A Water Vapour Monitor at Paranal Observatory

Florian Kerber*[a], Thomas Rose[b], Arlette Chacón[c], Omar Cuevas[c], Harald Czekala[b], Reinhard Hanuschik[a], Yazan Momany[d], Julio Navarette[d], Richard R. Querel[e], Alain Smette[d], Mario van den Ancker[a], Michel Curé[c], David A. Naylor[f]

[a]European Southern Observatory, Karl-Schwarzschild-Str.2, 85748 Garching, Germany; [b]Radiometer Physics GmbH, Birkenmaarstrasse 10, 53340 Meckenheim, Germany; [c]Grupo Astrometeorologia, Universidad de Valparaiso, Gran Bretana 1111, Valparaiso, Chile; [d]European Southern Observatory, Alonso de Córdova 3107, Vitacura, Santiago de Chile, Chile; [e]Universidad de Chile, Av. Beauchef 850, Santiago de Chile, Chile; [f]Institute for Space Imaging Science, University of Lethbridge, 4401 University Drive W, Lethbridge, AB, T1K 3M4, Canada

ABSTRACT

We present the performance characteristics of a water vapour monitor that has been permanently deployed at ESO's Paranal observatory as a part of the VISIR upgrade project. After a careful analysis of the requirements and an open call for tender, the Low Humidity and Temperature Profiling microwave radiometer (LHATPRO), manufactured by Radiometer Physics GmbH (RPG), has been selected. The unit measures several channels across the strong water vapour emission line at 183 GHz, necessary for resolving the low levels of precipitable water vapour (PWV) that are prevalent on Paranal (median ~2.5 mm). The unit comprises the above humidity profiler (183-191 GHz), a temperature profiler (51-58 GHz), and an infrared radiometer (~10 μm) for cloud detection. The instrument has been commissioned during a 2.5 week period in Oct/Nov 2011, by comparing its measurements of PWV and atmospheric profiles with the ones obtained by 22 radiosonde balloons. In parallel an IR radiometer (Univ. Lethbridge) has been operated, and various observations with ESO facility spectrographs have been taken. The RPG radiometer has been validated across the range 0.5 – 9 mm demonstrating an accuracy of better than 0.1 mm. The saturation limit of the radiometer is about 20 mm. Currently, the radiometer is being integrated into the Paranal infrastructure to serve as a high time-resolution monitor in support of VLT science operations. The water vapour radiometer's ability to provide high precision, high time resolution information on this important aspect of the atmosphere will be most useful for conducting IR observations with the VLT under optimal conditions.

Keywords: water vapour, atmosphere, Paranal, VLT, profile, radiosonde,

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 infrared (IR) astronomy, while in an operational sense reliable knowledge of the content of PWV during a given night is critical to the success and quality of science observations.

VISIR is the mid-IR imager and spectrograph on the VLT. It was built by a French-Dutch consortium (Service d'Astrophysique CEA and ASTRON - PI: P.O. Lagage, Co-PI: J.W. Pel) and has been operational since the end of 2004. It is located at the Cassegrain focus of unit telescope (UT) 3 (Melipal) at ESO's Very Large Telescope (VLT) on Cerro Paranal (2635m) in Northern Chile. The instrument provides diffraction-limited imaging at high sensitivity in the two mid-infrared (mid-IR) atmospheric windows: the N-band between 8 to 13 μm and the Q-band between 16.5 and 24.5 μm. In addition, it features a long-slit spectrometer with a range of spectral resolutions between 150 and 30,000.

*fkerber@eso.org; phone +49 89 32006757; fax +49 89 3206530; eso.org

In particular for the Q-band water vapour is determining the transmission of the atmosphere. Details of the instrument are given Lagage et al.[1] and at http://www.eso.org/sci/facilities/paranal/instruments/visir/

