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# PRECIPITABLE WATER VAPOUR OVER LA SILLA PARANAL OBSERVATORY

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RESUMEN

En apoyo a la caracterización de sitios potenciales para el European Extremely Large Telescope (E-ELT), la ESO (European Southern Observatory), ISIS (Institute for Space Imaging Science) y el grupo de Astrometeorología de la Universidad de Valparaíso han establecido conjuntamente una mejor comprensión del PWV (precipitable water vapour) sobre los Observatorio de ESO: La Silla y Paranal. Hasta ahora se han analizado estadísticamente 8 años válidos de espectros de alta resolución tomados con VLT-UVES para reconstruir la historia del PWV sobre Paranal. En el caso de La Silla se han usado 5 años de datos tomados con FEROS. En este análisis se utilizó un modelo de transferencia radiativa (BTRAM), desarrollado por ISIS. Tres campañas de medición fueron realizadas en mayo, agosto y noviembre de 2009 para entender mejor los errores sistemáticos presentes, y donde se validaron varios instrumentos y métodos con respecto a radiosondeos, que es la observación estándar en la investigación atmosférica. Después de corregirse los efectos sistemáticos, se encontró la mediana de PWV de 2.4 mm para Paranal mientras que el valor para La Silla es de 3.7 mm. Los resultados del estudio fueron presentados al Comité Asesor para la selección del sitio E-ELT en 2009. Se aprendieron lecciones valiosas para las operaciones del observatorio y ESO está planeando utilizar permanentemente un monitor de vapor de agua en Paranal como parte del proyecto para mejorar VISIR. Un monitor de PWV autónomo y de alta resolución será esencial para optimizar los resultados científicos de E-ELT.

ABSTRACT

In support of characterization of potential sites for the European Extremely Large Telescope (E-ELT) the European Southern Observatory (ESO), the Institute for Space Imaging Science (ISIS) and the astrometeorology group of the Universidad Valparaiso have jointly established an improved understanding of atmospheric precipitable water vapour (PWV) above ESO's La Silla Paranal Observatory. To this end we have statistically analysed 8 years worth of high resolution spectra taken with VLT-UVES to reconstruct the PWV history above Paranal. For Silla data from FEROS covering about 5 years have been used. In the analysis a radiative transfer model of Earth's atmosphere (BTRAM) developed by ISIS has been employed. In order to better understand the systematics involved three dedicated campaigns were conducted in May, August and November 2009 during which several instruments and methods were validated with respect to balloon-borne radiosondes, the established standard in atmospheric research. After correction for systematic effects a median PWV of 2.4 mm is found for Paranal whereas the value for La Silla is 3.7 mm. The results of the study were submitted to the E-ELT site selection advisory committee late in 2009. Valuable lessons for observatory operations have been learned and ESO is planning to permanently deploy a water vapour monitor on Paranal as part of the VISIR upgrade project. For the E-ELT we find that a stand-alone high time resolution PWV monitor will be essential for optimizing the scientific output.

*Key Words:* atmospheric effects — balloons — instrumentation: spectrographs — methods: observational — site testing — techniques: spectroscopic

## 1. INTRODUCTION AND GOALS

Precipitable water vapour (PWV) is the most important contributor to the opacity of Earth's atmosphere in the infrared domain. Hence the amount of PWV determines the transmission of the atmosphere which in turn is crucial for astronomical observations. On long time scales PWV determines how well a site is suited for IR astronomy, while in

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an operational sense reliable knowledge of the content of PWV during a given night is critical for the success and quality of science observations. For the project to characterize potential sites for the European Extremely Large Telescope (E-ELT) we set the following goals:

1. Reconstruct record of precipitable water vapour over Paranal and La Silla
2. Correlate results from archival data with satellite data to establish Paranal and La Silla as reference sites for E-ELT site evaluation
3. Evaluate merit of methods for operational use at an observatory

Goals 1 and 2 address the long-term aspect which is of course fundamental for site selection. Goal 3 was added in order to extract lessons for science operations of current and future observatories.

## 2. HISTORY OF WATER VAPOUR OVER LA SILLA PARANAL OBSERVATORY — GOAL 1

A number of methods exist for measuring the amount of water vapour in the atmosphere. It is usually given in units of mm representing the vertical column abundance of precipitable water vapour (PWV). In the context of site testing for all three ELT projects (Kerber et al. 2010a; Thomas-Osip et al. 2010; Otárola et al. 2010) significant progress has been made in this area. For our analysis we used the BTRAM code, a multi-layer atmospheric radiative transfer model (Chapman 2003) developed at the Institute of Space Imaging Science which enabled us to obtain precise PWV measurements from absorption line spectroscopy in the wavelength range 580–980 nm. The model uses input data from HITRAN (Rothman et al. 2009) and employs a profile of the distribution of water vapour in the atmosphere. A detailed description of the modeling approach is given in Querel et al. (2011).

