The water vapour radiometer of Paranal: homogeneity of precipitable water vapour from two years of operations

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The water vapour radiometer of Paranal: homogeneity of precipitable water vapour from two years of operations

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Abstract. A Low Humidity and Temperature Profiling (LHATPRO) microwave radiometer, manufactured by Radiometer Physics GmbH (RPG), is used to monitor sky conditions over ESO's Paranal observatory in support of VLT science operations. 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 ~2.4 mm). The instrument consists of a humidity profiler (183-191 GHz), a temperature profiler (51-58 GHz), and an infrared camera (~10 μm) for cloud detection. We present a statistical analysis of the homogeneity of all-sky PWV using 24 months of PWV observations. The question we tried to address was whether PWV is homogeneous enough across the sky such that service mode observations with the VLT can routinely be conducted with a user-provided constraint for PWV measured at zenith. We find the PWV over Paranal to be remarkably homogeneous across the sky down to 27.5° elevation with a median variation of 0.07 mm (rms). The homogeneity is a function of the absolute PWV but the relative variation is fairly constant at 2 to 3% (rms). Such variations will not be a significant issue for analysis of astronomical data. Users at ESO can specify PWV – measured at zenith – as an ambient constraint in service mode to enable, for instance, very demanding observations in the infrared. We conclude that in general it will not be necessary to add another observing constraint for PWV homogeneity to ensure integrity of observations. For demanding observations requiring very low PWV, where the relative variation is higher, the optimum support could be provided by observing with the LHATPRO in the same line-of-sight simultaneously. Such a mode of operations has already been tested but will have to be justified in terms of scientific gain before implementation can be considered. We plan to extend our analysis of PWV variations covering a larger parameters space for temporal and spatial resolution in the future. Also for climate studies such data sets will be relevant.

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1. Introduction

Water vapour is the main source of opacity in the Earth's atmosphere at infrared (IR) wavelengths. That opacity is the primary reason that ground-based astronomical observations are only made in certain wavelength regions, called windows, because of their relative lack of water absorption lines and other telluric absorption features. These windows are relatively well-defined and stable for most observations at temperate latitudes and moderate elevations above sea level. Atmospheric transmission is a function of the depth of air above the observer. This is true for almost all atmospheric constituents since gases such as O_2 are well-mixed throughout the atmosphere. In contrast, water can coexist in three phases at atmospheric temperatures, and hence, its atmospheric distribution is highly variable in altitude as well as geographical location and time. Atmospheric water vapour content can be expressed as precipitable water vapour (PWV) which is the equivalent condensed amount of water in an atmospheric column above the observer (as a depth in units of mm).

ESO's Very Large Telescope (VLT) is located on Cerro Paranal (24.6°S, 70.4°W, 2635 m.asl). Since November 2011 ESO operates a water vapour monitor in support of VLT science operations[1,2]. Paranal is a very dry site with a median PWV of ~2.4 mm offering excellent conditions for IR observations when real-time PWV information is taken into account. Before deployment of the LHATPRO monitor PWV was routinely derived from standard star observations at the 8-m unit telescopes (UTs) with the spectroscopic instruments UVES, X-Shooter, CRIRES and VISIR. The method for deriving PWV from such spectra taken at various wavelengths by fitting the observed spectrum with an atmospheric radiative transfer model is described in Querel et al[3]. The pronounced seasonal variation of PWV for sites in Northern Chile is well-documented[1,2,4]. In contrast the variation of uniformity of PWV across the sky at any given moment had not been studied; a first analysis has been presented by us[5] earlier this year and this contribution is an update of the previous work. A summary of the methods to monitor atmospheric water vapour is given in the excellent book by Kämpfer et al.[6].

2. LHATPRO

The Low Humidity And Temperature PROfiling microwave radiometer (LHATPRO), manufactured by Radiometer Physics GmbH (RPG), measures the atmosphere at two frequency ranges focusing on two prominent emission features: a strong H_2O line (183 GHz) and an 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 ~12 km[2,7] The spatial resolution is given by the size of the radiometer beam (1.4° FWHM). 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 LHATPRO offers a measurement duty cycle of >97%. Details of the radiometer are described in Rose et al[7].