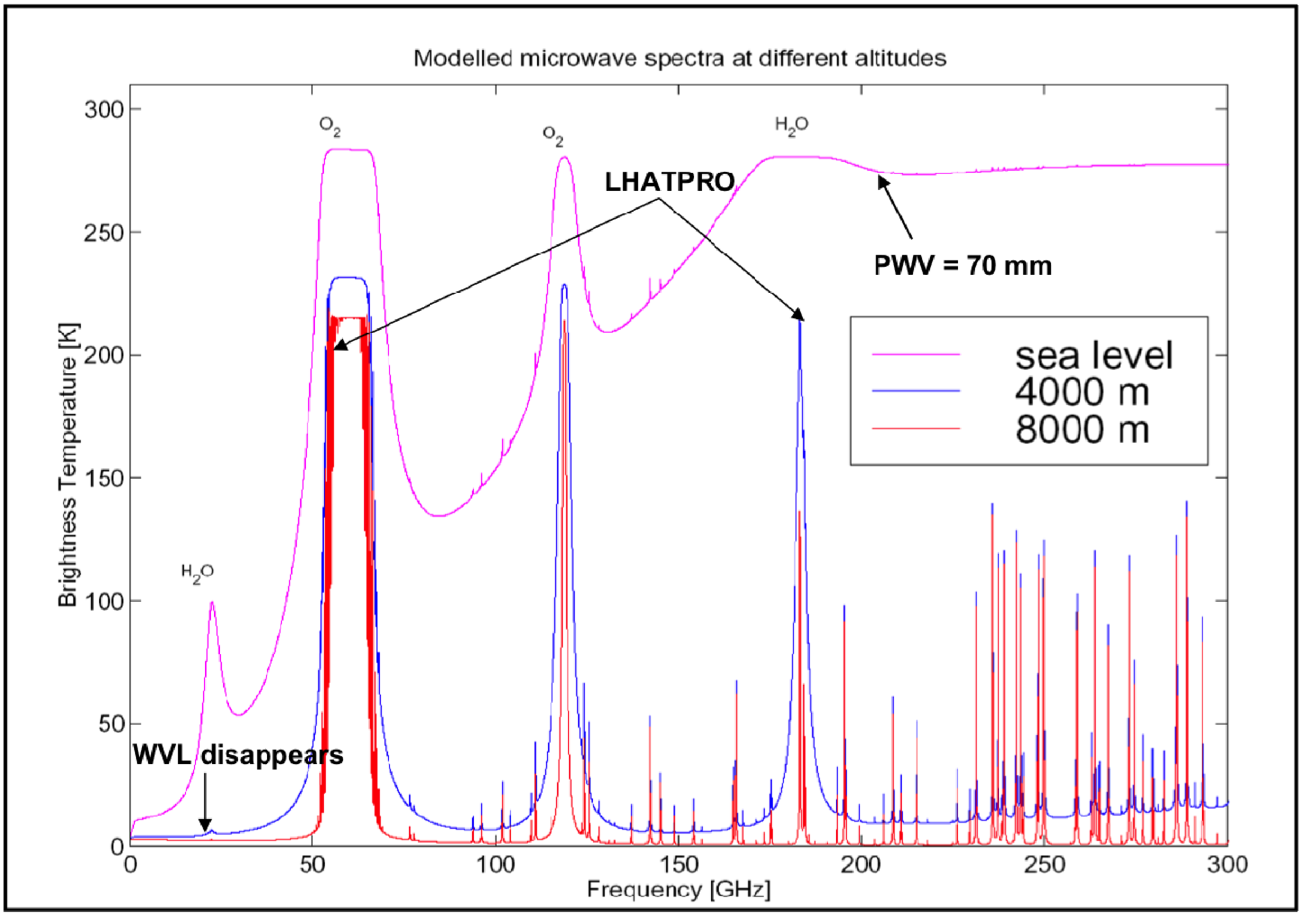

Figure 1. Atmospheric microwave spectrum below 300 GHz at different altitudes. For low PWV levels or altitudes of several thousand meters, the water vapour line at 22.24 GHz disappears while the strong water vapour line at 183 GHz can still be used to determine tropospheric water vapour profiles (From Feist/Univ. Bern).

ESO is currently conducting an upgrade of VISIR in order to enhance its scientific performance[2]. The latest status is detailed in Kerber et al. theses proceedings (8446-12).

The VISIR upgrade plan calls for monitoring of PWV on Paranal in order to use it as an observing and scheduling constraint parameter. Through analysis of archival data and dedicated campaigns conducted as part of E-ELT site characterization the history of PWV on Paranal has been re-constructed for a period of almost a decade. The result is summarised in table 1. After correction of instrumental effects and by comparison with various instruments the median PWV over Paranal is given as 2.4 mm[3].

Table 1: Median PWV for Paranal derived from ground-based optical spectroscopy (UVES) and remote-sensing by satellite (GOES) 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

An essential element in conducting service-mode observations at a ground-based observatory is the predictability of the quality of observations. The goal is to match the science needs of a particular observing program to the prevalent atmospheric conditions at the time of observations, thereby optimizing the scientific output of the observatory. The implementation of a PWV monitor on Paranal will allow us to introduce PWV as a user-defined constraint that directly relates to the actual atmospheric transparency in the infrared. In the long-term schedule observations covering a range of PWV constraints will be combined, while the information from the PWV monitor will support real-time decisions at the telescope as to which observations should be performed now. The PWV measurements will be made available to the VISIR users in the form of FITS header keywords. In addition, we expect that over time this will provide better insight into the atmospheric conditions on Paranal also in view of operating the European Extremely Large Telescope (E-ELT) on nearby Armazones[4]. See the presentation by M. van den Ancker for details of the operational aspects (8448-37).

2. THE VISIR UPGRADE AND WATER VAPOUR

The upgrade of ESO's mid-IR instrument VISIR is a project that combines improvements in hardware, software and operations (http://www.eso.org/sci/facilities/paranal/instruments/visir/upgradeproject.html). Tot his enda water vapour radiometer has been permanently deployed on Paranal in Oct 2011 as a new tool for supporting science operation at the VLT and the upgraded VISIR in particular. The instrument allows ESO to monitor in real-time with high precision and time resolution the water vapour content of the atmosphere above the observatory and to select the periods of low precipitable water vapour (PWV) which provide better atmospheric transmission for observations in the infrared.

The requirements for the monitor were guided by the lessons learned during the work to characterize potential sites for the European Extremely Large Telescope (E-ELT) in 2009[3, 5].
The requirements called for a high-precision, high time resolution stand-alone PWV monitor that provides water vapour information in (near-) real time. In addition the unit had to be compatible with weather conditions on Paranal and it should of course not interfere with observatory operations and require very limited calibration or maintenance effort.

