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Measured telluric continuum-like opacity beyond 1 THz

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Abstract

An extensive study of the atmospheric transmission at millimeter and submillimeter wavelengths has been performed since the early 1990s with a Fourier Transform Spectrometer (FTS) mounted on the Caltech Submillimeter Observatory (CSO) atop Mauna Kea (Hawaii), 4100 m above sea level. The goal of these observations is to compile a data base of accurately calibrated atmospheric transmission spectra for use in refining atmospheric models. In this context, the definition of the "quasi-continuum" opacity component is paramount. While our earlier work extending up to 1.0 THz has allowed the separation of the "wet" and "dry" quasi-continua components, with both shown to be following ν^2 laws in this regime, here we report on the extension of these observations to 1.6 THz. In the higher frequency regime, our preliminary results indicate that the ν^2 description may begin to fail due to proximity to the FIR band centers. Because the opacities in the potentially interesting atmospheric windows at 1.02, 1.35 and 1.5 THz have a large contribution from the quasi-continuum terms, accurate predictions for the transmissions in these windows require refinements in lower frequency models. Comparisons of our data below 1 THz with extant models give a remarkable agreement.

Keywords: Atmospheric spectrum; Fourier-transform spectroscopy; Radiative transfer; Collision-induced absorption

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1. Introduction

As ground-based radioastronomy extends its observing capabilities to increasingly higher frequencies, interest in a detailed model of the atmospheric absorption at these frequencies also increases. Furthermore, with the technical advances of the recent years, heterodyne instruments above 1 THz are now being built and are already in use at the Receiver Lab Telescope (RLT) and the Antarctic Submillimeter Telescope/Remote Observatory (AST/RO) and are envisaged for the Atacama Path Finder Experiment (APEX), the Atacama Submillimeter Telescope Experiment (ASTE), and possibly the Cornell/Caltech Atacama 25 m dish.

Exploratory ground-based atmospheric transmission Fourier-Transform Spectroscopy measurements have been performed in the past at frequencies up to 1.6 THz [1] or even up to 3 THz [2]. However, no analysis of the continuum-like opacity was attempted with those data sets. Our previous study [3] based on measurements up to 1080 GHz has shown that: (1) a dry continuum-like opacity exists in the atmosphere across the submillimeter range reaching a value $\simeq 0.125$ at 1 THz for Mauna Kea conditions, which seems to be well explained by collision-induced opacity involving N_2-N_2, N_2-O_2, and O_2-O_2 pairs; (2) an excess H_2O opacity also exists even if all water lines up to 10 THz are included with pressure-broadened Van Vleck–Weisskopf line shapes and collisional line widths from the HITRAN data base [4]. The two most widely cited explanations for this wet continuum are: (1) failure of the impact approximation to calculate the line shape beyond ~1 THz from the line center and (2) opacity due to weakly bound complexes such as H_2O-N_2, H_2O-O_2, and H_2O-H_2O (the last one would be negligible under the conditions of our experiment). This excess amounts to $\simeq 0.40$ nepers/mm at 850 GHz in Mauna Kea conditions. The frequency dependence of these two continuum-like terms was found in [3] to be very close to ν^2, at least for frequencies up to 1 THz.

Above 1 THz three main windows reaching opacity minima at 1022, 1350, and 1487 GHz attract the attention of astronomers. From the ground they are only expected to reach maximum transmission of 30–35% under the best possible conditions in present-day observatories [3] (partial pressure of water vapor below 0.2 mb) so that a comparison with laboratory measurements (e.g. [5]), involving much larger water vapor densities, is impossible. Theoretical models (see below), however, provide some ground for comparison with direct atmospheric measurements.

Section 2 is devoted to a quick description of the Caltech Submillimeter Observatory-Fourier Transform Spectrometer (CSO-FTS) and data acquisition on March 3, 2002 and January 21, 2003. Other complementary data sets used to validate our FTS measurements are also described in this section. Using the best spectra obtained, we extract and discuss the total continuum-like opacity above 1 THz in Section 3. Final discussions of our results compared to theoretical models are provided in Section 4. Finally, our conclusions are summarized in Section 5.

