Title: **The Atmospheric Attenuation in the THz to mid-IR band**

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Abstract

1 Introduction

1.1 Atmospheric Opacity

Atmospheric opacity plays a key role in Astronomical observations since it affects the absolute flux measurement determination. Assuming a plane-parallel and homogeneous atmosphere an astronomical signal will be attenuated by a factor

$$e^{-\tau_\nu \sec\zeta} \ , \tag{1}$$

where τ_ν is the optical depth at frequency ν in the Zenith direction and ζ is the zenith distance of the observing direction. Dependency of the attenuation with wavelength is qualitatively represented in Figure 1. It is well known that the atmospheric attenuation at visible wavelengths is very weak as well as for radio meter to decimeter wavelengths. However millimeter observations start to be attenuated, for this reason telescopes operating at frequencies above 100 GHz are located above ground level to reduce the atmospheric mass over the observatory, the higher the frequency the higher the observatory height. However, observations above 1 THz ($\lambda = 0.3$ mm) are extremely attenuated even when observing at $5,000$ meter above sea level with $\tau \leq 1$ only for a few days every year. At a frequency around 15 THz ($\lambda = 0.02$ mm) the atmospheric opacity significantly drops allowing observations at mid-altitude.

There are however, few works describing the THz to mid-IR range atmospheric opacity in detail. Pardo et al. (2001) developed a new model that computes the electromagnetic wave propagation through the atmosphere from 1 GHz to 2 THz. The authors wrote a computer program called ATM that is freely distributed and widely used in different observatories. Paine (2018) also developed an atmospheric model and produced a computer program called am which is widely used to compute the atmospheric transmission from 1 GHz to 1 THz. More recently Eriksson, P. and Buehler, S.A. and Davis, C.P. and Emde, C. and Lemke, O. (2011) have developed an atmospheric model that computes the radiative transfer between 3 mm ($\nu = 100$ GHz) and 0.001 mm ($\nu = 300$ THz). The *Atmospheric Radiative Transfer Simulator* (arts) is a public domain open source software written in C++ which in the present version 2 can handle scattering and spherical geometries.

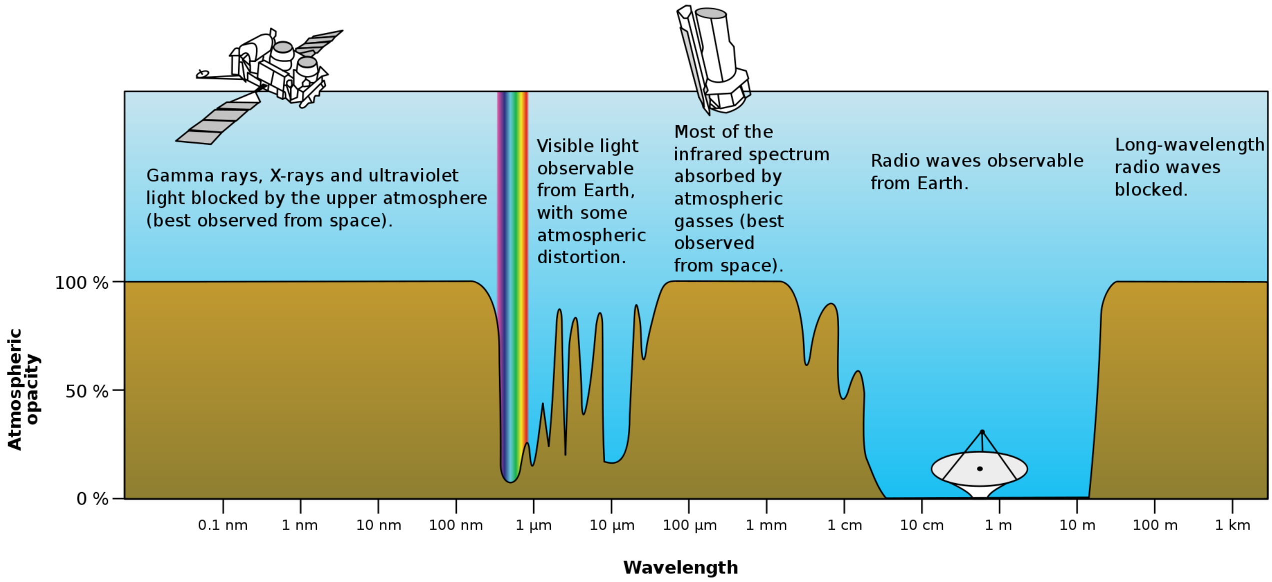


Figure 1: Zenith attenuation in percentage at ground level in function of wavelength. Credit: Wikipedia, and NASA.

1.2 High Frequency Solar Observations

Observations at high frequencies have revealed unknown features of the Solar flaring process. Kaufmann et al. (2004) have shown for the first time an event which its optically thin gyrosynchrotron decreasing tail spectrum stops at 200 GHz and then reverts, increasing with frequency. This unexpected behavior was later observed in other events (Silva et al., 2007; Lüthi et al., 2004; Kaufmann et al., 2009) and boosted observations at even higher frequencies. Kaufmann et al. (2013) used a mid-IR commercial camera installed in the focus of a small Newtonian telescope and observed a solar flare at $\nu = 30$ THz ($\lambda = 10$ μm) with a flux higher than that at submillimeter wavelengths and in good agreement with the time variation of the white light emission. Trottet et al. (2015) interpreted the mid-IR radiation as the thermal chromospheric response to the energy injected by accelerated particles. Later observations (Penn et al., 2016; Kaufmann et al., 2015; Miteva et al., 2016; Giménez de Castro et al., 2018) confirmed the presence of mid-IR radiation during flares and its close relation with white light. In the intermediate range between 1 and 30 THz, special photometers were designed (Kaufmann et al., 2014). Solar-T, a stratospheric balloon borne experiment with receivers for 3 and 7 THz successfully flew over Antarctica in January 2016. Now, the *High Altitude THz Solar photometers* (HATS), with a bolometer receiver and a passband filter centered around 15 THz ($\lambda = 20$ μm) is being built at CRAAM and will be installed in the *Observatorio Astronómico Félix Aguilar* (OAFA) in the Argentinian Andes at 2350 meter above sea level, its first light is expected for July 2020. Two 30 THz cameras are also operating on a daily basis, one at the OAFA observatory, the other at Mackenzie University.

