# Precipitable Water Vapour at the ESO Observatories: The Skill of the Forecasts

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**Atmospheric precipitable water vapour (PWV) above an observatory is a crucial parameter for the success and quality of submillimetre and mid-infrared science observations. High precision water vapour radiometers are deployed at the ESO observatories on Paranal (VLT) and Chajnantor (APEX and ALMA), providing continuous high time-resolution measurements of PWV. These data have been used to compare the actual conditions with the forecast delivered by the publicly available Global Forecast System provided by the National Oceanographic and Atmospheric Administration. The quality of these predictions has now reached a level at which it can contribute to optimising science operations.**

## Introduction

We are certainly used to the daily weather forecast and for many a plan for the weekend barbecue is based on, say, Thursday's forecast. While, for the Saturday afternoon party, some basic information such as lack of precipitation and temperatures above 22 degrees suffice. The situation is more complex for astronomical observations. ESO's service mode has been popular with European astronomers and its success derives from its ability to perform demanding science observations under the right environmental conditions. While some user-provided constraints, such as lunar phase and distance from the target, can be simply calculated in advance, other important constraints, such as seeing or atmospheric transparency, can only be known close to the time of observation (often called nowcasting). Any useful astro-meteorological forecast has to make quantitative predictions on very specific atmospheric properties above the observatory.

Modern atmospheric models have been successful in providing such forecasts for air travel, severe weather events, agriculture and other fields demanding specialised products (e.g., storm tracks) and, partly as a result, the weather for Saturday's barbecue has become more predictable than 20 years ago. PWV, however, is not easy to predict because of its intrinsic variability in time and location within the atmosphere. It is a very relevant question whether current state-of-the-art models are up to the task of providing forecasts for a given atmospheric parameter, such as PWV, that are good enough to help with the scheduling of service mode observations 12, 24 or even 48 hours in advance.

## Atmospheric water vapour

Atmospheric water vapour content (Kerber et al., 2012a), usually given as the height of the column of precipitable water vapour (in mm), has a strong impact on the transparency of the atmosphere in the infra-red (IR) and submillimetre domains. This parameter has only recently become important at ESO's observatories with introduction of operations for the Atacama Pathfinder EXplorer (APEX) and the Atacama Large Millimeter/submillimeter Array (ALMA) at Chajnantor and the upgraded VLT Imager and Spectrometer for mid-IR (VISIR) instrument on Paranal. For APEX and ALMA each antenna carries a bore-sight radiometer to determine the amount of water vapour in the line of sight. For ALMA, correcting for the phase delay introduced by the PWV is essential to ensure proper operations of the ALMA antennas as an array. On Paranal a low humidity and temperature profiling microwave radiometer (LHATPRO) was installed in support of VISIR and other IR instrumentation in late 2011 (Kerber et al., 2012b).

While there are several ways to determine the atmospheric PWV (Otarola et al., 2010; Querel et al., 2011), APEX, ALMA and Paranal have, for a number of practical reasons, decided to use microwave radiometers as operational monitors. The ALMA antennas each house a custom-made water vapour radiometer (WVR) built by Omnisys (Emrich et al., 2009) while both APEX and Paranal use a commercial radiometer (LHATPRO; Rose et al., 2005) developed and manufactured by Radiometer Physics GmbH (RPG). All of these instruments make use of the same technology and observe an intrinsically very strong $H_2O$ emission line at 183 GHz; see the feature in Figure 1. Hence this line can still be observed under extremely dry conditions (Ricaud et al., 2010; Kerber et al., in preparation). The median PWV on Paranal is 2.5 mm while on Chajnantor it is 1.2 mm. The use of this line and the very accurate and precise receiver technology guarantees that for both sites reliable information on PWV is available at the observatory sites under all — even the driest — conditions. This is crucial since the driest conditions offer the best transparency; in particular both ALMA and APEX are equipped to ob-serve at frequencies above 600 GHz, which become accessible only in very dry conditions from the high site at 5000 metres above sea level.

Here we compare the measured PWV data with a publicly available model (the Global Forecast System [GFS] provided by the US National Oceanographic and Atmospheric Administration) in order to determine whether such a model has enough predictive power or forecasting skill to support advance scheduling.

