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# Model to estimate Precipitable Water Vapor (PWV) from Clear Sky QUIJOTE spectral bands optical depth

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### Abstract

QUIJOTE (Q-U-I Joint Tenerife) is a polarimeter telescope system at Teide Observatory (OT) for the study of the cosmic microwave background as well as galactic and extragalactic sources through observations in the 10-40 GHz frequency range. QUIJOTE is equipped with instruments covering various spectral bands; one of them, the Multi-Frequency (10-20 GHz) Instrument (MFI) has been in operations since the end of 2012. This instrument has multi-array receivers centered at 11 GHz, 13 GHz, 17 GHz and 19 GHz, each with bandpass of a few GHz. We have used a multi-layer, line-by-line radiative transfer model, setup with higher vertical resolution profiles of pressure, temperature and water vapor of the atmosphere, to derive a mathematical function relating optical depth and precipitable water vapor (PWV) for the various operational bands of QUIJOTE. The model has two purposes: it gives the PWV during regular operations, and can be used to convert the many years of sky calibration data (skydips) to PWV values. Like this, an independent estimation of the PWV could be done, including the driest conditions at OT.

**Keywords:** *QUIJOTE, Precipitable Water Vapor, Optical Depth*

## 1 Introduction

QUIJOTE (Q-U-I Joint Tenerife) is a polarimetric instrument consisting of two telescopes (see Figure 1[1]) intended for the study of the cosmic microwave background as well as galactic and extragalactic sources through observations in the 10-40 GHz frequency range. This is installed at the Teide Observatory and has been in operations since 2012. An account of the first scientific results obtained with observations of this telescope/instrument setup has been included in the work of Rubiño-Martín et al. [1].

Figure 1: QUIJOTE telescopes.

For insights and information about the telescope design and its fabrication we refer the reader to the work in [2]. One of the telescopes has been fitted with two instruments, being these the Multi Frequency Instrument (MFI) operating in the 10-30 GHz range and the thirty-gigahertz instrument (TGI); the second telescope has been equipped with the forty-gigahertz instrument (FGI) [3].

The MFI polarimeters are all of similar design, including a cooled state feedhorn followed by a rotating polar modulator, an ortho-mode transducer that produces two signals, each of which goes through a Low Noise Amplifier stage to the Backend module. Details of the radio frequency (RF) and digital components of the polarimeters are explained in [3].

As far this study concerns, the important information is that the MFI includes polarimeter channels centered at 11 GHz, 13 GHz, 17 GHz and 19 GHz, and this is the frequency range in which we have focused the attention. Figure 2 shows the bandpass of the channels used in this study. For the 30 GHz and 40 GHz polarimetric channels there is no yet available transmission curves, therefore in those cases it is assumed a top-hat function centered at those frequencies.

## 2 Vertical profiles of temperature, barometric pressure and water vapor density at OT

Four full years, 2011 through 2014, of radio soundings launched from the Güímar Sounding station (World Meteorological Station #60018) at Tenerife, were used to derive the median profiles of temperature, barometric pressure and water vapor density for the section of the atmosphere above Teide Observatory (2.4 km up to 30 km above sea level). Figure 3 shows

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[1] Image obtained from http://www.iac.es/divulgacion.php?op1=16&id=950&lang=en

