First light from the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument

Martin G. Mlynczak,[1] David G. Johnson,[1] Harri Latvakoski,[2] Kenneth Jucks,[3] Mike Watson,[2] David P. Kratz,[1] Gail Bingham,[2] Wesley A. Traub,[4] Stanley J. Wellard,[2] Charles R. Hyde,[1] and Xu Liu[1]

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[1] We present first light spectra that were measured by the newly-developed Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument during a high-altitude balloon flight from Ft. Sumner, NM on 7 June 2005. FIRST is a Fourier Transform Spectrometer designed to measure accurately the far-infrared (15 to 100 μm; 650 to 100 wavenumbers, cm^{-1}) emission spectrum of the Earth and its atmosphere. The flight data successfully demonstrated the FIRST instrument's ability to observe the entire energetically significant infrared emission spectrum (50 to 2000 cm^{-1}) at high spectral and spatial resolution on a single focal plane in an instrument with one broad spectral bandpass beamsplitter. Comparisons with radiative transfer calculations demonstrate that FIRST accurately observes the very fine spectral structure in the far-infrared. Comparisons also show excellent agreement between the atmospheric window radiance measured by FIRST and by instruments on the NASA Aqua satellite that overflew the FIRST flight. FIRST opens a new window on the spectrum that can be used for studying atmospheric radiation and climate, cirrus clouds, and water vapor in the upper troposphere. **Citation:** Mlynczak, M. G., et al. (2006), First light from the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument, *Geophys. Res. Lett.*, *33*, L07704, doi:10.1029/2005GL025114.

1. Introduction

[2] We report the first light spectra from an instrument designed to open a new window for observation of the climate and energy balance of the Earth. The Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument successfully flew on a high altitude balloon on 7 June 2005 from Fort Sumner, New Mexico. FIRST is a prototype Fourier Transform Spectrometer (FTS) instrument developed through the NASA Instrument Incubator Program and is designed to enable global observations from space of the far-infrared (defined here as 15 to 100 μm) portion of the Earth's emission spectrum in conjunction with a portion of the mid-infrared. The instrument operated at an altitude of 27 km for about 5.5 hours and recorded approximately 15,000 interferograms on a focal plane array of ten identical discrete detectors.

[3] The scientific case for far-infrared measurements is given in *Mlynczak et al.* [2001]. Despite containing about one-half of the outgoing infrared energy from the planet [*Kratz*, 2001] and being responsible for much of the Earth's natural greenhouse effect [e.g., *Miskolczi and Mlynczak*, 2004], the far-infrared has rarely been directly observed from space platforms. The Atmospheric Infrared Sounder (*AIRS*) [*Aumann et al.*, 2003], and Moderate Resolution Imaging Spectrometer (*MODIS*) [*Salomonson et al.*, 1989] instruments presently on the EOS-Aqua satellite record the infrared spectrum between 3.8 and 15.4 μm. The Clouds and Earth's Radiant Energy System (CERES) [*Wielicki et al.*, 1996] instruments measure the total spectrally integrated emission shortward of 100 μm and the integrated emission in the atmospheric window between 8 and 12 μm, with no further spectral distinction. The far-infrared (to ~25 μm) was last directly observed from space by the IRIS instruments on the Nimbus series of satellites in 1969 and 1970 [*Hanel et al.*, 1970, 1971] and by instruments on the Russian *Meteor* series of spacecraft in the mid-1970's [*Spankuch and Dohler*, 1985].

[4] We define the far-infrared to start at 15 μm (because of the technology-related spectral cut-off of existing and planned spectral sensors such as AIRS and MODIS) and to end at 100 μm because essentially all infrared energy relevant to Earth's climate occurs at shorter wavelengths. The FIRST instrument is designed to cover 10 to 100 μm to allow overlap with the Aqua (or other mid-infrared) sensors during overflights of the balloon payload, enabling verification of calibration. The FIRST instrument provides a combination of high spectral resolution (0.625 cm^{-1} unapodized), high spatial resolution (0.2 km from balloon altitude, 10 km from orbit), with a goal of high calibration accuracy (<1% uncertainty). FIRST is also designed to provide global coverage from orbit, which is enabled by a 100-element (10 × 10) focal plane array operating in a cross-track scanning mode in orbit. Meeting these objectives requires demonstration of a high-throughput (0.47 cm^2 sr) interferometer to adequately fill the focal plane and a single broad-bandpass beamsplitter to pass the entire 10 to 100 μm spectral interval. The FIRST project met or exceeded each of these technology objectives as evidenced by the high-quality spectra shown below.