2. Observations

The observations were carried out on March 3, 2002 and January 21, 2003. The Mauna Kea (HI) site has an altitude of 4100 m above sea level. Typically, the pressure is around 620 mb and the ground temperature at night is usually within the range ~ -5 to $+5\,^{\circ}$C.

2.1. The CSO-FTS instrument

The basic instrumental setup of the FTS was described in [6], the atmospheric calibration technique can be found in [7], and some updates to this technique were described in [3]. In 2001, a new 1600 GHz low-pass filter was acquired after success with the 1100 GHz low-pass filter used in [3]. This new filter allows measurements of the whole 300–1600 GHz frequency range (the lower limit is imposed by the 20 arcsec light concentrator at the bolometer entrance). The beam splitter in this configuration is a 2 mil thick mylar sheet. Unfortunately, in this case the beam splitter passband deteriorates at the highest frequencies, resulting in higher noise than in the rest of the band, especially visible in the March 3, 2002 data due to the larger opacity.

In both observing runs, a few checks were carried out with known FTS configurations, prior to the observations with the new filter presented here, in order to check consistency. Due to the presence of very strong, saturated lines in the large frequency range covered (300–1600 GHz), the noise is larger than in FTS configurations using lower frequencies. It was thus decided to use a spectral resolution of 1 GHz for this study, which provides a good compromise between time for scan completion and spectral resolution needed to correctly measure the broad features of the atmospheric spectrum, including the continuum-like terms. Narrow features (mainly due to O_3) are then largely diluted. The calibration of the data was performed after each sky measurement against two different loads (ambient temperature and liquid N_2 temperature) and using the second-order corrections to the measured flux ratios described in [7]. All the steps described in that reference have been followed in order to ensure that the data quality is as high as in our previous publications. The two fully reduced spectra that we will use for our analysis are shown in Fig. 4.

2.2. Complementary data

On March 3, 2002 we operated simultaneously with the FTS a water vapor monitor (WVM) measuring the sky brightness in three double side band channels around the 183.31 water line [$\pm1.2, \pm4.2$ and ±7.8 GHz] described in [8]. These data were used to independently confirm our precipitable water vapor (PWV) estimate from the FTS measurement and are described in detail in a previous paper [9].

The January 21, 2003 night was windy and the atmosphere relatively opaque at the beginning but it evolved to be very dry with NRAO 350 μm τ-meter readings around 0.75 after midnight. This device measures the average zenith opacity over several tens of GHz in the 350 μm atmospheric window by means of tipping measurements of the sky brightness. The data from both nights are shown in Fig. 1. The extraordinary situation on January 21, 2003 is also confirmed by GOES-10 satellite water vapor maps, available at http://mkwc.ifa.hawaii.edu/satellite/index.cgi (see Fig. 2).

For both frequency runs further complementary data have been taken into account for the analysis performed below. These data were obtained from the telescope weather station, a hand held calibrated thermo/hygrometer, and atmospheric radiosondes launched twice a day from the nearby Hilo International Airport (see http://raob.fsl.noaa.gov, and Fig. 3).

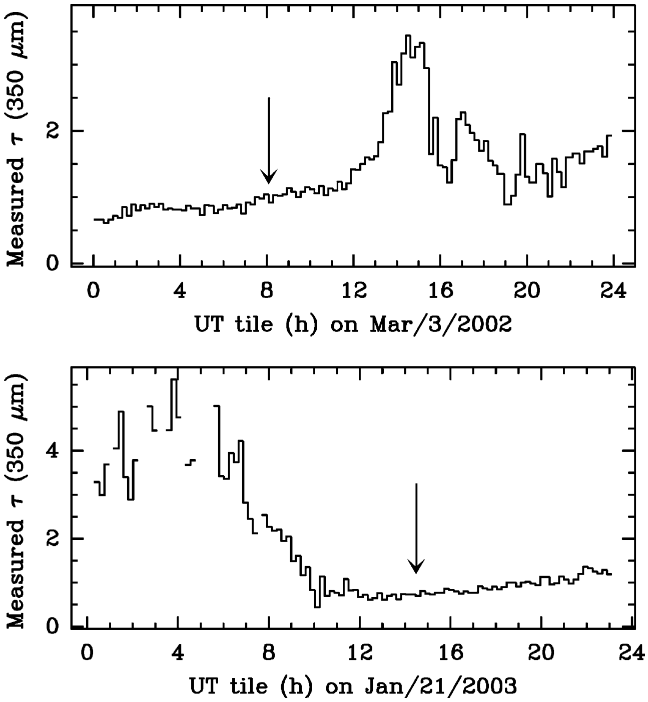

Fig. 1. Readings of the 350 μm atmospheric window NRAO opacity meter on March 3, 2002 and January 21, 2003. The arrows indicate when the FTS measurements discussed in this paper were performed.

