Precipitable water vapour content above the Roque de los Muchachos observatory from GPS estimations

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ABSTRACT

The requirements for current large and future extremely large telescopes as well as the quick development of IR instrumentation demand a proper characterization of precipitable water vapour (PWV) above astronomical sites. A comparison of PWV estimations from a photometer and a GPS (Global Positioning System) above the Observatorio del Roque de los Muchachos (ORM, La Palma, Canary Islands, Spain) was carried out and it was found a linear relation between both measurements. Such relationship will allow the calibration of the GPS measurements recorded at ORM for the period June 2001- December 2008. These large time series of PWV estimations from GPS were used to perform a statistical analysis of water vapour content above this astronomical site. Average annual value of night-time PWV of 4.86 mm was found. It was also found a clear seasonal behavior of the PWV above ORM, with smaller water-vapour columns during winter nights (average 3.36 mm). The largest values of PWV are reached in the summer nights (average 6.75 mm). The data indicate that a significant percentage of nights (~38%) are well suited for thermal infrared observations (with PWV < 3 mm), and 71% of nights present a "fair" or better IR observation opportunity at ORM.

Keywords: Site testing, infrared conditions, water vapor, GPS

1. INTRODUCTION

The infrared quality of an observing summit depends on the infrared atmospheric transmission. There are specific spectral regions showing high transmission and even uses to present a few transparent windows (Figure 1). Out of these windows, the atmosphere is opaque and observations at such wavelengths are only possible from space.

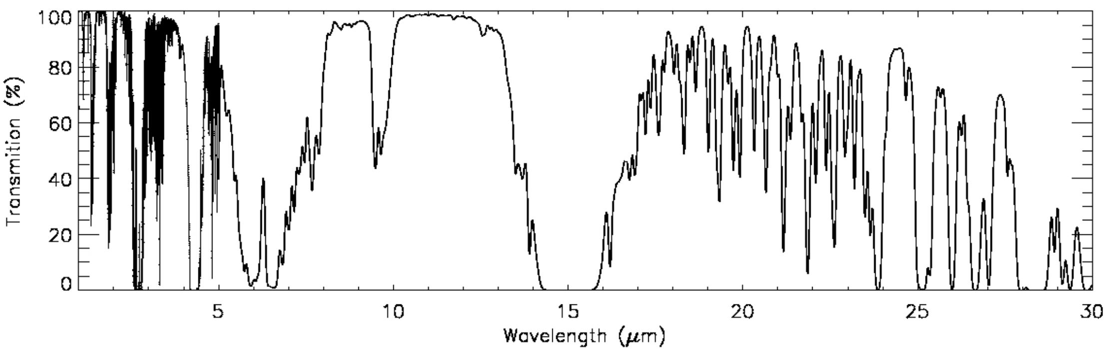

Figure 1: Zenith model atmospheric transmission spectrum from 1 to 30 µm above Mauna Kea for 1 mm precipitable water vapor (http://staff.gemini.edu/~kvolk/nirtrans.html).

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The amount of water vapour in the atmosphere strongly affects the IR observations from ground level reducing the transmission in the IR atmospheric windows and producing absorption bands that are difficult to correct during the data processing. In this sense, sites with smaller water vapor contents are the best for IR observations. The astronomical community assumes that sites placed at higher altitudes have lower water vapour content are more suitable for IR observations. However, this idea was discussed in terms of the troposphere thickness in García-Lorenzo, Fuensalida, & Eff-Darwich (2004) instead of the altitude of the site above the sea level. The issue seems to be not that simple, and, for example, the evaluation of the IR quality at the Observatorio del Teide (OT) in the Canary Islands, Spain (Mountain et al. 1985) and the comparison with predicted models (Cohen 1993) indicate that OT, at 2400 m above sea level, could be as good as Mauna Kea (4100 m) for IR astronomy in the 1-5 μm window (Hammersley, 1998). Observational results pointing to a similar conclusion have been found at the Observatorio del Roque de los Muchachos (ORM) on the island of La Palma (Canary Islands, Spain), also at 2400 m above sea level, when comparing infrared observations from the 3.58m Telecopio Nazionale Galileo (TNG) with data obtained at the 10m Keck telescope on Mauna Kea astronomical observatory (Hawaii, USA) (http://www.tng.iac.es/news/2003/03/21/nics_refurbish).

