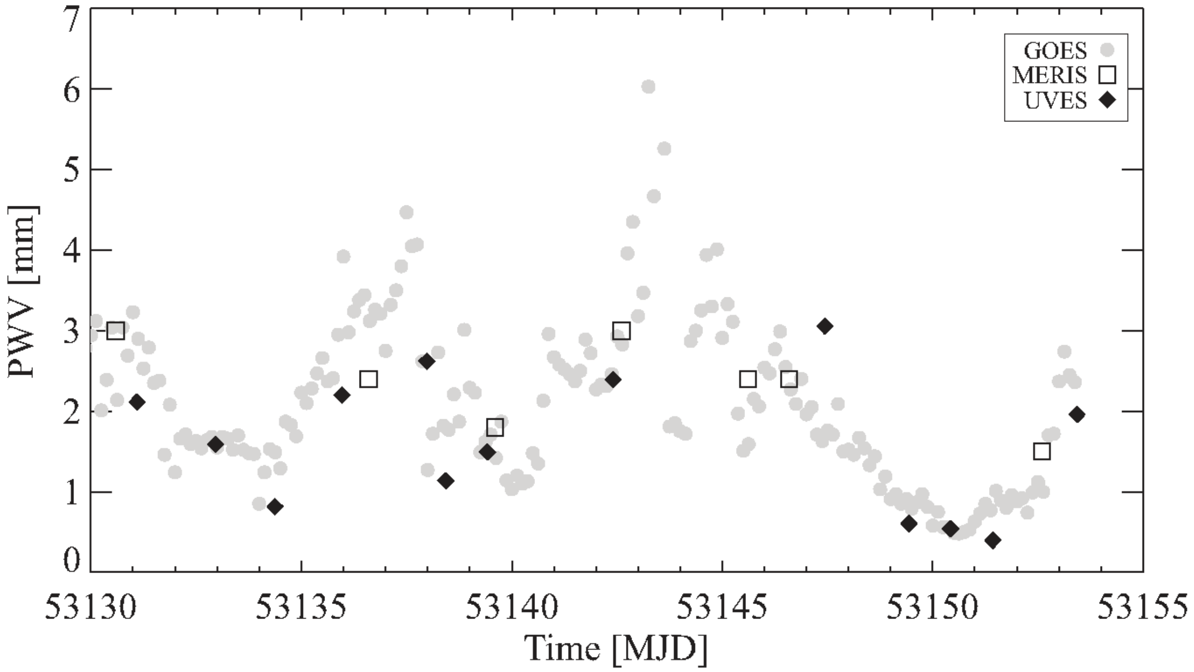

Figure 4: Enlarged section of Figure 3. Note the excellent quantitative agreement between the three data sets and between UVES and GOES also at very low PWV values.

3. DEDICATED PWV CAMPAIGNS

Two dedicated campaigns to measure PWV were conducted on Paranal during the periods July 31st-Aug 10th and Nov 9th-20th, 2009. Basic facts of the instruments used are given in table 2, while a statistical summary of the observations and data volume is presented in table 3. The goal was to operate several instruments in concert in order to get independent measurements of PWV over a statistically relevant period of more than a week. The schedule of the radiosonde launches was carefully aligned with times of GOES observations as well as the daily radiosonde launch at Antofagasta airport. The full launch schedule had been authorized 4 weeks in advance by the Chilean airspace authority. For each launch specific permission was confirmed by telephone 15 min before the launch. Details of the radiosonde campaign are described in Chacon et al[14]. Technical information on the VLT instruments is available at http://www.eso.org/sci/facilities/paranal/instruments.

Table 2: Statistical summary of the PWV campaigns conducted at Paranal and Armazones during July/Aug and November 2009.

