Balloons over the La Silla Paranal Observatory

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Precipitable water vapour (PWV) in the atmosphere is one of several key properties required to characterise overall quality of an astronomical site for observations at infrared wavelengths. Through analysis of archival data and by mounting a series of dedicated PWV measurement campaigns, we achieved our goal of establishing the Paranal Observatory as a reference site for evaluation of locations for the European Extremely Large Telescope (E-ELT) project. For the first time in an astronomical study, all measurement methods have been successfully validated with respect to balloon-borne radiosondes, the accepted standard in atmospheric research.

Atmospheric water vapour

Water vapour is the dominant source of opacity at infrared wavelengths (see Figure 1). Its vertical column abundance is expressed as precipitable water vapour in mm (Naylor et al., 2008). For reference, a "dry", PWV-excellent night on Paranal may have 1 mm PWV or less, while middle-European conditions may easily offer > 30 mm. In order to better understand the PWV above the La Silla Paranal Observatory, a collaboration was started in 2009 between ESO, the Institute for Space Imaging Science (ISIS) in Lethbridge, Canada, and the Astrometeorology Group of the Universidad de Valparaíso in Chile. 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, since low PWV values lead to drastically improved transmission in some wavelength domains (Smette et al., 2007); in fact such conditions can altogether open atmospheric windows that are completely opaque at higher values. 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 (see Figure 2), and for their scheduling. As part of site testing and evaluation for the European Extremely Large Telescope (E-ELT), we have addressed primarily the aspect of long-term quality for infrared (IR) astronomy. By comparing various methods to determine atmospheric PWV we also wanted to understand which methods were best suited to support IR science at the E-ELT in an operational sense.

History of PWV over La Silla Paranal Observatory

In order to reconstruct the history of PWV over the Paranal Observatory, we extracted about 1500 UVES flux standard observations from the archive, covering the period 2001 to 2008 (Figure 3). With their almost flat and featureless stellar continuum, these white dwarfs are particularly well-suited for this study (Kerber et al., 2010). While these pointed observations were originally reduced as flux standard star calibrations, we have reprocessed them for our project as science targets, with the same approach used in the UVES reprocessing project[1].

We have analysed the telluric absorption lines in the UVES flux-calibrated pipeline

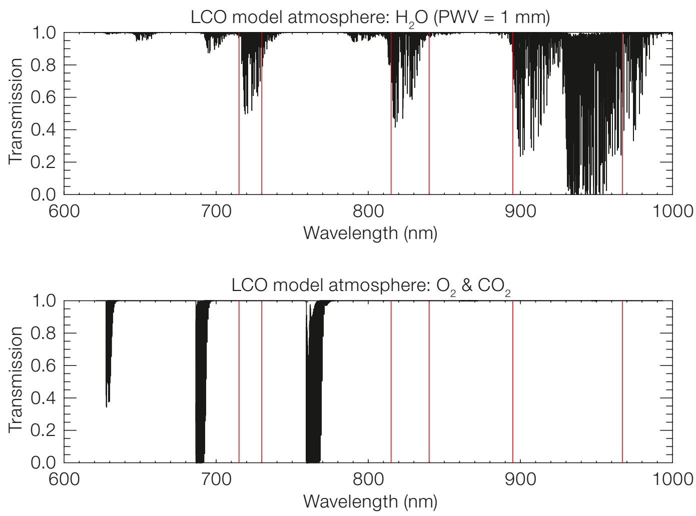

Figure 1. Atmospheric transmission in the optical to near-IR domain. Upper panel: absorption caused by 1 mm of H_2O. Lower panel: absorption resulting from O_2 and CO_2. The analysis described uses wavelength regions (denoted in red) in which absorption is from water vapour only, allowing the atmospheric content of PWV to be derived. This wavelength range was chosen for the analysis of the archival data, but suitable windows exist over a very wide wavelength extent.

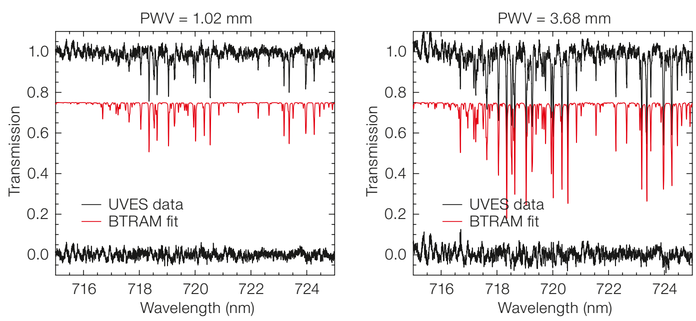

Figure 2. Sample UVES spectra analysed with the atmospheric model BTRAM illustrating conditions on Paranal: a) a dry night offering good conditions for IR observations, and b) a moderately wet night. From top to bottom are displayed: the UVES spectrum, the BTRAM fit, and the residuals between spectrum and fit.

