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Observations of downwelling far-infrared emission at Table Mountain California made by the FIRST instrument

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ABSTRACT

The Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument measured downwelling far-infrared (far-IR) and mid-infrared (mid-IR) atmospheric spectra from 200 to 800 cm^{-1} at Table Mountain, California (elevation 2285 m). Spectra were recorded during a field campaign conducted in early autumn 2012, subsequent to a detailed laboratory calibration of the instrument. Radiosondes launched coincident with the FIRST observations provide temperature and water vapor profiles for model simulation of the measured spectra. Results from the driest day of the campaign (October 19, with less than 3 mm precipitable water) are presented here. Considerable spectral development is observed between 400 and 600 cm^{-1}. Over 90% of the measured radiance in this interval originates within 2.8 km of the surface. The existence of temperature inversions close to the surface necessitates atmospheric layer thicknesses as fine as 10 m in the radiative transfer model calculations. A detailed assessment of the uncertainties in the FIRST measurements and in the model calculations shows that the measured radiances agree with the model radiance calculations to within their combined uncertainties. The uncertainties in modeled radiance are shown to be larger than the measurement uncertainties. Overall, the largest source of uncertainty is in the water vapor concentration used in the radiative transfer calculations. Proposed new instruments with markedly higher measurement accuracy than FIRST will be able to measure the far-IR spectrum to much greater accuracy than it can be computed. As such, accurate direct measurements of the far-IR, and not solely calculations, are essential to the assessment of climate change.

1. Introduction

The climate of the Earth is maintained by incoming shortwave radiation from the Sun at wavelengths less than 4 μm and outgoing longwave radiation emitted by the Earth and its atmosphere between 4 and 100 μm. Presently all orbiting spectral resolving sensors that measure the top-of-atmosphere infrared Earth radiance do so between approximately 4 and 15.5 μm (2500–650 cm^{-1}), largely for the purposes of atmospheric temperature and moisture profiling for weather forecasting. Examples of these are the Atmospheric Infrared Sounder (AIRS) [1], the Infrared Atmospheric Sounding Interferometer (IASI) [2], and the Cross-Track Infrared Sounder (CrIS) [3] instruments.

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Over the past 20 years several instruments [4–7] have been developed with the ultimate goal of measuring the Earth's far-infrared (far-IR, 15–100 μm) spectrum that is not presently observed directly from space. These instruments have observed the far-IR spectrum from the ground, from aircraft, and from high altitude balloons in the lower stratosphere. Concurrently, the importance of direct measurements of Earth's far-IR spectrum has become widely recognized [8]. The far-IR contains approximately one-half of the Earth's outgoing infrared radiation and greenhouse effect [9,10]. Earth's troposphere cools to space almost exclusively in this spectral region [11]. Cirrus clouds also have a strong radiative effect [12]. Numerous spectral fingerprints of climate change are found in the far-IR [13]. Consequently, measurements of the top-of-atmosphere far-IR spectrum are a critical component of the proposed NASA Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission [14].

In this paper we present measurements of the downwelling far-IR and mid-IR emission spectrum of Earth's atmosphere recorded by the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument during a field campaign at Table Mountain, California, in late summer and early autumn 2012. FIRST was deployed to the Table Mountain Facility (TMF) after completing a re-calibration of the instrument earlier that year [15,16]. During the field campaign radiosondes were periodically launched from TMF to provide temperature and moisture profiles needed for radiative transfer model computations of the downwelling spectral radiance to compare with FIRST measurements.

The purpose of this paper is to present a comprehensive uncertainty analysis of the difference between the modeled radiance and the measured radiance (i.e., the measurement residual). Known uncertainties from the recent absolute calibration of the FIRST instrument are combined with the computed uncertainties in the modeled radiances to provide the uncertainty in the measurement residual. This "combined uncertainty" allows quantitative assessment of the degree to which radiative closure is attained. The approach defined here will also serve as the basis for analysis of other far-IR radiative closure experiments such as the RHUBC-II campaign [17]. We have found that the FIRST measurements and the radiative transfer model calculations agree to within their combined uncertainties and that the uncertainty in the modeled radiance is larger than the measurement uncertainty.

In the next section we describe the FIRST instrument and its recent calibration for ground-based observations. Atmospheric conditions during the observation period reported here are described, including their impact on radiative transfer calculations. Comparisons between measured and modeled radiances are given, along with the detailed analysis of uncertainties. A discussion and summary concludes the paper.

2. FIRST instrument description

The Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument is a Fourier transform spectrometer (FTS) developed under the NASA Instrument Incubator Program for the purpose of demonstrating technology needed to measure the far-IR spectrum from a space-based instrument. FIRST was built in a partnership between the NASA Langley Research Center, the Space Dynamics Laboratory (SDL) of the Utah State University, and the Smithsonian Astrophysical Observatory. The instrument was initially designed to operate on a high altitude (~30 km) stratospheric balloon platform to simulate the measurement of top-of-atmosphere Earth radiance. The instrument successfully conducted an engineering demonstration flight in 2005 from the NASA balloon flight facility in Fort Sumner, New Mexico [6]. Measured radiance calibration was accomplished on-board during the flight by alternate views of an ambient temperature blackbody and a sky (or space) view through an open port. Subsequently, the instrument scene select assembly was modified to accommodate two calibration blackbodies (one heated above ambient temperature and one at ambient temperature) so as to enable FIRST to operate as a ground-based instrument and observe downwelling atmospheric radiance at Earth's surface. In 2009 FIRST participated in an atmospheric field campaign in the Atacama Desert in Chile [17]. Subsequent to this campaign FIRST was returned to SDL in late 2011 for absolute radiance recalibration in anticipation of future ground-based atmospheric observation campaigns. The instrument was calibrated in both the ground-based mode, with two calibration blackbodies [16], and in its stratospheric balloon operation mode, with an ambient blackbody and a liquid nitrogen cooled blackbody to simulate the space view from 30 km [15].

The FIRST instrument is described in the paper detailing the recalibration in ground-based configuration [16]. The interferometer is a porch swing design, recording double sided interferograms with a mirror travel of 0.5 cm either side of center (i.e., zero optical path difference). A helium-neon metrology laser is used to determine sampling location. FIRST samples every laser fringe and collects 24576 points for each interferogram. This results in 1.55 cm of total optical path difference change and 0.78 cm in total physical travel. After centering the interferogram and trimming the ends the realized spectral resolution is 0.643 cm^{-1}, corresponding to the distance from line center to the first zero of the sinc function instrument line shape. Data collection time for one scan is 11.5 s including turnaround time. The designed spectral coverage was 10–100 μm (1000–100 cm^{-1}) although the realized coverage spans 2200–50 cm^{-1}. The FIRST focal plane is comprised of 10 silicon bolometers cooled with liquid helium.

3. FIRST operations at Table Mountain, California

FIRST was deployed to the Table Mountain Facility (TMF, 34.4 °N, 117.7 °W, 2285 m) for eight weeks spanning August 2012 to October 2012. The TMF site is maintained by the NASA Jet Propulsion Laboratory. FIRST was operated at TMF inside a trailer that is used to transport it to and from field campaign sites. During measurements the trailer doors and windows were left open to keep the air inside the trailer at the same temperature as the outside