

# Determination of Submillimeter Atmospheric Opacity at El Leoncito, Argentina Andes\*

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**Abstract**—We present submillimeter wave atmospheric opacity determinations obtained at 212 GHz and 405 GHz for the site of El Leoncito, San Juan, Argentina Andes, located at an altitude of 2550 meters, using the Solar Submillimeter wave Telescope (SST). The use of SST allowed the comparison of three different methods of measurements: (a) indirect derivation from the sky brightness temperature variation with the elevation angle; (b) directly derived from solar signal attenuation with elevation angle; and (c) use of the product of solar brightness times the antenna coupling factor, as the reference source external to the atmosphere. It has been shown that the last method provides the most consistent measurements for the two frequencies. Preliminary results show that opacities (in nepers) for El Leoncito at 405 GHz are 5.5 times larger than at 212 GHz, smaller than model predictions, which suggest smaller opacities for shorter submm-waves at that site. Preliminary survey for 1999-2001 at El Leoncito indicate most probable values for zenith opacities of 0.18 nepers (212 GHz) and 0.9 nepers (405 GHz), which are comparable to a number of other sites at considerably higher altitudes.

**Resumo**—Apresentamos determinações de opacidade atmosférica obtidas em 212 GHz e 405 GHz para o sítio de El Leoncito, San Juan, Argentina, localizado a uma altitude de 2550 metros, fazendo uso do Telescópio Solar para Ondas Submilimétricas (SST). O uso do SST permitiu a comparação de três métodos diferentes para as medidas: (a) indireta, através da variação da temperatura de brilho do céu com o ângulo de elevação; (b) diretamente através da atenuação do sinal solar com o ângulo de elevação; e (c) uso do produto da temperatura de brilho solar pelo fator de acoplamento da antena, como fonte de referência externa à atmosfera. Mostrou-se que o último método apresenta a melhor consistência entre as medidas nas duas frequências. Resultados preliminares indicam que as opacidades (em nepers) obtidas para El Leoncito em 405 GHz são 5.5 vezes maiores do que em 212 GHz, fator menor do que previsões de modelos, sugerindo opacidades menores para ondas submilimétricas mais curtas neste sítio. Um levantamento preliminar para El Leoncito para 1999-2001 indicou valores de opacidade mais prováveis de 0.18 nepers em 212 GHz e de 0.9 nepers em 405 GHz, comparáveis a vários outros sítios situados em altitudes consideravelmente maiores.

**Index Terms**—atmospheric opacity, radio propagation, submillimeter wavelengths

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## I. INTRODUCTION

The terrestrial neutral atmosphere acts on the shorter radio wavelengths propagation, limiting the millimeter and submillimeter frequencies propagation to “windows” for which it becomes partially transparent at certain bands. These influences change with the wavelength (or frequency) and altitude of the observation site, elevation angle of observed source as well as with a number of local and global meteorological parameters.

The most important propagation attenuation factors for frequencies between 10 and 1000 GHz, are caused by clouds, water vapor and oxygen molecules [1]-[3]. In Figure 1 we show the atmospheric opacity and the most important absorption lines for mm-submm wave frequencies up to 1000 GHz [4].

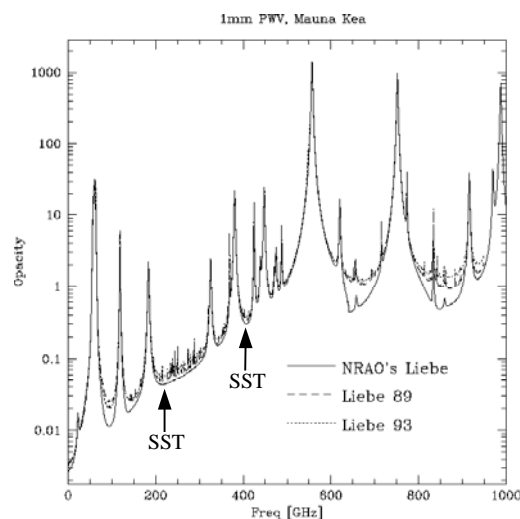


Fig. 1. Atmospheric opacity at Mauna Kea and according to model predictions [2][4], being indicated the two frequencies used for the present study.