Instrument	**Period**	**Data collected**
BACHES	Aug 1-10th	~140 spectra, cadence 15-30 min
UVES	July 31st –Aug 8th	10.5 h, ~475 spectra cadence up to 30s
VISIR	July 31st - Aug 16th	~40 spectra
CRIRES	July 29th – Aug 15th	~50 spectra
IRMA 11	July 29th –Aug 10th	~150 h; cadence seconds
Radiosondes	July 29- Aug 10th	23 successful launches each ~1.5 h of data, profile up to 20-25 km
IRMA 12	Aug 3rd-8th	~50 h each on Paranal & Armazones, cadence seconds
UVES	Nov 11th -17th	11 h, ~450 spectra cadence up to 30s
VISIR	Nov 10th - 21st	~25 spectra
CRIRES	Nov 9th - 21st	~60 spectra
IRMA 12	Nov 9rd - 20th, cont	~200 h Paranal, cadence seconds; left operating
Radiosondes	Nov 9th - 19th	29 successful launches each ~1.5 h of data, profile up to 20-25 km
IRMA 11	Nov 8th - 19th	~120 h Paranal, 85 h on Armazones cadence sec

For the second campaign (Nov 2009) scheduling of observations was optimized to maximize the number of parallel observations in order to cross-validate the various instruments and methods. Two IRMAs[1, 8] were operated in parallel on Paranal and Armazones, respectively for 5 nights (see section 3.3). Calibration of the IR radiometers was improved doing scans from zenith to horizon, so-called sky-dips. Data analysis was optimised making maximum use of ESO pipeline data reduction.

During the two campaigns on Paranal an unprecedented number of instruments has been used to derive PWV in an astronomical context resulting in unique data sets. Parallel coverage by more than one instrument has been achieved over extensive periods. Careful coordination with the launch schedule of the radiosondes has allowed us to directly validate the individual methods with respect to the radiosonde measurements - the accepted standard in atmospheric sounding; see section 3.1. Weather conditions have been good through most of the campaigns with some periods of high cirrus. PWV mostly varied between 1 and 4 mm with some periods as low as 0.5 mm giving us ample opportunity to sample the range 0-2 mm of interest to IR astronomy (Figs. 5 & 6). The excellent time coverage provided by the various instruments has allowed various comparisons and excellent agreement - few tenth of a mm - is found in many instances.

Calibration of the IR radiometers has been improved by performing scans from zenith to horizon, so-called sky dips. The increased line of sight through the atmosphere results in an increase of about an order of magnitude in the observed PWV column. When performed with two radiometers looking at the same region of the sky in parallel excellent cross-calibration can be achieved. In our case the improved calibration resulted in agreement between IRMA 11 and 12 at the 0.25 mm level over the range of 1-4 mm PWV.

Table 3: Summary of the instrumentation used during the dedicated PWV campaigns

Instrument	**Type**	**Location**	**Wavelength coverage**	**Spectral resolution**	**Data product**	**Comments**
Vaisala RS92	Radiosonde	Launched 50m below Paranal	n/a	n/a	Atmospheric profile of Temperature, humidity, PWV	In-situ measurement ascent to ~20 km
IRMA 11 & 12	IR radiometer	Paranal & Armazones	20 μm		IR spectrum - PWV	Autonomous units
BACHES	Optical cross-dispersed Echelle Spectrometer	Site testing telescope on Paranal summit	400-900 nm used: 710-730 nm	18000	Optical spectrum - PWV	Small commercially available Spectrometer
CRIRES	IR Pre-dispersed Echelle Spectrometer	Nasmyth platform of UT 1 (VLT on Paranal)	950-5000 nm; used: 5038-5063 nm	100000	Pipeline reduced IR spectrum – atmospheric model – PWV	ESO near-real time PWV monitor[7]
UVES	Optical cross-dispersed Echelle Spectrometer	Nasmyth platform UT 2 (VLT on Paranal)	350-1000 nm; used: 710-850 nm	20000-100000	Pipeline reduced spectrum, BTRAM fit algorithm - PWV, cf section 2	ESO near-real time PWV monitor[6]
VISIR	mid-IR spectrometer	Cassegrain UT 3 (VLT on Paranal)	19.34-19.66 μm	4500	Pipeline reduced IR spectrum – atmosph. model - PWV	ESO near-real time PWV monitor[7]