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products by fitting an atmospheric radiative transfer model (BTRAM) developed by ISIS. A large number of weak and strong isolated and blended lines can be used for the analysis resulting in accurate and robust PWV values, see Figure 2. Standard star observations (~ 1700 spectra) taken with FEROS have been used to make an equivalent analysis for La Silla, described in detail by Querel et al. (2010).

From this analysis, we find a mean PWV value for Paranal of 2.4 ± 0.3 mm (after correcting for a dry-bias, since standard star observations are only done under clear sky conditions). There are pronounced seasonal variations, with periods of high PWV occurring during the southern summer months when the site is partially affected by the *invierno altiplánico* or Bolivian Winter (most pronounced in January and February) when winds from the east bring moisture from the Amazon basin and clouds may spill over the Andes to the west into northern Chile. The fraction of nights with PWV < 2 mm (good for IR observations) is 47 %, while PWV < 1 mm occurs in 13.5 % of nights. The corresponding mean PWV for La Silla is considerably higher at 3.7 ± 0.4 mm (see also Thomas-Osip et al., 2007; Querel et al., 2008).

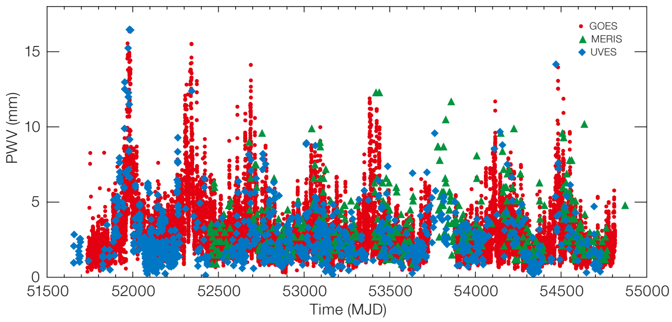


Figure 3. Record of precipitable water vapour over Paranal. Comparison of PWV data derived from UVES archival data and GOES and MERIS satellite data for the period 2001–8. Pronounced seasonal variations are evident as is the quantitative agreement between the different datasets.

Dedicated measurement campaigns

Three dedicated campaigns to measure PWV were conducted on La Silla (4–15 May 2009) and Paranal (31 July to 10 August and 9–20 November 2009). The goal was to operate several instruments in concert to gather independent measurements of PWV over a statistically relevant period of more than one week. We employed three main types of instruments: a) radiosonde launches to obtain atmospheric profiles; b) facility instruments for high resolution spectroscopy of telluric line systems; and c) high-cadence IR radiometer measurements. The IR radiometer (IRMA) was developed and built by ISIS (Naylor et al., 2008). It measures the transparency of the atmosphere around 20 μm in a pencil-beam column. In this carefully selected window, H_2O is the sole absorber (similar to Figure 1); by comparison with an internal blackbody and the BTRAM atmospheric model, the PWV is directly derived.

The astrometeorology group at the Universidad de Valparaíso, with support from ESO, carried out the radiosonde launches (Figure 4). On Paranal we launched up to three times a day for a total of 52 radiosondes. Their schedule was carefully aligned with the scanning times of the geostationary GOES weather satellite providing infrared and, in particular, water vapour images, as well as with the daily radiosonde launch at Antofagasta airport. The full launch schedule had to be authorised four weeks in advance by the Chilean aviation authority. This permission was confirmed by phone 15 minutes before each launch. More details about the radiosonde campaigns are described in Chacon et al. (2010).