## Operational need for forecasting at Chajnantor and Paranal

A major difference between APEX and ALMA (Chajnantor) on the one hand, and VLT (Paranal) on the other, apart from the difference in altitude, is that the former are carrying out science observations 24 hours a day, while Paranal's instruments only observe during the night. Another fundamental difference is that millimetre and submillimetre science is clearly driven by atmospheric transparency and hence PWV is the crucial parameter in terms of scheduling. For the optical and IR instrumentation on Paranal, more than one environmental constraint are usually specified by the users, e.g., good seeing, dark sky and photometric conditions may all have to be satisfied at the same time. A case in point are cirrus clouds. It is an observational fact that, on both Paranal and Chajnantor, PWV can be very low in the presence of high-altitude cirrus clouds that consist of ice crystals. Hence, during their formation some PWV is removed from the atmosphere and locked up in the ice crystals. While on Chajnantor, APEX and ALMA would therefore enjoy good atmospheric conditions, observations on Paranal would be negatively affected by the non-photometric conditions due to the cirrus cloud. As a result the PWV forecast provided by the GFS may be directly suitable to guide scheduling for APEX and ALMA, while for the VLT other information likely needs to be considered as well.

## Operational needs for APEX and ALMA (Chajnantor)

Both APEX and ALMA are operated exclusively in service mode to be able to make optimal use of the very different atmospheric transparency as a function of PWV. Figure 1 shows the impact of the range of PWV conditions observed at Chajnantor on the frequency coverage of the ALMA and APEX instrumentation. For conditions with PWV > 5 mm, only the windows below 200 GHz open up for observations with the ALMA Band 3 and 4 receivers. While Chajnantor is one of the best sites worldwide, six years of PWV measurements with the APEX radiometer (plotted as the mean annual variation in Figure 2) have shown that there are strong seasonal variations. In fact, conditions with PWV > 5 mm occur for 26 % of the time, as shown by the frequency distribution of PWV values in Figure 3, especially during the altiplanic winter between late December and mid-March. At APEX, no science operations are possible under such conditions, and major technical activities, such as generator maintenance and instrument installations, are planned during this period. Based on the first four years of PWV measurements, this shutdown period was shifted forward by ten days to make better use of the best weather conditions (see Figure 2). During the period of regular science operations, a reliable prediction of such PWV > 5 mm conditions allows the optimal scheduling of maintenance activities that are not time-critical.

If the PWV drops below 5 mm, more atmospheric bands become progressively available (see Figure 1). For APEX, the main difference in operations occurs when the PWV drops below 2 mm, where the bolometer arrays LABOCA (345 GHz;