2. FIRST Instrument

[5] The FIRST instrument consists of a scene select mirror, a Fourier transform spectrometer (FTS), aft optics,

[1]NASA Langley Research Center, Hampton, Virginia, USA.
[2]Space Dynamics Laboratory, Logan, Utah, USA.
[3]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA.
[4]Jet Propulsion Laboratory, Pasadena, California, USA.

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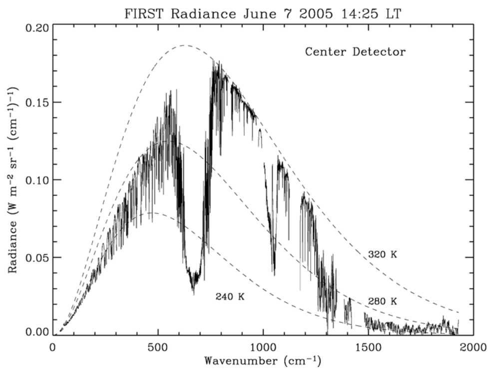

Figure 1. Infrared spectrum recorded by FIRST on 7 June 2005, on the central detector, covering 50 to 2000 cm^{-1}, demonstrating achievement of broad spectral bandpass in one beamsplitter and focal plane combination.

a detector assembly, and associated electronics [*Mlynczak et al.*, 2005]. The FTS and aft optics are cooled to ~180 K by liquid nitrogen, to reduce background and simulate spacecraft conditions. The detectors are cooled to 4.2 K, and the rest of the instrument is at ambient temperature. Thin polypropylene windows isolate the cold FTS optics from the scene select mirror and from the detector dewar. During balloon flights the scene select mirror alternates between a nadir view of the Earth, a high elevation angle space view that is used to estimate instrument background, and an ambient-temperature blackbody calibration source. The FTS is a compact plane mirror Michelson interferometer that achieves very high throughput (0.47 cm^2 sr) with a modest 7 cm diameter beam. Broadband response (50–2000 cm^{-1}) is made possible by the bilayer thin-film beamsplitter described below. FTS scanning and detector sampling are controlled by a separate metrology laser interferometer that monitors the position of the scan mirror. Interferometer alignment (for both the infrared and laser interferometers) can be adjusted if necessary during the balloon flight by remotely controlling the tip and tilt of the non-scanning interferometer mirrors. The FTS scans over optical path differences of ±0.8 cm for a nominal unapodized resolution of 0.625 cm^{-1}; the scan time varies from 1.4 to 8.5 s, depending on the detector sample interval. Trimming and centering the interferograms reduces the realized unapodized resolution to 0.643 cm^{-1}, which is the resolution of the FIRST spectra shown below. The aft optics focus the collimated FTS output onto an array of Winston cones coupled to discrete silicon bolometers in individual integrating cavities. The focal plane is 37.5 × 37.5 mm, large enough for a 10 × 10 array of cones and detectors, although for the demonstration flight the focal plane was populated with a total of 10 cones (2 in each corner and 2 in the center.) The focal plane is sized as such in order to demonstrate the technology required to obtain daily global coverage from a cross-track scanning instrument on an orbiting satellite.

[6] The design of the FIRST beamsplitter is based on the theory described by *Dobrowolski and Traub* [1996]. FIRST uses a multi-layer beam splitter with one layer of 1.05 microns germanium and one of 3.5 microns polypropylene. The total diameter of the beamsplitter is 17.8 cm, and reduced to a 12.7-cm mount for FIRST. We construct the beamsplitters by electron beam evaporation of germanium onto a pre-existing polypropylene film, using an ion assisted deposition technique to ensure an optical quality germanium layer. Polypropylene is used because it has relatively few absorption features throughout the wavelength span of FIRST compared to other materials. The beamsplitter performance is tested with the Smithsonian Astrophysical Observatory FIRS-2 spectrometer [*Johnson et al.*, 1995] to ensure the proper wavelength response for FIRST.