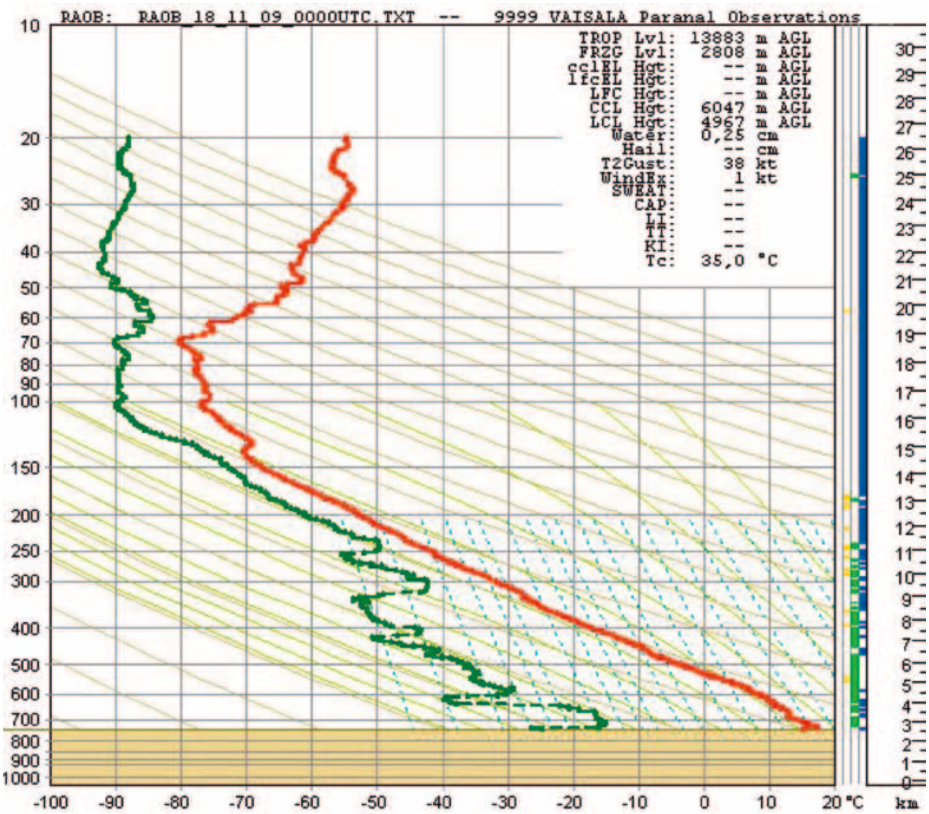
Radiosondes are the accepted standard method for atmospheric sounding. We have used their data to validate the various methods to measure PWV. The equipment employed in our campaign consisted of a Vaisala radiosonde RS92 (shown in Figure 4a) which comprises the following instrument package: a GPS receiver to track its location and deduce the wind speed, a silicon pressure sensor, a heated twin humidity sensor and a small fast temperature sensor; plus of course a transmitter for real-time telemetry to the mobile ground station at the launch site. The radiosonde payload is lifted by a helium-filled balloon with an initial diameter of about 1.5 m. During the 90-minute ascent the balloons drifted by as much as 80–150 km to the east. At an altitude of 20–25 km, the balloon — now more than 10 m in size — would finally burst, releasing the radiosonde package into free fall over the Cordillera de los Andes. Figure 4c shows an example record from one of the radiosonde ascents.

The absolute accuracy of PWV derived from radiosonde data is an important issue in this context. In the literature an overall value of 5 % is quoted, and of about 15 % in very dry conditions (Schneider et al., 2010). One has to keep in mind that a radiosonde samples data along an ascent trajectory controlled by the prevailing wind pattern. PWV is then derived from the profile for the whole column, although water vapour is concentrated in the lowest few kilometres. Hence the radiosondes and astronomical spectrographs are not sampling the same column of air, and a 1:1 agreement between retrieved PWV values is not to be expected even under very stable conditions.

A total of 69 radiosondes have been successfully launched during the three campaigns on La Silla and Paranal. Since the balloons ascend at a rate of a few m/s only a relatively short window of about 60–90 minutes 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.

As for the VLT instruments, we have used a total of 21.5 hours of UVES technical time and obtained more than 900 spectra of white dwarf standard stars, with a cadence of up to 30 s. These data were taken with a 10-arcsecond slit width, providing essentially seeing-limited spectral resolution of 40 000–50 000. Periodic observations during the nights of the campaign were also performed by VISIR (65 spectra) and CRIRES (110 spectra).