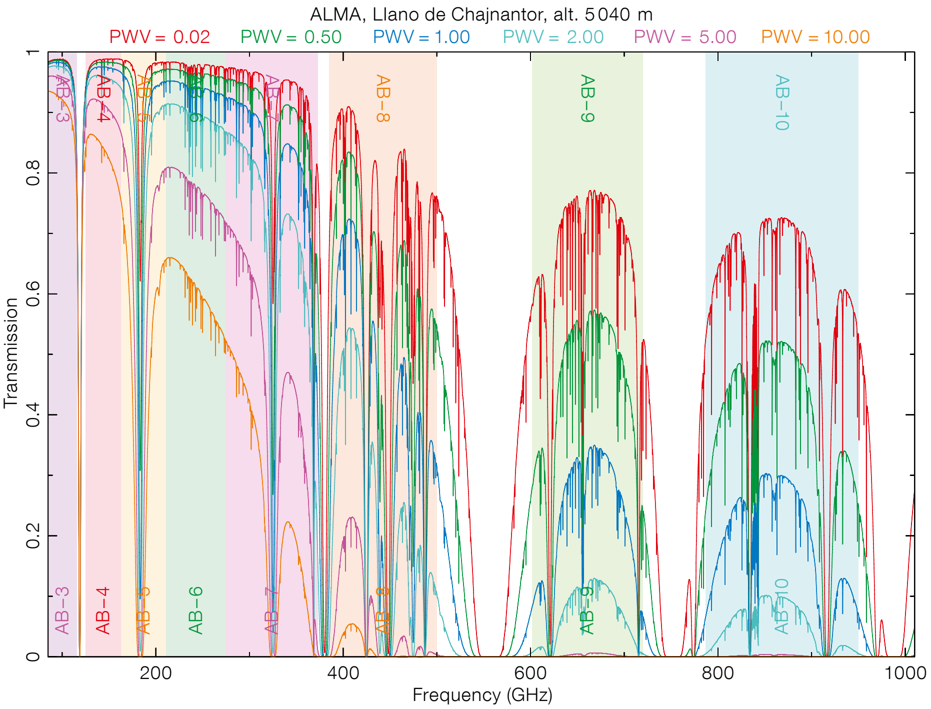
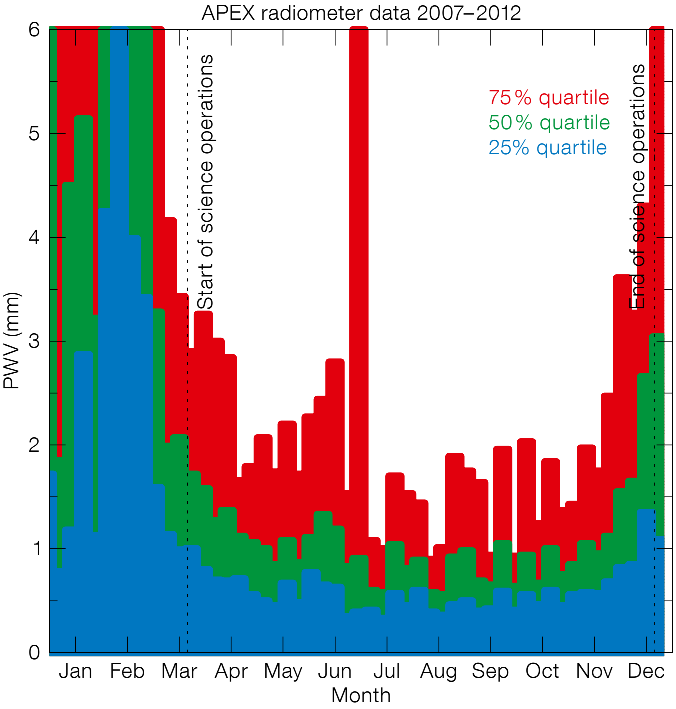


**Figure 1 (above).** Atmospheric transmission as a function of frequency for six different values of PWV distinguished by coloured lines. Note that at frequencies higher than 600 GHz, the atmosphere only becomes sufficiently transparent when the PWV drops below 1 mm. The coloured regions indicate the ALMA bands. Note that the 183 GHz $H_2O$ line used by the radiometers remains prominent even at minimal PWV.

**Figure 2 (below).** Annual variation of the PWV at Chajnantor as measured by the APEX radiometer. Months suitable for science operations deliberately avoid the altiplanic winter conditions from late December until early March. Based on the information from this plot, the timing of the shutdown period was shifted forward by ten days to make better use of the best weather conditions.



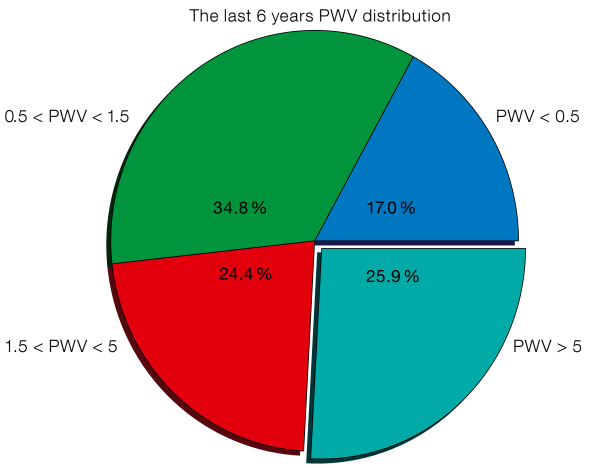


**Figure 3.** Pie chart of the distribution of the PWV values at Chajnantor as measured by the APEX radiometer.

Siringo et al., 2007) and SABOCA (850 GHz; Siringo et al., 2010) can observe. Both instruments are cooled with liquid helium, which requires a daily refill and recycling procedure at the telescope to allow the observations. If the PWV forecast predicts that such conditions will not occur during the next 24-hour period, the cryocooler in these instruments does not need to be recycled, allowing savings to be made on expensive helium consumption. As both LABOCA and SABOCA are installed in the Cassegrain cabin of APEX and the cryostats need to be within ~ 15° from vertical during the condensation phase, there are also restrictions on the elevation of the observations during recycling. If the PWV forecast indicates that a recycling is not needed, these restrictions do not have to be taken into account in the observing plan, allowing the observing time to be used more efficiently.

