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Sub-millimeter Atmospheric Opacity Over "El Leoncito" Site

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Abstract

Ground-based radio telescopes observing at millimeter/sub-millimeter wavelengths need information on atmospheric attenuation to recover the corrected brightness temperature of astrophysical objects. To determine the zenital opacity, several methods have been used. In comparison with other techniques, the solar brightness method allows determining the atmospheric opacity up to high values and only depends on estimating, as accurately as possible, the product $P = \eta T_\odot$ where η is the beam efficiency and $T_\odot$ is the Sun brightness temperature at the observation frequencies. Although $T_\odot$ and η are not known individually, we assume that P must be constant. In this work, we reported the measured the zenith opacity at 212 GHz, τ_{212}, and 405 GHz, τ_{405} using the solar brightness method, over "*El Leoncito*" site (2550 m altitude above sea level) for the period 2006-2014. We found a linear correlation between τ_{212} and τ_{405} with $R = 0.90$, the resulting relation $\tau_{405} = 0.07 + 6.90\,\tau_{212}$, allows to estimate the opacity at 405 GHz. Our result also shows that the ration of opacities (τ_{405}/τ_{212}) is ≈ 7, which indicates an excellent agreement with the value of model prediction (≈ 7). As expected, a clear seasonal pattern of opacity measurements is observed along the years. Finally, we also confirm that there is a significance correlation between the opacities obtained and the precipitable water vapor content (PWV) over "*El Leoncito*" site, between 2011 and 2014.

1 Introduction

The water vapor content of the atmosphere is the main source of attenuation from the infrared to radio band. The resulting absorption can vary on a short time scale due to the rapid variations of the water content. As the atmospheric water vapor depends on altitude, sub-millimeter astronomical observations must be carried out in dry and high altitude sites in order to reduce the atmospheric effects [9]. The measurement of opacity (τ_ν) plays an important role because it allows recovering the corrected brightness temperature of astrophysical objects, that allows understand the physical processes that occur in the Sun and other astronomical sources. For solar purposes, the radio observations in high frequencies are fundamental for understanding the origin of solar radio emissions during a solar flare, and this depends fundamentally on the interpretation of the flux density (**S**) in this frequency. However, in practice, radio solar observations are critically affected by atmospheric absorption [4].

To calculate τ_ν in the sub-millimeter wavelength range, several methods are used. Dicke et al.[1] measured τ_ν with a radio telescope, using a technique called "tipping". This method estimates the atmospheric absorption based on sky brightness temperature variations as a function of the elevation angle, assuming a plane-parallel atmosphere. In the "*El Leoncito*" site, Melo et al.[5] measure sub-millimeter opacities at 212 GHz, τ_{212}, and 405 GHz, τ_{405}, using three different methods, including the tipping method. The other two methods depend on measuring the excess of temperature produced, with a fine beam of the radio telescope, during a solar scan. The method know as solar brightness, has many advantages in comparison with the other two, because allow the determination of atmospheric opacity up to high values, and depends only on calculate as accurately as possible one parameter, the product $P = \eta T_\odot$, where $T_\odot$ is the solar brightness temperature and η is the beam efficiency.

In this work, we present results of sub-millimeter atmospheric opacity measurements at 212 and 405 GHz. These values were estimated using the solar brightness method in the period between 2006 and 2014 over "*El Leoncito*" site. Previous studies by Cassiano et al.[2] and Valle Silva et al.[8] have shown that millimeter and sub-millimeter atmospheric opacities are well correlated with the precipitable water vapor (PWV). Finally, we also discuss the excellent correlation found between sub-millimeter opacities and PWV.

2 Instrumentation

The Solar Sub-millimeter wave Telescope (SST) is located at "*El Leoncito*" Astronomical complex (CASLEO), at an altitude of 2550 m above sea level in San Juan Province, Argentina. The SST is a multi-beam radio telescope that observes the Sun using six beams: four beams at 212 GHz and two at 405 GHz, respectively. The beams are much smaller in diameter than the diameter of the solar disk, as described in detail by Kaufmann et al. [4].

We also used AERONET (AErosol RObotic NETwork) data recorded by a ground-based Sun photometer at CASLEO station between January 2011 and July 2014. This instrument measures direct Sun and sky radiance at different wavelengths providing information about atmospheric aerosol properties [3]. We use the high quality Level 2 AERONET data. Pérez-Ramirez et al. [7]. reported PWV measurements with errors until 10%.

3 Methodology

A ground-based radio telescope collect radiation from the following contribution sources: (i) the external source attenuated through the atmosphere and (ii) the self-absorbed emission from the sky. Assuming a plane-parallel atmosphere and the Rayleigh-Jeans approximation, the observed brightness temperature (T_{obs}) of an external source with temperature (T_{source}) for a given elevation angle (El) can be expressed through the radiative transfer equation:

$$T_{obs} = T_{source} e^{-\tau_v/sin(El)} + T_{sky}(1 - e^{-\tau_v/sin(El)}) + T_{off} \quad (1)$$

where τ_v is the optical depth or the zenithal opacity for a given at frequency and expressed in nepers; T_{sky} is the sky temperature expressed in kelvin and T_{off} is an offset temperature.

