Atmospheric Opacity Above 1 THz: Evaluation for the ALMA Site and for Laboratory Developments

Juan R. Pardo, Eugene Serabyn. José Cernicharo, and Martina C. Wiedner

***Abstract*—This contribution is aimed at reviewing the impact of the atmosphere for millimeter and submillimeter wave observations performed from platforms inside the Earth's atmosphere with special focus on the supra-THz regime. The current models have also been applied to typical laboratory conditions, because absorption and pathlength fluctuations there have to be taken into account when developing and measuring characteristics of Supra-THz components.**

***Index Terms*—Atmospheric Measurements and Models, Terahertz Technology, Longwave Astronomy and Remote Sensing.**

I. Ground-Based Fourier Transform Spectroscopy and Water Vapor Radiometry of the Atmosphere

An extensive study of the atmospheric transmission at mm and submm wavelengths has been performed since the early 1990s with a Fourier Transform Spectrometer (FTS) mounted at the CSO telescope atop Mauna Kea (4100 m above sea level). The goal of this work, described in [1] has been to compile a data base of accurately calibrated spectra for use in refining atmospheric models.

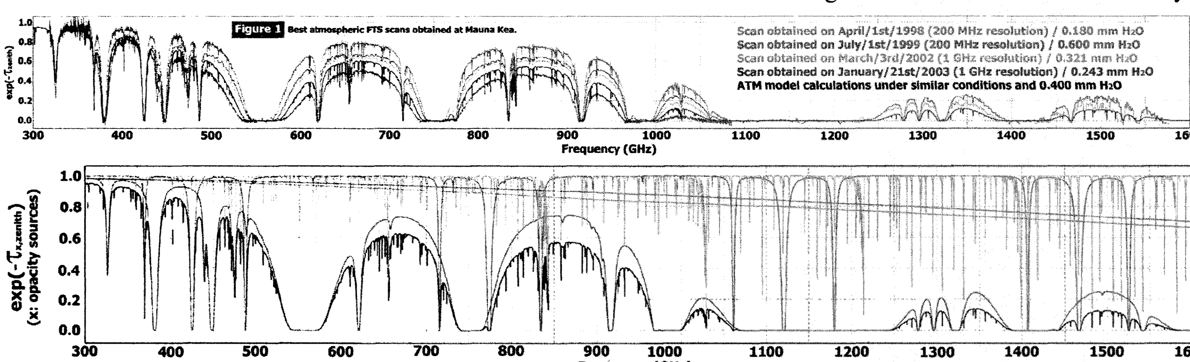

Fig. 1. Top panel: Best Atmospheric Fourier Transform Spectroscopy Scans obtained at Mauna Kea during the period 1995-2003. The estimated zenith water vapor column has been obtained from fitting the data with the model presented in [1]. Bottom panel: Resulting atmospheric transmission model for Mauna Kea for 0.4 zenith water vapor column (dark curve) and its splitting in different opacity sources (see [1]).

In this context, the separation of the resonant (lines) and non-resonant opacity terms is paramount. Due to the access to very dry conditions, we have been able to successfully separate the "wet" and "dry" non-resonant opacity terms up to 1.6 THz for the first time. The best spectra obtained in this series of experiments (see [1], [2] and [3]), and the resulting model, are shown in Figure 1.

A 3-channel water vapor radiometer, described in [4] operating near the 183.31 GHz water line has also been used for different site testing studies at Mauna Kea, included a cross-comparison with the FTS [5]. The instrument was a first prototype of a kind of device intended for monitoring of water vapor fluctuations on very short time scales to perform phase corrections for interferometry.

A. Latest Results on Non-Resonant Absorption at Frequencies above 1 THz

While our earlier work extending up to 1 THz [1] allowed the separation of the "wet" and "dry" non-resonant atmospheric opacity components with both shown to be following ν^2 laws in this regime, in [3] we report on the extension of these observations up to 1.6 THz. In the higher frequency regime, our results indicate that the ν^2 description may begin to fail due to the proximity of the FIR band centers. The far wings of lines above 2 THz account only for a very small fraction of the total opacity so that errors in them can explain the non-resonant continuum-like atmospheric opacity. This can be seen in in the results plotted in Figure 2.

Reanalysis of the data presented in Fig 2, plus new data (of better quality) acquired in 2003 (all data can be found in Fig. 1) confirm the new findings about the non-resonant atmospheric absorption beyond 1 THz. The total continua extracted from the FTS measurements (dots in Fig. 3), are

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compared to the result of combining the N_2-N_2 + N_2-O_2 + O_2-O_2 collision induced absorption (dashed line in Fig. 3) and the ν^2 foreign-H_2O continuum (dotted line in Fig. 3). The overestimate above 1.2 THz of the combined result (solid line in Fig. 3) appears evident. The black crosses represent the total foreign-H_2O absorption according to the model presented in [6]. The dry non-resonant absorption, on the other hand, seems to be well described by the model presented in [7].