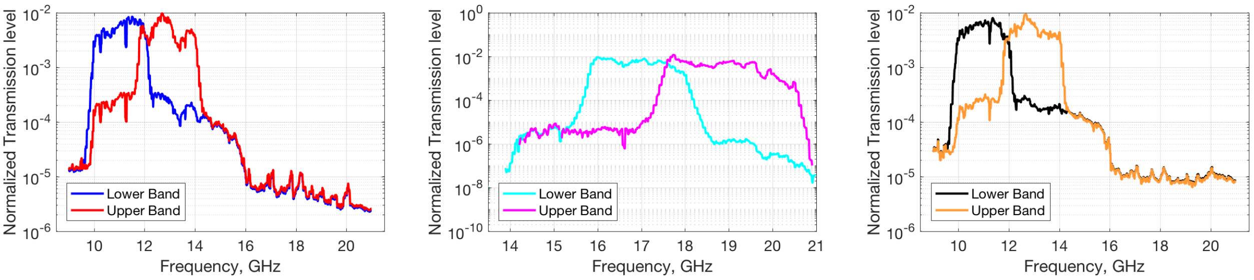

Figure 2: QUIJOTE Bandpass for horns 1(left), 2 (center) and 3 (right). Each figure shows the lower and upper bandpass transmission curves (normalized to the total area under the corresponding bandpass curve)

the median seasonal vertical profiles computed from the four years of soundings. For barometric pressure only the overall annual median profile is shown.

The integral of the water vapor density profile (see Eq. 1) gives a measure of the amount of water that one would be able to obtain if were possible to condensate all the moisture in the atmospheric column. This is the so-called precipitable water vapor (PWV) value.

$$PWV = \int_{z0}^{zmax} \varrho(z)\,dz \tag{1}$$

The median seasonal profiles of water vapor density clearly show that there is higher amount of moisture near the ground during summer season, while spring, winter and fall show a profile with lower values of moisture near the surface and higher in the mid-levels of the atmosphere between 7 km and 12 km above sea level (this is about 4.7 km to 9.9 km above the Teide Observatory ground level).

Water vapor molecules absorb energy at various spectral regions. One of this absorption regions, the (J',J") → (6,5) vibrational transition of the water vapor molecule at 22.235 GHz, falls within the operational spectral bands of QUIJOTE. The spectral width of the absorption line is dominated by pressure broadening mechanism (i.e. the collision time between molecules), consequently when the bulk of water vapor is located closer to the ground level (i.e. higher barometric pressure) the absorption band will be broader. Therefore, a given amount of PWV, where the absolute humidity is distributed near the ground, has a higher absorption effect (i.e. higher optical depth) than if the same amount of water were to be located at higher levels in the atmosphere.

During regular operations, QUIJOTE performs a procedure to measure the atmospheric radiance at various zenith angles (airmass) at a fix azimuth orientation of the telescope. The azimuth orientation is not important if it is assumed the water is distributed isotropically in all directions. The isotropic condition of the PWV field has been reported in other works [4,5]. The slope of atmospheric radiance as a function of airmass gives a measure of the atmospheric zenith optical depth ($\tau_0$) in the spectral band at which the sky calibration has been done. In the next section a model is derived as to convert the observed QUIJOTE optical depths to the PWV level at the time of the calibration. The radiative transfer model implemented for this effect uses the median vertical profiles shown in Fig. 3, and will help understand how the functional relationship between optical depth (in the QUIJOTE spectral bands) and PWV changes with seasons and give a sense of the uncertainty in using a simple functional relationship.

## 3 Setup of a radiative transfer model for Teide Observatory in the 0-50 GHz spectral range

The AM (Atmospheric Model) version 9.0 [6], including primarily the $O_2$ and $H_2O$ molecular absorption lines, as well as the dry and wet continuum absorption, was setup with 100 m vertical resolution layers, using the median profiles of