There are many parameters accounting for the quality of an astronomical site, such as seeing, cloud cover, ground winds, high-altitude winds, etc (See Muñoz-Tuñón et al. 2007 for a summary of these parameters at the ORM). The water vapour content is the parameter affecting the IR quality of astronomical sites. The progress in the development of IR instrumentation and the requirements for current large and future extremely large telescopes demands a proper characterization of PWV. Statistical studies with high temporal databases covering years are necessary. The fraction of nights with good IR conditions (small column of water vapour) along the months of the years will allow defining the optimum telescope scheduling.

2. TECHNIC AND DATA

The total atmospheric water vapour contained in vertical column of unit cross-sectional area extending between any two specified levels is labeled as precipitable water vapour and it is commonly expressed in terms of the height to which that water substance would stand if completely condensed and collected in a vessel of the same unit cross section (American Meteorological Society 2000). PWV is also referred to as the total column water vapour (Ferrare et al. 2002). Measurements of PWV can be obtained in a number of ways, from in situ measurements (radiosondes) to remote sensing techniques (photometers, radiometers, GPS, Imaging Spectroradiometers on satellites). Radiosondes have been the primary in situ observing systems for monitoring water vapour, but their use is restricted by their high operational costs and decreasing sensor performance in cold dry conditions (Li et al. 2003). Usually, radiosondes are expected to measure PWV with an uncertainty of a few millimetres, which is considered to be the standard accuracy of PWV for meteorologists (Niell et al. 2001). Errors of 20% or below are estimated for PWV measurements using radiometers and photometers in the range 3-10 μm, whereas errors in the 0.5-1μm range can be as high as 40% (Quesada 1989). GPS is an increasingly operational tool for measuring PWV, which has gained a lot of attention in the meteorological community. Agreements of 1-2 mm of PWV between GPS, radiosondes and microwave water vapour radiometers (WVR) have been reported (Emardson et al. 2000; Niell et al. 2001; Li et al. 2003).

The Roque de los Muchachos Observatory (ORM hereafter) is located at latitude 28^0 45´ N, longitude 17^0 53´ and an altitude of 2346 m above sea level on the island of La Palma (Canary Islands, Spain). The ORM is one of the best positioned candidate sites for the location of the European Extremely Large Telescope (E-ELT). Different campaigns to obtain measurements on PWV above ORM were carried out during the Gran Telescopio de Canarias (GTC) site prospection using two photometers operating in the 940-nm water vapor band (Kidger et al 1998; Kidger, Pinilla, & Rodriguez-Espinosa 2002; Pinilla, Kidger, & Rodriguez-Espinosa 2002; Pinilla 2003). The reference photometer instrument for GTC site prospection was labelled IAC2 (Pinilla 2003), which will be also adopted as the reference in this work in order to calibrate GPS estimations of PWV.

2.1 Photometer measurements

The basics of the photometer measurement and its calibration were presented in Pinilla (2003) and it is briefly summarized here. For details on technical aspects of the photometers used in the GTC campaigns see Kidger et al.

(1998). The photometer measures the entire 0.94 nm water vapour absorption line and nearby continuum pointing to the Moon (Quesada et al. 1989; Gao et al. 1993). This remote sensing technique assumes a plane-parallel atmosphere, so it is only satisfactory for measurement near the Zenith. Moreover, it is limited to bright enough nights (from first quarter to last quarter moon).

The monitoring of the precipitable water vapor above ORM carried out during the GTC site prospection span from February 2000 to July 2002. Two photometers were used in the firsts GTC campaigns from February 2000 to July 2001. Both photometers were previously calibrated in a range from 0.5 to 25 μm of water vapour and it was shown a great agreement between both instruments. IAC2 was selected to be the reference instrument for the rest of the GTC prospection campaigns, and it was also adopted as the reference for PWV measurements in this work.

From June 2001 to July 2002 – period where GPS data were also recorded –, 243 individual PWV estimations above the ORM were obtained using IAC2, which are monthly distributed as it is shown in figure 2. The last photometer campaign at the ORM was in summer 2002. Photometer measurements were taken about 30 minutes each.

