Título: PRECIPITABLE WATER VAPOUR AT THE CANARY ISLANDS ASTRONOMICAL OBSERVATORIES

Nombre: Castro Almazán, Julio A.

Universidad: Universidad de La Laguna

Departamento: Astrofísica

Fecha de lectura: 22/04/2019

Programa de doctorado: Programa de Doctorado en Astrofísica por la Universidad de La Laguna

Dirección:

> **Director:** CASIANA MUÑOZ TUÑÓN

> **Codirector:** Ángel Alonso Sánchez

Tribunal:

> **presidente:** EMILIO CUEVAS AGULLO

> **secretario:** FRANCISCO GARZÓN LÓPEZ

> **vocal:** ALMUDENA ALONSO HERRERO

Descriptores:

> ASTRONOMIA Y ASTROFISICA

> CIENCIAS DE LA ATMOSFERA

> METEOROLOGIA POR SATELITES

El fichero de tesis ya ha sido incorporado al sistema

Localización: PRECIPITABLE WATER VAPOUR AT THE CANARY ISLANDS ASTRONOMICAL OBSERVATORIES

Resumen: The Canary Islands (Spain) host two of the best considered astronomical observatories in the World, Teide Observatory (OT), on the island of Tenerife, and Roque de los Muchachos Observatory (ORM), on the island of La Palma. A crucial parameter to carry out astronomical observations in the infrared (IR) and microwave (μW) bands, is the content of precipitable water vapour (PWV). In this thesis dissertation I have studied the PWV statistical behaviour in the Observatories, after set-up, optimize and calibrate two monitors based on the Global Navigation Satellite System (GNSS) technique.

The main objective of this work is to validate continuous real-time PWV monitors at both Observatories based on the GNSS signal delays. The system had to be optimized and calibrated. The achievement of this goal allowed both, supporting an efficient operation of the astronomical facilities at the Observatories, and a reliable characterization of the PWV conditions.

In the thesis I have:
\begin{itemize}

\item Reviewed the previous works on PWV for Astronomy at the Observatories.
\item Analyzed the behavior of the surface climatological parameters related to the amount of PWV at the Observatories.
\item Revised the water vapour fundamental optical and thermodynamical properties in the atmosphere, the impact on Astronomy and the implications in the GNSS atmospheric delays.
\item Reviewed the GNSS technique for PWV determination.
\item Studied the bias and error sources, propagated them and identified the dominant components.
\item Identified and implemented updates and improvements of the technique, reducing the errors, to optimize the use of GNSS antennas as high precision PWV monitors.
\item Estimated the method detection limit.
\item Setup local 24h$/365$d PWV routine monitors at both Observatories, based in the public data of the GNSS antennas forming part of the international Geodesy networks (GNSS PWV Monitors, PWVMo).
\item Developed a general semi-empirical error model (SEEM) for PWV retrieval with radiosoundings, to validate them as accurate calibrators for the PWVMo.
\item Analyzed the PWV vertical structure of the local troposphere at the Canary Islands based on the empirical parameters obtained in the setup of the SEEM.
\item Calibrated the PWVMo at the Observatories using a set of simultaneous high resolution radiosounding profiles, and obtained formulas for the calibration and for the final errors.
\item Generated and calibrated a 9-year continuous time-series of PWV data at both Observatories.
\item Carried out a statistical analyses, generated normal values, and thresholds with focus in the night-time IR astronomical observations.
\item Pushed further works and applications based on the results, and potential future researches.
\end{itemize}

The principal results are following. The mesoscale climate conditions at the Canarian Observatories show that the temperature is dominated by a soft profile, with very sporadic and moderate extremes events and with the daily temperature ranges also low. Rainfall is very rare an with no extreme episodes. The median rainfall is 287~mm~a^{-1}.

The two PWV monitors based on the GNSS technique operate in two modes: real time values based on predicted $ultra-rapid$ orbits (\emph{rapid} mode), and archive values based on $rapid$ (close to definitive) orbits (\emph{final} mode). We validated the technique, analyzed the bias and error sources. To optimize the monitors, we have set up local high precision barometers and obtained a local weighted average temperature of the atmosphere as a function of the surface temperature ($T_m = 55.3 + 0.79~T_s~\textrm{[K]}; \rm{rmse}=2.6\,\textrm{K}$). This result reduce to close than a half the rmse previously reported in the literature. The raw PWV un-calibrated error estimation is ≈0.65~mm.

The median relative error obtained with SEEM (error model) for PWV retrieval from radiosounding balloons is $2.0\pm0.9\%$. This result reduces by more than a half the uncertainties previously reported in the literature. The empirical parameters obtained for SEEM show that the PWV experiences an extremely fast decay, while ascending in the troposphere over the Canary Islands, compared with other sites in different latitudes.

The direct comparison of the GNSS measurements with an independent dataset of simultaneous values retrieved from 50 high resolution radiosounding balloons (50 flights spanning 1 year), gave a correlation of 0.994 with a rmse of the residuals of 0.44~mm in the most favourable case, the OT, where the maximum proximity with the balloon launching station is achieved, and 0.70~mm at ORM. The calibration equations are PWV$=0.99\cdot\text{PWV}_\text{PWVMo-OT}\,-1.04$~[mm] and PWV$=0.97\cdot\text{PWV}_\text{PWVMo-OT}\,-1.39$~[mm], for OT and ORM, respectively.

The final errors for the calibrated PWV values obtained with the PWVMo at the Observatories are ~0.8 and ~1.0~mm, for PWV conditions up to 4~mm at OT and ORM, respectively. The difference is due to the larger distance between the launching station of the calibration balloons and the ORM. The error equations are $\epsilon_{OT,final}=0.02\cdot(\text{PWV}^2+1575)^{1/2}$~[mm] and $\epsilon_{ORM,final}=0.05\cdot(\text{PWV}^2+~391)^{1/2}$~[mm].

The detection limit of the PWVMo has been estimated to the 95\% of confidence, at both observatories, obtaining 1.33~mm at OT and 1.68~mm at ORM (\emph{final} mode). With sustained PWV conditions of at least 2 hours, the detection limit falls to less than 0.6 and 0.75~mm, at OT and ORM, respectively. These results significantly reduces the detection limit previously reported in the literature and allow to consider the PWVMo as valid tools for characterizing extremely low PWV conditions.

The median calibrated PWV is 3.4 and 3.9~mm, for OT and ORM, respectively (night-time values). The difference of 0.5~mm is explained by the ~200~m of difference in altitude between both antennas. The 25% of the time, the PWV is lower than 1.7~mm. The average percentage of time with sustained optimal conditions (PWV<2~mm) for periods up to 2~h is 27%, and for periods up to 6~h is 18%. A strong homogeneity and correlation is found between both Observatories.

All these results together demonstrate that the Canary Is. Observatories (ORM and OT) present very good conditions for IR astronomical observations, in terms of stability and low PWV content, with a significant part of time with optimal conditions. The GNSS technique has been validated and prepared to efficiently support daily operation in the IR and μW. Additionally, GNSS has become the ideal technique for validating other ongoing projects of operational tools, such as the numerical PWV forecasting.