The LHATPRO water vapour radiometer (WVR) was commissioned during a 2.5 week period in October and November 2011 during which the calibration was tested with respect to balloon-borne radiosondes, the established standard in atmospheric physics[2]. The LHATPRO measures PWV in the range 0-20 mm with an accuracy of better than 0.1 mm and an internal precision of about 30 μm. The 183 GHz line is intrinsically very strong and reliable readings can be obtained even in the driest of conditions encountered on Paranal. 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 the detection of high altitude clouds, e.g. cirrus, that consist of ice crystals but contain practically no liquid water (see Kerber, Querel and Hanuschik[8]). The IR radiometer can be fully synchronized for scanning with the microwave radiometer.

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The operational scheme currently set-up on Paranal was devised to meet the needs of VLT science operations and has been strictly followed for more than 2 years now:

- 2-D all-sky scan: step size of 12° azimuth, 12.6° elevation (duration 6 min, repeated every 6h; 1.7% of 24 h period)
- Cone scan at 30° elevation (Hovmöller): step size 6° (duration 2.5 min, repeated every 15 min; 16.7% of 24 h period)
- Routine observations set to zenith-staring mode (81.6 % of 24 h period)

The resulting measurements are processed by the RPG software, corrected for air mass, and so PWV values at zenith are available nearly continuously and are displayed in the Paranal VLT control room in near-real time. More details about the scanning process are given in Querel & Kerber[5].

3. Data Analysis and Results

In a previous paper we had analysed the 2D scans only[5]; now we have used data from both scanning modes. The 2D scans cover a 21 months period from June 2012 to March 2014, while the Hovmöller cone scans were acquired during a 2 year period June 2012 to June 2014. The scans contain very similar information with two important differences: the 2D scans provide better spatial coverage but worse spatial and temporal sampling, while the Hovmöller scans cover only an annulus in the sky (30° elevation) hence limited spatial coverage but with higher (factor 2) spatial and much better (factor 20) temporal sampling. We have used a total of 2588 2D scans and 67284 cone scans. The data have been treated in the same way. Only 17 scans have been excluded because of some problem with the measurement. After correcting for air mass all individual measurements in a given scan have been averaged and the standard deviation derived. The results are very similar for both kinds of scans.

Table 1. Homogeneity of PWV over Paranal. Shown in the table is the variation in PWV across the sky: Standard deviation [mm] for the 2D scans (2588 sky-scans over 21 months, representing day and night conditions); and the 30 degree cone scans (67284 scans over 24 months). The 10, 25, 50, 75, and 90 percentiles were computed. The median values are shown in boldface.

Percentiles	PWV variation SDev 2D scan [mm]	PWV Variation SDev cone scan [mm]
10	0.035	0.022
25	0.049	0.032
50	**0.066**	**0.057**
75	0.131	0.113
90	0.218	0.205

The distribution of PWV above Paranal is remarkably uniform (table 1). The variation of PWV increases as a function of the absolute PWV value (Tables 2 & 3) but is fairly constant when the fractional variation (in %) is considered. For the median variation a value of about 2-3% is found. This suggests that a PWV constraint for zenith will be sufficient to secure the correct conditions for arbitrary pointings for most science applications.

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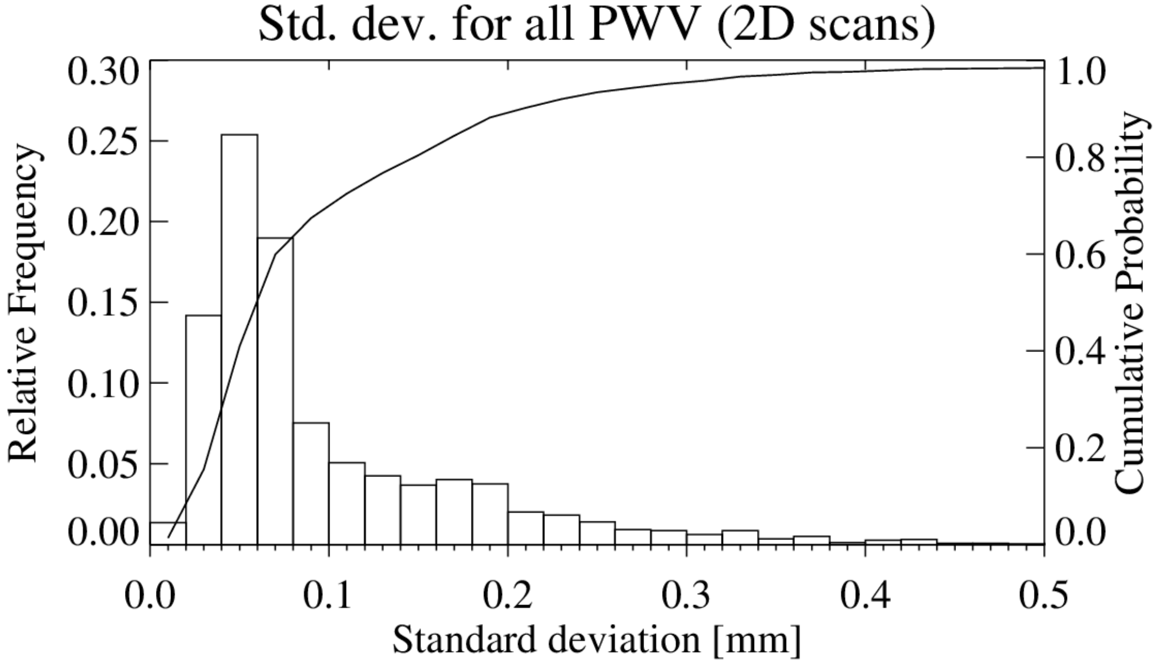