The absorption underlying level is caused by water vapor, which reduces considerably with altitude. The submm-wave observation sites are thus usually located at dry and high altitude sites. Although the altitude is the main controlling factor, other meteorological parameters are important to be taken

into account to describe the quality of the site for this range of frequencies.

In this study we compare different techniques to determine the total atmospheric opacity with observations done at 212 and 405 GHz by the Solar Submillimeter-wave Telescope operated at the El Leoncito site, San Juan, Argentina [5]. Preliminary results are compared to other high altitude sites for which there are opacity data available in the 225 GHz band.

*A. Theory*

An electromagnetic wave is attenuated when propagating in an absorbing medium. This means that the observed brightness temperature from a source external to the Earth atmosphere is smaller than its actual value. The basic relationships used to obtain the atmospheric emission and self-absorption are derived from the radiative transfer equations [6]. We can define the atmospheric opacity by the optical depth,  $\tau$ :

$$\tau = \int_L k dL \tag{1}$$

where  $k$  is the absorption coefficient and  $L$  the length the wave propagates in the atmosphere. We can use a “plane atmosphere” approximation to describe the dependence between the distance ( $L$ ) and the elevation angle of the external source as illustrated in the simplified diagram of Figure 2. This approximation is usually acceptable for elevation angles larger than 25°.

The external radiation intensity  $I_1$  is attenuated by an exponential factor when observed through the atmosphere,  $\tau$  is the optical depth, in nepers, and  $H$  the elevation angle:

$$I = I_1 e^{-\frac{\tau}{\sin H}} \tag{2}$$

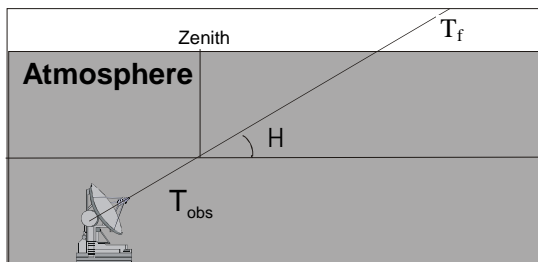


Fig. 2. Geometry for the “plane atmosphere” approximation

The intensities can be expressed in terms of equivalent noise temperatures. The complete expression for the observed temperature is given by:

$$T_{obs} = T_{sky} \cdot \left( 1 - e^{-\frac{\tau}{\sin H}} \right) + T_f \cdot e^{-\frac{\tau}{\sin H}} \tag{3}$$

where  $T_{obs}$  is the observed temperature,  $T_{sky}$  is the sky emission temperature and  $T_f$  is the external source temperature. The first term in the right hand of Eq. (3)

represents the self-absorbed emission from the sky, while the second term is the external source attenuated by the propagation in the atmosphere.

*B. Instrumentation*

The atmospheric opacity determinations were obtained at 212 GHz and 405 GHz for the site of El Leoncito, using the recently installed Solar Submillimeter-wave Telescope (SST) [5]. The El Leoncito Astronomical Complex (CASLEO) is located in an extended and dry reservation in the Argentina Andes, Province of San Juan, where nearly 300 clear days per year are available for observations. The SST has been installed in April 1999 near the existing CASLEO facilities at an altitude of 2550 meters. While SST was undergoing tests, integration and optimization works, solar and sky observations started during many short 1-2 weeks campaigns in 1999 and 2000. Nearly regular daily observations began in April 2001.

