Monitoring Atmospheric Water Vapour over Paranal to Optimise VISIR Science Operations

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A water vapour radiometer has been permanently deployed on Paranal as a new tool for supporting science operations at the Very Large Telescope. The instrument allows the water vapour content of the atmosphere above the observatory to be monitored in real time with high precision and time resolution and periods of low precipitable water vapour (PWV) to be selected, providing better atmospheric transmission for observations in the infrared. The PWV measurements will be made available to VISIR users in the form of FITS header keywords. In addition, we expect that over time these data will allow a deeper insight into the atmospheric conditions on Paranal, with implications also for the operation of the European Extremely Large Telescope (E-ELT) on nearby Cerro Armazones.

The VISIR upgrade and water vapour

The upgrade[1] of the Very Large Telescope (VLT) Imager and Spectrometer for the mid-infrared instrument (VISIR) is a project that combines improvements in hardware, software and operations. As part of the latter operations programme, a water vapour radiometer was deployed on Paranal in October 2011. The information provided by this monitor of precipitable water vapour in the atmosphere above the observatory will be used for direct support of service mode observations with the upgraded VISIR.

The requirements for the monitor were guided by the lessons learned during the work to characterise potential sites for the E-ELT in 2009 (Kerber et al., 2010a, b; Querel et al., 2010). The requirements called for a high-precision, high time-resolution stand-alone PWV monitor that provides water vapour information in (near-) real time. While several ways exist to measure PWV, it quickly became clear that a dedicated radiometer operating at 183 GHz would be the most suitable technical solution. An open call for tender resulted in the selection of the Low Humidity Atmospheric PROfiling radiometer (LHATPRO) produced by Radiometer Physics GmbH (RPG).

The instrument probes the atmosphere in two frequency ranges, focusing on two prominent emission features: an H_20 line (183 GHz) and an O_2 band (51–58 GHz). Using six and seven filters to sample the two bands, respectively, the radiometer retrieves the profile of humidity and temperature up to an altitude of about 12 kilometres (Rose et al., 2005). The radiometer is designed and built for continuous operations without human interaction and can also be fully controlled remotely. In terms of environmental conditions it is qualified for the temperature range −50 to +45 °C and an air blower and heater system protects the instrument in extreme humidity and temperature conditions.

The primary interest for VISIR is the integrated water vapour column that represents the amount of water which would result from condensing the vertical atmospheric column, expressed in millimetres. The water vapour line near 183 GHz is intrinsically very strong and still prominent at very low humidity levels, thus making it suitable for monitoring a dry site such as Paranal. Paranal has a median PWV of 2.5 mm, but with pronounced seasonal and short term variations (Kerber et al., 2010a). The PWV values encountered during any year range from nearly zero to more than 15 mm. Early results from the first few months of operations demonstrate that the radiometer starts to saturate at 20 mm — well beyond the original requirements (5 mm, with a goal of 10 mm), and hence it will be able to accurately measure all regular humidity conditions over Paranal. LHATPRO has an all-sky pointing capability and can scan the whole sky within a few minutes.

Radiometer performance validation

The radiometer underwent a qualification and acceptance test at the Umweltforschungsstation (UFS) Schneefernerhaus[2] located a little below the summit of the Zugspitze (Figures 1a, b), the highest mountain peak in Germany. During a two-week period in September 2011 the instrument's functionality and operations were rigorously tested with respect to the original requirements and technical specifications. The UFS Schneefernerhaus site was chosen for a number of reasons: low PWV values can be expected in central Europe during summer/autumn only at high elevations; the altitude of Schneefernerhaus (2650 metres) almost exactly matches the final destination of the unit, the telescope platform on Paranal (2635 metres). In addition, the UFS hosts a number of instruments measuring properties of the atmosphere, including a water vapour radiometer operating at 22 GHz and a light detection and ranging (LIDAR) instrument, allowing for parallel observations between these instruments and the new PWV monitor.

After successful completion of the provisional acceptance, the radiometer was shipped to Chile and commissioning on Paranal took place during late October/early November 2011 (see Figure 2).