Using the Tipping method, the zenithal opacity (τ_v) can be estimated from the sky brightness variation as a function of the elevation angle and assuming a plane-parallel atmosphere. Thus, equation 1 can be expressed:

$$T_{obs} = T_{sky}(1 - e^{-\tau_v/sin(El)}) + T_{off} \quad (2)$$

The opacity is obtained fitting equation 2 to the observed profile. However,in opaque conditions, this method produces large errors in the determination of τ, as reported by Melo et al.[5].

On the other hand, the atmospheric opacity also can be computed from the observed antenna temperature difference between the quiet Sun and the sky (ΔT_{ant}) in a solar scan obtained at any elevation angle El. This technique is named as the solar brightness method. From equation 1, ΔT_{ant} can be expressed as:

$$\Delta T_{ant} = P e^{-\tau_v/sin(El)} \quad (3)$$

The term ΔT_{ant} is defined as: $\Delta ADC/K$, where ΔADC is the difference of the levels between the quiet Sun and the sky in a solar scan, obtained at any elevation angle El and measured in ADCu (Analogical to digital converter) units; K is the voltage-to-antenna temperature factor; and P is the parameter named as "product" and defined as $P = \eta T_{\odot}$, where η is the beam efficiency and $T_{\odot}$ is the solar brightness temperature. Although η and $T_{\odot}$ values are not well known individually, we assume that P should be constant.

According to equation 3, the zenithal opacity can be calculated as:

$$\tau = sin(El)[ln(P) - ln(\frac{\Delta ADC}{K})] \quad (4)$$

The advantage of using this method is that it allows determining τ up to high values, and τ only depends on P.

In this work, we use the solar brightness method to determine the zenithal opacity. The selected database for this analysis corresponds to 1613 clear days recorded by SST between June 2006 and December 2014. For each SST beam, we estimated the value of the product (P) using equation 3.

To estimate P, an initial value of τ_{input} is required, and for this we use the tipping method only during clear sky conditions.

4 Results

4.1 The Sub-millimeter Atmospheric Opacity

First, we estimated the $\overline{P}$ value for each SST beam considering the measurements of P with low opacities, i.e. $\tau_{212} \leq 0.10$ nepers and $\tau_{405} \leq 0.80$ nepers, and elevation angles $El \geq 25$ and $El > 35$ degrees, at 212 and 405 GHz, respectively, as shown in Table 1. We also estimated the error propagation of P measurements and assumed that uncertainties are around 10% and 15% at 212 and 405 GHz, respectively. These values are derived from the error propagation in the measurements of ΔADC, K and τ_{input}.

Table 1. The mean value $\overline{P}$ for all the six beams of SST.

Frequency	SST Beams	$\overline{P}$ (K)
212 GHz	1	2450 ± 150
	2	2470 ± 190
	3	2520 ± 240
	4	2330 ± 210
405 GHz	5	3280 ± 330
	6	3320 ± 280

Using the solar brightness method, we calculate the atmospheric opacity for the whole period replacing the $\overline{P}$ value into equation 4. To derive the opacity in 212 GHz, we considered the average of measurements of τ obtained in beams 2 and 4. For 405 GHz, we considered the measurements of τ obtained in beam 5.

A linear regression between opacity values at 212 and 405 GHz was performed for 1056 days of observation: τ_{405} = 0.07 + 6.90 τ_{212}, with a correlation coefficient of R = 0.90 (as shown in Figure 1), indicating a good correlation between both quantities. From this empirical relation, one can estimate τ_{405} even under opaque atmospheric conditions. In addition, we found an excellent approximation of the ratio $\tau_{405}/\tau_{212} \approx 7$ using the solar brightness method with the value of model predict ($\tau_{405}/\tau_{212} = 7$). A similar analysis for the "*El Leoncito*" site was made by Melo et al.[5] using the solar brightness method. Comparing both the ratios, we found that Melo's result ($\tau_{405}/\tau_{212} \approx 4.5$) is smaller than our result ($\tau_{405}/\tau_{212} \approx 7$). We suppose that this difference is probably due to repairs made at the radio telescope in

2006 and also due to the resulting increase of the beam efficiency (η), as reported by Kaufmann et al. [4].

Figure 2 (a) and (b) show the distributions of atmospheric opacities obtained at 212 and 405 GHz, and their respective cumulative distribution (c) and (d). We found that the most likely opacity at "*El Leoncito*" site is around of 0.10 - 0.15 nepers (a) and 0.60 - 1.0 nepers (b), at 212 and 405 GHz, respectively. The cumulative distributions of opacities indicate that 50% of the time $\tau_{212} < 0.16$ nepers (c) and $\tau_{405} < 1.08$ nepers (d).