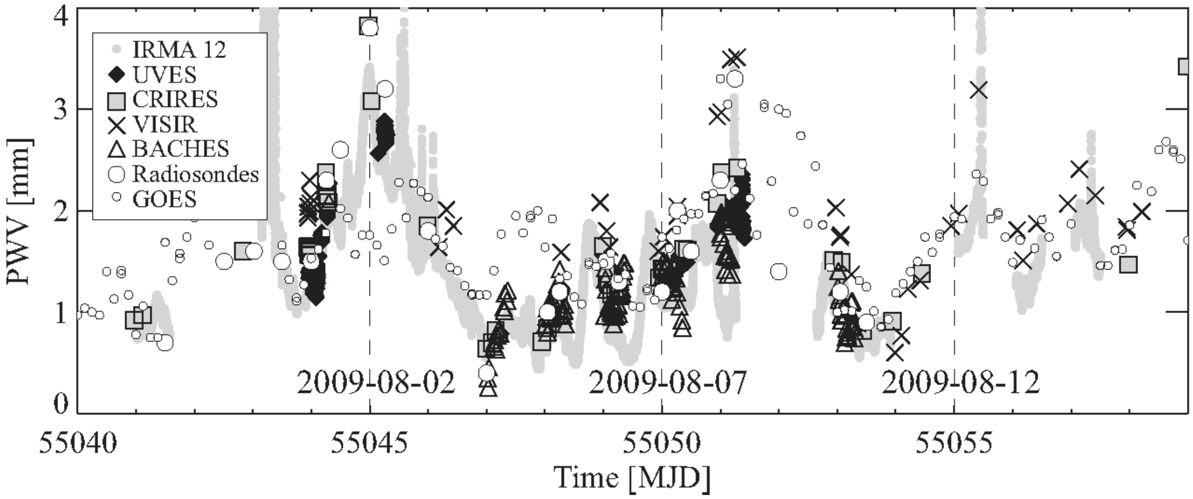

Figure 5: Comparison of PWV data derived from the various methods during the PWV campaign on Paranal during July and August 2009. Sharp spikes of high PWV correspond to periods with some cloud cover.

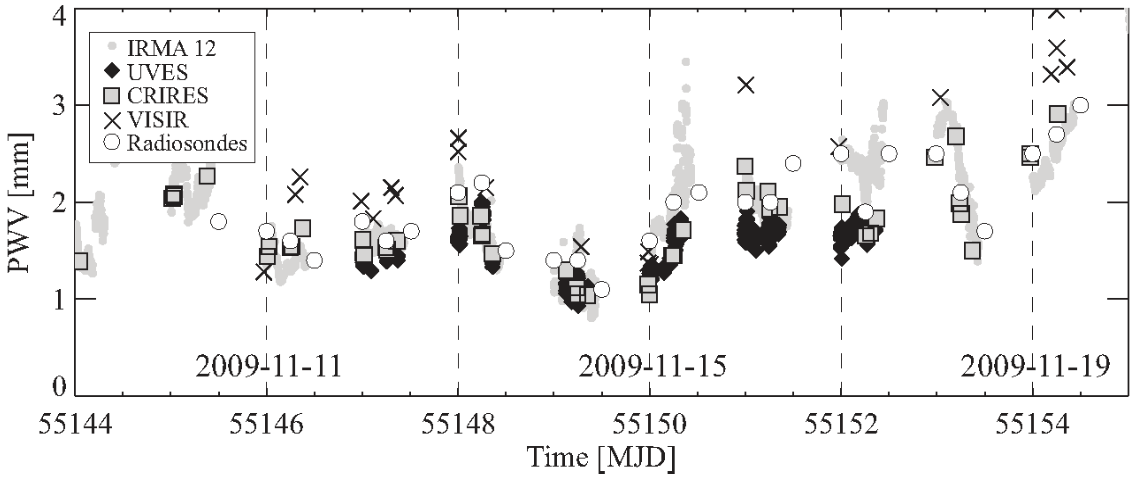

Figure 6: Comparison of PWV data derived from the various methods during the PWV campaign on Paranal during November 2009.

3.1 Comparison of methods and validation with respect to Radiosondes

Radiosondes are the accepted standard method for atmospheric sounding. Other methods for determining an atmospheric parameter by remote sensing are usually validated by comparison with radiosonde launches. We have followed this accepted approach in our efforts to validate the various methods to measure PWV (table 4).