The commissioning of the RPG LHATPRO was closely modelled after the highly successful PWV campaigns conducted in 2009 as part of E-ELT site characterisation. Through technical time we had access to several VLT instruments: CRIRES, UVES, X-shooter, and of course VISIR. For these optical and infrared (IR) instruments, PWV is extracted from absorption or emission line spectra using an atmospheric model. An accuracy of about 15–20 % had been demonstrated during the 2009 campaigns (Kerber et al., 2010a) with this approach and full details of the spectral fitting procedure are given in Querel et al. (2011). In addition we

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Figure 1a. On 19 September 2011 almost half a metre of snow had to be cleared on the terrace of the UFS Schneefernerhaus before the LHATPRO radiometer could be set up for its test period in Europe.

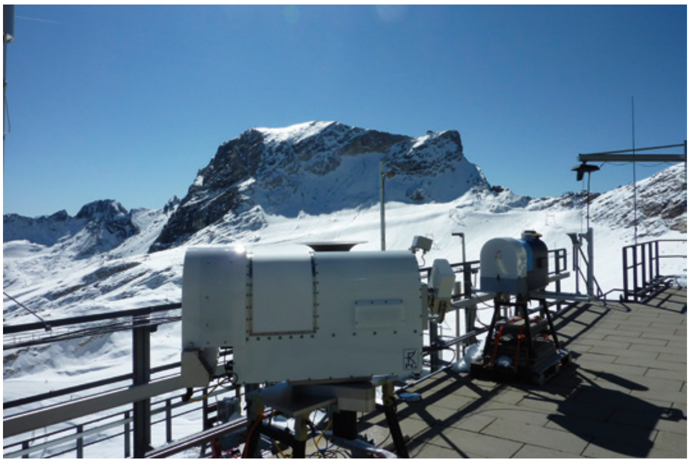

Figure 1b. Later during the test period very good conditions with low water vapour were prevalent. Note that the UFS Schneefermerhaus and Paranal are almost exactly at the same altitude of about 2650 metres above sea level.

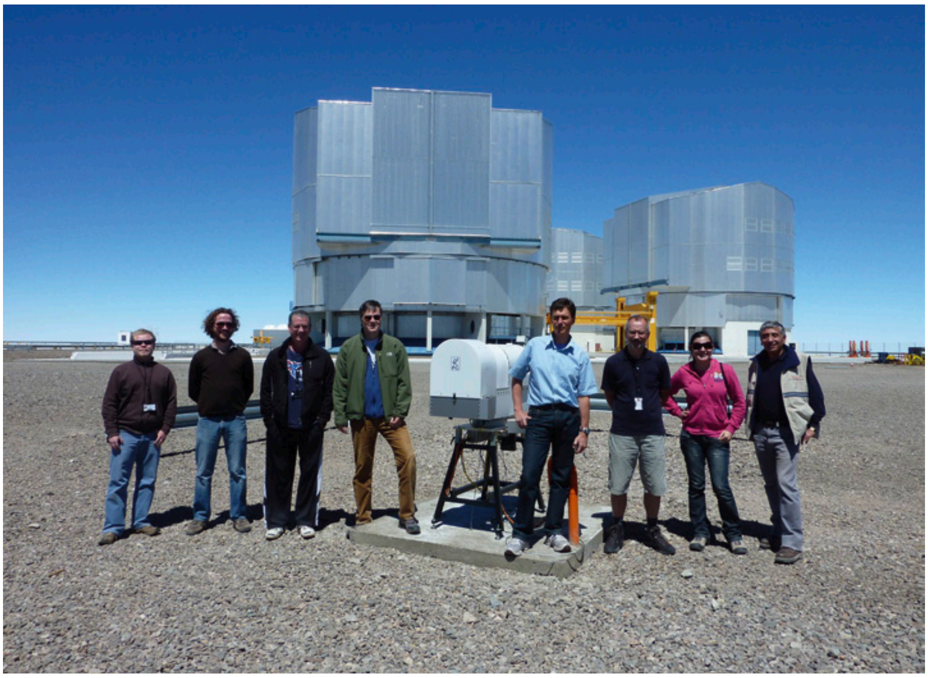

Figure 2. Members of the commissioning team next to the water vapour radiometer at its final location at the eastern end of the platform behind Unit Telescope 4 (from left to right: Omar Cuevas, Richard Querel, Greg Tompkins, Florian Kerber, Thomas Rose, Reinhard Hanuschik, Arlette Chacón, Julio Navarette; Mario van den Ancker is missing from this picture following a night of science support).

operated an infrared radiometer built by the University of Lethbridge (Canada) and provided on loan from the Giant Magellan Telescope (GMT). Finally, we had a total of 22 radiosonde launches conducted by the astrometeorology group at the Universidad de Valparaiso, Chile, again following the template of the 2009 PWV campaigns (Chacon et al., 2010).