For the very best weather conditions with PWV < 0.15 mm, even the three THz-frequency windows open for ground-based observations. Such conditions are very rare, occurring only 1.4 % of the time. Currently, only APEX has instruments available to observe at these high frequencies, but feasibility studies have been started to build ALMA Band 11 filters for these wavelengths (Yassin et al., 2013). In order to make optimal use of these best-weather conditions, it is essential to have a reliable PWV prediction to adapt the science observations schedule. In particular, as such instruments are used only rarely, there are fewer calibration plan observations, and it is advantageous to start early within an excellent weather slot to allow sufficient time for the science target observations. The current GFS PWV predictions provide not only a warning several days in advance (Figure 4) that such conditions are likely to occur, but also an indication of the length of time that these THz windows will remain open.

## Operational needs for the VLT (Paranal)

Less than half of the observations at the VLT are performed on site by the astronomers who submitted the proposal, assisted by Paranal staff. The remainder are used for service mode observations, which are executed by ESO staff on behalf of the scientific users. In this case all observations are fully prepared (Phase 2) by the astronomer at his/her home institute using ESO-provided software. The observations are organised into self-contained units, known as observation blocks (OBs), of maximum duration one hour. These are checked for consistency and observing strategy by ESO's User Support Department in Garching, and, once released, are ready for execution at the VLT. As part of the preparation of these OBs the astronomer can impose constraints on the environmental conditions under which each OB will be executed. One such constraint parameter is lunar phase, which can be limited to ensure that very faint targets are only observed during dark time. Similarly, PWV is now being used as constraint for several IR instruments, such as VISIR and CRIRES.

Since OBs are relatively short, several OBs from different programmes can be executed during a given night, e.g., OBs requiring dark time can be executed

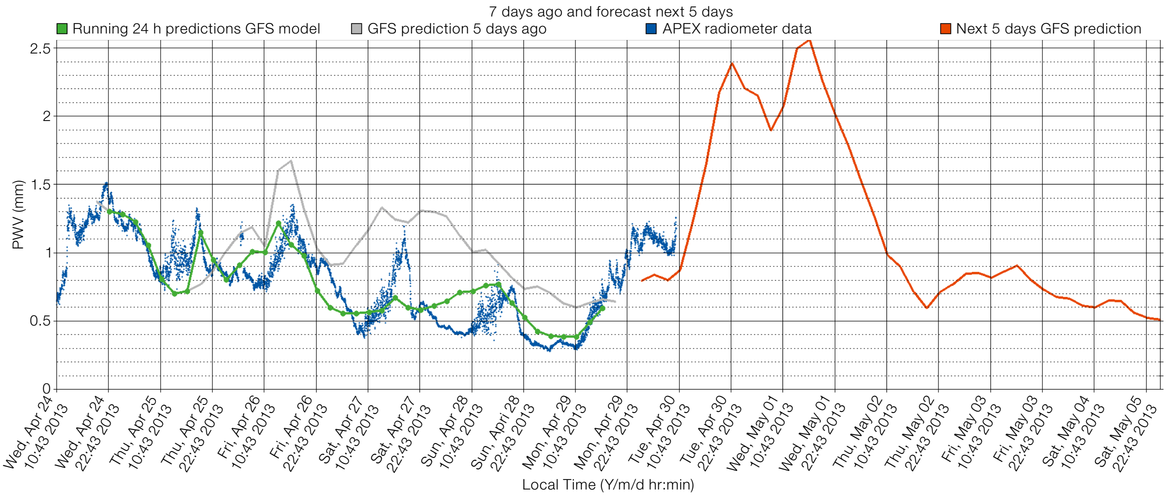


**Figure 4.** GFS PWV predictions for Chajnantor for the following five days (red line). This plot is continuously updated and available[2]. It is used by both APEX and ALMA to plan observations. To judge the reliability of the forecast, the 24-hour and five-day predictions of the last week (green and grey lines respectively) are compared with the APEX radiometer observations (blue dots).

