8.1 THE FAR-INFRARED SPECTROSCOPY OF THE TROPOSPHERE (FIRST) PROJECT

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Abstract. The radiative balance of the Earth is influenced strongly by radiative cooling associated with emission of radiation by water vapor at far-infrared (far-IR) wavelengths greater than 15 µm and extending out beyond 60 µm. The distribution of water vapor and associated far-IR radiative forcings and feedbacks are well-recognized as major uncertainties in understanding and predicting future climate. Up to half of the outgoing longwave radiation (OLR) from the Earth occurs beyond 15.4 µm. Cirrus clouds also modulate the outgoing longwave radiation in the far-IR. Despite this fundamental importance, far-IR emission (spectra or band-integrated) has rarely been directly measured from space, airborne, or ground-based platforms. Current and planned operational and research satellites typically observe the mid-infrared only to about 15.4 µm. The Far-Infrared Spectroscopy of the Troposphere (FIRST) project is an investment by NASA through the Instrument Incubator Program (IIP) to develop a space-based capability to measure the spectrally resolved infrared spectrum to 100 µm.

1. INTRODUCTION

The radiation budget of the Earth system was the first quantitative measurement to be made from orbiting satellites, as proposed by Suomi [1957]. Since that time, radiation budget measurements have consisted of the total (reflected solar plus emitted thermal infrared) radiation and the reflected solar radiation; these are spectrally integrated or broadband measurements with little spectral discrimination. The emitted longwave radiation is obtained by subtraction of the two classic energy flows. These measurements provide the integral constraints on the Earth's climate and energy budget. The response of and feedbacks within the Earth's climate system are determined by the terms of the integral, i.e., the absorption and emission spectra. Since the first observations by Suomi, radiation budget measurements have been refined significantly in terms of their spatial resolution, angular sampling capability, and radiometric calibration [Wielicki et al., 1996]. Temporal sampling is improved by placing additional sensors in different orbit planes or, as planned in the near future, by placing radiation budget sensors in geostationary orbit [Harries and Crommelynck, 1999]. Despite these continuous improvements, radiation sensors are still making the same basic measurements as 40 years ago with little additional spectral distinction.

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As pointed out by Wielicki ***et al***., sensing of the Earth's energy balance is an eight dimensional sampling problem. The improvements noted above in spatial, angular, and temporal sampling address seven of the eight dimensions. The remaining critical dimension, the spectral dependence of the radiation balance, and the far-IR in particular, have yet to be comprehensively observed from space. The Far-Infrared Spectroscopy of the Troposphere (FIRST) program represents NASA's investment in the technology required to measure the Earth's emission spectrum in order to achieve a significant advance in climate sensing.

2. RELEVANCE OF THE FAR-IR TO THE GLOBAL ENERGY CYCLE, CLIMATE, AND WATER VAPOR PROFILING

2.1 Clear-Sky Radiative Cooling and TOA Radiation

The scientific case for measuring the far-infrared emission directly is reviewed by Mlynczak et al. [2002] and references therein. We define the far-IR to encompass wavelengths between 15 and 100 µm because, as discussed below, this portion of the Earth's emission spectrum is not directly observed from space despite its fundamental importance. The radiative balance of the troposphere, and hence climate, is influenced strongly by radiative cooling associated with emission of infrared radiation by water vapor at far-IR wavelengths extending out beyond 60 µm. Water vapor absorption and emission are principally modulated by the pure rotation band, which includes both line and continuum absorption. Water vapor is the principal greenhouse gas, absorbing a significant fraction of the upwelling radiation and providing much of the downwelling longwave flux that warms the Earth's surface (i.e., the greenhouse effect). The distribution of water vapor and associated radiative forcings and feedbacks (which occur in the far-IR) are well recognized as major uncertainties in understanding and predicting future climate.