Figure 1: Histogram and cumulative probability distribution of the PWV variation across the sky down to 27.5° elevation (2D scans, 2588 samples), reproduced from Querel & Kerber[5].

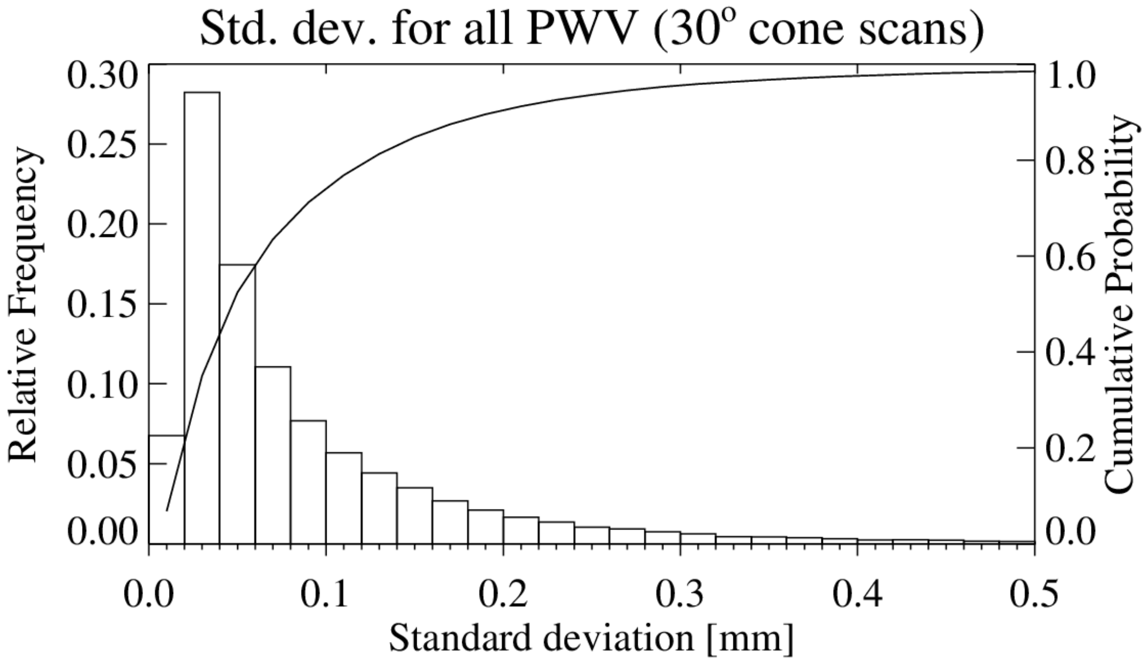

Figure 2. Histogram and cumulative probability distribution of the PWV variation of the cone scans at 30.0° elevation (Hovmöller, 67284 samples).