A radiosonde consists of a very compact meteorological instrument package tethered to a helium-filled balloon. On launch it provides *in situ* measurements of the atmosphere along its ascent trajectory to an altitude of about 25 kilometres where the balloon bursts. Since the balloon is a passive device, the trajectory is the result of the lift provided by the helium and the action of the local wind. The sensors of the radiosonde provide high time-resolution profiles of temperature and dew point (humidity) over the course of about 90 minutes after launch and such a dataset is the accepted standard in atmospheric and climate research.

Observations with the VLT instruments were strategically scheduled to allow for parallel observations during the radiosonde launches while LHATPRO would operate continuously (and the Canadian IRMA operated during the night). The resulting time series is shown in Figure 3. The variation in PWV was very pronounced over the two-week commissioning period, but agreement between LHATPRO and the radiosondes is excellent (at the 1% level) across the whole PWV range. Based on an absolute calibration using liquid nitrogen and comparison with the radiosondes, an accuracy of about 0.1 mm has been demonstrated for the PWV radiometer with an internal precision of 30 μm. This ensures that reliable readings can be obtained in the driest of conditions encountered on Paranal, which of course are the most valuable periods for IR astronomy.

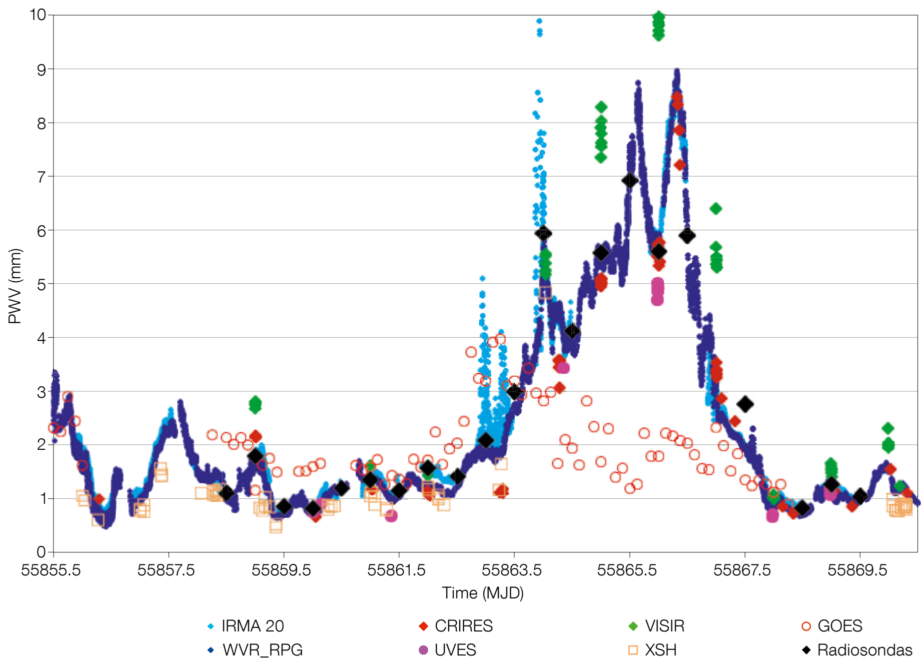

Figure 3. Time series of the water vapour measurements by various instruments during commissioning (19 October – 4 November 2011). Excellent agreement is found between the RPG radiometer (dark blue points) and the radiosondes (black diamonds). Very high PWV values were recorded during an unusual weather pattern that trapped humidity at lower elevations. Note that this water vapour is not recognised by the GOES remote sensing satellite.