The importance of the far-IR in the Earth's energy balance is readily assessed by computing the fraction of radiant energy emitted by the Earth-Atmosphere system at those wavelengths. Line-by-line radiative transfer calculations discussed by Kratz [2002] indicate that approximately 50%, 30%, 12% and 6% of the Earth's clear-sky thermally emitted power (outgoing long-wave radiation, OLR) occurs at wavelengths longer than 15, 20, 30, and 40 µm, respectively. Approximately 60%, 40%, 18%, and 10% of the atmospheric thermally emitted power occurs at wavelengths longer than 15, 20, 30, and 40 µm, respectively, depending on latitude and season. Measurements of the far-IR will contribute significantly to understanding how the Earth is responding to various natural and anthropogenic forcings, which is a fundamental goal of NASA's Earth Science Enterprise.

One of the basic roles water vapor plays in the climate system is in the radiative cooling of the troposphere [Clough et al., 1992], who showed conclusively that the middle and upper troposphere cool almost exclusively in the far-infrared at wavelengths longer than 20 µm. The strong radiative cooling in the far-infrared is due to water vapor rotational and continuum emission and occurs primarily between 100 and 500 cm^{-1}. These and other calculations demonstrate that the bulk of the free troposphere cools radiatively in the far-IR portion of the spectrum.

2.2 Clear-Sky Greenhouse Effect

Water vapor is also a principal factor the Earth's greenhouse effect, a measure of which is provided by the difference between the (Planck blackbody) emission from the Earth's surface and the energy emitted to space. The factor indicates the energy trapped by the atmosphere and is called the greenhouse parameter. Line-by-line calculations show that greenhouse trapping is caused by the ν_2 band of water vapor above about 1400 cm^{-1}, ozone at 1060 cm^{-1}, CO_2 between 600 and 700 cm^{-1}, and the pure rotation band of water vapor between 0 and about 800 cm^{-1}. This latter water band is extremely intense, especially at band center around 200-300 cm^{-1}, and so emits to space from the upper troposphere, precisely where the temperature is low enough to move the peak of the Planck function to this same wavenumber range. This effect is the physical cause of the far-infrared cooling discussed above. Spectral measurements, with complete spectral coverage of the infrared to 100 µm, will enable a comprehensive assessment of the Earth's greenhouse effect including forcings and feedbacks.

2.3 The Influence of Cirrus Clouds

The above discussions relate to clear-sky conditions. We also note that the outgoing far-infrared radiation will be modulated by cirrus clouds. The prevalence and persistence of cirrus cloud systems, especially in the tropical upper atmosphere, implies that cirrus clouds play an important role in climate [e.g., Liou, 1986]. Cirrus clouds have always represented a formidable modeling challenge owing to the extreme conditions under which the ice crystals form and to their complex radiative interactions. Bulk radiative studies of cirrus clouds show that cirrus clouds may radiatively heat or cool the upper atmosphere at infrared wavelengths depending upon the height, thickness and microphysical size of the clouds. Cirrus clouds have also been implicated as important components of feedback loops to climate forcings. The effects of cirrus in attenuating the far-IR OLR to 25 µm have been shown from the space measurements made by the Russian ***Meteor*** spacecraft [Spankuch and Dohler, 1985] and, for example, in the calculations of Stackhouse and Stephens [1991].

2.4 Improvement in Water Vapor Profiling

Spectral measurements of the far-IR may also offer the potential for increased accuracy in water vapor profiles retrieved from emission measurements [Mertens et al., 2002]. Water vapor, particularly in the upper troposphere, is the dominant greenhouse gas and largest known feedback mechanism for amplifying global warming, contributing more than two-thirds of the total feedback by water vapor. The processes that govern its concentration have been the subject of long-standing debate and still remain uncertain partially reflecting the lack of adequate observations of water vapor [Bates et al., 2001]. Model predictions of global temperature increases resulting from continued buildup of greenhouse gases depend on the treatment of water vapor and on the absence of a negative feedback by water vapor in the upper troposphere, the occurrence of which is not yet certain. Improved measurements of water vapor and far-IR emissions will help address this issue.

