Numerical model for atmospheric microwave absorption

A. Kies, A. S. A. Dib, A. H. Belbachir and R. Bouamrane

Abstract. In this paper we propose a numerical model to calculate microwave absorption in the earth's atmosphere. This model combines Monté Carlo methods imbeded in the efficient simulation open-source toolkit Geant4, and standard physical models of the atmosphere where experimental data such as pressure, temperature and air composition have been compiled for many years. Also, from high-resolution transmission molecular absorption database, we generated spectral data at any altitude as input into our model. We were able to successfully reproduce known absorption results for a simple case previously calculated using other methods. This new approach is promising when tackling microwaves physics in more realistic atmospheric models.

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1 Introduction

The interaction of electromagnetic radiation with Earth's atmosphere has been and still is highly studied with various mathematical models. In the microwave region, which is the focus of this work, these interactions are primarily associated with reversible quantum transitions in the vibrational-rotational states of gaseous molecules, particularly oxygen and water. Important absorption occurs in several known bands. The atmospheric spectrum between 1-100 GHz has been studied in detail by many highly cited authors such as Hans Liebe [7] (a reference model), Philipp Rosenkranz [5] (another classical study), Juan R. Pardo [9] (ATM model), Scott Payne [8] (AM model), Stephan Buehler [4] (ARTS model) and several others. All these authors provide detailed descriptions about the spectroscopy, the physics and the mathematics involved in the radiative transfer calculations. They also provide experimental results to support their detailed models. In this paper, we do not intend to repeat what is well documented elsewhere. For a global review on the subject, see for example [10] and references therein.

This paper is organized as follows. Section 2 describes the mathematical and numerical atmospheric model used to evaluate pressure, temperature, refractive index and

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absorption coefficient profiles. In Section 3 we intoduce how to conduct the calculations using the Monte Carlo methods imbeded in the well knows high energy physics open source simulation toolkit "Geant4". Results and discussion are given in Section 4. Finally, conclusions and perspectives are presented in section 5.

2 Atmospheric modelling

Radio waves propagating through ionosphere experience different attenuation mechanisms such as absorption, reflection, refraction, scattering, polarization, etc. In regions other than ionosphere, radio waves lose their energy mainly due to absorption by water molecules in various form (cloud, rain, snow, hail or fog). At frequencies above 10 GHz, rain is considered to be the major cause of attenuation. The U.S. Standard Atmosphere is a static atmospheric model of how pressure, temperature, density, and viscosity of the Earth's atmosphere change as function of altitude. The model, based on an existing international standard, was first published in 1958 by the U.S. Committee on Extension to the Standard Atmosphere, and was updated in 1962, 1966, and also in 1976 [13]. To some extent, this data is publicly available in many ways depending on the objective of the study. Among these, in addition to atmospheric thermodynamic state data, the pycraf Python package [11] provides functions and procedures for spectrum-management. It includes an implementation of the ITU-R Recommendation P.452-16 for calculating path attenuation. It also supports NASA's Shuttle Radar Topography Mission (SRTM) data for height-profile generation. And also includes a full implementation of ITU-R Recommendation P.676-10[12], which provides two atmospheric models to calculate the attenuation for paths through Earth's atmosphere. Figures 1 and 2 show typical temperature and pressure profiles generated by pycraf which were used in our work. There exists other packages such as HITRAN Application Programming Interface (HAPI), which is a set of routines in Python aimed to provide a remote access to functionality and data given by the project HITRAN [6] (acronym for High-resolution Transmission molecular absorption database). HITRAN is a compilation of spectroscopic parameters that a variety of computer codes use to predict and simulate the transmission and emission of light in

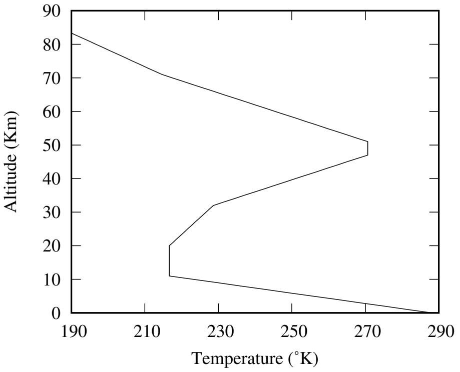

Figure 1: Temperature profile

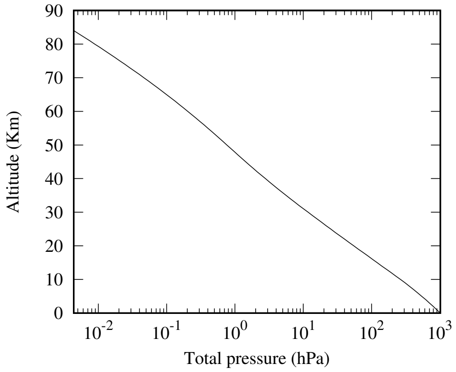

Figure 2: Total pressure profile

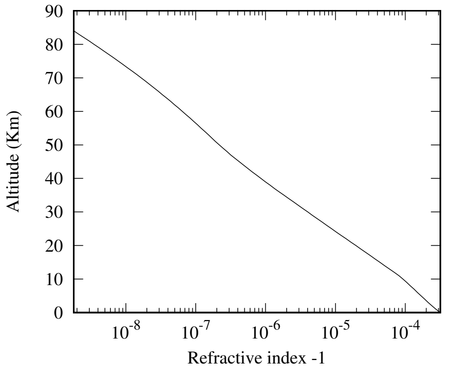

Figure 3: Refractive index -1 for (1-100 GHz) frequencies

the atmosphere. However, pycraf is straightforward and is specific to millimetric and submilimetric waves (a frequency range from 1 to 1000 GHz). Figures 3 and 4 show refractive index and absorption data from pycraf which will later be used to carry out our simulation as described in the subsequent sections.