For reconstructing the history of PWV over the La Silla Paranal Observatory we used about 1500 UVES flux standard calibration observations from the archive taken during the period 2001 to 2008 (Kerber et al. 2010a). With their almost flat and featureless stellar continuum these white dwarfs are particularly well suited for this study. Similarly standard star observations (≈1700 spectra) taken with FEROS have been used to make an equivalent analysis for La Silla (2005–2009 data) which is described in detail by Querel et al. (2010).

A median PWV of 2.4 mm is found for Paranal (Table 1) based on UVES data covering the period 2001–2008 and accounting for a dry-bias. The standard deviation given describes the scatter seen between the years, while the number in parenthesis indicates the seasonal variations within a year. This value is in excellent agreement with the previous PWV results reported for site testing for VLT. For La Silla a value of 3.7 mm is found (Table 2) in good agreement with the findings of the GMT group for Las Campanas (Thomas-Osip et al. 2007, 2010).

It is important to note that PWV over both Paranal and La Silla shows pronounced seasonal variations. As a result conditions encountered during the course of a year will be significantly better as well as worse than what one would expect from the median. Tables 1 and 2 therefore also list the percentage of nights with PWV conditions well suited for IR observations. These seasonal variations are stable over the years, with periods of high PWV occurring during the Southern summer when the sites are partially affected by the invierno altiplanico.

In order to better understand the systematics we conducted three campaigns over La Silla (May 2009) and Paranal (Aug and Nov 2009) launching a total of 70 radiosonde balloons mostly during night time (Kerber et al. 2010a; Querel et al. 2010; Chácon et al. 2010). The absolute accuracy of PWV derived from radiosondes is an important issue in this context. In the literature an absolute accuracy of 5% overall is reported and of order 15% in very dry conditions (Wang et al. 2007; Schneider et al. 2010). One also has to keep in mind that a radiosonde samples data along its trajectory which carries it to about 20 to 25 km altitude over the course of about an hour while traveling a horizontal distance of 80–150 km. PWV is then derived from the profile for the whole column although water vapour is concentrated in the lower few kilometers. Hence the radiosondes and astronomical spectrographs are not sampling the same column of air and a 1:1 agreement between retrieved PWV is not to be expected even under very stable conditions. Very good agreement between various instruments and the radiosondes has been found with the infrared radiometer IRMA providing the best agreement (Naylor et al. 2008; Kerber et al. 2010a). These results have been used to correct for small (10%) systematic effects in the archival data. It is important to note that the actual distribution of water vapour in the atmosphere is unknown for all archival data regardless of the source, since this can only be provided by contemporaneous radiosonde launches. The scale height of water vapour is variable, therefore all results based on archival data are affected by unknown and uncorrectable systematic errors of up to 20% as a consequence of using a median profile.

TABLE 1

HISTORY OF PWV OVER PARANAL 2001–2008

| Instrument | Median PWV [mm] | Fraction of nights with PWV | | |
|---|---|---|---|---|
| | | <1 mm | <1.5 mm | <2 mm |
| UVES | $2.1 \pm 0.3$ (2.2) | 13.5% | 32% | 47.3% |
| GOES | $2.4 \pm 0.5$ (1.8) | 4.8% | 18.9% | 38% |
| MERIS | $2.7 \pm 0.3$ (2.0) | 1.5% | 7.9% | 29% |

TABLE 2

HISTORY OF PWV OVER LA SILLA 2005–2009

| Instrument | Median PWV [mm] | Fraction of nights with PWV | | |
|---|---|---|---|---|
| | | <1 mm | <1.5 mm | <2 mm |
| FEROS | $3.4 \pm 0.4$ (2.4) | 3.3% | 9.2% | 18.4% |
| GOES | $5.9 \pm 0.5$ (2.5) | 0.4% | 0% | 1.8% |
| MERIS | $3.6 \pm 0.5$ (2.3) | 0.8% | 11.2% | 20% |



## 3. CORRELATION WITH SATELLITE DATA — GOAL 2

The UVES/FEROS data sets are essential in providing the ground truth for the calibration of satellite data taken with the geostationary GOES satellite and ENVISAT in sun-synchronous, low Earth orbit. GOES and MERIS provide rather different data in terms of spatial and temporal resulotion and use different measuing techniques, see Kerber et al. (2010a) and Querel et al. (2010) for details.