The primary interest for VISIR is the integrated water vapour column which represents the amount of water which would result from condensing the vertical atmospheric column, expressed in mm. 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. The water vapour line near 183 GHz is intrinsically very strong hence it is still prominent at very low humidity levels making it suitable for a dry site such as Paranal which has a median PWV of 2.4 mm with pronounced seasonal and short term variations[3]. The PWV values encountered during any year range from nearly 0 to more than 15 mm.
An open call for tender resulted in the selection of the Low Humidity Atmospheric PROfiling radiometer (LHATPRO) by Radiometer Physics GmbH (RPG; http://www.radiometer-physics.de). In addition to the required staring mode at zenith the LHATPRO has an all-sky pointing capability and can scan the whole sky within a few minutes.

3. LHATPRO CHARACTERISTICS

The instrument probes the atmosphere in two frequency ranges focusing on two prominent emission features: an H_20 line (183 GHz) and O_2 band (51-58 GHz). Using 6 and 7 channels, respectively, the radiometer retrieves the profile of humidity and temperature up to an altitude of about 12 km[6]. 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 RPG-LHATPRO radiometer is a two receiver system, one for water vapour and the other one for temperature profiling. These individual receiver packages have independent optical inputs (corrugated feed horns) due to their large frequency separation. The two beams are superimposed by a polarising wire grid combiner to illuminate an imaging parabola reflector with an effective aperture diameter of 250 mm. This reflector is scanning in elevation in a range of +/-90° and periodically encounters the internal ambient temperature target for calibration purposes. For a full calibration with absolute standards an additional external calibration target, cooled down to the boiling point of liquid nitrogen (LN2), is used. The receivers are mounted to a two stage thermal control system which is capable of maintaining the receiver's physical temperatures within 30 mK. This extraordinary stability is required to reduce calibration cycles to a minimum. The RPG-LHATPRO therefore offers a measurement duty cycle of $> 97\%$.

The 50-60 GHz (V-Band) radiometer is realized as a direct detection filter bank receiver. Its design focuses on maximum thermal and electrical stability, a compact layout with a minimum of connectors and thermally drifting components, an integrated RF design, low power consumption and weight.

Its parallel channel layout allows for measuring the oxygen line profile with the highest possible duty cycle, thus maximizing observation time. Among other advantages over frequency sweeping radiometers, this leads to a high temporal resolution of 1 second sampling rate while measuring the temperature profile with a noise level of < 0.1 K.

Both receivers are equipped with a precision noise injection section to be able to perform a complete calibration cycle in combination with the built-in ambient temperature target. The noise source is periodically turned on and off (10 Hz) to cancel amplifier gain drifts. Its radiation equivalent temperature (brightness temperature) is determined during an absolute calibration and after that it serves as a secondary calibration standard. The precision of the noise standard is on the order of 0.3-0.5 K while the ambient temperature target precision is better than 0.2 K.

In contrast to the direct detection V-band radiometer, the 183 GHz water vapour receiver is a double sideband heterodyne system with 6 parallel channels (6 independent detection lines). The advantage of the parallel design, a high duty cycle close to 100%, is also available as for the temperature profiler, while the implementation of a double sideband detection increases the sensitivity by a factor of sqrt(2). Both water vapour line wings are converted into the mixer's IF signal.

The 183 GHz mixer is operated in sub-harmonic mode (second harmonic) with a local oscillator frequency at approximately 91.7 GHz. The channel splitting and filtering is performed within the IF section. For each channel there is a dedicated band pass filter, booster amplifier and detector unit to achieve a true parallel data acquisition.

The key component is a powerful noise source developed by RPG which delivers approximately 14 dB excess noise (7500 K!) in the range 170 GHz to 200 GHz. As with the V-band receiver, the noise standard allows for a continuous full auto-calibration scheme.

In addition ESO's LHATPRO is equipped with an IR radiometer (10.5 µm) to measure sky brightness temperature down to -100° C. This allows for detection of high altitude clouds, e.g. cirrus, that consist of ice crystal but contain no liquid water. The IR radiometer can by fully synchronized for scanning with the microwave radiometer (see section 5).