**II. METHODS TO DETERMINE THE ATMOSPHERIC OPACITY**

1. There are four most common methods to determine the atmospheric opacity: (a) the tipping method, which measures the sky temperature at different elevation angles; (b) the absolute method which measures transmission of a signal external to the atmosphere for different elevations; (c) the measure of a known apparent brightness temperature of a source external to the atmosphere at any elevation angle; and (d) the difference between the sky and ambient load temperatures. We have used and compared the first three methods to measure the atmospheric opacity at El Leoncito, at 212 and 405 GHz.

*A. Tipping method*

The atmospheric opacity is derived from the sky brightness temperature variation with the elevation angle (see simplified sketch in Figure 3)

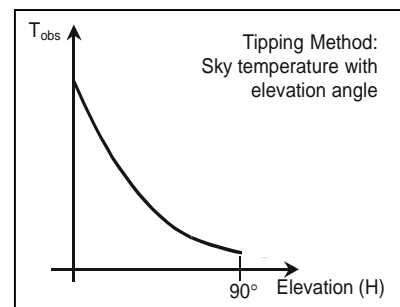


Fig. 3. Plot showing simplified sky temperature variation with elevation angle.

This method is practical to be used when the aperture of the detector is too small to measure any signal external from the atmosphere (such as the Sun or Moon) or when using large reflectors that cannot be pointed to the Sun – as are most of the existing submm-wave radio telescope antennas. The method, however, have uncertainties because the sky temperature measured as a function of elevation angle

may contain parasitic contributions not well known, especially from reflections, spillover and undesired ground contributions. This method produces large errors in determination for high values of  $\tau$  ( $> 1.5$ ).

**B. Absolute method**

The attenuation is derived from solar (or lunar) signal attenuation with elevation angle as shown in the simplified plot in Figure 4. This method is very accurate, and independent from any assumption on solar or sky brightness temperatures, and on other instrumental quantities (calibration factors, beam efficiencies, spillover, etc.).

For two elevation angles the optical depth can be derived from equation (3):

$$\tau = \frac{\ln\left(\frac{T_{obs2}}{T_{obs1}}\right)}{\left(\frac{1}{\sin H_1}\right) - \left(\frac{1}{\sin H_2}\right)} \quad (4)$$

where  $T_{obs1}$  and  $T_{obs2}$  are the mean values of the sun detected signal and  $H_1$  and  $H_2$  are the elevation angles for the solar scans 1 and 2, respectively, assuming that  $\tau$  has not changed. However this method presents two major limitations: the observations need to be made at low successive and close solar elevation angles - since at high angles the differences in antenna temperatures become too small for precise measurements - and for large attenuation conditions the observed solar antenna temperature differences might become too small to be well measured at low elevation angles, adding large errors in the determinations.

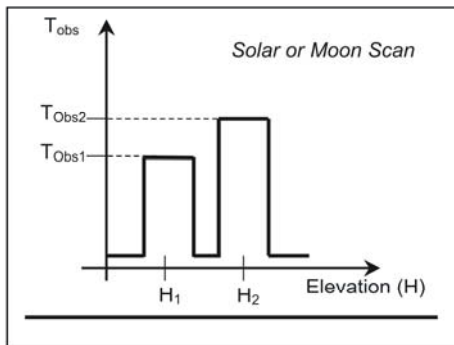


Fig. 4. Successive drift scans over the Sun or Moon

**C. Apparent brightness method**

This is a very practical method that allows the opacity determination from the solar observed antenna temperature at any elevation angle, adopting a parameter defined as the product of the solar brightness temperature  $T_*$ , times the coupling coefficient efficiency  $\eta$ , between the antenna and the source (approximately equivalent to the beam efficiency):

$$T_{app(Sun,Moon)} = \eta T_* \quad (5)$$

Replacing the equation (5) in the equation (3) we

find:

$$\tau = -\sin H \cdot \ln\left(\frac{T_{obs}}{\eta T_*}\right) \quad (6)$$

Although the two magnitudes, the solar brightness temperatures at the two submm-wave frequencies  $T_{app}$ , and the beam efficiencies  $\eta$ , are not well determined or measured, their product, which correspond to the apparent observed solar temperature outside the atmosphere, can be well determined using the absolute method for days with small opacities. This method can be used for opacity determinations at any elevation angle, and becomes particularly useful for nighttime determinations using the Moon.

