# 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 cirrus clouds and associated far-IR radiative forcings and feedbacks are well-recognized as major uncertainties in understanding and predicting future climate. 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 infrared spectrum to 100 µm.**

## I. Introduction

The radiation budget of the Earth system was the first quantitative measurement to be made from orbiting satellites, as proposed by Suomi [1]. 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 measurements of Suomi, radiation budget measurements have been refined significantly in terms of their spatial resolution, angular sampling capability, and radiometric calibration [2]. Despite the continuous improvement, radiation sensors are still making the same basic measurements as 40 years ago with little additional spectral distinction.

Remote sensing of the Earth's energy balance is an eight dimensional sampling problem [2]. The improvements over the years in spatial, angular, and temporal [3] 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.

## II. Relevance Of The Far-Infrared

The scientific case for measuring the far-infrared emission directly is reviewed by Mlynczak et al. [4] and references therein. We define the far-IR to encompass wavelengths between 15 and 100 µm because this portion of the Earth's emission spectrum is not directly observed from space despite its fundamental importance. Earth's 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. The free troposphere cools radiatively almost exclusively in the far-IR. Water vapor is also 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 far-IR radiative forcings and feedbacks are well recognized as major uncertainties in predicting future climate.

We also note that outgoing far-infrared radiation is 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 [5]. The effects of cirrus in attenuating the far-IR to 25 µm have been shown by the Russian *Meteor* spacecraft [6]. Spectral measurements of the far-IR may also offer the potential for increased accuracy in water vapor profiles retrieved from emission measurements [7]. Measurements of the far-IR will contribute significantly to understanding how the Earth is responding to various natural and anthropogenic forcings.

## III. FIRST TECHNOLOGY

To achieve the above science from a space instrument, we would require the following measurement capability:

- Spectral coverage: 10 - 100 µm
- Spectral resolution: 0.6 $cm^{-1}$
- Nadir viewing IFOV, 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 100µm (requirement)

The spectral coverage and spectral resolution are driven by the need to measure the unobserved far-IR together with the $CO_2$ 15 µm band for simultaneous temperature retrievals and validation against existing mid-IR sensors. 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.

To achieve the FIRST science three technologies are being pursued that will be incorporated into a single, functioning sensor: a high throughput Fourier Transform Spectrometer; a broad bandpass beamsplitter; high sensitivity detectors with a thermal design suitable for space applications. The demonstration of the FIRST technologies will occur by deploying the FIRST instrument on a high-altitude balloon platform in the year 2004.

### *A. The FIRST Fourier Transform Spectrometer (FTS)*

The FIRST system consists of three optical modules, scene selection and calibration (SS&C), the interferometer dewar (ID), and the detector dewar (DD). This arrangement was chosen to provide an economical approach to the functional demonstration. Most components and interfaces are commercial vacuum fittings and vessels. The scene selection mirror rotates to insert ground target, warm calibration source, or space view radiation into the interferometer aperture. For ground calibration, vacuum flanges on the SS&C assembly allow a space view simulator and a variable temperature precision calibration source to be sealed to the sensor. The module can be rotated to allow the ground view port to look upward for sky measurements. A polypropylene window is located between the SS&C and the evacuated interferometer. The electronics are pressurized to assure proper cooling of the COTS components at balloon altitude.

The heart of the FIRST instrument is a cryogenically compatible, compact plane mirror Michelson FTS (Figure 1). The throughput of the FIRST system has been maximized to demonstrate the possibility of operation with a passively cooled detector FPA. The FTS provides the required +/- 0.8 cm optical path difference (OPD) and provides mirror alignment accuracy of +/- 2 µrad, adjusted as required. OPD position and +/-1 percent scan velocity are provided by a HeNe laser based sampling control system. The FTS has a 7.0 cm IR beam diameter with a 0.12 rad (6.7°) divergence angle. The interferometer, aft optics can be operated at any temperature between ambient and 4 K, with small modifications. In the far IR, surfaces above 10 K radiate at detected wavelengths and background radiance must be carefully considered in the design. The FIRST interferometer will operate at 180 K, to demonstrate functionality with passively cooled detectors should that technology be matured before the satellite system design is completed.

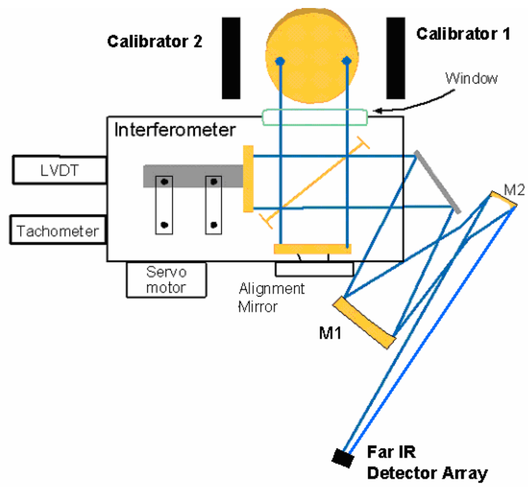


Figure 1. The FIRST FTS optical system concept, showing the scene selection mirror and calibration sources.