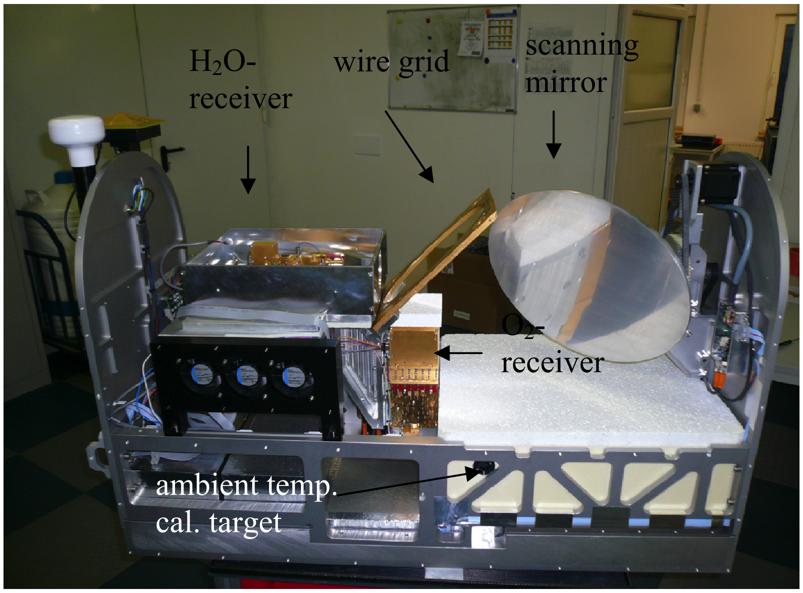

Figure 2. Left: The RPG-LHATPRO internal system layout, comprising the 6 channel 183 GHz water vapour receiver and the 7 channel 50-60 GHz temperature profiling receiver, both mounted to a 2-stage thermal control system. The signal from the sky is focused by a scanning off-axis parabolic mirror onto a wire grid diplexer to feed the two receivers. The two This mirror antenna also frequently scans the internal blackbody target for calibration. Right: LHATPRO deployed on Paranal with the dome of UT4 in the background.

4. RADIOMETER PERFORMANCE VALIDATION

The water vapour radiometer (WVR) underwent a qualification and acceptance test at the Umweltforschungsstation (UFS) Schneefernerhaus (http://www.schneefernerhaus.de) located a little below the summit of Zugspitze (Figures 3a, b) the highest mountain peak in Germany. During a 2-week period in Sep 2011 the instrument 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/fall only at high elevations, incidently the altitude of Schneefernerhaus (2650 m) almost exactly matches the final destination of the unit, the telescope platform on Paranal (2635m). In addition the UFS hosts a number of instruments measuring properties of the atmosphere including a water vappour radiometer operating at 22 GHz and a lidar 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. The commissioning of RPG's LHATPRO was closely modeled after the highly successful PWV campaigns conducted in 2009 as part of E-ELT site characterisation[3, 5, 7]. Through technical time we had access to several VLT instruments: CRIRES, UVES, X-shooter, and, of course VISIR. For these optical and IR instruments PWV is extracted from absorption or emission line spectra using an atmospheric model. An accuracy of about 15-20% has been demonstrated during the 2009 campaigns[3] for this approach and full details of the spectral fitting procedure are given in Querel et al.[8]. In addition we operated an infrared radiometer built by the University of Lethbridge (Canada).

Figure 3. Left: On September 19th, 2011 almost half a meter 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. Right: 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 m above sea level.

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 campaign[7]. A radiosonde consists of a very compact meteorological instrument package that is launched tethered to a helium-filled balloon and which provides in-situ measurements of the atmosphere along its ascent trajectory to an altitude of about 25 km 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 radiosonde's sensors provide high time resolution profiles of temperature and dew point (humidity) over the course of about 90 min after launch and such a data set 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 the LHATPRO would operate continuously (and the Canadian IRMA during night time). The resulting time series is shown in Figure 4. The variation in PWV was very pronounced over the 2-week commissioning period but agreement between LHATPRO and the radiosondes is excellent (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. 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/goal 10 mm, section 4.1), and hence it will be able to accurately measure all regular humidity conditions over Paranal.