Table 4: Comparison of various methods with radiosondes

Instrument	Wavelength range used	Number of data points	PWV range [mm]	Correlation slope, intercept; R^2	As Col 5 intercept=0, R^2	Adopted accuracy
BACHES	710-850 nm	26	0.35 – 10	0.77+0.22; 0.97	0.82; 0.96	15%; ≥ 0.3 mm
UVES	710-850 nm	29	0.4 – 3.3	0.62+0.49; 0.79	0.84; 0.68	15%; ≥ 0.3 mm
CRIRES	5038-5063 nm	48	0.4 – 2.9	0.75+0.32; 0.74	0.92; 0.70	15%; ≥ 0.3 mm
VISIR	19.3-19.7 μm	26	0.6 – 4	1.22+0.01; 0.64	1.22; 0.64	20%; ≥ 0.3 mm
IRMA all	20 μm	57	0.4 – 10	0.96+0.04; 0.93	0.97; 0.93	5%; ≥ 0.25 mm
IRMA Paranal	20 μm	45	0.4 – 3.8	0.87+0.11; 0.84	0.92; 0.83	5%; ≥ 0.25 mm
GOES La Silla	6.7, 10.7 μm	17	3 – 10	0.54+2,74; 0.43	0.97; 0.12	25%; ≥ 0.5 mm
GOES Paranal	6.7, 10.7 μm	52	0.4 – 4	0.20+1.60; 0.05	0.95; -0.76	25%; ≥ 0.5 mm

The absolute accuracy of PWV derived from radiosondes is an important issue in this context. In the literature an absolute accuracy of 5% overall is reported and of order 15% in very dry conditions[15, 16]. One also has to keep in mind that a radiosonde samples data along its trajectory which carries it to about 20 to 25 km altitude over the course of about an hour traveling a horizontal distance of 80-150 km. PWV is then derived from the profile for the whole column although water vapour is concentrated in the lower few kilometers. Hence the radiosondes and astronomical spectrographs are not sampling the same column of air and a 1:1 agreement between retrieved PWV is not to be expected even under very stable conditions.

A total of 70 radiosondes have been successfully launched during the two campaigns on La Silla and Paranal. Since the balloon ascends at a rate of a few m/s only a small window of about 30-60 min is available to conduct meaningful parallel observations with other methods. For a stand-alone high time resolution monitor such as IRMA this is relatively easy to achieve, while for instruments on the VLT careful planning and flexibility is essential.