A two mirror, f/6.5 aft optical system couples the interferometer output into the externally mounted, 4.2 K detector Dewar. The interferometer and the aft optics are mounted on a thermally controlled optical bench to minimize stray light variations between calibration periods. All of the optical components except the beamsplitter and windows are gold-coated aluminum for low cost and high reflectivity in the far infrared. The FPA array is assembled from individual, commercially available f/6.50 Winston cones on 3.25 mm centers. The cones limit the warm view of the detectors to the reflective components of the optical system. Each cone of the partially populated array is mated to an integrating cavity containing the detector element. The cooled cones convert the f/6.5 input beam to an f/0.5 beam; filling the hemisphere view of the detector with light from the aperture.

### *B. The FIRST Beamsplitters*

The most ideal beam splitter for the FIRST instrument is one with nearly 50% reflection and transmission over the entire spectral range of FIRST. This is not possible with traditional single material dielectrics because they will either have many minima and maxima or have poor reflectance over much of the range. These properties are typically defined by the thickness of the material.

Multiple layered pellicle beam splitters have recently been developed that solve the deficiencies of dielectric beam splitters. These designs have 2 layers with high and quantitatively different indices of refraction. One material should have an index between 1.4 and 2, and the other over 3.5. For the latter, Germanium is the ideal material. For the lower index material, plastics are the current best option. Such beam splitters have recently been used for far infrared FTS instruments for atmospheric observations from balloon, much like will be done with the FIRST instrument.

Since the FIRST instrument requires continuous spectral coverage over the range from 100 to 1000 $cm^{-1}$, the chosen materials must not have significant absorption over the same region. Of the plastic dielectrics that currently exist, polypropylene is the only material that meets these requirements. The next best option is mylar, but it has a significant absorption between 700 and 750 $cm^{-1}$, which is an ideal region for temperature sounding in the $CO_2$ band.

In order to construct these beam splitters, we evaporate Germanium onto commercially available films of polypropylene that have a thickness of less than 4.0 microns. Because Ge does not form a good optical surface on plastics, ion assisted deposition is required during the evaporation. The main problem with this technique is removing all the heat produced both from the evaporation and the ion source. The heat will easily melt the plastic. We have developed techniques to take away the heat from the film during the evaporation and still get reasonable quality optical surfaces. The current beam splitters have beam splitter efficiencies (4xRxT) of better than 70% over the entire wavelength range of FIRST.

*C. The FIRST Detectors*

We have designed the FIRST spectrometer around room temperature detectors that achieve the thermal noise limited detectivity of $1.8 \times 10^{10}$ cm $Hz^{1/2}$ / W. Meeting the FIRST signal-to-noise ratio requirements with a 10 by 10 array of such detectors requires a spectrometer with very high throughput, while keeping the throughput within physically achievable limits requires that we maximize the signal flux on the detector. We achieve the maximum possible flux concentration by fabricating the focal plane array from an array of Winston cones [8] coupled to individual detector elements. To reduce cost for the IIP demonstration we have included just 10 detectors within the footprint of a 10 by 10 array of cones. The detectors will be placed at the corners of the array as well as in the center so as to demonstrate that the spectrometer has the required throughput. Because the best presently available uncooled detectors are still an order of magnitude short of the thermal noise limited detectivity, we are using conventional helium-cooled silicon bolometers operating at 4.2 K. We are not using composite bolometers, so that the radiation is absorbed and the temperature is sensed by the same 0.3 mm square block of silicon. The small size of the absorbing element enables a thermal time constant of less than a millisecond while still achieving nearly photon noise limited performance. To simplify the aft optics we have chosen f/6.5 cones with a 3.3 mm diameter entrance aperture.

*D. FIRST Calibration*

Calibrating FIRST requires addressing basic issues of absolute radiometric response, frequency scale, phase alignment, linearity, contrast efficiency and self-apodization. Techniques for quantifying and modeling these effects have been thoroughly developed in the literature and these same techniques are directly applicable to the FIRST instrument. We will use blackbody sources to provide well-calibrated flat radiance fields for absolute calibration and for measuring variations in detector response, phase alignment, and beam contrast across the focal plane array (FPA). We will record two-sided interferograms to enable accurate determination and removal of phase error. Point source scans will provide field-of-view characteristics.

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