3 Geant4 Modelling

Geant4 is a toolkit for the simulation of the passage of particles through matter[1, 2]. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. Over the past several years, major changes have been made to the toolkit in order to accommodate the needs of user communities, and to efficiently exploit the growth of computing power made available by advances in technology. Basically, Geant 4 requires supplying three building blocks: the source (radiation), the detector (matter) and interactions. In our case, the source is the microwave radiation which we suppose is coming from outer-space. The detector is the earth's atmosphere consisting of many layers each of which has it's own state pa-

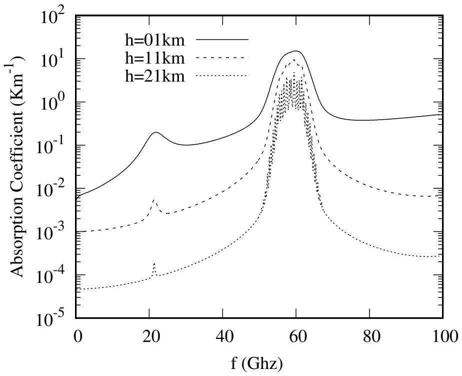

Figure 4: Coefficient of Absorption at different altitudes for (1-100 GHz) frequencies

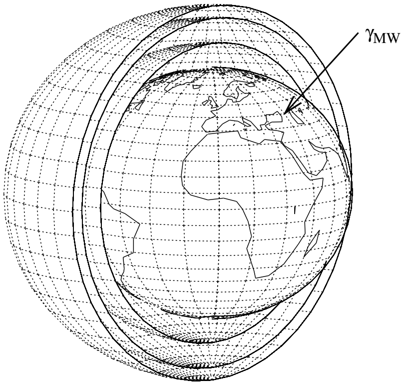

Figure 5: Geant4 model

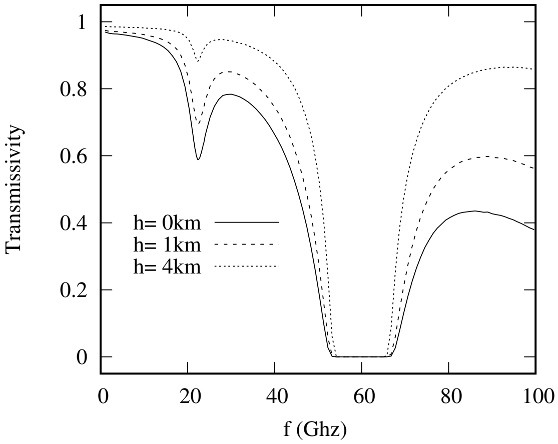

Figure 6: Zenith transmitivity for (1-100 GHz) frequencies, source at h = 32 km

rameters (pressure, temperature and composition). Finally, the interactions we have considered for now are essentially absorption and refraction phenomena(see figure 5).

4 Simulation results and discussion

The simulation was carried out starting with a sufficient number of microwave photons in order to obtain accurate final results. For our calculation we started with 500000 photons for each frequency, at a given altitude, aimed vertically (Zenith) down to Earth surface. To illustrate our approach, we have focused on the frequency interval [1,100] Ghz where we exhibit the well known water vapor and oxygen absorption peaks, respectively at 22Ghz and 60 Ghz. In the present example, we have considered 32 equally spaced layers from 0 km to 32 km altitude. The state parameters and interaction properties are supposed to be uniform within each 1 km thick layer. If more precision is needed, then, the number of layers may be increased or adapted at critical heights. The next step is to specify measuring points (detectors) where the number of surviving photons is estimated and ratio to initial flux is calculated. From these ratios we obtain the values of Zenith transmitivity spectrum. We have written a python script that generates the necessary source c files related to the Geant 4 detector layer construction and also generates absorption and refraction data for each layer. This python script uses package mentioned in the previous sections which provides functions and procedures for various tasks related to spectrum-management. For now, we have considered a clear atmosphere. On figure 6, we have plotted the Zenith transmitivity from altitude 32 km down to several different heights. The plots obtained are qualitatively very similar to those found in the literature. Quantitatively speaking and for the sake of comparison, let us focus on ground Zenith transmitivity values (h = 0 km). On figure 7, we have plotted the transmitivity at h = 0 km for a source at h = 32 km obtained from our approach, a first order estimation (Appendix A) and a result given on [10]. Results show very good agreement. For a