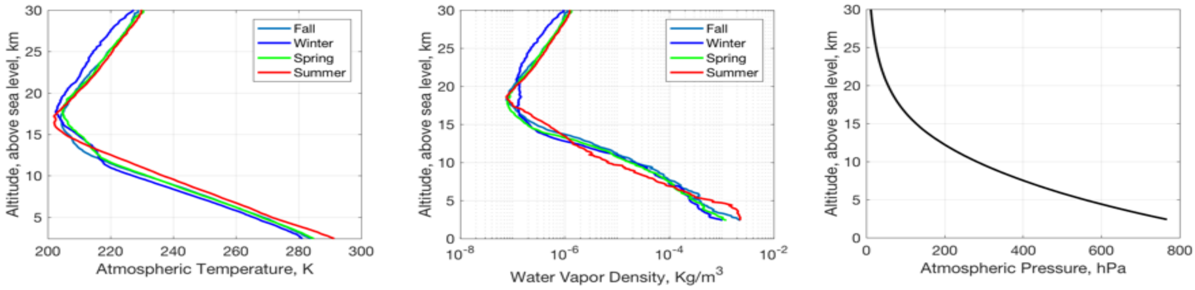

Figure 3: The median seasonal profiles of water vapor density clearly show that there is higher amount of moisture near the ground during summer season, while spring, winter and fall show a profile with lower values of moisture near the surface and higher in the mid-levels of the atmosphere between 7 km and 12 km above sea level (this is about 4.7 km to 9.9 km above the Teide Observatory ground level)

atmospheric temperature, pressure and water vapor profile. The water vapor profile was normalized so that the integral PWV was 1 mm. A partial view of the script generated to run the AM model is shown in Table 1. This script admits one input parameter (Nscale) which is useful to scale the water vapor profile so that its integral will give a desired level of PWV for which the optical depth spectral profile is needed.

Running the AM model with a script (as shown in Table 1) will produce an output file including optical depth (in nepers), atmospheric brightness temperature (in K) and atmospheric transmission as a function of frequency in the range 0 to 50 GHz, this with a frequency resolution of 0.01 GHz. Figure 4 shows the optical depth profile as a function of frequency obtained using the median atmospheric soundings for spring season and for various levels of PWV. The figure is good to illustrate that the clear sky optical depths (atmospheric absorption) in the QUIJOTE band has contributions from the far wing of the 60 GHz $O_2$ (molecular oxygen) absorption band as well as the 22.235 GHz water vapor vibrational absorption line.

```
f 0 GHz 50 GHz 0.01 GHz
output f GHz tau neper Tb K tx none
tol 0.0001
T0 2.7 K
Nscale h2o %1
layer
Pbase 11.826186 mbar
Tbase 228.252946 K
column dry_air hydrostatic
column h2o 0.000032 mm_pwv
:
Each layer is setup with their corresponding
pressure, temperature at the base of the layer and
the content of water vapor in the given layer.
:
layer
Pbase 766.923655 mbar
Tbase 283.999125 K
column dry_air hydrostatic
column h2o 0.057668 mm_pwv
```

Table 1. am_ElTeide.amc script.

## 4 Setup of a radiative transfer model for Teide Observatory in the 0-50 GHz spectral range

The mean optical depth <τ>, in a receiving system with spectral band transmission Φ(ν) can be computed by the expression given in Eq. 2, where τ(ν,PWV) is the spectral profile of optical depth for a given level of atmospheric absorption (given by the PWV) and as a function of frequency.

$$\langle\tau\rangle=\frac{\int_{\nu 1}^{\nu 2}\tau(\nu,PWV)\cdot\Phi(\nu)\,d\nu}{\int_{\nu 1}^{\nu 2}\Phi(\nu)\,d\nu} \tag{2}$$

The spectral band functions for QUIJOTE shown in Figure 2 where applied to the seasonal optical depth profiles obtained from the line-by-line, layer-by-layer AM atmospheric model for varying level of PWV, as that shown in Figure 4. This helped derive for each QUIJOTE spectral band a dataset that included mean optical depth for a given PWV level. The results for the spectral bands centered at 11 GHz, 13 GHz, 17 GHz and 19 GHz are shown in Table A1 (see Appendix A) for the annual median conditions of the atmosphere. The 30 GHz and 40 GHz mean optical depths are also included, but for these ones a top-hat transmission band from 27 GHz to 35 GHz[2] is being used for the 30 GHz spectral band, and a 2 GHz top-hat transmission band has been used for the 40 GHz channel. Better mean optical depths values can be obtained once the exact passband profiles for the 30 GHz and 40 GHz spectral bands are known.