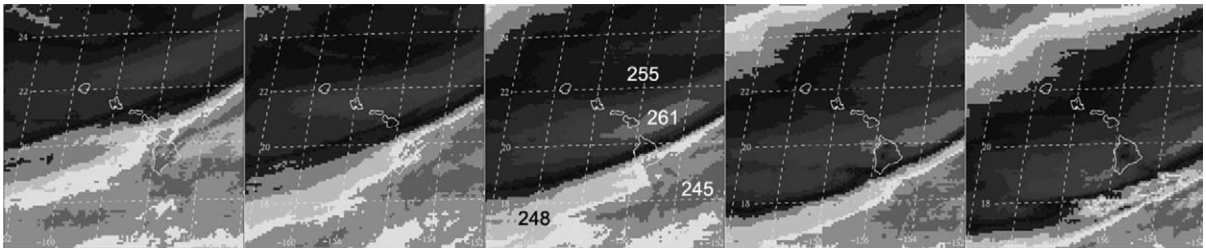

Fig. 2. GOES-10 water vapor maps (12.66 μm channel) over Hawaii on January 21, 2003 at UT times from 6:00 to 14:00 every 2 h (from left to right). For reference, some contour levels are given in the central map. Temperatures above 260 K indicate extremely low water vapor columns.

3. Continuum separation

The first step in our analysis is to show that in the newly measured frequency range (1.0–1.6 THz) an excess opacity exists on top of the line opacity alone, as demonstrated also below 1.0 THz in [3]. To do this we will follow the same strategy of [3]. First, we retrieve the zenith PWV corresponding to each spectrum using only a frequency range where the continuum-like opacity is already known (so that our fit is as independent of it as possible). We have selected the frequency range 557–980 (where the transmission of the mylar sheet is best) to perform a fit to both spectra

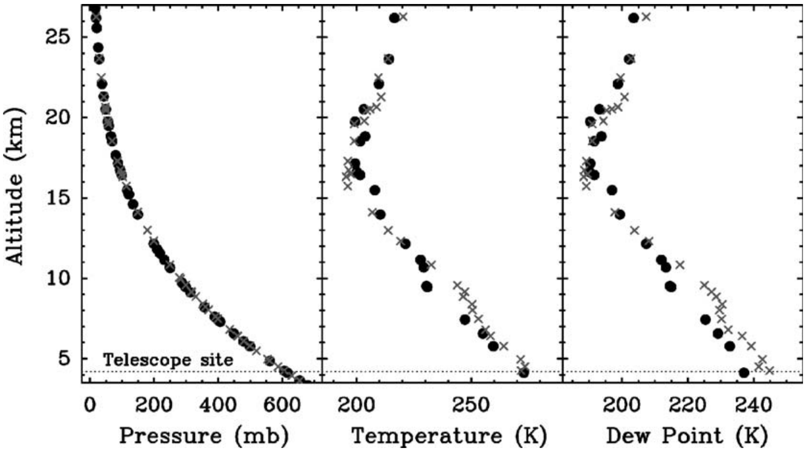

Fig. 3. Pressure, temperature and dew point temperature above the altitude of the CSO site according to the closest (in time) Hilo International Airport radiosonde data. The dots correspond to March 3, 2002 (4 h time difference between the radiosonde and the FTS scan) and the crosses to January 21, 2003 (10 h time difference because the 12 UT radiosonde was lost).

using the opacity terms derived in [3] and included in the model described in [10]. For this, we also need an a-priori atmospheric profile built according to the following information: (1) ground pressure and (2) ground temperature, from the weather station near the telescope, (3) ground relative humidity, as measured with a calibrated thermo/hygrometer, (4) water vapor scale height, (5) tropospheric temperature lapse rate, estimated from the Hilo Airport radiosonde data, (6) altitude of the site above sea level, (7) primary pressure step (mb) and (8) pressure step factor (no units). The meaning of the last two parameters was described in [9].