Variations are relatively slow in time and we have not found strong random fluctuations on the spatial and temporal scales accessible to analysis with the data available. Recently, we have obtained additional 2D data over a smaller area but at 1 degree resolution to address smaller scales. In the future we plan to use VISIR the VLT mid-IR instrument to also study PWV-induced variations of the sky

background at very high time resolution. Large variations in PWV are found to be associated with the exchange of air masses with different properties over Paranal such as large-scale frontal systems. This is consistent with the concept of a frozen flow for atmospheric processes[9, 10].
PWV can be very low on Paranal[11] enabling new science taking advantage of increased atmospheric transmission outside of established astronomical windows. This kind of science is directly dependent on the actual transmission and hence PWV along the line-of-sight towards the target. Since the variation of PWV is, relatively speaking, the highest for low PWV conditions such variations may in fact negatively impact photometric measurements. Therefore it may be prudent to consider introducing an additional constraint on the PWV representing its variation during an observation.

Table 2. The standard deviation [mm] of the PWV variations binned by zenith PWV value. Using 2588 2D sky-scans over 21 months, representing day and night conditions, the 10, 25, 50, 75, and 90 percentiles were computed. The median values are shown in boldface.

Percentiles	0-1 mm	1-2 mm	2-3 mm	3-4 mm	4-6 mm	6-8 mm	8-10 mm
10	0.021	0.037	0.029	0.045	0.069	0.148	0.140
25	0.031	0.048	0.037	0.056	0.091	0.173	0.163
50	**0.047**	**0.058**	**0.054**	**0.082**	**0.139**	**0.199**	**0.204**
75	0.059	0.069	0.075	0.119	0.195	0.269	0.263
90	0.068	0.087	0.114	0.184	0.261	0.345	0.325
Number	252	818	567	262	332	191	92

Table 3. The standard deviation [mm] of the PWV variations binned by zenith PWV value. Using 67284 cone scans (30 degree elevation) over 24 months, representing day and night conditions, the 10, 25, 50, 75, and 90 percentiles were computed. The median values are shown in boldface.

Percentiles	0-1 mm	1-2 mm	2-3 mm	3-4 mm	4-6 mm	6-8 mm	8-10 mm
10	0.015	0.019	0.024	0.041	0.058	0.080	0.078
25	0.019	0.024	0.033	0.058	0.084	0.111	0.108
50	**0.027**	**0.034**	**0.049**	**0.090**	**0.130**	**0.163**	**0.159**
75	0.041	0.052	0.079	0.149	0.204	0.250	0.250
90	0.062	0.079	0.127	0.232	0.315	0.374	0.410
Number	4569	21533	17351	6598	7513	4324	2718

Even better support to the science exploitation of such data could be given by measuring the PWV along the same air column traversed by the science light from the target (line-of-sight) simultaneously with the science observation. The LHATPRO radiometer is capable of all-sky pointing and tracking and thus line-of-sight support. The spatial resolution is limited by the size of the radiometer beam (1.4° FWHM). This mode has been technically implemented by RPG and has been tested on Paranal. Implementation of such a mode will require careful planning and would have to be justified by clear scientific gain.

The observational scheme followed over the past two years on Paranal is driven by the needs of VLT Science Operations. It is quite simple and focuses on zenith observations. The spatially resolved scans provide valuable information on the distribution of PWV acorss the sky. Since water vapour is the most important greenhouse gas and its variation in the atmopshere is highly important for climate studies we expected that we would be able to compare our findings with dedicated studies for other sites. Still when looking for similar studies of PWV homogeneity in the literature we have found that apparently only very few publications address the issue of spatial homogeneity of PWV over one specific location. In fact to the best of our knowledge our data set seems to be unique in terms of cadence and number of 2D scans over a single site obtained with a high precision microwave radiometer. Schneebeli and Mätzler[12] have obtained all-sky maps over Zimmerwald Observatory in Switzerland using the scanning all-sky radiometer ASMUWARA during the period of one week in Feb 2007 and analysed the spatio-temporal behaviour of PWV and found a high degree of spatial coherence. Morland and Mätzler[13] have studied the PWV field over Switzerland using data from a network of 31 GPS receiver stations. Specifically they have studied the passage of frontal systems and find a good correlation between the measurements at different stations again fully consistent with the frozen flow concept and our findings for Paranal.

4. Conclusion

The uniformity of PWV across the sky over Paranal is remarkably high at a level of a few percent. Variations over Paranal are consistent with the "frozen flow" concept in which most of the observed change is attributed to air masses with different properties passing over a given site. This suggests that a PWV constraint for zenith will be sufficient to secure the correct conditions for arbitrary pointings for most science applications. A more in-depth analysis of the all-sky PWV data, including diurnal and seasonal trends in the variations is in preparation. Our data set might be relevant for a better understanding of atmospheric PWV also in the context of climate change.

5. References

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