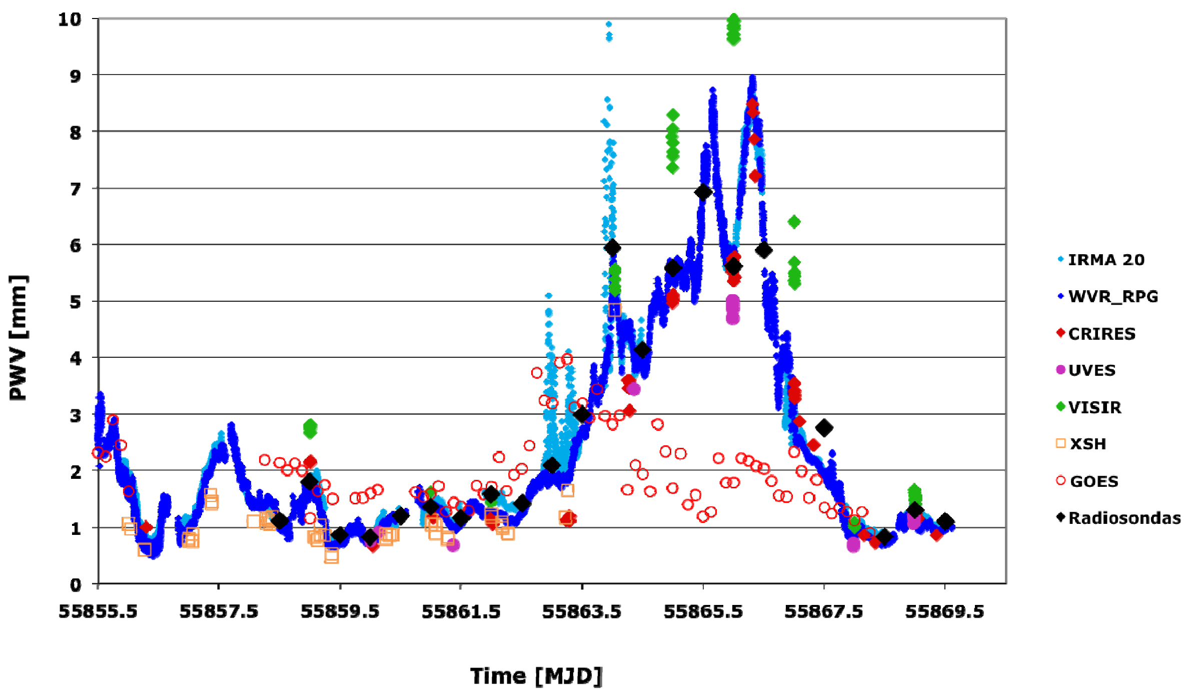

Figure 4. Time series of the water vapour measurements by various instruments during commissioning (Oct 19th- Nov 4th, 2011). Excellent agreement is found between the RPG radiometer (dark blue) and the radiosondes (black diamonds). Very high PWV values were recorded during an unusual weather pattern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

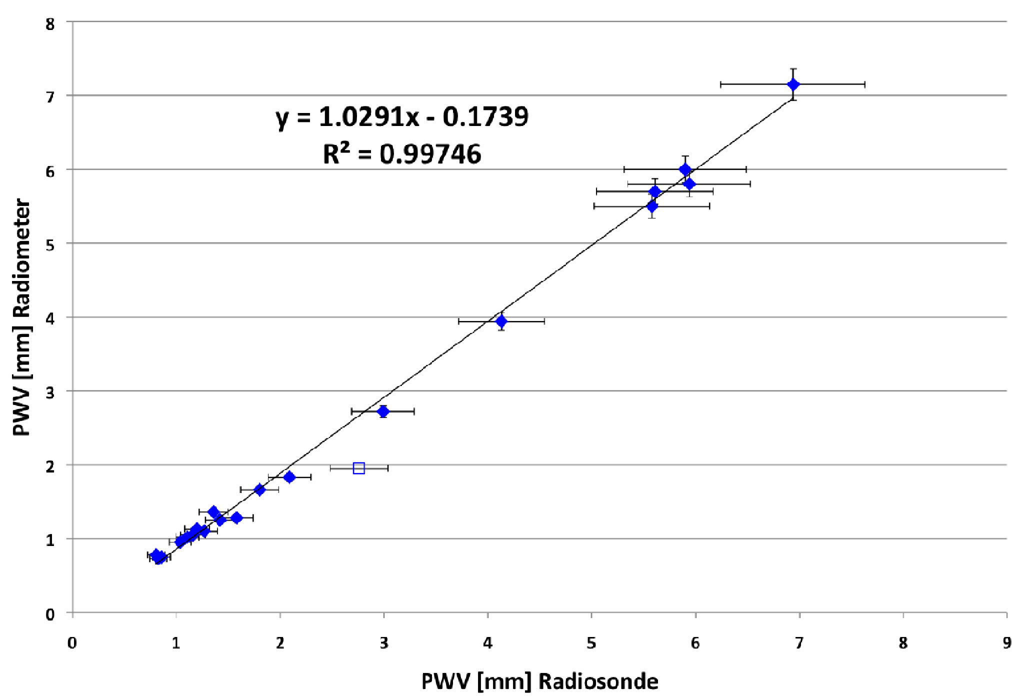

Figure 5. Excellent agreement is found between PWV measured by the RPG radiometer and 22 radiosondes – the accepted standard in atmospheric research - launched from Paranal during the commissioning campaign. The open square denotes a radiosonde with imperfect calibration.

4.1 Saturation

All-sky scans have also been used to evaluate the useful range of the WVR. This was done by comparing the actually observed values of PWV at 30° elevation with the value expected from the measurement at zenith. The onset of saturation is then marked by the PWV value at which the WVR starts to underestimate the value expected from zenith. This kind of analysis is of course possible only for conditions when the distribution of PWV is highly homogeneous across the sky. Fortunately, this condition is well met on Paranal for a large fraction of the time. Figure 6 shows that the LHATPRO starts to saturate at 20 mm far exceeding the original specification of 5 mm and the goal of 10 mm. This also ensures that practically all conditions likely to occur on Paranal will be within the measurement range of the radiometer allowing us to obtain a meaningful statistic for PWV over Paranal all year.