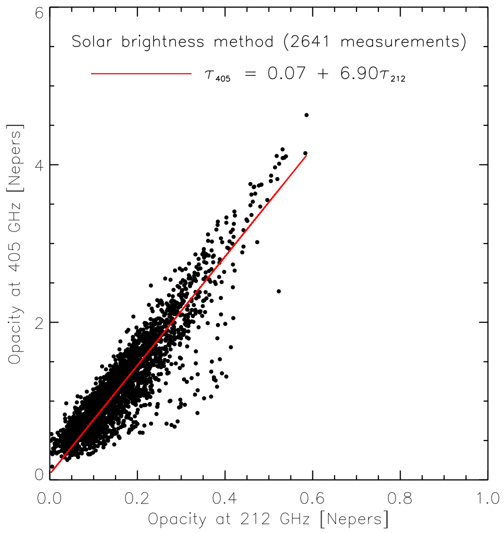

Figure 1. Relationship between the simultaneous measures τ_{212} and τ_{405} at "*El Leoncito*" site. The red solid line represents the best fit: $\tau_{405} = 0.07 + 6.90\tau_{212}$.

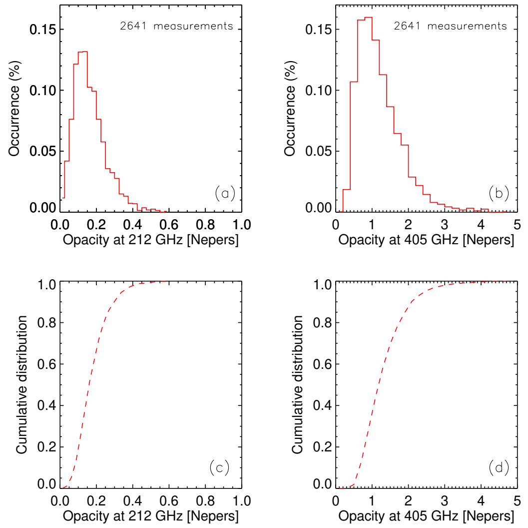

Figure 2. Distribution of the atmospheric opacities at 212 (a) and 405 GHz (b) and their respective cumulative distribution (c) and (d), obtained using the solar brightness method for the period of 2006 to 2014.

Figure 3 shows the daytime opacities τ_{212} and τ_{405} for the whole database at "*El Leoncito*" site using the solar brightness method. The data gaps in this figure are generally due to equipment outages and discarded data for cloudy days. Using this ratio ($\tau_{405}/\tau_{212} = 6.90$), we can estimate opacities in 405 GHz up to 8.11 nepers in comparison with another method. In fact, Figure 3 shows a remarkable seasonal variation at "*El Leoncito*" along the years. Under good atmospheric conditions in winter months (from May to October), opacity is low with mean values of 0.15 ± 0.04 and 1.08 ± 0.25 nepers for 212 and 405 GHz, respectively. During summer months (from November through April), opacity is higher with mean values of 0.20 ± 0.06 and 1.42 ± 0.37 nepers for 212 and 405 GHz, respectively.

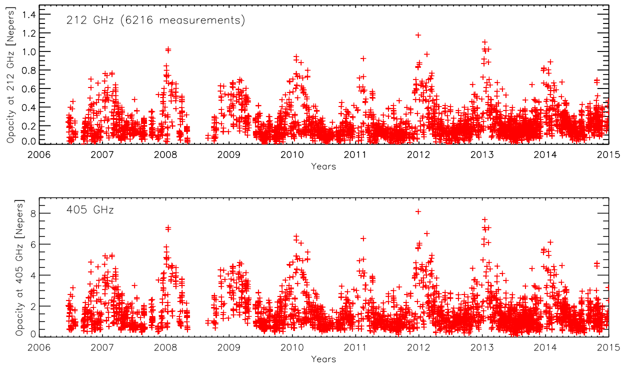

Figure 3. Daytime atmospheric opacity at 212 GHz (top panel) and 405 GHz (bottom panel) obtained using the solar brightness method for the period of 2006 to 2014.

4.2 Comparison with PWV

The correlation between the atmospheric opacity and precipitable water vapor (PWV) is showed in Figure 4. The τ_{212} was derived by the solar brightness method at 212 GHz, and PWV was recorded by AERONET station in CASLEO. The data used in this analysis correspond to the period of January 2011 to July 2014. The main criterion adopted is that PWV and τ_{212} measurement times must not differ by more than 20 min. Then, we fitted the measured data using a linear regression given by:

$$PWV = a + b.\tau_{212} \tag{5}$$

From this fitting, we obtained the following coefficients: $a = 0.05 \pm 0.03$ and $b = 14.62 \pm 0.11$ [mm/nepers]. As expected, an excellent correlation is obtained between PWV and τ_{212}, with a coefficient of R = 0.97. Based on equation 5, we can calculate the PWV values for periods when PWV measurements are not available or vice versa. A similar result between these two quantities also was reported by Cassiano et al.[2] between January 2011 and September 2013. Likewise, Valle Silva et al.[8] also reported that millimeter opacities are well correlated with PWV measured. This result confirms the strong relationship between the sub-millimeter/millimeter opacities and PWV in the "*El Leoncito*" site.