We shall mention here a fourth method that is possibly the simpler one: opacity is derived by taking the calibration temperature scale as the difference between a reference temperature,  $T_{ref}$  (which could be at the ambient temperature,  $T_{amb}$ ) and the temperature of the sky  $T_{sky}$ , at a given angle (see Eq. (3)) [1] [3]:

$$\Delta T = T_{ref} - T_{sky} (1 - e^{-\frac{\tau}{\sin H}}) + T_{paras} \quad (7)$$

Where  $T_{paras}$  are the spurious noise temperature contributions due to undesirable reflections and spillover. Adopting the approximation  $T_{ref} \approx T_{sky} \approx T_{amb}$ :

$$\tau \approx \sin H \ln\left(\frac{\Delta T}{T_{amb}}\right) \quad (8)$$

This method requires careful determination of the spurious contributions for each channel, as a function of elevation angle, and was not used in the present study.

**III. RESULTS**

In Figure 5 we show in the upper three graphs the relationship between atmospheric opacities at 212 GHz and 405 GHz for El Leoncito, as derived for the same data set using the three methods, for 5 months of daily data obtained in 2001. The absolute and solar brightness methods have provided similar qualitative results, with more pronounced dispersion of data obtained with the absolute method. The solar brightness method (third plot from the top) shows a much better consistency between optical depths at the two frequencies.

The apparent brightness method has been used again for a larger number of daily measurements for 2 months obtained in 2002 (May and June). The results are shown in the Figure 6, confirming the previous findings. The correlation coefficient found between optical depths at 405 and 212 GHz using the solar brightness method ( $\cong 5.5$ ) is smaller than model predicted factor ( $\cong 7.5$ ) [2] [4].

For opacities measured at Mauna Kea [4], for example, we can estimate  $(\tau_{400}/\tau_{200}) \approx 7.5$ .

Measurements at 495 GHz and 220 GHz made at Pampa la Bola and Rio Frio, northern Chile have indicated  $(\tau_{495}/\tau_{220}) \approx 21.2$ , comparable to results obtained at Mauna Kea  $((\tau_{492}/(\tau_{225}-0.1)) \approx 20)$ [7]. Both results agree approximately with model predictions [2] [4].

present maxima at 0.18 nepers for 212 GHz and 0.9 nepers for 405 GHz, which are the provisional most probable values for the site.

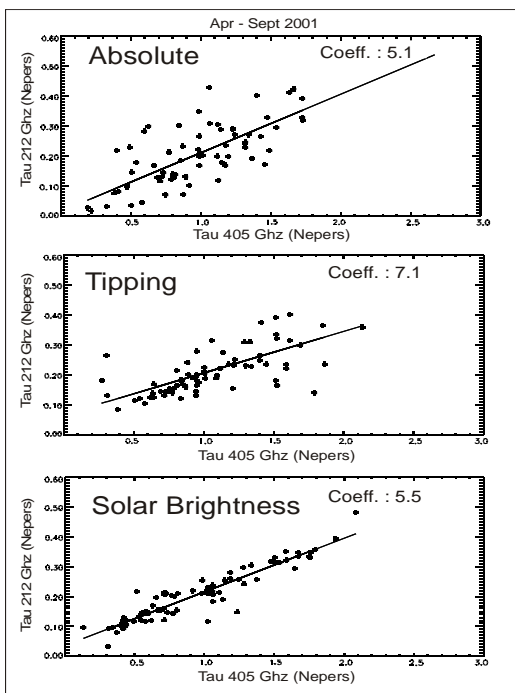


Fig. 5. Correlation plots for optical depth measured at 212 and 405 GHz using the three methods described in the text, for the same data set.