The last three parameters are common: (6) 4.1 km, (7) 10 mb, (8) 1.5. According to the information acquired in each case, the values of the other parameters were:

- March 3, 2002: (1) 623.0 mb; (2) 269 K; (3) 11.30%; (4) 2.2 km; (5) −7.5 K/km;
- January 21, 2003: (1) 621.0 mb; (2) 270 K; (3) 3.3%; (4) 2.2 km; (5) −5.6 K/km.

The fits provide the following values of the zenith PWV: 0.321 mm for March 3, 2002 (just slightly different from the value obtained in [9] due to the different frequency range used, but within the error bars given there) and 0.243 mm for January 21, 2003. The retrieval errors can be analyzed by considering the following maximum uncertainties expected for parameters (1), (2), (4), and (5) (the other parameters have a null or negligible impact): 1.5 mb, 2 K, 0.4 km, 2.5 K/km. For the conditions analyzed in this paper, this analysis gives a maximum of 4% uncertainty in the retrieved zenith PWVs. With the results of the fit below 980 GHz we can predict the line opacity beyond that frequency and subtract it from the measurement to get the measured "excess of opacity" for both cases (see Fig. 5). The results are only shown for those frequencies where the transmission exceeds 13.5%. In [3] we used a more conservative cut-off of 15%, but we are now exploring regions of higher opacity so we decided to relax the limit (Fig. 4).

The "excess opacity" in Fig. 5 cannot be due to a measurement error, nor to an error in determining PWV, as the later is less than 4% and can neither account for its amount, nor for its

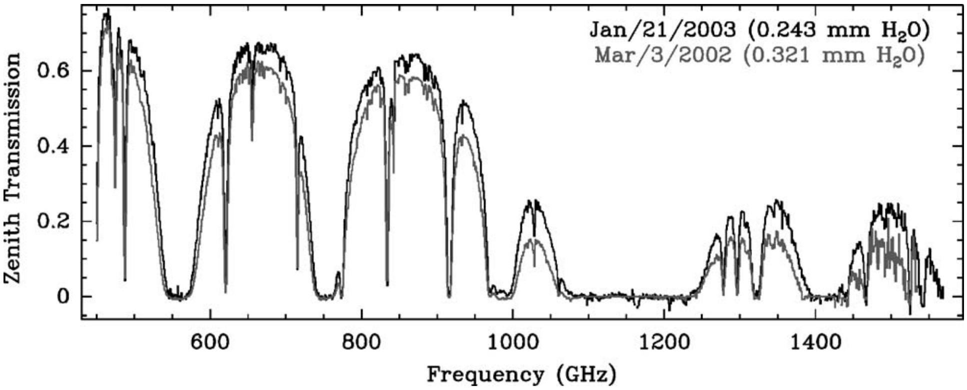

Fig. 4. Fully reduced FTS atmospheric transmission measurements considered for this work.