B. *Water Vapor Retrievals and Phase Correction.*

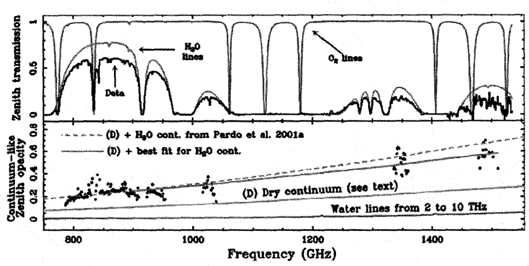

Fig. 2. Atmospheric FTS data acquired on 2002 March 3 above 750 GHz (upper panel) with the predicted contribution from O_2 and H_2O lines. The resulting excess of (non-resonant) absorption is represented by the dots in the lower panel. Considering the dry component of this non-resonant absorption to be as described in [7], it follows that the wet part of it departs form a ν^2 behavior.

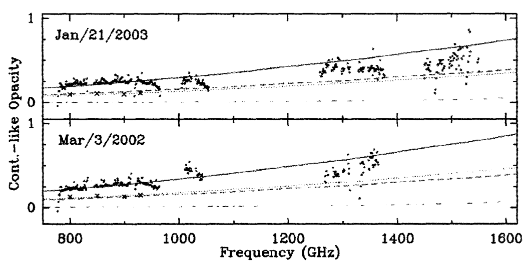

Fig. 3. Reanalysis of the data presented in Fig. 2 plus new data acquired in 2003 that confirm that the foreign-H_2O continuum in the Earth's atmosphere no longer follows a ν^2 behavior (see text).

In an atmosphere without spectroscopic lines, the index of refraction would be non dispersive so that the extra phase difference due to different water vapor columns in two different geometric paths scales linearly with frequency. Water vapor fluctuations are fast and can act on all spatial scales. Since H_2O has strong lines in the submillimeter-wave domain, it is the main responsible for phase fluctuations affecting interferometric measurements that are, in addition, dispersive. In order to translate the phase difference measured at one frequency to other frequencies, it is necessary to take into account the dispersive terms calculated from the water line absorption coefficients by using the Kramers-Kroning relations, as described in [1].

In order to explore water vapor retrieval techniques for ALMA, we started a comparison campaign involving the FTS mounted at the Caltech Submillimeter Observatory and the Water Vapor Monitor (WVM) mounted on one of the antennas of the Smithsonian Millimeter Array. Both devices were therefore separated by only 250 m. Using the ATM model to derive the sky coupling of the WVM and to perform water vapor retrievals from the data provided by both instruments has shown that it is possible to achieve an agreement of about 0.02 mm in the retrieved zenith water vapor column in time scales of several minutes (see Fig. 4). Therefore, a combination of WVMs for each antenna plus an accurate mm/submm model (based on extensive FTS work) provides a suitable tool for ALMA calibration in situations with less than 1.5 mm of zenith water vapor column. See [5] for details. WVM devices are currently being developed for ALMA by Cambridge and Chalmers. Another device has ben developed for APEX and is currently being tested.

II. The Impact of the Atmosphere on THz Laboratory Developments.

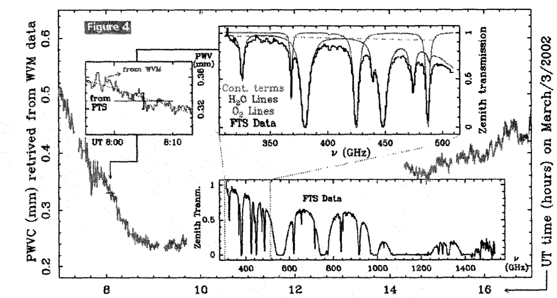

Fig. 4. Precipitable Water Vapor (PWV) zenith column obtained from fitting the WVM data recorded on 2002 March 3. At 8:00-8:10 UT we recorded an FTS spectrum (lower right inset). The 310-510 GHz data (upper right inset) was used to determine the PWV independent of the non-resonant absorption.
The detailed comparison of PWV retrieved from both instruments is shown in the left inset.
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The detailed comparison of PWV retrieved from both instruments is shown in the left inset.