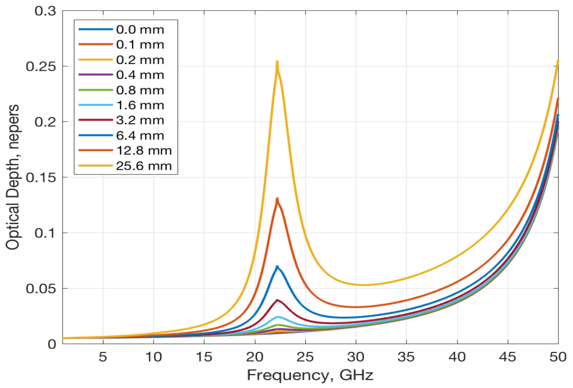

Figure 4: Optical depth profile for varying level of PWV.

A linear fit to the PWV and optical depths series, as shown in Eq. 3, was done for each of the spectral bands and median seasonal states of the atmosphere. The best fitted coefficients (c1,c2) and the RMS of the fit found for each case are summarized in Tables A2 to A5 (see Appendix A)

$$PWV=c1\cdot\tau+c2 \tag{3}$$

## 5 Analysis and recommendation

An example of the mean optical depths, obtained with the line-by-line, layer-by-layer AM radiative transfer model and PWV level, as well as best fit functions for the various seasons and annual conditions are shown in Figure 5 (top-left) for the 17 GHz. The Figure 5 (bottom-left) shows the residuals PWV when computed using the annual and seasonal functional relationships. The differences in PWV gives an estimate of the uncertainty in the derivation of PWV from the QUIJOTE optical depths in the 17 GHz channel. Similar information, for the 19 GHz channel, is shown on the right side of Fig. 5. The 17 GHz and 19 GHz channels are located on the left wing of the 22.235 GHz water vapor absorption line and along a section of steep change in optical depth with water vapor (see Figure 4), and then, excellent to obtain the PWV.

In Figure 5 is possible to see residuals up to 0.005 mm in PWV at low levels of optical depth. For the case of the 17

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[2] Private communication (R.T. Génova. 5/26/2017)

GHz (Horn 2) band, an optical depth of 0.0075 nepers will translate into 0.296 mm of PWV (the conversion uses the coefficients shown in Table A3 for the annual overall relationship, PWV = 1470.724 × $\tau_{17GHz}$ – 10.734 [mm]) and then, a residual of 0.005 mm is only at the 1.7% level. One important conclusion is that the residual errors, between annual and seasonal functions, are small compared to the RMS in the fitting of the optical-depth/PWV functions, and therefore, it is recommended using only the annual relationship for estimating PWV from QUIJOTE optical depth data.

| *Horn* | **ν [GHz]** | *relationship for PWV [mm]* | *RMS [mm]* |
|---|---|---|---|
| 1 | 11 | PWV = 5896.413 × τ – 35.767 | 0.104 |
| 1 | 13 | PWV = 4219.462 × τ – 26.797 | 0.096 |
| 2 | 17 | PWV = 1470.724 × τ – 10.734 | 0.057 |
| 2 | 19 | PWV = 0667.382 × τ – 05.269 | 0.032 |
| 3 | 11 | PWV = 5898.229 × τ – 35.683 | 0.102 |
| 3 | 13 | PWV = 4120.631 × τ – 26.212 | 0.096 |
|  | 30 | PWV = 0668.708 × τ – 11.446 | 0.092 |
|  | 40 | PWV = 0670.113 × τ – 24.781 | 0.148 |

Table 2. Functional relationships recommended for computing PWV from the QUIJOTE optical depths.

Table 2 summarizes the functional relationships recommended for computing PWV from the optical depths obtained with the QUIJOTE telescope at the various operations spectral bands. The linear functions in Table 2, together with the optical depths obtained during QUIJOTE sky calibrations provide an alternative way to assess the PWV statistics for OT. QUIJOTE is a detector highly sensible to atmospheric water vapor and can be used to get the PWV in the driest conditions. It is proposed as complementary to the routine determination with GPS technique [7,8].