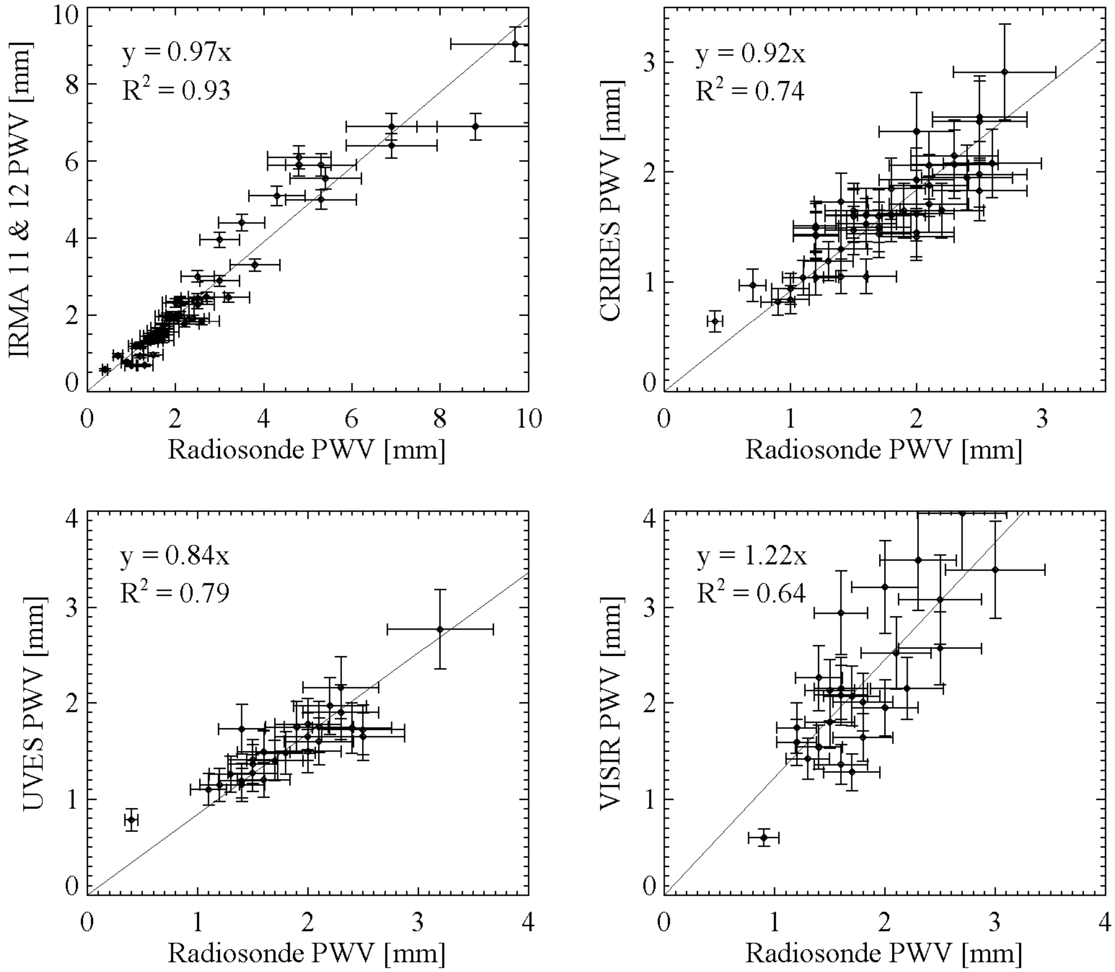

Figure 7: Comparison of PWV measured by radiosondes with IRMA (upper left), CRIRES (upper right), UVES (lower left) and VISIR (lower right) during Aug and Sep 2009.

The correlation between PWV derived from radiosondes data and measured by other methods is very well defined (Fig. 7; a few data points taken during cloudy conditions have been excluded). For IRMA which was available on both Paranal and La Silla it is very well defined over the PWV range 0.5-10 mm with a slope very close to one and a minimal zero-point off-set. Within the accuracies of the methods we find complete agreement between their PWV results. This is despite the fact that IRMA samples a pencil-beam at the zenith, while the radiosonde samples along its trajectory which covers a significant distance both in horizontal direction and altitude. The result shows that the black-body calibration of the IRMA yields very reliable results. For the astronomical spectrographs on Paranal the relation holds very well over the range of 0.5–4 mm. It is quite remarkable that this is realized over the wavelength range of 0.7 to 20 µm.

In support of science operations on Paranal PWV measurements taken with various VLT instruments are used in near-real time. For details see the two ESO web sites[6, 7] and Smette et al.[5].

3.2 Comparison with GOES

We also compared the PWV data from GOES with the radiosondes and in a purely statistical sense the agreement found is rather reasonable (Fig 8a). The numerical correlation values with the radiosondes are in fact excellent (column 6 in Table 4) fully consistent with the findings from the UVES archival data. Hence it is safe to assume that GOES data can be used successfully for characterization of sites in terms of PWV provided a substantial time base is used and provided the environment is very homogeneous as is the case for Northern Chile. Both these conditions are fulfilled for Paranal and good agreement between GOES and other methods is found.

Closer inspection of the data taken during the campaigns on both La Silla (high to moderate PWV) and Paranal (low PWV) shows that GOES values can deviate significantly from radiosonde results (Fig 8b). This is also born out in a numerical sense once the precondition of a zero intercept is lifted (column 5 in table 4). In fact the distribution for the Paranal data (Fig 8b) show a curious butterfly pattern in which over- and underestimates of PWV by GOES cancel such that a naïve regression with intercept zero mimicks a linear correlation. Similarly, comparison between IRMA - which is a very good proxi for radiosondes data (Fig. 7a) - and GOES data in the period Aug/Sep 2009 show only a very weak correlation.