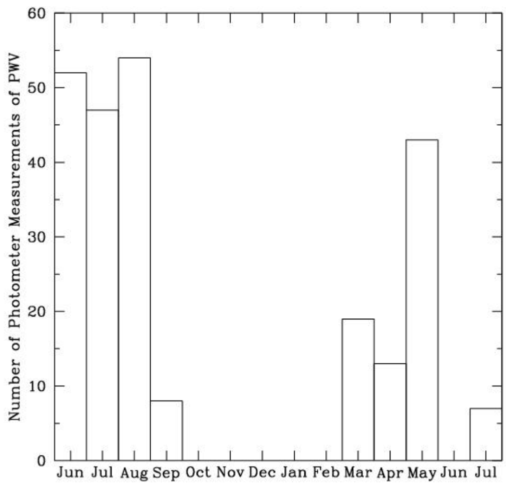

Figure 2: Distribution of precipitable water vapour measurements obtained through the reference photometer for GTC prospection campaigns from June 2001 till July 2002.

2.2 GPS measurements

The refraction index of the troposphere (n_t) depends on the air pressure, temperature and water vapor pressure. Variations of n_t can drastically affects the propagation of electromagnetic waves, inducing a delay in any signal crossing it. This delay is due to two distinct effects: a hydrostatic and a water vapor delay. The hydrostatic delay is very stable and has a direct relationship with local atmospheric pressure. The second component is directly related to the local water vapor in the atmosphere at the site where the measurements are taken and can vary more rapidly in time being difficult to measure and predict. It has been found (e.g. Bevis et al. 1994; Boccolari et al. 2006; Jin et al. 2008) that it is possible to estimate the water vapor to a high degree of accuracy through calculating the overall tropospheric delay at a GPS station.

The Spanish Instituto Geográfico Nacional (IGN) has installed permanently a GPS receiver at ORM since May 2001. The GPS antenna is placed on a very stable monument which ensures that the GPS satellite data recorded at the station does not contain any spurious antenna movement that could affect the scientific exploitation of the GPS data. This permanent GPS is part of an international network of GPS stations called EUREF (Bruyninx 2004; www.euref.eu). Soluciones Avanzadas Canarias S.L. (www.sacsl.es) has processed the data of the GPS station at ORM based on the previous accumulated experience in the company in GPS processing for the International Global Navigation Satellite Systems Service (Romero et al. 2003) and has derived the propagation delay and the associated PWV for the period June 2001 to December 2008. Global GPS data has been processed using the dual frequency data recorded at around 35 stations worldwide including the labeled LPAL station at ORM. The daily data processing runs take 2+24+2 hours of data from each station using all the data available above 10 degree of elevation at every ground station every 5 minutes. The satellite orbits are considered fixed as downloaded from the International Global Navigation Satellite Systems

Service (IGS, www.igs.org; Dow et al. 2005). The tropospheric zenith delay (*TZD*) derived is used to estimate the PWV as follows. The *TZD* is composed of two contributions, the hydrostatic (*ZHD*) and the wet (*ZWD*) delays. The *ZWD* accounts for the PWV in the atmosphere. The *ZHD* can be calculating through the latitude (φ) and altitude (*H* in meters) of the GPS station (Saatamoinen 1972; 1973) and the atmospheric pressure (*P* in hPa) as:

$$ZHD = 22.768 \times 10^{-4} \times \frac{P}{1 - 26.6 \times 10^{-4} \cos(2\varphi) - 0.28 \times 10^{-6} \times h} \quad (1)$$

ZWD is derived by subtracting *ZHD* from the *TZD* value. PWV is calculated as a proportion of the estimated *ZWD* through the following equation (Boccolari et al. 2002):

$$\text{PWV} = \frac{10^6}{\rho R_V \left[\left(k_3 / T_m\right) + k_2\right]} \quad (2)$$

where ρ is the density of liquid water, R_V is the specific gas constant for water vapor, k_2=70.4 K mbar^{-1}, k_3=3.739 10^5 K^2 mbar^{-1} are constants (Bevis et al. 1994; Askne et al. 1987), and T_m is a weighted mean temperature of the atmosphere calculated through:

$$T_m = 70.2 + 0.72\ T_s \quad (2)$$

being T_s the surface temperature at the site (Bevis et al. 1992). Unfortunately, there is not a weather station at the precise location of the GPS; hence a model (Boehm 2007) of the pressure and temperature at the longitude, latitude and height of the station for each date was used. We are exploring the use of data from a nearby meteorological weather station to derive the PWV. The final GPS time series for ORM includes more than 31500 individual estimations of the PWV for the period June 2001 to December 2008.