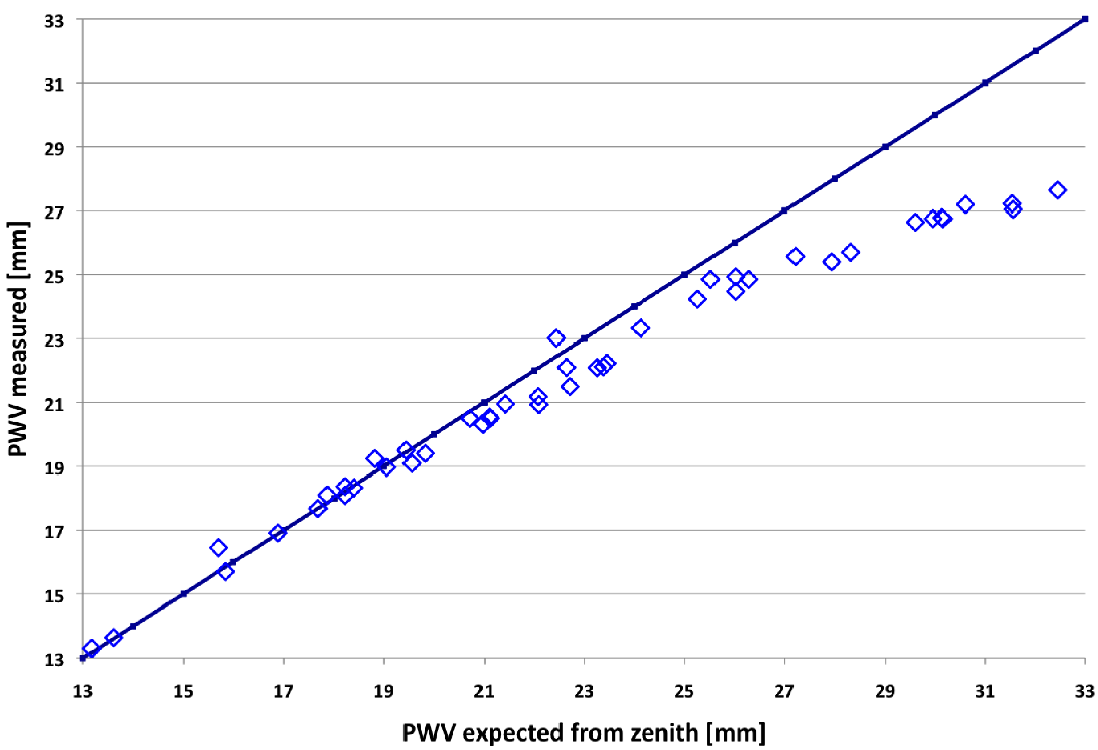

Figure 6. The saturation of the LHATPRO starts a PWV value of 20 mm. In the diagram the PWV measured in all-sky scans down to 30° elevation is plotted against the expected PWV based on the value at zenith. Saturation is indicated by a deviation of measured versus expected PWV.

4.2 Comparison with previous PWV measurements on Paranal

PWV has been routinely measured on Paranal for the past several years. A number VLT instruments (CRIRES, UVES, VISIR and X-shooter have been used and their absorption or emission spectra analysed with the help of an atmospheric model[8]. All theses methods had been validated with respect to radiosonde data during the E-ELT site characterization[3] and their accuracy is on the range of 15-20%. With this approach a few PWV measurements per night were acquired at best. The new WVR provides much higher precision and accuracy and continuous coverage at high time resolution. Finally, it removes the need for using valuable time on the 8-m UTs for this purpose.

5. 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 (s/w related) for the water vapour channel is below 2 %.

An IR radiometer is also part of the instrument package providing measurements of the brightness temperature of the sky down to -100 C. 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 anyway but the most common form is high altitude cirrus consisting of ice crystals only. Such clouds can be reliably detected as an increase in 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. Still it is safe to say that the IR channel is perfectly capable of detecting extremely thin cirrus and promises to become a useful operational tool in the future.

The PWV and IR sky brightness temperature are available in real-time as part of the Automated Site Monitor (ASM) information in the control room. Thus periods of low PWV can readily be identified by the astronomers on duty. In service mode real-time decisions can be made to select the most suitable observing programs for the current atmospheric conditions thereby matching the constraints provided by the PIs. All data taken by the radiometer are also archived and will be available for more specialized use on request.

5.1 Observing sequence

The observations done by the water vapour radiometer are described in definition files which are then again combined in a batch file to give the final observing sequence. The process is straightforward after some training. The definition files can be prepared remotely and uploaded to the control PC. The WVR can be commanded to repeat an observation sequence n-times resulting in months of unsupervised operations if needed. The IR channel is mounted on the same azimuth stage and can be commanded to perform its elevation scan in lock with the water vapour radiometer resulting in fully synchronous and parallel observations in the IR channel as well. The scheme currently set-up on Paranal and covering a period of 24 hours is described below.

- 2-D all-sky scan: step size of 12° (duration 6 min, repeated every 6 h)
- Cone scan at 30° elevation: step size 12° (durations 2.5 min, repeated every 15 min)
- Rest of the time observations in staring mode at zenith

All data can be corrected for air mass and hence information of the PWV at zenith is available for close to 100% of the time and is displayed in the Paranal control room.

The cone scan is repeated every 15 minutes and the resulting time series is plotted as a water fall diagram for a 24 hour period. Since the scan is performed at 30° elevation this diagram provides an early warning for changes in conditions, whether it is water vapour content or clouds. This kind if information has proved very useful for the work of the weather officer on Paranal.

In the future the WVR may also provide line-of sight support for VLT instruments such as VISIR by pointing at the same target as VISIR resulting in a measurement of the PWV in the air column traversed by the science light. The spatial resolution is limited by the size of the radiometer beam (1.4° FWHM). This mode has been technically implemented and will be tested in the next few months. In the future this mode might be used to derive oblique atmospheric profiles of humidity and temperature that can serve as input for modeling atmospheric transmission. In a more long-term development this may then enable us to replace some telluric observations of stars by the modeled atmospheric transmission.