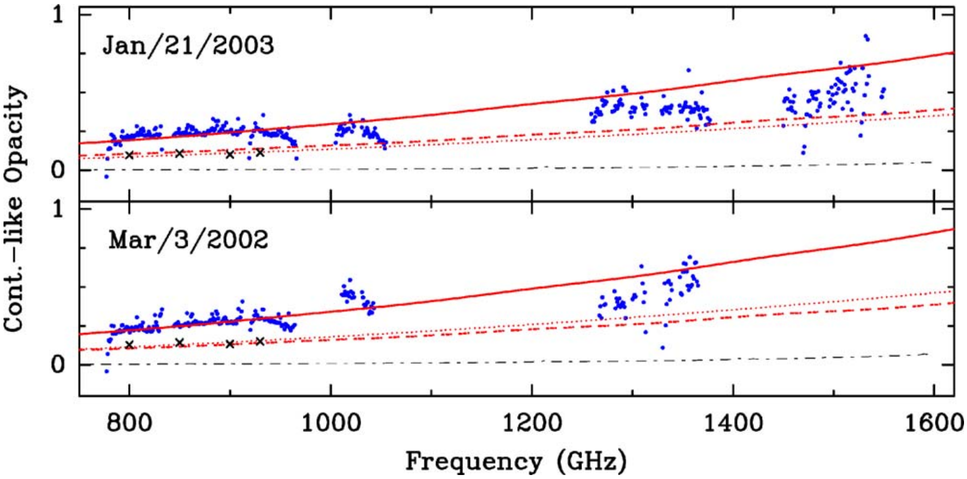

Fig. 5. Total continua extracted from the measurements (dots), compared to the result of combining the N_2-N_2 collision induced opacity of the model presented in [12] scaled by 1.34 (see text) and the foreign water vapor continuum derived in [3] extended above 1 THz (solid line). Dashed lines: the dry continuum alone multiplied by the factor 1.34 (the same in both cases). Dotted lines: the foreign water continuum alone from [3] in each case. Dashed-dotted lines: far wings of water lines above 2 THz using the classical line parameters (see text). Crosses: total H_2O excess of absorption respect to all lines up to 10 THz according to the Ma and Tipping [13] model. A correction has been applied because the original model gives the excess opacity respect to all water lines up to 1 THz only (see text).

frequency dependence. Hence an alternative explanation of this measured "excess opacity" has to be considered (as in [3]).

3.1. Possible contribution of lines above 2 THz

The first question that arises is whether or not the far wings of the water lines between 2 and 10 THz have a significant impact on the 1.0–1.6 THz opacity so that part of the excess opacity that we measure can be explained by errors in their classical line parameters. Other than the assumed far wing line shapes, the only parameter that can in fact suffer from large errors and that would have an impact here is the line width. In order to make an evaluation we extracted from the best fit model the line opacity of only those lines above 2 THz [$\tau_{2\,\mathrm{THz}+}(v)$] and then varied their pressure-broadening coefficients in a range of ±30% around their value given in [4]. The impact is very small: $\tau_{2\,\mathrm{THz}+}(1350\,\mathrm{GHz}) = 0.11 \pm 0.02$ and $\tau_{2\,\mathrm{THz}+}(1487\,\mathrm{GHz}) = 0.17 \pm 0.05$ mm of PWV, out of a total measured opacity excess ranging from 0.4 to 0.6 in these two windows for less than 0.35 mm of PWV. Given this small contribution, the excess opacity is not related to uncertainties in the classical line parameters. Hence we will call this excess "continuum-like" opacity from now on.

4. Discussion of continuum-like term

It was already known that the continuum-like opacity represents a large fraction of the total atmospheric opacity at frequencies above 200 GHz. In fact, at least up to about 1 THz, it was demonstrated in [3] that it has a frequency dependence very close to v^2. In [3] we have further separated the continuum-like opacity into a dry component (independent of the amount of precipitable water vapor) and a wet component that scales linearly with water vapor number density under dry conditions. There are two methods to separate the dry and wet contributions:

1. If two or more measurements for different PWV are available, the dry and wet continuum can be separated due to their different dependence on PWV, as was shown in [3].
2. We can use the relatively well understood theory of the dry term (see [11] and Section 4.1) and look at the remaining wet term.

Because the two data sets considered here correspond to a small PWV difference, it translates into a large scatter in the separated continua. In addition, the March 3, 2002 data quality beyond 1.4 THz is poor. For these two reasons, we have decided to follow the second option with these data.

4.1. Dry continuum

The dry continuum seems to be well explained by collision-induced opacity due to N_2-N_2, N_2-O_2 and O_2-O_2 (see [3]). Borysow and Frommhold [12] have modeled the collision-induced opacity due to N_2-N_2, which needs to be multiplied by a factor in order to also account for the N_2-O_2 and O_2-O_2 collisions. With extremely simple assumptions the factor found in [3] was 1.29. Further confirmation and refinement of this conclusion has come from a recent work [11] based on detailed theoretical calculations of the collision-induced opacity due to N_2-N_2, N_2-O_2, and O_2-O_2. Their ratio factor $R(v,\mathrm{T})$ with respect to N_2-N_2 alone is 1.34 up to about 3 THz for the 200–350 K temperature range. Both results (1.29 and the more rigorous 1.34) are in excellent agreement given the precision of the measurements presented in [3]. We are therefore confident that the dry part of the measured continuum-like opacity in this work is well described by the N_2-N_2 model in [12] scaled by a factor $R(v,\mathrm{T}) = 1.34$ (see Fig. 5). In fact, it would be impossible to distinguish between 1.29 or 1.34 in our measurements above 1 THz because, for example, at

1.5 THz this $R(v, \mathrm{T})$ difference translates to an opacity difference of 0.012, well below the noise level at that frequency.