2.3 Comparison of GPS and photometer measurements

Two-hourly data from June, July, August, September 2001 and March, May, June, and July 2002 were used for the comparison of the photometer (IAC2) and the GPS PWV measurements recorded at the ORM. The two hours sampling is the standard in the GPS data processing to calculate the Tropospheric Zenith Delay (TZD). The different temporal resolution and coverage of both techniques reduced the dataset to be compared to a total of **55** individual estimations of PWV.

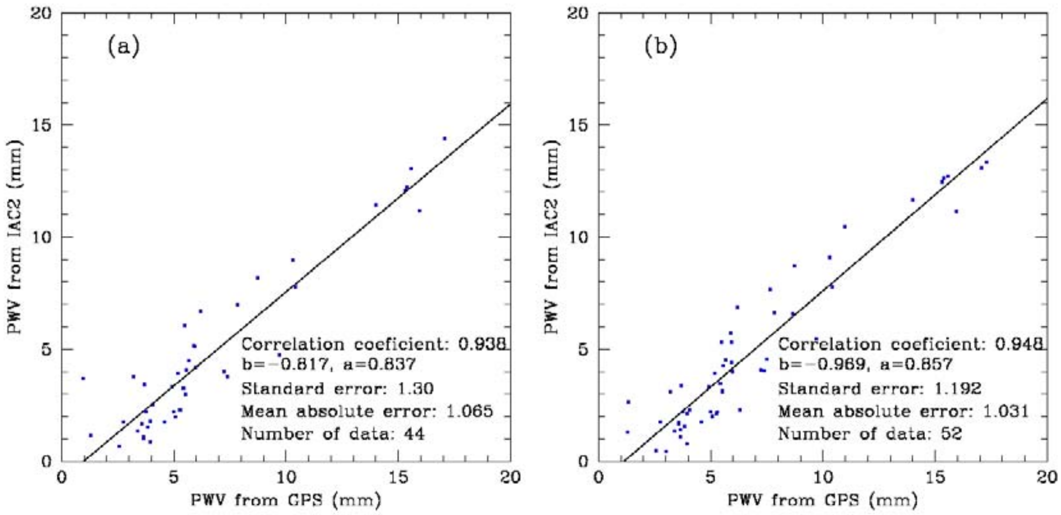

Figure 3: Comparison of PWV estimations from GPS measurements and the IAC2 photometer data: (a) Comparison of the closest IAC2 measurement (in a range of +/- 30 minutes) to the GPS estimations. (b) Comparison of the re-sampled IAC2 data to the GPS temporal resolution (see text). The number of considered data is indicated and some data were omitted due to a 3σ exclusion. The degree of correlation is larger than 0.90 in both cases, showing an excellent

agreement between both techniques to derived the PWV above ORM. IAC2 is taken as the reference instrument to calibrate the whole dataset of GPS PWV estimations (data from 2001 to 2008).

The first attempt (1) to compare both sets was to select the closest (in time) estimation on both datasets, allowing a maximum temporal difference of 0.5 hours. Figure 3a shows the comparison of PWV estimations from IAC2 and GPS, bringing up an excellent agreement between both techniques. The second attempt (2) was the re-sampling of IAC2 dataset to the same temporal resolution than GPS measurements. The procedure consists on averaging the photometer measurements in steps of two hours (about four photometer estimations), following the GPS processing procedure (e.g. for the data corresponding to 02 UT, we average all the individual IAC2 measurements in the range from 01UT to 03UT). The comparison of the smoothed IAC2 data and the GPS measurements is presented in Figure 3b, showing a high level of correlation between both data sets. Although the results from procedures (1) and (2) are quite similar, the second approach was adopted for the calibration of the GPS data series, which produced the best correlation statistics. Therefore, to calibrate in relation to IAC2 the current PWV time series derived by processing the GPS data as explained above, the following relation should be applied:

$$\mathrm{PWV} = 0.857 \times GPS_{estimation} - 0.969 \qquad (3)$$

The standard error associated to the calibration found for the GPS data is about 1.2 mm. The normalized root mean square deviation is about 11%, while the mean absolute error is 1.03 mm. These results are comparable to those in Pinilla (2003). These results are also comparable to the results found when comparing radiosondes and GPS measurements of the PWV (e.g. Li et al. 2001). 1.2 mm is adopted as the uncertainty associated to PWV estimation from GPS data.