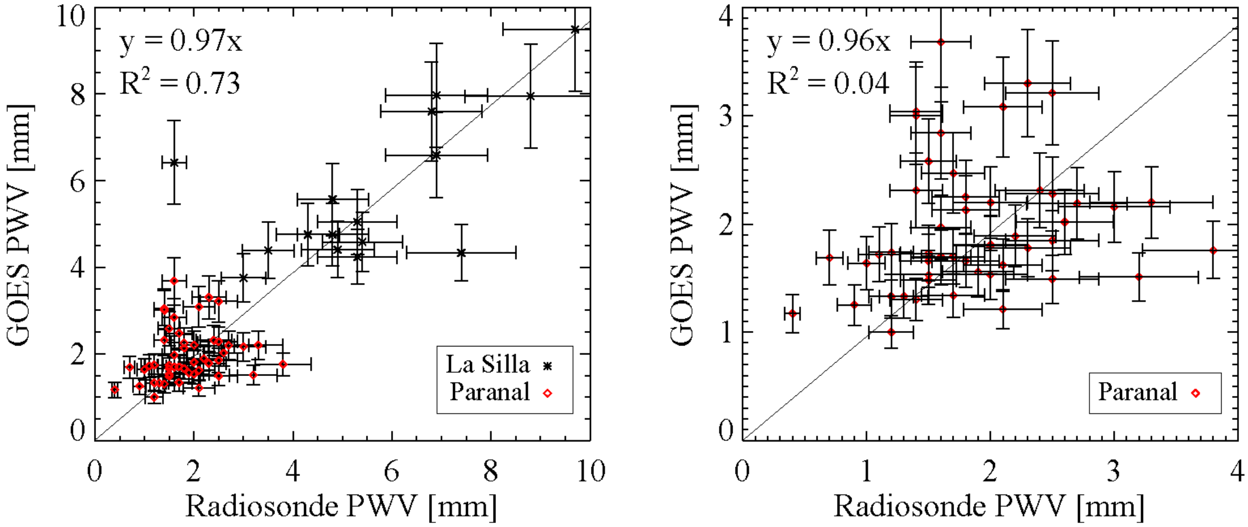

Figure 8: a) Comparison of PWV measured by radiosondes and GOES, the regression values given are for La Silla and Paranal combined (left); b) **:** Same for low PWV on Paranal. Note the curious butterfly pattern.

We conclude that GOES measurements are not suitable to derive PWV with the accuracy required for use in observatory operations such as scheduling observations based on PWV constraints. Reasons for this are in the limited spatial resolution of GOES observations and the approximation of actual the distribution of water vapour in the atmosphere by a median profile. This effect is even more pronounced for a site like La Silla where wetter regions are present in the same GOES footprint. See the contribution by Querel at al[11] for a more detailed discussion.