One IRMA unit was installed on Paranal, giving 350 hours of near-continuous coverage (with a cadence of seconds). A second IRMA unit was temporarily installed on Cerro Armazones, the designated site of the E-ELT, and provided



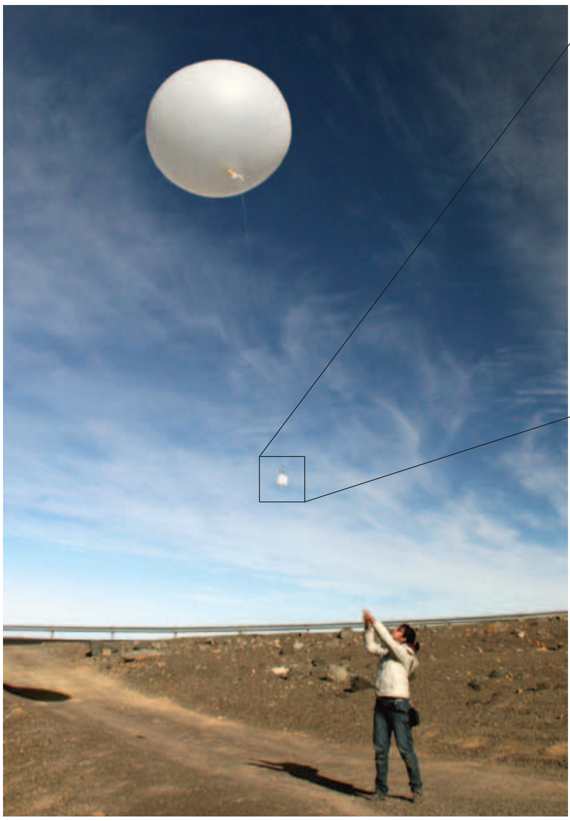


Figure 4. Left: Launch of a helium-filled balloon (upper left), equipped with a radiosonde. Upper: The instrumentation payload (Vaisala RS92-SGP) of a radiosonde. Top: The measured temperature (red, bottom scale) and dew point (green) profile during the radiosonde ascent on 18 November 2009. Altitude in km is indicated at right, pressure scale in mb is on the left. Those regions where the two curves come closest contribute most to the total PWV column, which is 2.5 mm in this example.

> 100 hours coverage. This IRMA unit was also used on Paranal for cross-correlation with the first IRMA.

Findings of the PWV campaigns

The main result from the comparison of the different instruments used during the campaigns is that all of them measure PWV with good fidelity (Figures 5 and 6). Using PWV values as derived by radiosonde as our reference, we find that agreement with the IR radiometer IRMA is excellent, providing results that are indistinguishable after taking into account the associated errors (Figure 6 left). Moreover, IRMA provides information pertaining to the air mass directly above the observatory. The internal precision of the IR radiometer data is ~ 3 % while the accuracy is estimated at 5 %, but not better than 0.25 mm. Relative agreement between the two IRMA units measuring in the same direction at the same site is extremely good on time scales of a few seconds up to several hours.

The variation of PWV over time is smooth, although significant changes can occur within one hour. Variations of PWV of a few percent were seen to occur on time scales of seconds or a few minutes as recorded by the IRMAs (see Figure 5). For Cerro Armazones a dry offset of 0.3 mm is found which can be mostly attributed to its difference in altitude ~ 400 m above Paranal. We saw local PWV variations of a few tenths of a millimetre, so horizontal variations are important even for closely adjacent sites.

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 *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 detected as temporal variations in the observations of a transit instrument (IRMA) as well as by variations in the PWV found for pointed observations (from optical spectroscopy).

Comparison with the GOES satellite

We also compared the PWV data from the Geostationary Operational Environmental Satellite (GOES) that monitors the atmosphere with the results obtained from the radiosonde launches. In a statistical sense the agreement found is rather reasonable, while for a given day deviations can be significant. The numerical correlation values with the radiosondes are in fact excellent and fully consistent with the findings from the UVES archival data. Hence it is safe to assume that GOES data can be used successfully for the characterisation of sites in terms of PWV provided both a substantial timebase is used and the environment is very homogeneous, as is the case for northern Chile. These two conditions are fulfilled for Paranal and good agreement between GOES and other methods is found.

Continued PWV monitoring

In support of science operations on Paranal, PWV measurements taken with various VLT instruments are used in near real time. Whenever a flux standard star (on UVES), or a telluric standard star on CRIRES, X-shooter or VISIR, are measured, automatic procedures are employed to analyse the pipeline-processed spectra and derive a new PWV data point. More details are provided on the ESO web[2,3]. A similar procedure will soon become available for La Silla as well.

Implication for E-ELT site selection and future use of PWV measurements

Our multi-instrument campaigns in 2009 have produced a dataset that is unique in both quality and quantity. Very good agreement has been found for all methods, with IRMA delivering the best accuracy combined with the highest time resolution. From the results of our analysis, Paranal can be used as a reference site for northern Chile. For Cerro Armazones (Otárola et al., 2010) an offset of 0.3 mm with respect to the PWV at Paranal is found based on an altitude difference of about 400 m.