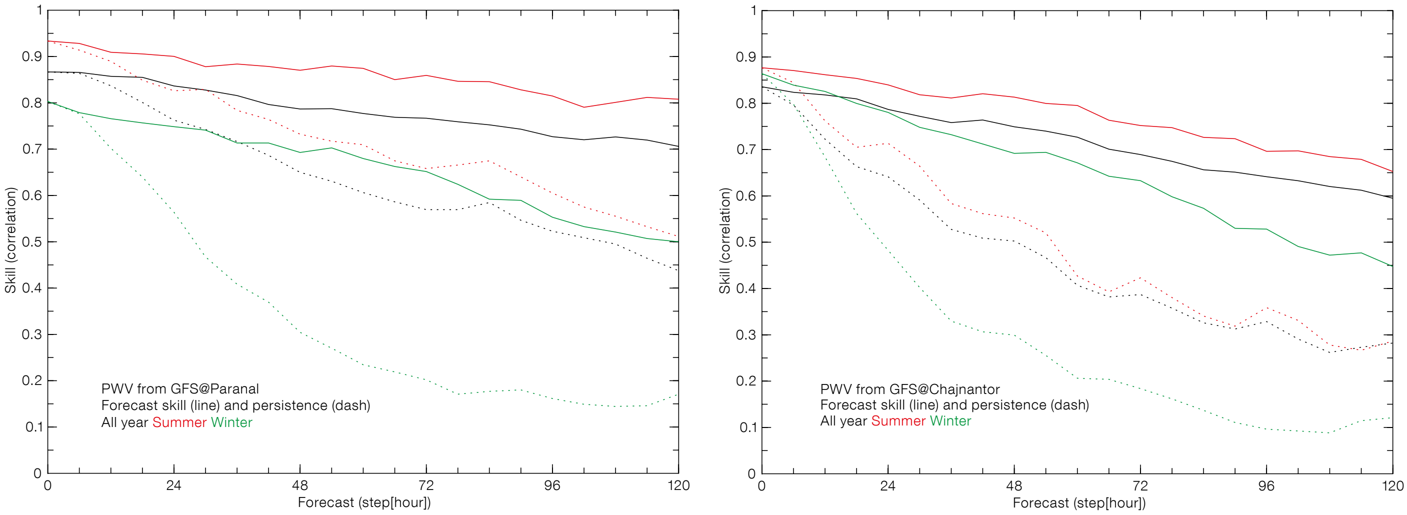


**Figure 5.** GFS PWV forecast skill (as given by the Pearson correlation coefficient) at Paranal (left) and Chajnantor (right) as a function of forecast step up to five days, compared to persistence (dashed lines) for the whole year (in black), summer (red) and winter (green).

before the Moon rises, or after it sets. As the VLT can switch between instruments within about 15 minutes, the flexibility at the telescope is high and the support astronomer can react to changing environmental conditions. Currently, the ESO support astronomer has to select the OBs for execution in real time assisted by scheduling tools which take into account the scientific priority assigned by the Observing Programmes Committee, as well as the probability that the requested conditions such as PWV or seeing are realised. While this works relatively well, it would be highly advantageous if our ability to forecast atmospheric conditions some hours ahead were good enough to prepare a full night of observations in advance. This would enable the use of much more sophisticated scheduling algorithms that could further optimise the scientific output of all telescopes on Paranal. In the context of PWV, a forecast that would reliably predict conditions with an accuracy of about 1.0 mm would permit a general pre-selection of OBs, while an accuracy of 0.25 mm would allow for highly detailed planning. As observations are only done during the night, such a forecast would have to cover a period of eight hours to a maximum of 14 hours with 24 hours advance notice.

## GFS model and output products

The Global Forecast System (GFS) is a global numerical weather prediction system run by the US National Oceanographic and Atmospheric Administration[1]. The GFS model is run four times per day at 0, 6, 12 and 18 UTC. The GFS output is fully public and a web page[2] was designed for ESO in autumn 2010 by the University of Valparaiso to support APEX operation at Chajnantor, displaying up to five days of GFS forecasts of PWV above the Chajnantor Plateau (see Figure 4).