3. STATISTICAL ANALISYS

The time series derived from GPS measurements include day-time and night-time estimations of PWV at ORM level (see Figure 4). GPS allows to having the PWV almost continuously measured. Data from ORM GPS were processed in 2 hours intervals. Figure 5 presents the distribution and cumulative distribution of PWV. The average PWV is 4.97 mm and the median values is 3.97 mm considering all the estimations in the PWV time series. The average daytime PWV is 5.11 mm, while average night-time PWV is 4.86 mm.

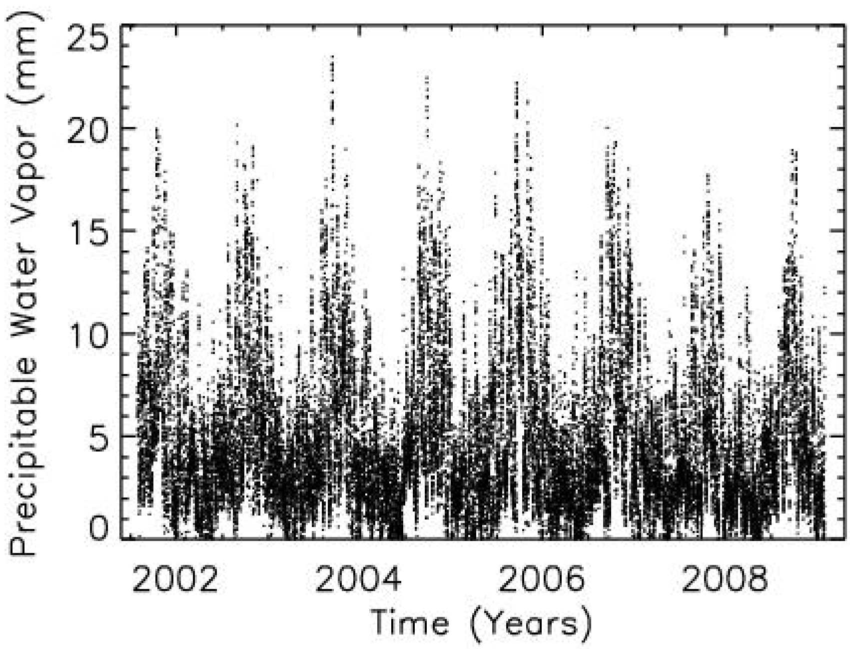

Figure 4: The 2-hourly time series of PWV estimations from GPS measurements from June 2001 to December 2008.

Table 1 includes the global and seasonal statistical results derived considering all the data in the PWV time series (day-time and night-time data together). The smallest PWV corresponds to winter and spring times, while the largest occurs in summer. PWVs exceed 8 mm only in a 18% of the cases, while it is under 4mm in a 53% of the time. Optimum values of 2mm can occur at any time, being under this value a 22% of the time. PWV values less than 1 mm occurs in 9% of the total time series.

Table 1: Global and seasonal statistical results (including day and night time data) of Precipitable Water Vapour above ORM.

All data **(Day+night time)**	Global 28/06/01-31/12/08	Winter (22/12-20/03)	Spring (21/03-21/06)	Summer (22/06-23/09)	Autumn (24/09-21/12)
Mean	4.97	3.40	3.54	6.78	5.65
σ	3.63	2.24	2.33	4.26	3.73
N	31145	6962	7308	8662	8213
10%	1.32	0.97	0.94	2.16	1.54
25%	2.35	1.80	1.85	3.34	2.67
Median	3.97	2.96	3.11	5.77	4.83
75%	6.69	4.48	4.76	9.40	7.93
90%	10.26	6.32	6.64	12.90	11.06