3.3 PWV offset between Paranal (2635m) and Armazones (3050m)

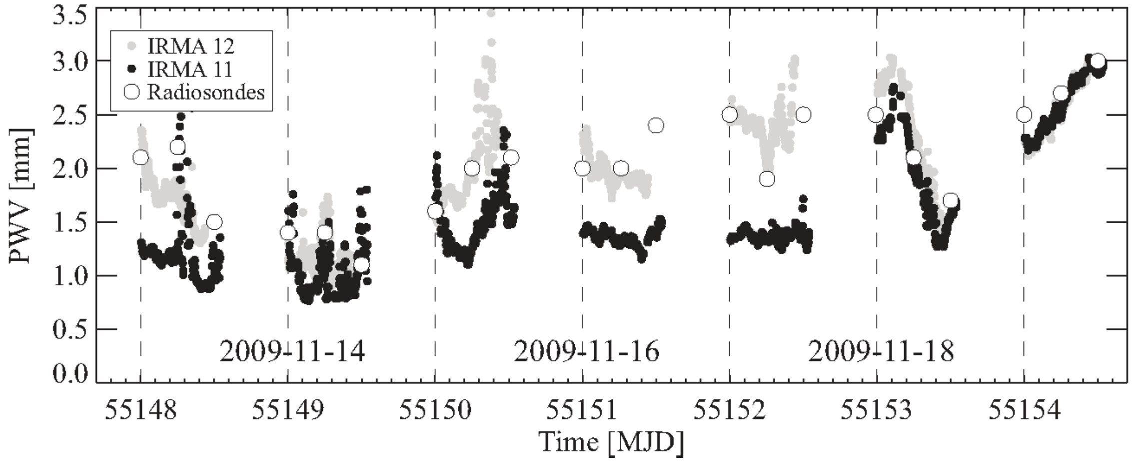

Figure 9: Natural variation in the offsets in PWV between Paranal and Armazones. Note that during MJD 55148 to 55152 IRMA 11 and 12 were located on Armazones and Paranal, respectively, resulting in a noticeable offset. During the rest of the campaign both units were co-located on Paranal showing excellent agreement in PWV.

Based on the analysis of radiosonde profiles and IRMA observations at both sites we find that an average off set of 0.3±0.2 mm is to be expected which is consistent with the difference in altitude. Local variations will be important as we have seen during a – very limited – period of parallel measurements. For 5 days and nights two IRMAs were located on Paranal and Armazones (Fig. 9). The off set related to altitude is evident as are natural horizontal and local PWV variations at the fractional mm level. The largest off set observed is around 1 mm and it seems to be lowest at low PWV. Note that both methods – radiosondes and IR radiometers – are at their limiting accuracies in this PWV domain. During site testing for TMT Otarola[17] devised a clever scheme to derive PWV from surface weather data; they find a median value of 2.9 mm for Armazones.

3.4 Findings of the PWV campaigns

The main result from the intercomparison of various instruments during the campaigns is that all of them measure PWV with good fidelity. Using radiosondes as the reference we find that agreement with the IR radiometer IRMA is excellent providing results that are indistinguishable taking into account the errors associated. Moreover, the IRMA provides information of the air mass directly above the observatory. The internal precision of IR radiometer data is about 3% while the accuracy is estimated at 5% but not better than 0.25 mm. Relative agreement between two IRMA units measuring at the same site is extremely good on time scales of a few seconds to hours. The variation of PWV over time is smooth although significant changes can occur over one hour. Variations of PWV of a few percent occur on times scales of seconds or a few minutes as recorded by the IRMAs.

The internal precision of PWV data from optical and IR spectroscopy is about 7% whereas accuracy is estimated to be about 15-20% but not better than 0.3 mm. Quantitative agreement between the individual ground-based remote sensing techniques and and in-situ measurements (radiosondes) is very good (10-20%). Structure in the spatial distribution of water vapour in the sky - at the few 0.1 mm level - can be directly evidenced as temporal variations in the observations of a transit instrument (IRMA) as well as variations in the PWV found for pointed observations (optical spectroscopy).

4. CONCLUSION

The PWV history over Paranal has been reconstructed for the period 2001-2008 by analysis of UVES archival data. The near-IR part of the spectrum has been analysed using the BTRAM atmospheric model. In addition dedicated measurement campaigns have been conducted enabling us to quantitatively validate various astronomical spectrographs covering a wavelength range of 700-20000 nm with respect to radiosondes the accepted standard in atmospheric research. Very satisfactory agreement has been found for all methods with IRMA delivering the best accuracy combined with high time resolution. GOES PWV data

Taking into account a small dry-bias for the UVES data the median PWV for Paranal is derived at 2.3 mm in excellent agreement with GOES remote sensing data (2.4 mm). Based on our analysis Paranal can be used as a reference site for Northern Chile. For Armazones an offset of 0.3 mm is found based on altitude difference of about 400 m but local variations of a few tenth of a millimeter are present so horizontal variations are important even for closely adjacent sites.

The goals of the PWV project have been met in full. The results of this study have been communicated to the Site Selection Advisory Committee contributing directly to the site selection process for the future E-ELT.

From analysis of archival data and the results from the campaigns it is obvious that PWV can successfully be monitored. Actually PWV values for Paranal and now routinely monitored using spectra taken with CRIRES, UVES, VISIR and X-shooter[6, 7]. We conclude that PWV should be used as a constraint in planning observations. Steps to this end are planned for the immediate future for Paranal observatory. For the E-ELT a stand-alone high time resolution PWV monitor will be an essential part of the infrastructure in order to optimize the scientific output of the operations.

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