4.2. Wet continuum

If we take the best-fit v^2 model for the wet continuum from [3] and add it to the above dry continuum, we find a good match below 1 THz to the derived continua in Fig. 5. Recently, Ma and Tipping [13] have performed detailed Lanczos calculations of the H_2O-O_2 and H_2O-N_2 opacity terms. We have plotted their results as crosses in Fig. 5. In this comparison it has been necessary to take into account that we extract the excess of opacity respect to all lines up to 10 THz, whereas the model in [13] gives the excess opacity respect to all lines up to 1 THz only (as in Liebe [14] and Liebe et al. [15] models). At 800 GHz, for instance, water lines above 1 THz account for a zenith opacity of 0.190 nepers/mm in dry Mauna Kea conditions, a value that has to be subtracted from the results in [13] for a proper comparison. The agreement is very good, giving consistency to the whole scenario below 1 THz. The current Lanczos theory is applicable for frequencies of interest far from the peak of the pure rotational H_2O transitions. These calculations have not yet been extended beyond 1 THz.

Above 1 THz, our best-fit v^2 model from [3] seems to overestimate the continuum-like opacity. If the wet continuum is due to opacity induced by colliding pairs of H_2O-O_2 and H_2O-N_2 molecules, we can imagine that, just as in the dry continuum theory, the excess water opacity should also reach a maximum somewhere in the far infrared. The exact determination of the frequency power law above 1 THz is difficult with the present data because (a) the scatter in the extracted continuum data points is large above 1.2 THz and (b) the exponent (2.0 below 1 THz) is most probably changing in the frequency range 1.0–1.6 THz. Fig. 5 nevertheless suggests that the exponent is below 2 for frequencies above 1.1 THz. As the data presented here are to our knowledge the only published results against which the excess opacity in the 1.0–1.6 THz range has been studied, more complete measurements in this frequency range would be very valuable in defining the H_2O continuum contribution at those frequencies.

5. Conclusions and future work

The continuum-like opacity was previously measured and separated into its dry and wet components up to a frequency of about 1 THz in [3]. In the present work initial measurements up to 1.6 THz have been made and we have reached the following conclusions:

1. Continuum-like opacity has clearly been detected beyond 1 THz.
2. Assuming the same type of pressure-broadened line profiles for H_2O above 2 THz as at lower frequencies, an analysis of the measurements shows that even considering relatively large uncertainties in the broadening parameters of water lines between 2 and 10 THz, their impact on the retrieved continuum terms is very small.
3. Our models using line opacity and previously derived best-fit dry and wet continuum-like terms [3] provide a good description of the measured continuum-like opacity in the new FTS opacity data up to 1 THz.

4. Assuming that the dry continuum is well described by N_2-N_2 collision induced models scaled by a factor of 1.34 even beyond 1 THz, it follows that the water vapor foreign continuum below 1 THz in the new data would match very well our own results in [3], and the a model [13]. Its contribution to the total opacity beyond 1 THz reaches $\tau \simeq 0.95/\text{mm}$ (at 1487 GHz). In the newly measured frequency region we may be seeing the flattening of this water vapor foreign continuum.

Further measurements above 1 THz under very dry conditions (as in [3]) would allow better definition of the H_2O continuum in this high frequency regime. However, due to the rarity of the necessary extremely dry nights, the acquisition of the needed data could take some time. On the other hand a large data base of carefully calibrated FTS spectra for $\nu < 1$ THz has already been compiled during 1995–2003 for zenith PWV ranging from 0.185 to ~6.0 mm. Our next step will thus be to use this extensive data base to provide a global best-fit analysis of the atmospheric opacity below 1 THz.

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