2 Scientific Program

2.1 Objectives

The main goals of the present Postdoctoral fellowship are

- Model the atmospheric optical depth τ at selected frequency windows in the range 0.1 to 30 THz, understanding its dependency with local atmospheric variables (temperature, pressure, humidity). We are particularly interested in the following frequency windows: 0.65, 0.85, 1.5, 15 and 30 THz.

- Develop semiempirical analytical formulae to obtain τ from prominent atmospheric variables, like the *precipitable water vapor* (PWV), and with the optical depth at other frequencies.

- Determine τ for the sites where CRAAM presently has installed instruments in Argentina and Brazil, and in candidates sites for solar instruments.

- Analyze the observed τ at 30 THz from the available data and compare with models.

- Compare the outcomes from the different models: ATM, am and arts for $\nu \leq 2$ THz.

2.2 Methodology

Theoretical modeling will be done by using the ATM, am and arts for $\nu \leq 2$ THz and arts above. These programs need as input the local atmospheric profile, which is normally obtained from radiosonde data. Since we do not have radiosonde data, we can use the *COSPAR International Reference Atmosphere*, (CIRA-86, Fleming E.L. and Chandra, S. and Barnett, J.J. and Corney, M., 1990), which is a data set of zonally averaged monthly mean climatologies of several atmospheric parameters, freely available on the Internet. The *Global Data Assimilation System* (GDAS, NOAA-ARL, 2004) can be also used to derive the local atmospheric profiles. GDAS data are publicly available free of charge via the *Real-time Environmental Applications and Display System* (READY). The *National Centers for Environmental Prediction* (NCEP) of the *US National Weather Service* runs atmospheric computer analyses and forecasts multiple times per day. One of those systems is GDAS, which combines meteorological measurements with predictions from forecast models. GDAS data are available in 3-hourly, global, 1° latitude-longitude datasets. GDAS data have been successfully used by the Pierre Auger Collaboration to model the atmosphere above the observatory (Keilhauer, 2015).

While we are interested in modeling atmospheric opacity at OAFA and CASLEO[1] site, we also want to study the *Long Latin American Millimeter Array* (LLAMA) site. LLAMA is a joint Argentinian and Brazilian collaboration to build an operate a millimeter / submillimeter telescope in the Atacama region of Argentina at 4800 meter above sea level. The site will also host the *Q& U Bolometric Interferometer for Cosmology* (QUBIC) experiment. This site is a good candidate for new solar submillimeter instruments in the future.

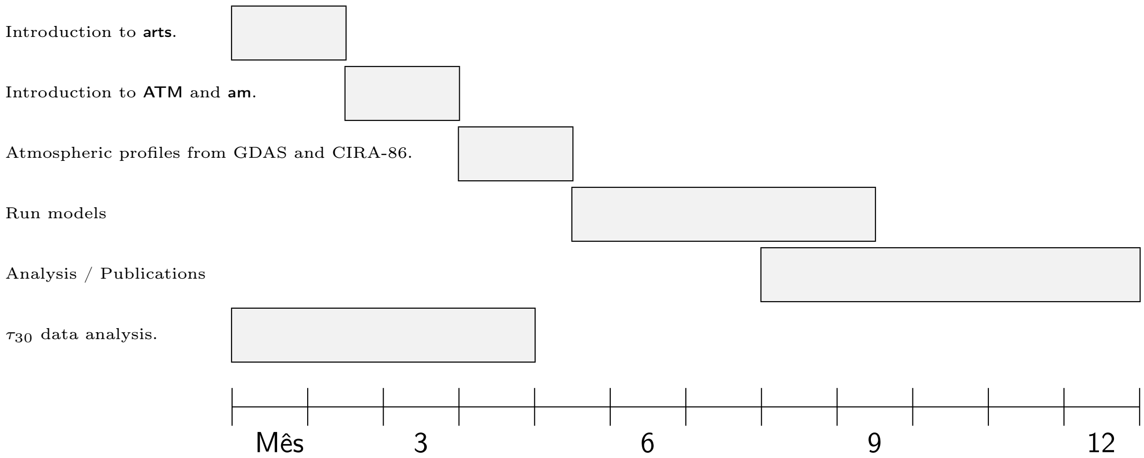
What we expect as results are frequency distributions of τ in terms of days per year for the selected frequencies at the selected sites, and semiempirical formulae that relate τ with PWV or with τ at other

[1] *Complejo Astronómico El Leoncito*, San Juan, Argentina, is where the Solar Submillimeter Telescope (SST, Kaufmann et al., 2008) is installed.

frequencies. Similar results at other frequencies can be found in Melo et al. (2005) and Cassiano et al. (2018) for 212 and 405 GHz at CASLEO and in Cortés et al. (2017) for $\lambda = 350\ \mu$m.

The available data allow to determine daily mean values of the optical depth at 30 THz. This can be done using Eq. (1) and fitting the observed solar temperature in a daily transit over the observatory. This method assumes that τ varies only very slowly in time and that the atmosphere is homogeneous, but is a first approximation that may be used to compare with models.

2.3 Schedule



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