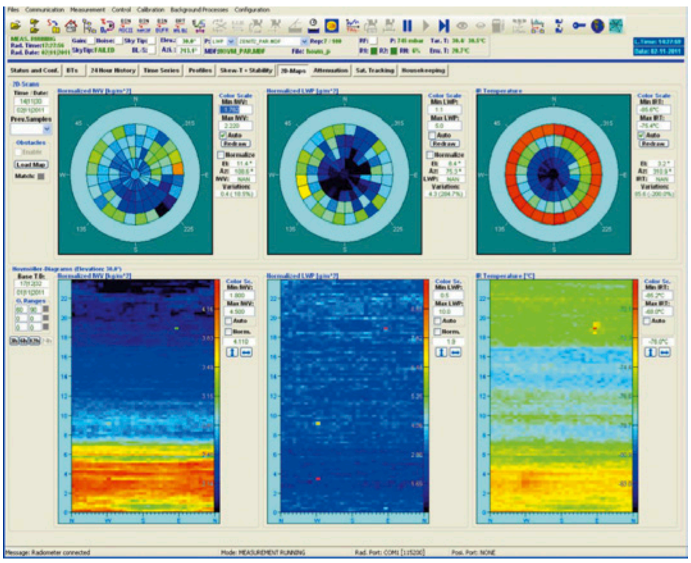

Figure 4. Operational display of the water vapour radiometer as available on Paranal. In the upper row all-sky scans of PWV, liquid water and IR sky brightness temperature taken every six hours are displayed (from left to right) which can reveal high cirrus clouds. In the bottom row Hovmoeller plots of the same parameters show a 24-hour time series of a cone scan (elevation 30 degrees) taken every 15 minutes.

Radiometer operations

As a result of the commissioning, the PWV radiometer went into trial operations, demonstrating excellent performance and high reliability under all conditions encountered. Failure of one component rendered the temperature profiling unusable for a period, while the down time for the water vapour channel is below 2 %.

Currently, the radiometer measures PWV in zenith for most of a 24-hour period interrupted by an all-sky scan (duration about 7 minutes) every 6 hours. In addition a cone scan (360 degrees in azimuth) at an elevation of 30 degrees is performed every 15 minutes. From these data a Hovmoeller diagram is created showing the conditions at any given time over the past 24 hours and serving as an early warning for incoming fronts (see Figure 4 for a view of the display from LHATPRO). An IR radiometer is also part of the LHATPRO instrument package providing measurements of the brightness temperature of the sky down to −100 °C. Thus this specific model makes it possible to detect not only water-bearing clouds, which are considerably warmer, but also cold, high altitude clouds.

Clouds are rare on Paranal, but the most common form is high altitude cirrus consisting only of ice crystals. Such clouds can be reliably detected as an increase in the sky brightness temperature of a few to a few tens of degrees with respect to a clear sky, which can be as cold as −95 °C on Paranal. This operating mode is still being tested and needs to be calibrated in terms of the extinction resulting from the clouds and hence the impact on photometry. Nevertheless, the IR channel is perfectly capable of detecting extremely thin cirrus and promises to become a useful operational tool in the future. This information is already being routinely used by the Paranal weather officer to assess the quality of a given night.

The PWV and IR sky brightness temperature are available in real time as part of the automated site monitor information in the control room. Thus periods of low PWV can be readily identified by the astronomers on duty. For service mode observations, real-time decisions can be made to select the most suitable observing programmes for the current atmospheric conditions, thereby matching the constraints provided by the Principal Investigators. All data taken by the radiometer are also archived and will be made available for more specialised use on request.