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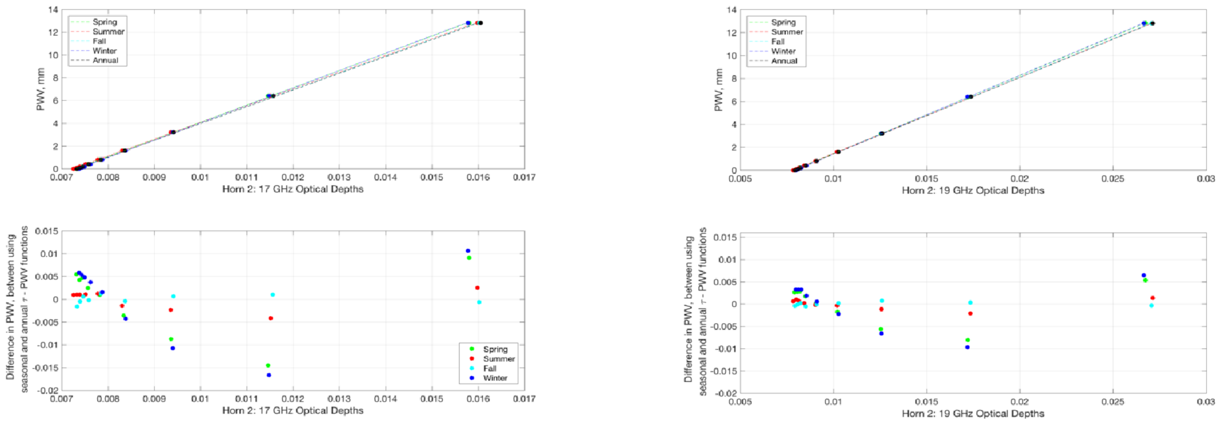

Figure 5: LEFT side: (top) PWV derived from clear-sky 17 GHz QUIJOTE optical depths, and best fit function for median seasonal state of the atmosphere and overall median annual conditions. (bottom) Difference in PWV between the annual and seasonal functional relationships. RIGHT: Similar information for the 19 GHz channel.

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# A Appendix

| **PWV** | **Horn 1**<br>**mean optical depth** | | **Horn 2**<br>**mean optical depth** | | **Horn 3**<br>**mean optical depth** | | | |
|---|---|---|---|---|---|---|---|---|
| | **11 GHz** | **13 GHz** | **17 GHz** | **19 GHz** | **11 GHz** | **13 GHz** | **30 GHz** | **40 GHz** |
| 0.0 | 0.006079 | 0.006367 | 0.007327 | 0.007930 | 0.006063 | 0.006379 | 0.0167201 | 0.0371481 |
| 0.1 | 0.006095 | 0.006388 | 0.007392 | 0.008076 | 0.006078 | 0.006401 | 0.0168536 | 0.0372779 |
| 0.2 | 0.006110 | 0.006410 | 0.007457 | 0.008222 | 0.006094 | 0.006423 | 0.0169873 | 0.0374079 |
| 0.4 | 0.006141 | 0.006454 | 0.007586 | 0.008513 | 0.006125 | 0.006468 | 0.0172552 | 0.0376690 |
| 0.8 | 0.006203 | 0.006541 | 0.007846 | 0.009097 | 0.006187 | 0.006557 | 0.0177934 | 0.0381950 |
| 1.6 | 0.006329 | 0.006718 | 0.008367 | 0.010269 | 0.006313 | 0.006738 | 0.0188791 | 0.0392623 |
| 3.2 | 0.006585 | 0.007077 | 0.009422 | 0.012625 | 0.006569 | 0.007107 | 0.0210875 | 0.0414586 |
| 6.4 | 0.007117 | 0.007822 | 0.011574 | 0.017391 | 0.007101 | 0.007869 | 0.0256528 | 0.0460971 |
| 12.8 | 0.008259 | 0.009412 | 0.016052 | 0.027137 | 0.008242 | 0.009497 | 0.0353749 | 0.0563544 |