The accuracy of global weather models is improving constantly, but is also very variable, depending on the parameter concerned and the location for which the prediction is made (populated areas are better modelled because more initialisation data is available). It is thus a requirement, before trusting such a product, to compare it to local measurements during a time span long enough to be representative of the weather conditions in the area. This was done at Chajnantor using the APEX radiometer database[3] and the results were convincing enough to extend the service to the Paranal Observatory. Only after enough data had been collected there by the new Paranal PWV monitor could we compare the forecast skill at both observatories, which is the purpose of this article. For this comparison we have used two years of APEX radiometer data at Chajnantor (2011–2012) and one year at Paranal (2012). In Figure 5, the Pearson correlation coefficient of the forecast with the ground-based data is compared to the persistence (i.e., in the absence of a forecast, simply assuming that the current situation persists without change). It is clear on both sites that forecasting winter conditions is more difficult due to higher variability (the correlation of persistence drops below 50% in less than 24 hours). However in all cases the GFS forecasts provide a clear improvement of the extrapolated knowledge of observing conditions on both sites.

One limitation of the model is the spatial resolution of about 40 kilometres per grid point. Hence local effects cannot be expected to be reflected by the model. When local radiometer data is available in real time, it is possible to correct for local biases by applying a Kalman filter trained on, say, the past 14 days of the GFS forecast. Figure 6 shows that Kalman filtering is able to remove the offsets between GFS forecasts and local measurements on both sites. Evidently, the use of the Kalman filter results in excellent statistical agreement between the observed and modelled PWV distribution.

The confidence in the model results can be expressed in terms of hit rate, i.e., the fraction of time that the prediction falls in the same class (distinguished as best, average or worst conditions defined by 33% and 66% of the distribution) as the measured value. The hit rate for the 24-hour forecasts is reported for Chajnantor and Paranal in Tables 1 and 2, respectively, showing that the best conditions are successfully forecast by

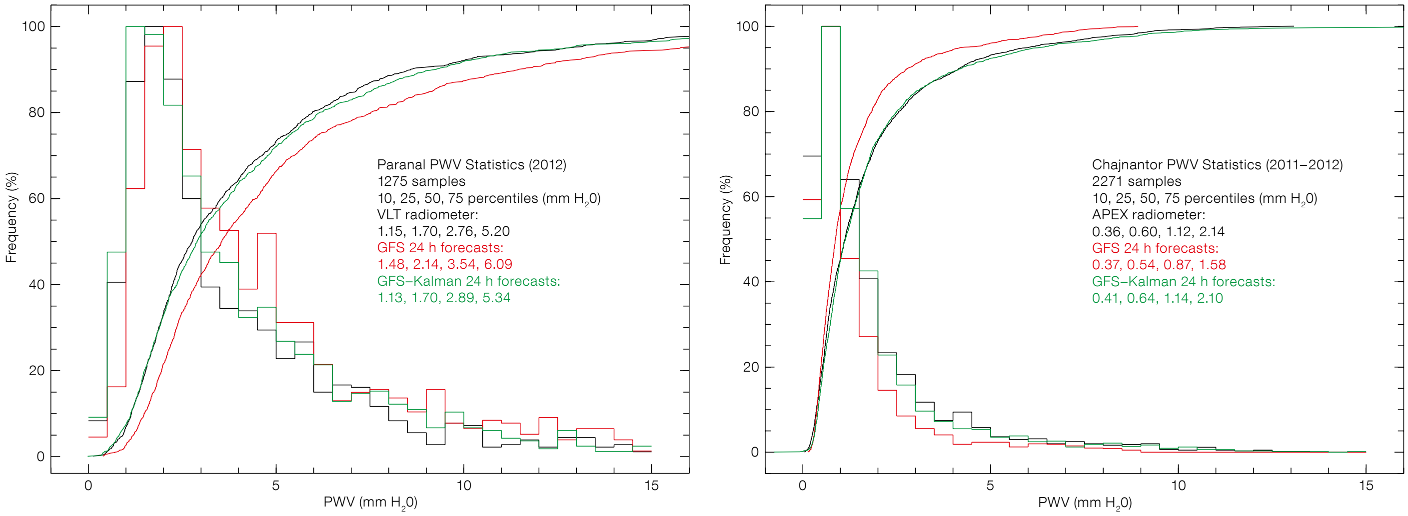


Figure 6. Comparison of the GFS 24-hour PWV forecast, before (red) and after (green) Kalman filtering, to the local radiometer statistics (black) at Paranal (left) and Chajnantor (right) show as normalised histograms and cumulative distributions. The value of the PWV for the 10, 25, 50 and 75 percentiles of the respective database is given in the three cases.