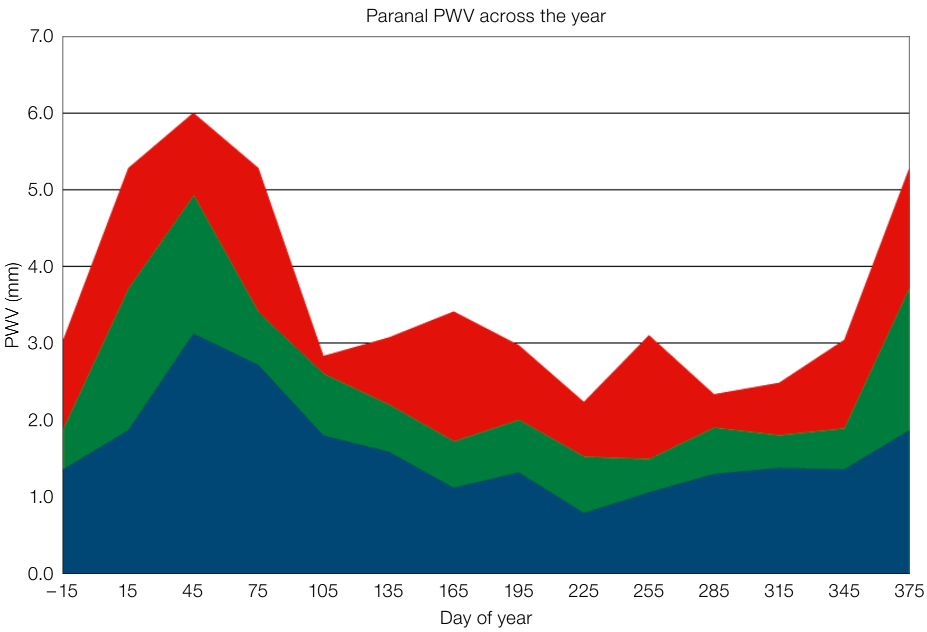

Figure 5. PWV conditions over Paranal based on the analysis of about a decade of UVES data (Kerber et al., 2010a). A pronounced seasonal variation is evident, but very low PWV (< 1.5 mm) conditions are available at the 25% level for most of the year.

- 75% quartile
- 50% quartile
- 25% quartile

Support of science operations

Water vapour is one of the main sources of opacity in the Earth's atmosphere in the thermal IR, the operating range of VISIR. Moreover, the PWV content of the atmosphere above Paranal is strongly variable, both on short timescales, and with pronounced seasonal variations (see Figure 5). However, not all IR observations are equally affected by the PWV conditions: whereas imaging and spectroscopy in the *Q*-band atmospheric window from 17–21 μm will strongly benefit from being performed under conditions of relatively low water vapour, imaging in most wavelength regions of the *N*-band window (9–12 μm) would be less sensitive to PWV content.

The introduction of the new PWV monitor on Paranal offers a clear opportunity to optimise the scientific return of infrared instruments like VISIR by matching the PWV needs of each observation carried out in service mode to the actual conditions measured in real time by the PWV monitor. Hence PWV will be introduced as a formal observing constraint, analogous to seeing or sky transparency in the optical, for VISIR observations from ESO Period 90 onwards (October 2012). Apart from allowing the observatory to better match the needs of each observation to the actual atmospheric conditions at the time of observation, this new feature of the operation of VISIR will also allow the scheduling of a limited number of service mode observations under particularly dry (PWV < 1 mm) conditions, allowing the detection of fainter targets in the *Q*-band, or enabling particularly demanding observations, such as the detection of water in discs. The upgraded VISIR instrument will become available to the ESO community from October 2012. The instrument web page[3] as well as the user manuals will be updated with information concerning PWV to assist users in their proposal preparation.

Outlook

The LHATPRO radiometer has demonstrated the ability to measure the PWV above Paranal with high precision and accuracy and provide real-time information for support of science operations. For the first time, atmospheric PWV is now routinely monitored and brought into use for selecting the most suitable astronomical observations for the prevailing conditions. The PWV conditions during the time of observation will be documented for the user in the VISIR science headers. Since the PWV data are also archived, a set of temperature and humidity profiles, which provide a means of characterising the properties of the atmosphere, will be built up over time. We anticipate that this dataset will enable new insights to be derived into the atmospheric conditions over the ESO sites in northern Chile and we expect that such knowledge will prove useful for science operations of the VLT, and later the E-ELT.

Acknowledgements

The commissioning team is grateful to Paranal staff for their excellent support during the commissioning and early operations. We particularly thank Paranal Science Operations for enabling flexible scheduling of technical time which was crucial to obtain parallel observations with VLT instruments during the radiosonde launches. It is a pleasure to thank the staff at the UFS Schneefernerhaus for their assistance during the test campaign in Europe.

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Links

[1] VISIR upgrade project webpage: http://www.eso.org/sci/facilities/paranal/instruments/visir/upgradeproject.html
[2] Umweltforschungsstation Schneefernerhaus: http://www.schneefernerhaus.de
[3] VISIR web page: http://www.eso.org/sci/facilities/paranal/instruments/visir/overview.html