When comparing the PWV values derived from the ESO archival spectra and the satellite data one has to keep in mind that these approaches are different in a number of important aspects. In the ground-based case the observations sample a very small volume of the atmosphere – a single line of sight towards a star. The satellite-borne instrument looks down recording an average of PWV over its field of view a few square kilometers in size. The ground-based telescopes use a stellar continuum as a background source while the satellites rely on sun light reflected by the Earth (MERIS) or emission from the Earth's atmosphere (GOES). In all cases a model of the Earth's atmosphere including a profile of the spatial distribution of water vapour is required to derive PWV from the measurements. For Paranal very good quantitative agreement between UVES and the satellite data is found. No zero-point offsets or scaling factors have been applied when comparing the data sets. For GOES data a value of 2.4 mm is reported while for MERIS the median PWV is slightly higher at 2.7 mm. A detailed analysis shows that MERIS systematically overestimates PWV under very dry conditions, leading to a wet bias in the median (Kerber et al. 2010a). Hence Paranal can be used as a reference site for calibration of remote sensing data taken by satellites.

In the case of La Silla (Table 2) for which no good local atmospheric profile is available substantial deviations between the FEROS data and satellite observations have been found for GOES which also has limited spatial resolution while agreement with MERIS is very satisfactory.

It is important to note that GOES data are not suitable for supporting nightly observatory operations because significant deviations of PWV (both over- and underestimations) have been found depending on conditions. Still, it is safe to assume that GOES data can be used successfully for statistical characterization of sites in terms of PWV provided a substantial time base is used and provided the environment is very homogeneous as is the case for Northern Chile.

## 4. MERIT OF METHODS FOR SCIENCE OPERATIONS — GOAL 3

An essential element in conducting service-mode observations in a ground-based observatory is the predictability of the quality of observations. Ideally, one matches the science needs of a particular observ-

TABLE 3

PWV AS A USER DEFINED CONSTRAINT FOR PARANAL

| Period of Year | Mean PWV (monthly) [mm] | Fraction of UT time time needed by VISIR | PWV constraint [mm] |
|---|---|---|---|
| Aug – Nov | 1.5–1.8 | 3.5–7% | 0.6–1.1 |
| Dec – Mar | 2.5–5 | 4–11% | 1.2–2.5 |
| Apr – Jul | 1.8–2.7 | 5.5–11% | 0.9–1.25 |

ing programme to the prevalent conditions at the time of observations, thereby optimizing the scientific output of the observatory. In the optical regime, ESO has pioneered this approach by allowing the user to specify the seeing, sky brightness and atmospheric attenuation etc. under which observations can be carried out. However, no such information is available on atmospheric transparency in the IR.

We plan to deploy –as part of the VISIR upgrade project (Kerber et al. 2010b)– a high time-resolution, high precision, stand-alone PWV monitor providing data in near-real time which is fully integrated in the Paranal infrastructure. This will allow us to introduce PWV as a user-defined constraint, and will thereby enable us to match the scientific needs of each observing programme to the actual atmospheric transparency in the IR. Users will be provided with information on the impact of PWV as a function of wavelength and instrument mode in the VISIR Exposure Time Calculator (`http://www.eso.org/observing/etc`), based on which they will set a reasonable constraint on PWV. For this, some knowledge of the fraction of time under which a certain PWV value occurs on Paranal is necessary. Observations with VISIR account for about 6.5% of UT3 time in a given period. An analysis taking into account the actual distribution of VISIR targets in the sky resulted in achievable PWV constraints (final column) as a function of the seasons (Table 3).

This development will take place in the course of the VISIR upgrade project during the remainder of 2011 and early 2012 and will become available to the observers by mid-2012.

## 5. CONCLUSION

All three goals of the PWV project have been met and the results have been forwarded to the site selection advisory committee for the E-ELT in time for their evaluation. Paranal has been validated as a reference site for using remote sensing data. It is representative for other sites in Northern Chile and offers considerably better conditions for IR astronomy than La Silla. Further work to better understand the role of atmospheric PWV and its systematics is currently underway in collaboration with the TMT and GMT groups. A PWV monitor will be permanently deployed on Paranal as part of the VISIR upgrade project and similar monitoring will be most useful for operations of the ELTs in order to maximise the sceintific output.

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