Infrared water vapor vertical profiling from space for the past 30 years in both operational and research sensors has been limited to measurements of thermal emission in the ν_2 band centered at 6.3 µm. However, some of the very first space-based measurements attempted for the purpose of water vapor profiling were in the far-IR with the SIRS-B instrument [Wark et al., 1970]. Due to strong emission from the upper troposphere in the far-IR, there is a very high probability that the combination of (simultaneous) far-IR and conventional mid-IR radiance measurements will result in more accurate water profiles with higher vertical resolution than is available from measurements of the 6.3 µm band alone, especially in the upper troposphere.

3. Instrument And System Requirements For Far-IR Space-Based Measurements

To achieve the above science from a space instrument, we would require the following measurement capability, as discussed further by Johnson [2002]:

- Spectral coverage: 4 - 100 µm
- Spectral resolution: 0.6 cm^{-1}
- Nadir viewing IFOV, satellite instrument: 10 km spatial footprint
- Broad cross-track observational capability to provide global coverage on a daily basis

· NEΔT: 0.2 K 10 to 100 µm (goal); 0.2 K 10 to 60 µm, 0.5 K 60 to 100 µm (requirement)

The spectral coverage is driven by the need to measure the unobserved far-IR together with the CO_2 15 µm band for temperature retrievals and validation against existing mid-IR sensors. The spectral resolution of 0.6 cm^{-1} is driven primarily by the requirement to simultaneously retrieve temperature profiles. The IFOV is driven by the need to be able to isolate clear and cloudy fields of view. The daily global coverage capability, which impacts primarily the detector focal plane array, is to ensure global observations of water vapor and that as much as possible of the natural spatial variability in the radiation and cloud fields is observed. The temperature sensitivity of 0.2 K is required for temperature profiling and to detect the climate change fingerprint.

4. FIRST Technology Development

4.1 FTS Subsystem

FIRST uses the compact all-reflective aft optical system developed for the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) sensor being developed by NASA Langley Research Center and the Space Dynamics Laboratory of the Utah State University, scaled to FIRST aperture size and f/#. The interferometer will use the 45Y beamsplitter design that has flown successfully on several missions (EXCEDE I, II, SPIRIT, CIRRIS-1A and BAMM) and that is also being used on the GIFTS. This design uses a precision machined, solid block flex-pivot porch swing suspended carriage and provides a full +/- 0.8 cm drive range with mirror alignment accuracy better than +/- 2 µrad and repeatability better than 0.2 µrad. Metrology is provided by a laser based quadrature sampling control system that counts fringes through the carriage turnaround. While the space flight system would use a stabilized diode laser, a HeNe laser will be used in FIRST. Frequency stability better than 1 part in $5x10^6$, is required. Errors that arise from scan velocity variations are minimized by a precision scan drive and optical path difference (OPD) velocity servo system to control the scan speed to better than +/-1 percent. The nominal beam diameter and divergence angle are 7.0 cm and 0.1 rad, respectively, giving a spectrometer throughput of 0.475 cm^2 sr. The design will be optimized for accurate radiometric imaging. A diagram of this system is shown in Figure 1.

The FIRST optics will be gold-coated aluminum for low cost and high reflectivity in the far infrared. The optic system is f/4.4 and allows the interferometer to handle a 6º beam divergence. The FIRST optical aperture (on the interferometer mirrors) is sized to match the FPA assembly (the 10 x 10 array of Winston cones which couple the detectors to the optical beam.) To reduce cost, the 10x10 array will be only partially filled. Standard cones from Infrared Laboratories, Inc. (Model F4.40#00, f/4.40) have been used in this design. The cones are mated to 254 µm diameter sensor elements, spaced in an array on 2.2 mm centers.