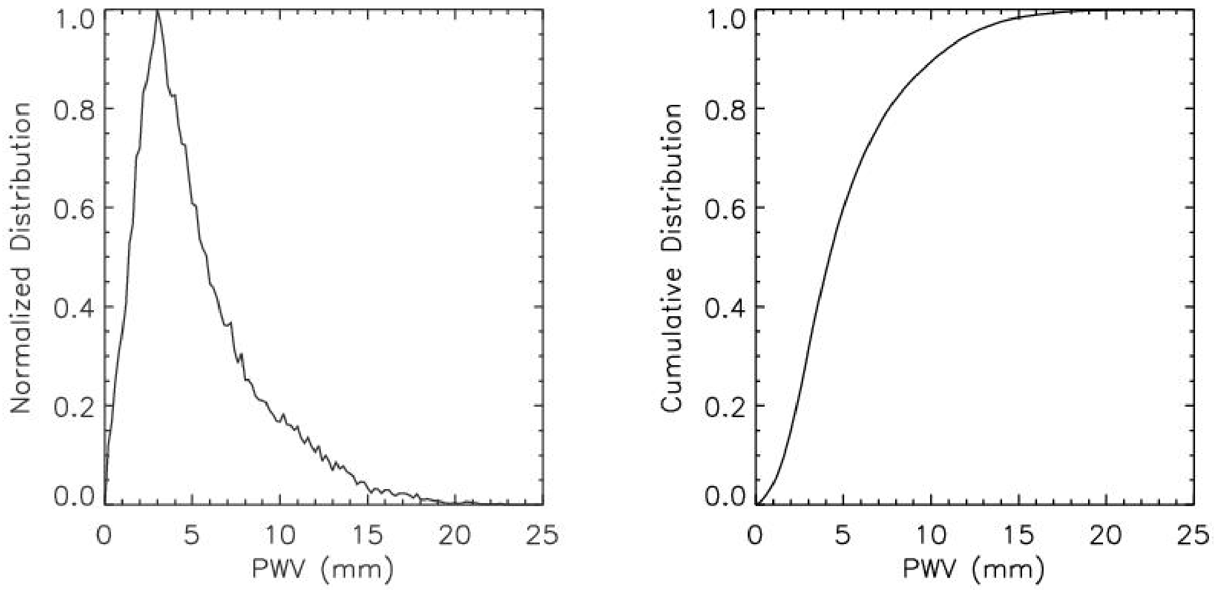

Figure 5: Probability distribution (left) and associated cumulative distribution (right) of PWV above the ORM including day and night time data.

3.1 Night-time statistics

At an astronomical site, the quality for IR observations can be inferred from the PWV conditions during night-time. The statistical PWV for night-time has been calculated defining the night with the Ephemerides from the Nautical Almanac of the Real Observatorio de la Armada de San Fernando (http://www.armada.mde.es). The night time PWV series are formed by 18051 individual data. Table 2 presents the statistics for night-time PWV and its seasonal behavior. The night time statistical values of PWV are slightly smaller that the ones derived considering all the data (see table 1) in the time series (day and night time).

Table 2: Night-time global and seasonal statistical results of Precipitable Water Vapour above ORM derived from GPS data for the period June 2001-December 2008.

Night time data	Global 28/06/01-31/12/08	Winter (22/12-20/03)	Spring (21/03-21/06)	Summer (22/06-23/09)	Autumn (24/09-21/12)
Mean	4.86	3.36	3.40	6.75	5.58
σ	3.63	2.26	2.34	4.34	3.68
N	18051	4380	4039	4758	4874
10%	1.25	0.93	0.88	2.06	1.55
25%	2.23	1.72	1.71	3.21	2.63
Median	3.85	2.91	2.95	5.76	4.72
75%	6.58	4.46	4.56	9.44	7.84
90%	10.17	6.33	6.46	13.04	10.90

The lowest night time PWV values are also found in winter-spring and the highest in summer, as in the case of the global statistics. 55% of the night-time PWV values are equal or smaller than 4 mm. Values larger than 8 mm are only observed in 18% of the nights. In 24% of the nights the PWV is equal or lower than 2 mm, while the PWV equal or less than 1 mm appears in a 10% of such PWV estimations. During summer, a 22% of the nights are good for IR observations (PWV < 3mm), while this percentage increase to 52% during winter. In general, 38% of the nights present PWV < 3mm, being acceptable for thermal IR observations.

Following the criteria defined in Kidger et al. (1998) to classify the observational conditions, and according to the statistical results here presented for the ORM from nightly GPS data, the ORM presents the following percentage of nights in five divisions:

Table 3: Quality conditions for thermal IR observations at ORM according to the classification based on the Precipitable water vapour above the site.