5.2 Homogeneity of PWV across the sky

Every six hours the WVR produces an all sky scan from zenith to 30° elevation in 15° steps. Based on about 4 months of data we have evaluated the homogeneity of the distribution of water vapour over the sky. Figure 7 shows that across the range 0.5 to 5 mm the variations (ptv) are usually in the range 0.1 to 0.4 mm. Larger variations exist and are associated with more humid air masses moving over Paranal. Since the scan provides full 2D information, such fronts can easily be recognized by the weather officer on Paranal. We plan to extend this preliminary analysis to a full year of data and provide the results also in the manual of VISIR in order to provide guidance to the user community.

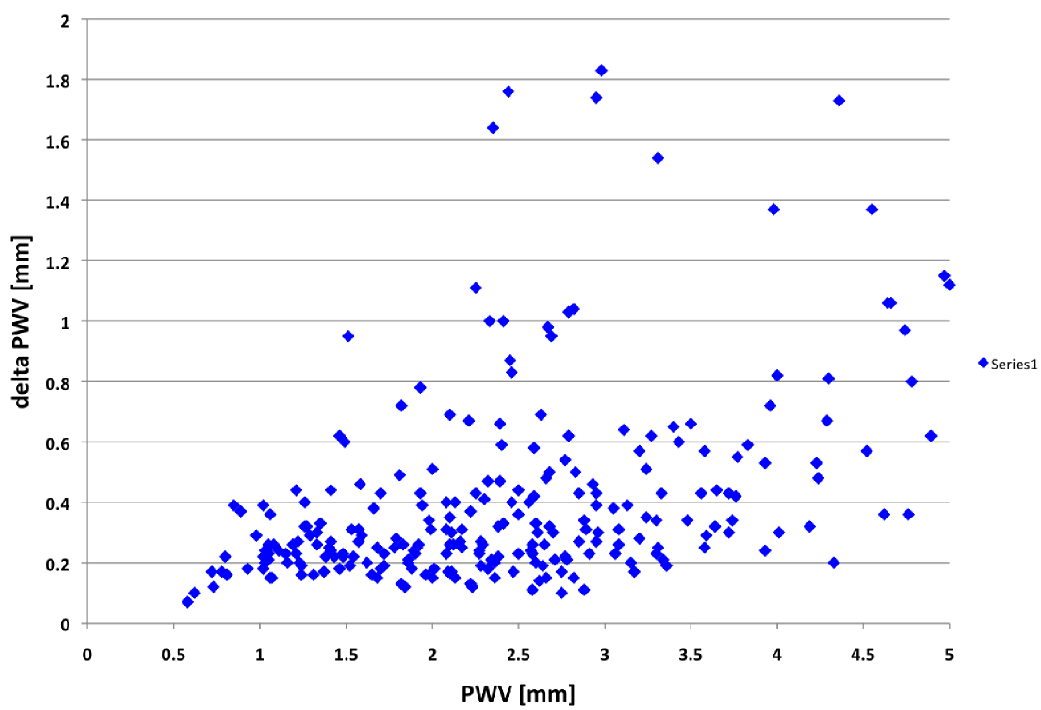

Figure 7. Variation of PWV as measured in an all-sky scan down to an elevation of 30°. For most conditions the measured differences are between 0.1 and 0.4 mm.

5.3 Hovmoeller plot

A Hovmoeller plot is a waterfall diagram that is constructed from a series cone scans at a fixed elevation; in our case 30°. It shows the azimuth directions 0-360° on the x-axis and time on the y-axis. As detailed such a cone scan is performed on Paranal every 15 min and the resulting 24h time series is on display in the control room. An example is shown in Figure 8. A 24 h time series of cone scans is shown for PWV (left) and IR sky brightness temperature (IRT, right). It is obvious that more discrete structures are visible in the IRT channel. Theses are ice clouds that are recorded as an increase in temperature with respect to the clear sky. Since the IR radiometer can measure down to -100° C it will also detect very high and thin clouds containing no liquid water droplets. This set-up is well tailored to the conditions on Paranal where clouds are rare anyway but when present they are usually at high altitude. The lower panels of Fig. 8 illustrate this further: they show a cut through the upper panels due South. For the PWV low values (1 to 1.5 mm) are recorded with a slow variation, for IRT the baseline is around -80° C while abrupt peaks with an amplitude of about 10° C indicate the presence of thin clouds. The combination of different measurements is being routinely used by the observatory's weather officers to assess the quality of a night. Since the cone scan is done at only 30° elevation is serves as an early warning of changes in conditions in particular.