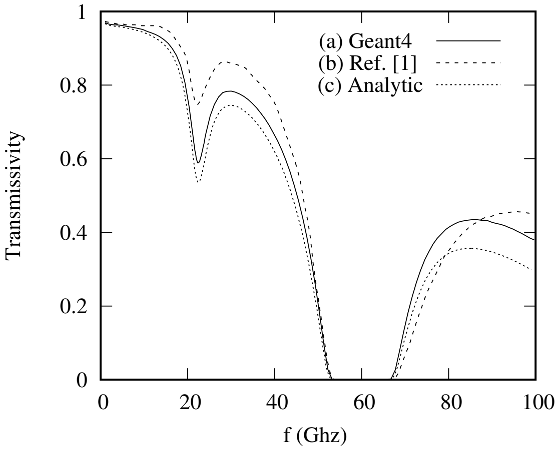

Figure 7: Zenith transmissivity at h = 0 km: (a) this work; (b) same conditions from [10]. ; (c) result from Appendix A.

clear atmosphere, we have also noticed that above 20 km, the numerical values do not significantly change because absorption at these altitudes is too small. Also, we have checked that microwave beams are deflected only a few centimeters on Earth ground, which represents less that a second of arc.

5 Conclusion

In this paper, we have studied a simple case of microwave beam falling down to Earth ground from high altitude using a Monte Carlo Geant4 approach. As a proof of concept and work, we have considered only data for a clear atmosphere model in order to compare with known results. We believe that this approach can tackle more realistic situations, including dynamic models where time evolution is considered. Geant4 has proven to be very effective in many complex physics systems at all energy scales. In a future long version of this work, we plan to address more realistic situations. This new tool will help compute with precision atmosphere influence on microwave radiation and in return enable us to use experimental microwave radiation measurements to retrieve various atmospheric parameters.

A First order estimation

A simple calculation can be carried out starting from absorption coefficient $\alpha_i(dB/km)$ for each layer i. Considering that initial photon number at highest altitude is I_n, we have

$$I_{n-1} = I_n \exp{(-\alpha_n d_n)}. \tag{A.1}$$

from which, we obtain at ground level

$$I_0 = I_n \exp\left(-\sum_{k=1}^{n} \alpha_k d_k\right). \tag{A.2}$$

Our layers are equally spaced, and so $d_k = 1km$. Therefor, the transmitivity at ground level is given by

$$T = \frac{I_0}{I_n} = \exp\left(-\sum_{k=1}^{n} \alpha_k\right). \tag{A.3}$$

As can be clearly seen on figure 7, this result is an underestimation of the transmitivity since only absorption was taken into account.

References

[1] S. Agostinelli, et al., *Geant4-a simulation toolkit*, Nuclear Instruments and Methods in Physics Research A 506 (2003), 250-303.

[2] J. Allison, et al., *Geant4 Developments and Applications*, IEEE Transactions on Nuclear Science 53, 1 (2006), 270-278.

[3] J. Allison, et al., *Recent developments in GEANT4*, Nuclear Instruments and Methods in Physics Research A 835 (2016), 186-225.

[4] S. A. Buehler, P. Eriksson, T. Kuhn, A. Von Engeln and C. Verdes, *ARTS, the atmospheric radiative transfer simulator*, Journal of Quantitative Spectroscopy and Radiative Transfer 91 (1) (2005), 65-93.

[5] D. Cimini1, P. W. Rosenkranz, M. Y. Tretyakov, M. A. Koshelev, and F. Romano, *Uncertainty of atmospheric microwave absorption model: impact on ground-based radiometer simulations and retrievals*, Atmospheric Chemistry and Physics 18 (2018), 15231-15259.

[6] R. V. Kochanova, I. E. Gordon, L. S. Rothman, P. Wcislo, C. Hill and J. S. Wilzewsk, *HITRAN application programming interface (HAPI): A comprehensive approach to working with spectroscopic data*, Journal of Quantitative Spectroscopy and Radiative Transfer 177 (2016), 15-30.

[7] H. J. Liebe, *MPM-An atmospheric millimeter-wave propagation model*, International Journal of Infrared and Millimeter Waves 10 (2003), 250-303.

[8] S. Paine, *The am atmospheric model*, SMA Technical Memo #152, vn 9.2, Smithsonian Astrophysical Observatory, 2017.

[9] J. R. Pardo, J. Cernicharo and E. Serabyn, *Atmospheric transmission at microwaves (ATM): An improved model for millimeter/submillimeter applications*, IEEE Trans. Antennas Propag. 49 (12) (2001), 1683-1694.

[10] F. T. Ulaby and D. G. Long, *Microwave Radar and Radiometric Remote Sensing*, University of Michigan Press, Ann Arbor, 2014.

[11] B. Winkel and A. Jessner, *A. Spectrum management and compatibility studies with Python*, Advances in Radio Science 16 (2018), 177-194.

[12] ***, *Attenuation by atmospheric gases and related effects*, International Telecommunication Union, Recommendation P.676 , 2019.

[13] ***, *U.S. Standard Atmosphere, 1976*, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration and United States Air Force, Washington, D.C., October 1976.

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