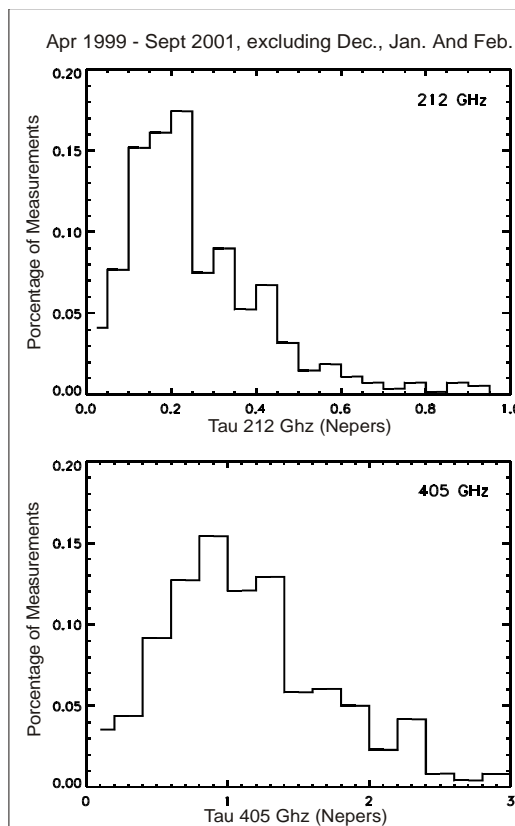


Fig. 7. Preliminary distribution of optical depths for El Leoncito SST site, at 212 GHz and 405 GHz.

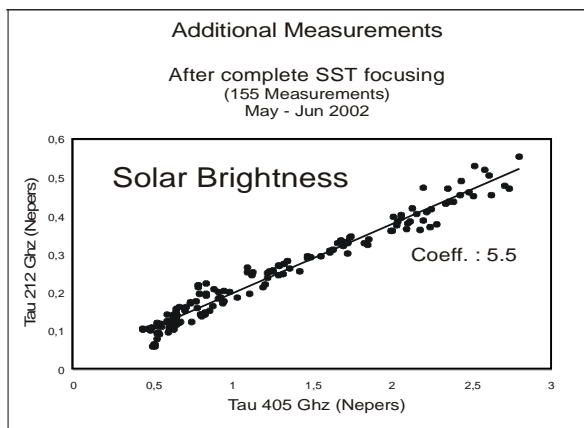


Fig. 6. This plot was obtained for another and larger data set using the solar brightness method

**IV. EL LEONCITO SUBMM-WAVE OPACITIES**

One preliminary survey of atmospheric opacity for El Leoncito was done with measurements taken from April 1999 – September 2001, using the absolute method. It contains 542 measurements, taken at several observing campaigns along the period, with exception of the months of December through February during which there were no campaigns. Data are presented in the form of distributions of optical depth (in nepers). The histograms shown in Figure 7

In Figure 8 we show a qualitative comparison of 212, 215 and 225 GHz atmospheric opacities (in % of measurements) for different submm-wave sites for which data were found available ([8][9] and web sites). The preliminary opacity distribution found for El Leoncito at 212 GHz is comparable to sites located at much higher altitude.

However one must be careful when analyzing these plots because the data sampling were very different for other sites. El Leoncito measurements were taken only on daytime. Some sites do not take into account nearly five months around summer. A most appropriate and uniform comparison should also take into account different methods used at other sites and the number of clear days for each site. El Leoncito has nearly 300 clear days per year.

**V. CONCLUSIONS**

Three different methods of atmospheric transmission determination were used and compared for the first time for the El Leoncito site, where the Solar Submillimeter wave Telescope is located, at 2550-m altitude: the tipping; the attenuation of the signal from the sun vs. elevation, and using the apparent solar brightness as a reference.