It is also important to consider the effect of the atmosphere when testing THz components in the laboratory. Even a column of air of about 1 meter can produce significant absorption beyond 1 THz and also can produce some "turbulence" due to pathlength or phase fluctuations due to water in that short column of air. These effects were considered and discussed in a recent paper [8]. We have included here some calculations of this effect (see Figure 5). A laboratory situation with ambient pressure of 990 mb, ambient temperature of 20 C and two different relative humidity values (55% and 20%) have been considered, The Figure provides the expected attenuation (represented in terms of transmission) through 1 meter of air in those conditions, as well as the total extra pathlength introduced by water vapor.

III. Availability of ATM

A Linux executable version of the code is available to the community upon request via e-mail at the following address: pardo@damir.iem.csic.es. Please describe briefly the type of calculations you need to perform so that a convenient macro can be prepared and delivered together with the executable. Within the ALMA project, a C++ interface is now under development for use in the official software. People involved in ALMA may ask also about this interface. For more information about this code and related works: http://damir.iem.csic.es/PARDO/pardo.html.

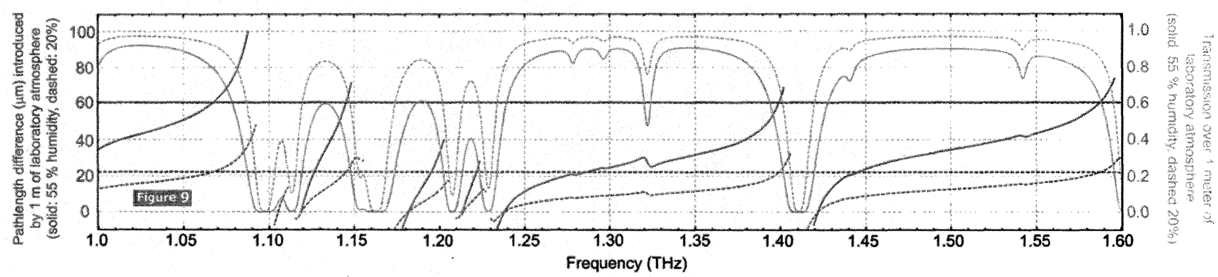

Fig. 5. The impact of the atmosphere (both absorption and extra pathlength) in the laboratory for 990 mb and 20° C of ambient pressure and temperature.

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REFERENCES

[1] J. R. Pardo, E. Serabyn, and J. Cernicharo, "Submillimeter atmospheric transmission measurements on Mauna Kea during extremely dry El Niño conditions:Implications for broadband opacity contributions," *J. Quant. Spectr. and Radiat. Transfer*, vol. 68, pp. 419-433, Jan. 2001.

[2] J. R. Pardo, J. Cernicharo, and E. Serabyn, "Atmospheric Transmission at Microwaves (ATM): An Improved Model for mm/submm applications," *IEEE Trans. on Antennas and Propagation*, vol 49, pp. 1683-1694, Dec. 2001.

[3] J.R. Pardo, E. Serabyn, M.C. Wiedner, and J. Cernicharo, "Measured telluric continuum-like opacity beyond 1 THz," *J. Quant. Spectr. and Radiat. Transfer*, vol. 96, pp. 537-545, Dec. 2005.

[4] M. C. Wiedner, R. E. Hills, J. E. Carlstrom, and O. P. Lay, "Interferometric Phase Correction Using 183 GHZGHz Water Vapor Monitors", *Astrophysical Journal*, vol. 553, pp. 1036-1041, Jun. 2001.

[5] J. R. Pardo, M. Wiedner, E. Serabyn, C. D. Wilson, C. Cunningham, R. E. Hills, and J. Cernicharo, "Side-by-side comparison of Fourier Transform Spectroscopy and Water Vapor Radiometry as tools for the calibration of millimeter and submillimeter ground-based observatories," *Astrophysical Journal Suppl. Ser.*, vol. 153, pp. 363-367, Jul. 2004.

[6] Q. Ma, and R. H. Tipping, "The frequency detuning correction and the asymmetry of line shapes: The far wings of H_2O-H_2O". *J. Chem. Phys.*, vol. 116, pp. 4102-4115, Dec. 2002.

[7] J. Boissoles, C. Boulet, R. H. Tipping, A. Brown, Q. Ma, "Theoretical calculation of the translation-rotation collision-induced absorption in N_2-N_2, O_2-O_2, and N_2-O_2 pairs," *J. Quant. Spectrosc. Radiat. Transfer*, vol. 82, pp. 505-516, Dec. 2003.

[8] J. W. Kooi, J.J.A. Baselmans, A. Baryshev, R. Schieder, M. Hajenius, J.R. Gao, T.M. Klapwijk, B. Voronov, and G. Gol'tsman, "Stability of Heterodyne Terahertz Receivers", *J. Appl. Phys.*, in press, 2006.