	PWV Range	Global	Winter	Spring	Summer	Autumn
Excellent	PWV < 2 mm	21%	31%	30%	9%	17%
Good	PWV 2-3 mm	17%	21%	21%	13%	13%
Fair or mediocre	PWV 3-6 mm	33 %	36%	36%	30%	31%
Poor	PWV 6-10 mm	18 %	10%	11%	26%	25%
Extremely poor	PWV $\geq$10 mm	11 %	2%	2%	22%	14%

The results derived from the GPS estimations of PWV above ORM are in good agreement with the idea of considering the troposphere thickness as the parameter to account for the infrared conditions of an astronomical (García-Lorenzo, Fuensalida & Eff-Darwich 2004). The tropopause level at La Palma is at its highest altitude (lower pressure level in summer, in coincidence with the largest PWV contents above the ORM site. La Palma presents the thinnest troposphere during winter, in agreement with the lowest PWV statistical values.

3.2 Comparison with PWV at Mauna Kea

Mauna Kea is known to be an excellent astronomical site, especially for thermal IR observations. The Caltech Submillimeter Observatory (CSO) has two monitors (Latitude 19.8224995, Longitude -155.475844; Altitude: 4070 m) of atmospheric opacity, one operating at 225 GHz and another at a wavelength of 350 μm permanently installed since the nineties. The characteristics of this kind of radiometers have been extensively described (see e.g. Liu 1987; McKinnon 1987; Chamberlin & Bally 1994; http://puuoo.submm.caltech.edu). Previous work (Davis et al. 1997) has shown that the atmospheric opacity at 225 GHz, τ_{225GHz}, is related to the column abundance of water vapour in mm by:

$$PWV = 20\ (\tau_{225GHz} - 0.016) \qquad (2)$$

Opacities at 225 GHz and 350 μm are empirically related by (Smith et al 2001):

$$\tau_{350\mu m} = 23\ \tau_{225GHz} \qquad (3)$$

More information about these monitors is provided in http://puuoo.submm.caltech.edu/, “The CSO Tau monitor webpage”.

We have download τ_{225GHz} data from the CSO archive for the period June 2001 to December 2008 in order to derive the statistical values of PWV above Mauna Kea. Figure 6 shows the full time series downloaded.

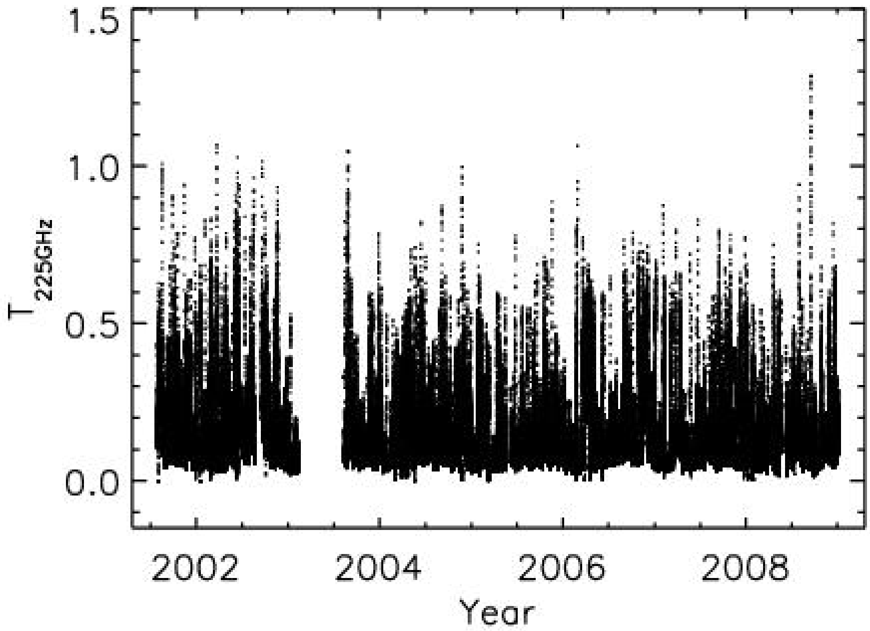

Figure 6: CSO optical depth measurements at 225 GHz (τ_{225GHz}) from Jun 2001 to December 2008. Equation (2) should be applied to obtain the precipitable water vapour.