Table 1. 24-hour PWV forecast performance at Chajnantor. Columns refer to the radiometer measurements, while rows refer to the forecasts. The percentage of forecasts falling in each measurement class (Best: PWV < 0.7 mm; Average: 0.7 < PWV < 1.7 mm; and worst: > 1.7 mm) are listed. Percentages in parentheses are obtained after Kalman filtering.

| GFS (Kalman) PWV | Radiometer PWV | | |
|---|---|---|---|
| | Best | Average | Worst |
| Best | 86(67) | 13(29) | 1(4) |
| Average | 27(18) | 66(62) | 7(20) |
| Worst | 5(2) | 35(23) | 60(75) |

Table 2. 24-hour PWV forecast performance at Paranal. Columns refer to the radiometer measurements, while rows refer to the forecasts. The percentage of forecasts falling in each measurement class (Best: PWV < 2.0 mm; Average 2.0 < PWV < 4.2 mm; and Worst: PWV > 4.2 mm) are listed. Percentages in parentheses are obtained after Kalman filtering.

| GFS (Kalman) PWV | Radiometer PWV | | |
|---|---|---|---|
| | Best | Average | Worst |
| Best | 56(70) | 36(25) | 8(5) |
| Average | 9(26) | 62(53) | 29(21) |
| Worst | 1(2) | 9(19) | 90(79) |

GFS 86 % of the time at Chajnantor, with a negligible risk of being misled. When using Kalman filtering, the hit rate reaches 70 % for the best conditions at Paranal. Note that the Kalman filter can add non-physical noise which may reduce the hit rate, e.g., in presence of strong diurnal trends. An optimisation study is underway.

## Outlook for ESO

We have *post facto* compared the values of PWV observed at Chajnantor (two years) and Paranal (one year) with the forecasts provided by a standard atmospheric model (GFS). Agreement is very reasonable and by use of a two-week Kalman filter, excellent statistical agreement can be achieved. A comparison with the persistence assumption shows that the GFS model has significant predictive power. The GFS forecast is particularly useful for ALMA and APEX since their science performance is mostly driven by atmospheric transparency and hence PWV. In addition such a forecast helps to optimise the cooling cycles of instruments, with a direct impact on operational costs.

For Paranal and the VLT instruments, PWV is of course only one aspect of the relevant properties of the atmosphere and more than one constraint needs to be met for optimal science performance. For this more sophisticated application, (meso-scale) models will be required. Such work is also in progress at ESO.

The GFS-based model has demonstrated its value for science operation at ESO observatories. PWV forecasts are now available for Chajnantor[4] and Paranal[5]. We expect that forecasts of specific atmospheric properties will become routine in the era of extremely large telescopes, helping to optimise their scientific performance.

### Acknowledgements

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### References

Emrich, A. et al. 2009, 20th International Symposium on Space Terahertz Technology, 174
Kerber, F. et al. 2012a, Proceedings of the SPIE, 8448, 84463N
Kerber, F. et al. 2012b, The Messenger, 148, 9
Otarola, A. et al. 2010, PASP, 122, 470
Querel, R. R., Naylor, D. A. & Kerber, F. 2011, PASP, 123, 222
Ricaud, P. et al. 2010, IEEE Transactions Geoscience and Remote Sensing, 48, 1365
Rose, T. et al. 2005, Atmospheric Research, 75, 183
Siringo, G. et al. 2007, A&A, 497, 954
Siringo, G. et al. 2010, The Messenger, 139, 20
Yassin, G. et al. 2013, 23rd International Symposium on Space Terahertz Technology, Tokyo, in press

### Links

[1] Global Forecast System (GFS): http://www.ncdc.noaa.gov/model-data/global-forcast-system-gfs
[2] GFS PWV prediction plot for Chajnantor: http://www.apex-telescope.org/weather/RadioMeter/index.php
[3] APEX radiometer database: http://archive.eso.org/eso/meteo_apex.html
[4] Chajnantor PWV forecast: http://www.eso.org/astclim/forecast/gfs/APEX/index.php
[5] Paranal PWV forecast: http://www.eso.org/astclim/forecast/gfs/VLT/index.php