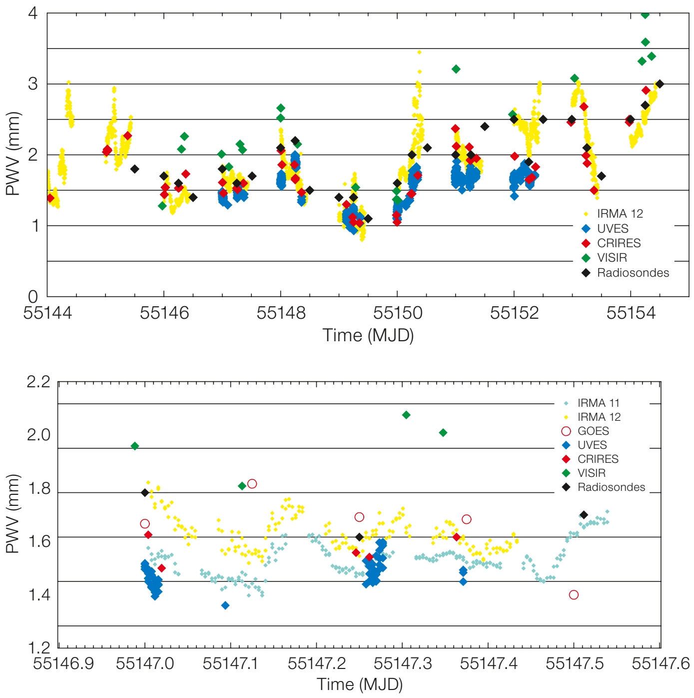


Figure 5. Top: Comparison of PWV data derived from the various methods during the PWV campaign on Paranal during November 2009. Bottom: enlarged section centred on MJD 55147.3 (12 November 2009), showing the limiting precision of about 0.25 mm. This plot includes data from both IRMA radiometers working in parallel on Paranal. The open circles represent data points from the GOES weather satellite.

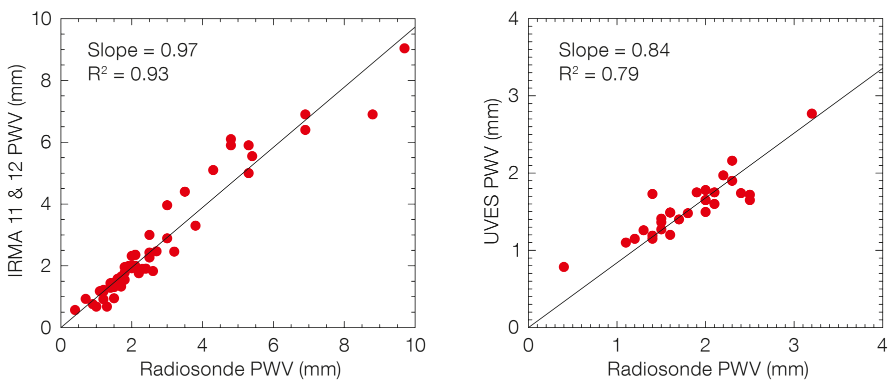


Figure 6. A comparison of PWV measured by IRMA (left) and UVES (right) with respect to the radiosonde data is shown as an example. Similar results have been derived for all other astronomical instruments (BACHES, CRIRES, FEROS, HARPS, VISIR and X-shooter) validating all of them with respect to the established standard in atmospheric research.

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. We continue to work on a detailed treatment of systematic effects which will result in better absolute accuracy of our PWV results.

From analysis of archival data and the results from the campaigns it is obvious that PWV can successfully be monitored. At present PWV values for Paranal are now routinely monitored using periodic spectra taken with CRIRES, UVES, VISIR and X-shooter. We conclude that PWV could 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 optimise the scientific output of the operations.

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Links

[1] UVES reprocessing project: http://www.eso.org/qc/reproUVES/processing.html
[2] PWV trend reporting: http://www.eso.org/observing/dfo/quality/GENERAL/PWV/HEALTH/trend_report_ambient_PWV_HC.html
[3] Paranal PWV monitoring: http://www.eso.org/sci/facilities/paranal/sciops/CALISTA/pwv/data.html

The VLT Laser Guide Star facility in action, creating a guide star for adaptive optics correction. Image taken at Paranal in 2007.