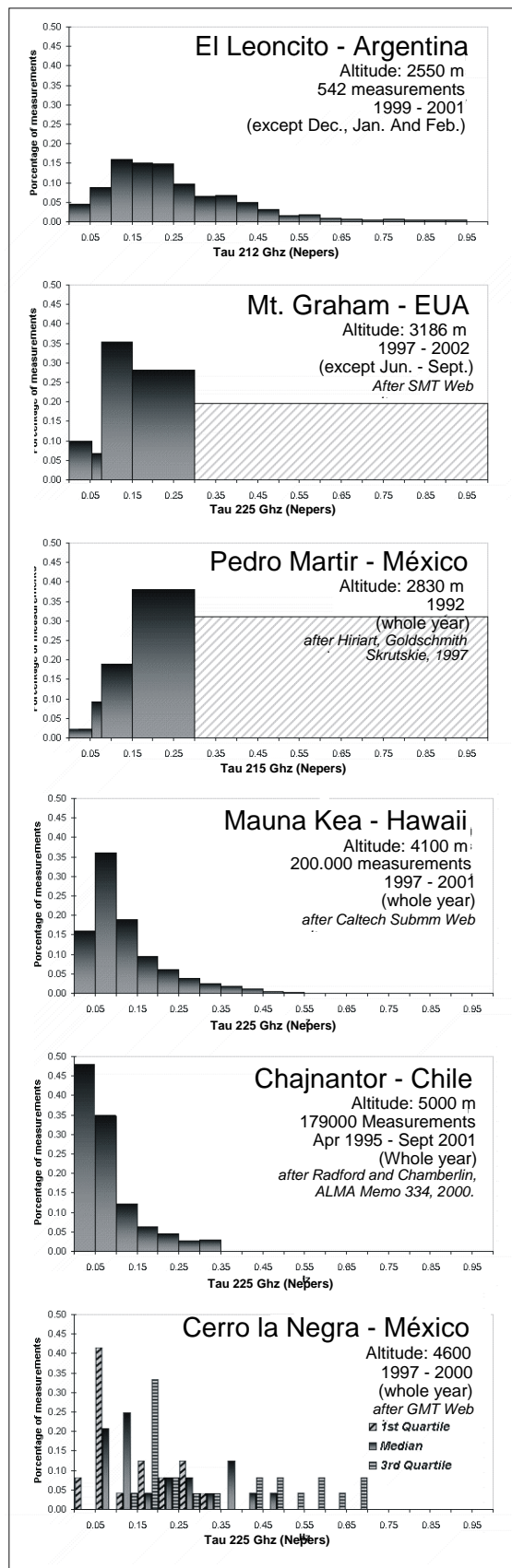


Fig. 8. Distribution of optical depth in the 200 GHz band for El Leoncito (top) compared to other submm-wave best sites of the world.

We found that the three methods provide similar

qualitative results for 212 and 405 GHz. However the data derived from the apparent brightness temperature presents a much better consistency for the measurements taken at the two frequencies. The ratio  $(\tau_{405}/\tau_{212}) \approx 5.5$  obtained for El Leoncito is smaller than values derived from model predictions [2] [4] suggesting that the El Leoncito sky is more transparent for higher frequencies in the submm-wave range, compared to other sites. Indeed the most probable 495 GHz opacities found for Pampa la Bola and Rio Frio (sites above 4000-m altitude), concentrate around 0.8 nepers [7], which extrapolated to 400 GHz after Fig. 1 [4] would predict 0.24 nepers at that site. On the other hand the results for those Chilean locations at 495 GHz are comparable to the 405 GHz results (0.9 nepers) for El Leoncito at a considerably lower altitude (2550-m) as shown in Fig 7.

The excellent submillimeter wave opacities obtained for El Leoncito at a relatively low altitude (2550 m) might be connected to a net reduction in the total water vapor content in a micro-climate typical to the region between the two large mountain ranges of the Andes: the pre Cordillera in the east and the main Cordillera at the west. Atmospheric transmission measurements are being planned for several sites with higher altitudes in El Leoncito area, for which lower opacities are expected.

## VI. REFERENCES

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