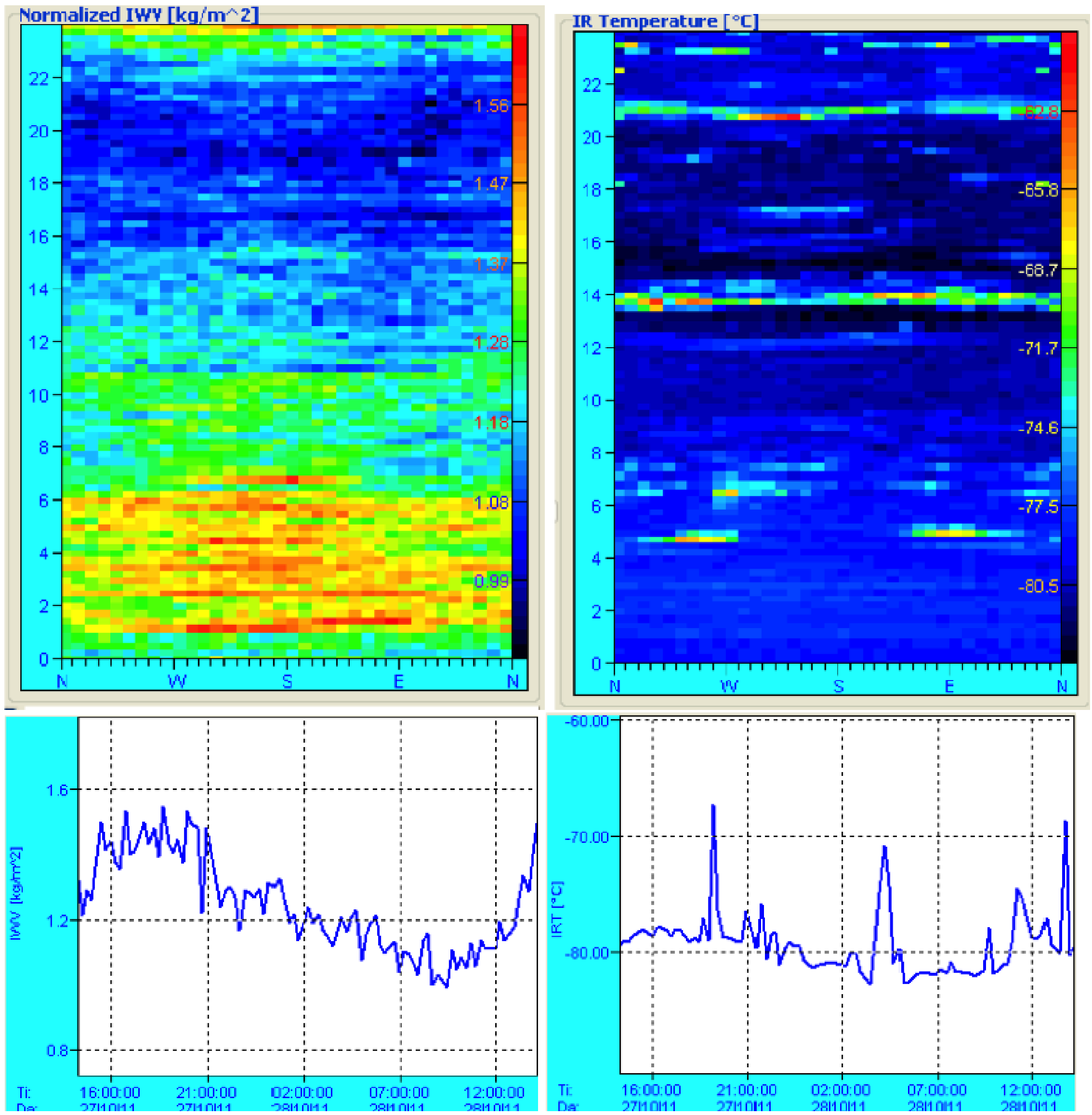

Figure 8. Hovmoeller plots of PWV (upper left) and IR sky brightness temperature (upper right) show a 24 h time series of a cone scan (elevation 30°) taken every 15 min. A vertical cut in the Southern direction is shown in the lower panels. Ice Clouds at high altitudes (e.g. cirrus) seen as bright lines in the IRT plot can be reliably detected by the IR radiometer.

6. SUPPORT OF SCIENCE OPERATIONS

Water vapour is one of the main sources of opacity in the Earth's atmosphere in the thermal infrared, 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. However, not all infrared observations are equally affected by the PWV conditions: whereas imaging and spectroscopy in the Q-band atmospheric window from 17-21 micrometers will strongly benefit from being done 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 contents. The introduction of the new PWV monitor on Paranal offers a clear opportunity to optimize 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 Oct 2012 onwards. 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 operations of VISIR will also allow the scheduling of a limited amount 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 disks. More details on this new development are given in the presentation by M. van den Ancker et al. (8448-37). The upgraded VISIR instrument will become available to the ESO community starting October 2012 and the instrument web pages (http://www.eso.org/sci/facilities/paranal/instruments/visir/overview.html) as well as the user manuals will be updated with information concerning PWV to assist the users in their proposal preparation.

7. OUTLOOK

The LHATPRO radiometer has demonstrated the ability to measure with high precision and accuracy the PWV above Paranal and provide real-time information for support of science operations. For the first time atmospheric PWV is now routinely measured by a dedicated monitor removing the need for valuable UT time and brought to 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, ESO will build up over time a set of temperature and humidity profiles which provide a means of characterizing the properties of the atmosphere. We anticipate that this data set will enable ESO to derive new insights into the atmospheric conditions over its sites in Northern Chile and we expect that such knowledge will prove useful for science operations of the VLT and later the E-ELT.

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