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Atmospheric absorption of terahertz radiation and water vapor continuum effects

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ABSTRACT

The water vapor continuum absorption spectrum was investigated using Fourier Transform Spectroscopy. The transmission of broadband terahertz radiation from 0.300 to 1.500 THz was recorded for multiple path lengths and relative humidity levels. The absorption coefficient as a function of frequency was determined and compared with theoretical predictions and available water vapor absorption data. The prediction code is able to separately model the different parts of atmospheric absorption for a range of experimental conditions. A variety of conditions were accurately modeled using this code including both self and foreign gas broadening for low and high water vapor pressures for many different measurement techniques. The intensity and location of the observed absorption lines were also in good agreement with spectral databases. However, there was a discrepancy between the resonant line spectrum simulation and the observed absorption spectrum in the atmospheric transmission windows caused by the continuum absorption. A small discrepancy remained even after using the best available data from the literature to account for the continuum absorption. From the experimental and resonant line simulation spectra the air-broadening continuum parameter was calculated and compared with values available in the literature.

1. Introduction/Background

The Earth's atmosphere is full of absorbing species. Many of these species can render the atmosphere nearly opaque in specific frequency bands. Water for example has hundreds of rotational and vibrational absorption lines from the radio wave range through the terahertz region. Since water vapor pervades the entire atmosphere, the propagation of radiation can only occur in parts of the electromagnetic spectrum that is not wholly absorbed by water. These atmospheric windows are located between the strong resonant absorption lines; however, some radiation is still absorbed even in the atmospheric windows. Water vapor absorption is usually separated in two parts to describe this phenomenon, absorption due to the resonant rotational or vibrational lines and that due to the continuum. Continuum absorption is most often empirically determined and defined as the difference between the experimentally observed spectrum and the calculated resonant absorption line spectrum.

Much work has been performed to characterize and understand the absorption peaks of water vapor [1–3] as well as to determine the functional form of the continuum contribution to water vapor absorption in the terahertz regime [4–8]. The continuum contribution to the absorption coefficient scales as the square of the frequency and has a negative dependence on temperature in the microwave [8–10], however, at higher frequencies only a limited

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number of studies have shown a quadratic dependence on frequency in the terahertz regime [11–13]. Further complicating the continuum absorption, there is uncertainty as to the values of the continuum parameters within any given model. This ambiguity is due to the heavy dependence of the parameters on the line shape function and the number of absorption lines used in the model as well as a limited number of experimental studies at terahertz frequencies. The water vapor absorption spectrum has been extensively studied, but until recently the terahertz region of the spectrum has received little attention for experimental work. Only a few broadband studies have been performed in the terahertz region, most of which were performed in a laboratory environment using either pure nitrogen or oxygen gas as the foreign broadening gas [12–15]. This method allows for control over the experimental conditions at the expense of using a foreign gas that is not of the same composition as Earth's atmosphere. Other studies have been performed using atmospheric air [11,16–18], however these studies lack control of the experimental parameters and are often performed at remote high altitude locations.

The present work is one of the few to be performed under laboratory conditions using dry air. This method provides for both control over the experimental parameters as well as a broadening gas with the same composition of the atmosphere. The experimental data between 0.3–1.5 THz were taken over multiple path lengths and humidity levels and were used to determine the total absorption coefficient of atmospheric air. Using these results coupled with calculated absorption coefficient values using the parameters in the 2008 HITRAN Database (HITRAN) [19], the foreign continuum coefficient for air was calculated and compared with other experimental data in the frequency region.

2. Experimental setup

Transmission data were collected using a Pike Technologies variable path length gas cell coupled to a Bruker Vertex 80 V Fourier Transform Infrared (FTIR) Spectrometer. A mercury arc lamp was used as the incident radiation source and the transmitted radiation was detected using a liquid He cooled silicon bolometer from IR Labs. In order to increase sensitivity the temperature of the bolometer was further reduced to 1.6 K by use of a vacuum pump. The cell was secured vertically in the sample chamber of the FTIR with the top protruding out. The FTIR's sample chamber was covered to allow the chamber to be purged with nitrogen gas to decrease atmospheric absorption from the optical path external to the cell. For the same reason, the FTIR's interferometer compartment, which is isolated from the sample chamber by polyethylene windows, was evacuated to below 1.5 Torr.

Fig. 1 shows the schematic of the absorption cell. The cell is able to achieve 1–16 m path lengths in 1 m increments. A micrometer at the top of the cell was used to adjust between different path lengths without a need to realign the setup. The cell was equipped with a Honeywell HIH-4000 relative humidity sensor and two Swagelok valves. One valve was connected to a vacuum pump for evacuating the cell while the second was connected to external sample containers. The pressure inside the cell was monitored using two capacitance manometer pressure sensors from MKS Industries. The sensors allowed for measurements ranging from 1000 Torr down to 10 mTorr.

Prior to the measurements the cell was evacuated to below 10 mTorr and then sealed. Background scans were completed for path lengths of 1–6 m consecutively. The distilled water vapor was then introduced into the cell, allowing adequate time for the pressure sensors to equalize. Following this, dry air purchased from Airgas East was introduced into the cell bringing the total pressure inside the cell to approximately 760 Torr. Finally sample scans with path lengths ranging from 1 to 6 m were completed.

The spectral region of interest was 300–1500 GHz and the spectral resolution of the FTIR was 3 GHz. The setup was optimized for this region by employing a 125 μm Mylar beamsplitter in the FTIR as well as a cold filter on the bolometer that attenuated any radiation with a frequency higher than 1500 GHz. A total of 6 transmission scans were collected at four relative humidity levels giving a total of 24 datasets. Relative humidity levels of 17.89%, 36.79%, 48.03%, and 70.84% were used. The partial pressure

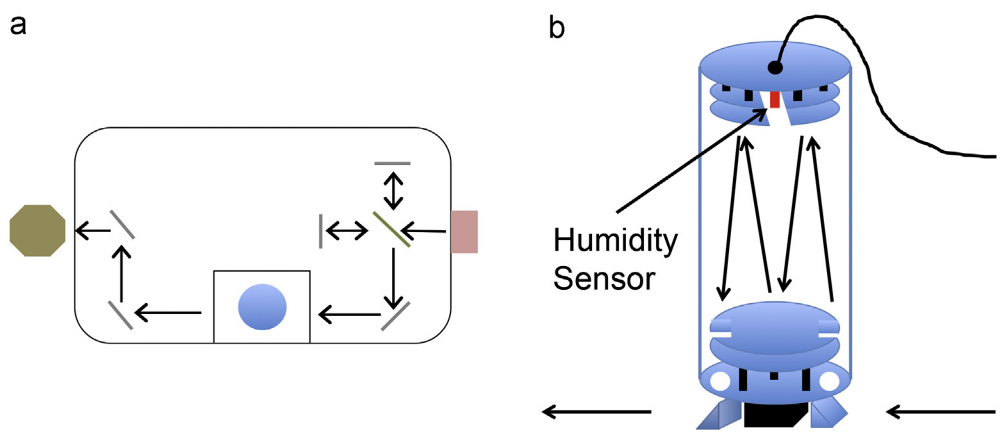

Fig. 1. A schematic of the setup used in the experiment is shown in (a). A diagram of the white cell used with the addition of the humidity sensor shown in red is displayed in (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)