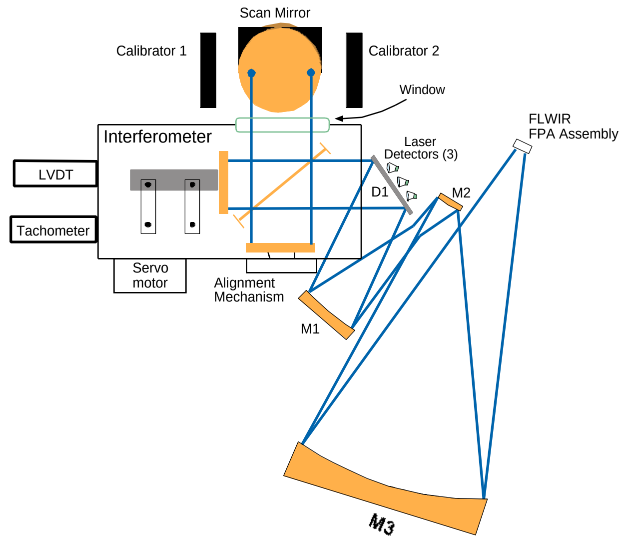

Figure 1. FIRST FTS layout.

4.2 The Beamsplitters

The recent development of wide-band beamsplitters that work well in the far infrared now make it possible to use a single FTS to cover the 10-100 µm band. These include lithographic polarizing (for Martin-Puplett interferometers) and bilayer beamsplitters (for conventional Michelson interferometers), both of which have demonstrated nearly ideal performance over the required band. The FIRST beamsplitters will be developed at the Smithsonian Astrophysical Observatory (SAO) as part of its ongoing programs of FIRS-2 instrument development and high-resolution stratospheric measurements. These beamsplitters are constructed of 2 thin layers, one dielectric and one metallic, with thickness chosen to give nearly equal 50% transmission and reflection coefficients over a very wide wavelength range in the far and near infrared. The spectral range covered by these beamsplitters includes the entire range required by the FIRST design.

A preliminary version of the bilayer beamsplitter has been deployed in the FIRS-2 instrument to obtain atmospheric observations. This beamsplitter (Ge on Mylar) gave us the expected spectral response when flown on a balloon at long wavelengths (120 to 14 µm), however the performance between 14 and 6 µm fell short of optimum due to unwanted absorption features in the Mylar between 14 and 6 µm. Optically, polypropylene is a significantly more transparent material in the far infrared than Mylar, with only a few weak and narrow absorptions near 11 µm, so it is an ideal replacement material from this point of view. However, the bulk thermal and mechanical properties are not as ideal for evaporative deposition as that of Mylar as it melts easily under evaporation chamber heat loads. A method has been devised that allows us to cope with the heat load, and which allows us to deposit 1 μm thick layers of Ge onto thin polypropylene sheets with optical quality surfaces. We have access to an evaporator with all the necessary features for this process and have already made several very promising test versions of this beamsplitter design. We will continue to manufacture and test these beamsplitters in order to produce one that is ideal for FIRST with nearly unit efficiency between 120 and 9 μm.

4.3 The Detectors

The major challenge to measuring far-infrared spectra is having detectors with sufficient sensitivity and sampling speed to achieve a high signal-to-noise spectrum in the approximately one second of scan time required by a space-based instrument. The FIRST team is investigating several detector technologies including some that do not require cooling to liquid helium temperatures as in previous sensitive far-IR sensors. The FIRST detector technology will be chosen shortly.

4.4 FIRST Flight Plan

The FIRST instrument is being built and integrated at the Space Dynamics Laboratory of the Utah State University in Logan, UT. It will be calibrated in facilities there. The demonstration of the FIRST technologies will occur by deploying FIRST on a high-altitude balloon platform in the year 2004. The FIRST team has chosen a balloon platform for technology demonstration to minimize acoustic and mechanical vibrations sometimes encountered on aircraft. Subsequent to successful technology demonstration and validation of the measured far-infrared spectra, the FIRST team will propose this instrument for field campaigns and ultimately will develop a space-based version.

5. ACKNOWLEDGEMENT

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