Table A1: Mean optical depths as a function of PWV at the QUIJOTE MFI, TGI, FGI instruments bands: for annual median state of the atmosphere (temperature, water vapor density and pressure profiles).

| | **Horn 1**<br>**11 GHz** | | | **Horn 1**<br>**13 GHz** | | |
|---|---|---|---|---|---|---|
| | ***c1*** | ***c2*** | **RMS** | ***c1*** | ***c2*** | **RMS** |
| SPRING | 6079.054 | -36.841 | 0.091 | 4355.352 | -27.630 | 0.086 |
| SUMMER | 5950.577 | -35.849 | 0.101 | 4244.946 | -26.753 | 0.094 |
| FALL | 5910.578 | -35.877 | 0.104 | 4232.828 | -26.895 | 0.097 |
| WINTER | 6110.901 | -37.264 | 0.088 | 4389.513 | -28.031 | 0.083 |
| **ANNUAL** | **5896.413** | **-35.767** | **0.104** | **4219.462** | **-26.792** | **0.096** |

Table A2: Best fit coefficients for the optical depths vs PWV linear functions, QUIJOTE Horn 1.

| | **Horn 2**<br>**17 GHz** | | | **Horn 2**<br>**19 GHz** | | |
|---|---|---|---|---|---|---|
| | ***c1*** | ***c2*** | **RMS** | ***c1*** | ***c2*** | **RMS** |
| SPRING | 1511.353 | -11.020 | 0.050 | 680.598 | -5.368 | 0.028 |
| SUMMER | 1470.205 | -10.632 | 0.055 | 664.644 | -5.195 | 0.031 |
| FALL | 1476.707 | -10.785 | 0.058 | 669.996 | -5.293 | 0.032 |
| WINTER | 1525.966 | -11.215 | 0.049 | 686.151 | -5.458 | 0.027 |
| **ANNUAL** | **1470.724** | **-10.734** | **0.057** | **667.382** | **-5.269** | **0.032** |

Table A3: Best fit coefficients for the optical depths vs PWV linear functions, QUIJOTE Horn 2.

| | **Horn 3**<br>**11 GHz** | | | **Horn 1**<br>**13 GHz** | | |
|---|---|---|---|---|---|---|
| | ***c1*** | ***c2*** | **RMS** | ***c1*** | ***c2*** | **RMS** |
| SPRING | 6077.712 | -36.734 | 0.090 | 4251.990 | -27.023 | 0.084 |
| SUMMER | 5952.425 | -35.764 | 0.100 | 4145.529 | -26.174 | 0.093 |
| FALL | 5912.404 | -35.793 | 0.103 | 4132.855 | -26.308 | 0.095 |
| WINTER | 6108.559 | -37.148 | 0.087 | 4283.707 | -27.406 | 0.081 |
| **ANNUAL** | **5898.229** | **-35.683** | **0.102** | **4120.631** | **-26.212** | **0.096** |

Table A4: Best fit coefficients for the optical depths vs PWV linear functions, QUIJOTE Horn 3.

| | **Horn**<br>**30 GHz** | | | **Horn**<br>**40 GHz** | | |
|---|---|---|---|---|---|---|
| | ***c1*** | ***c2*** | **RMS** | ***c1*** | ***c2*** | **RMS** |
| SPRING | 710.837 | -11.798 | 0.081 | 695.787 | -25.682 | 0.131 |
| SUMMER | 692.614 | -11.335 | 0.089 | 680.650 | -24.725 | 0.146 |
| FALL | 690.985 | -11.492 | 0.093 | 671.496 | -24.851 | 0.150 |
| WINTER | 716.444 | -12.038 | 0.079 | 698.468 | -26.143 | 0.127 |
| **ANNUAL** | **688.708** | **-11.446** | **0.092** | **670.113** | **-24.781** | **0.148** |

Table A5: Best fit coefficients for the optical depths vs PWV linear functions, QUIJOTE Horn 30 & 40 GHz.