The night-time τ_{225GHz} measurements were selected using the Ephemerides from the Nautical Almanac of the Real Observatorio de la Armada de San Fernando to define the nights. The total number of nightly τ_{225GHz} data is 141883. Estimations of PWV have been obtained from these τ_{225GHz} through equation (2). The average and median PWV above Mauna Kea derived from the downloaded time series are 2.50 and 2.32 mm, respectively. Table 4 presents the global and seasonal statistical PWV above Mauna Kea and table 5 classify the data following the criteria in Kidger et al. 1998.

Table 4: Night-time global and seasonal statistical results of Precipitable Water Vapour above Mauna Kea derived from τ225GHz measurements for the period June 2001-December 2008.

Night time data	Global 28/06/01-31/12/08	Winter (22/12-20/03)	Spring (21/03-21/06)	Summer (22/06-23/09)	Autumn (24/09-21/12)
Mean	2.50	2.40	2.35	2.41	2.75
σ	1.70	2.52	2.21	1.95	2.49
N	141883	32484	28103	36788	44508
10%	0.63	0.49	0.65	0.72	0.71
25%	0.98	0.76	0.98	1.08	1.06
Median	1.70	1.41	1.59	1.74	1.88
75%	3.18	3.12	2.84	3.14	3.48
90%	5.58	5.80	5.08	4.94	6.28

Table 5: Quality conditions for thermal IR observations at Mauna Kea according to the classification based on the Precipitable water vapour above the site.

	PWV Range	Global	Winter	Spring	Summer	Autumn
Excellent	PWV < 2 mm	58%	63%	61%	56%	53%
Good	PWV 2-3 mm	15%	11%	16%	17%	17%
Fair or mediocre	PWV 3-6 mm	18 %	17%	16%	21%	19%
Poor	PWV 6-10 mm	7 %	7%	6%	5%	9%
Extremely poor	PWV ≥10 mm	2 %	2%	1%	1%	2%

The PWV above Mauna Kea is stable along the year, with small differences over the seasons. The comparison of tables 2 and 4 indicates that ORM presents similar PWV content during winter and spring in ~50% of the nights. Comparison of tables 3 and 5 indicate that conditions are good or excellent for thermal IR observations in Mauna Kea at ~73.5% of the time in average, while at ORM such conditions occur in a 38.75% of the nights in average. In winter and spring, proper conditions increase to more than 50% of the nights at ORM. The reader should take into account that Mauna Kea is at an altitude of ~4100 m above sea level, whereas ORM is at ~2400 m.a.s.l. In spite of this difference in altitude, the IR conditions at ORM are as good as in Mauna Kea in 78 % of the nights during winter and spring, which is in agreement with the idea that the tropopause thickness could be as important as the altitude to account for IR quality of an astronomical site (Garcia-Lorenzo et al. 2004).

4. SUMMARY AND CONCLUSION

Comparisons between the PWV estimations derived from GPS and photometer measurements at ORM (La Palma, Canary Islands, Spain) have been performed. The agreement between both techniques is excellent, giving a linear correlation coefficient larger than 0.9, with an error comparable to the techniques intrinsically uncertainties.. The calibration equation derived from such comparison and taken as reference the photometer data is $PWV=0.857*GPS_{estimation}-0.969$. The uncertainty associated to PWV values derived from GPS data has been estimated to ~1.2mm. Applying the calibration, the water vapour content above ORM have been studied through a large time series derived from GPS data covering the period from June 2001 to December 2008. τ_{225GHz} measurements were also downloaded for the same period of time to derive the PWV statistics above Mauna Kea site. The PWV distribution above ORM derived from GPS data have the following properties:

1. The median PWV above the ORM at ~2400 m during night-time is 3.85 mm. The median value including night and day time estimations increase to 3.97 mm.
2. Seasonal variations in PWV are large and they can be as large as 40% of the mean value.
3. Statistically, winter and spring present the best conditions in terms of PWV, with a median value of 2.91 y 2.95 mm, respectively.
4. The conditions at the ORM to perform IR observations are good or excellent in 38% of the night-time and over 50% in winter and spring.
5. The quality of ORM is as good as Mauna Kea for IR thermal observations in 78% of winter and spring nights.

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