[7] As demonstrated below, the FIRST project met the goals of developing a high-throughput interferometer as evidenced by the spectra recorded in the central and corner detectors. It also exceeded the goals of measuring 10 to 100 μm (1000 to 100 cm^{-1}) as the spectra indicate the instrument recorded spectra between 50 and 2000 cm^{-1}, which corresponds to the entire energetically significant portion of the Earth's emission spectrum. Comparisons below with measurements from the Aqua satellite (shown below) indicate a well-calibrated FIRST instrument.

3. FIRST Flight Spectra

[8] The FIRST instrument was launched June 7 2005 on a gondola provided by the NASA Jet Propulsion Laboratory. It was carried aloft on an 11 million cubic foot balloon filled with helium. The float altitude was approximately 27 km and the instrument operated there for about 5.5 hours, recording nearly 15,000 interferograms in total on its 10 detectors. As float altitude winds were relatively weak the payload stayed within about 80 km of the launch site and was readily visible from the ground during the entire flight. At approximately 2:25 p.m., local time, the NASA Aqua satellite flew over the FIRST payload, offering the possibility of comparing measurements with the AIRS, CERES, and MODIS instruments on that satellite. The footprint of an individual FIRST detector on the ground from the balloon altitude is approximately 200 meters diameter and the entire focal plane projects a footprint of approximately 2.4 km on a side. By comparison, the AIRS, CERES, and MODIS footprints are nominally 14 km, 20 km, and 1 km, respectively.

[9] Figure 1 shows an individual spectrum recorded by the FIRST instrument from one of its central detectors at the time of the Aqua satellite overpass. Figure 2 shows an

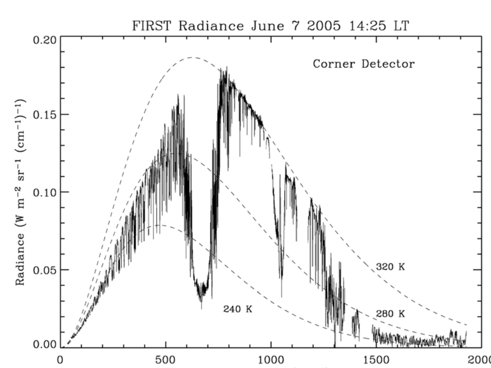

Figure 2. Infrared spectrum recorded by FIRST on 7 June 2005, on a corner detector, demonstrating achievement of the high throughput requirement.

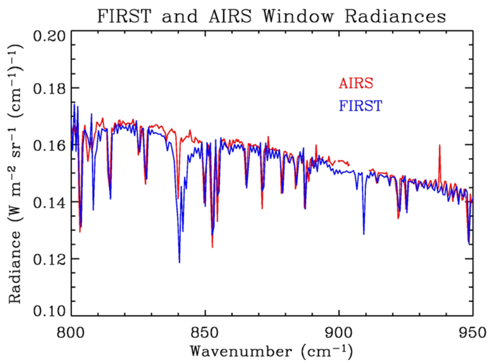

Figure 3. Comparison of FIRST (blue) and AIRS (red) spectra in the atmospheric window region. The broad feature in the FIRST spectrum near 840 cm^{-1} is due to absorption in the FIRST beamsplitter that has not yet been completely removed in the data processing.

individual spectrum recorded at the same time in a corner detector. The measured interferograms are Fourier transformed and phase corrected, the complex instrument background is subtracted, and the result is calibrated to produce these spectra. The calibrations are presently based on a reference blackbody carried in flight. These two spectra confirm that the FIRST instrument achieved the optical throughput necessary to achieve daily global coverage from a low earth orbiting satellite. We note that although there is a difference in the maximum optical difference for the center and corner detectors, the instrument line shapes for the center and corner detectors are similar because the optical system was designed to avoid self-apodization. The only effect we need to correct for is a simple spectral scale factor due to the difference in maximum optical path difference.

[10] The FIRST spectra are observed to cover the range from approximately 50 to 2000 cm^{-1}, confirming the achievement of a broad bandpass beamsplitter and demonstrating the ability to observe the entire energetically significant portion of the infrared emission spectrum of the Earth and its atmosphere in a single instrument. To our knowledge, this is the first ever measurement of the entire infrared spectrum from a space-like vantage point, at high spectral and spatial resolution. *Christensen and Pearl* [1997] presented a globally averaged spectrum of the entire Earth recorded by the Thermal Emission Spectrometer instrument on the Mars Global Surveyor satellite covering 200 to 1600 cm^{-1} at 5 to 10 cm^{-1} spectral resolution. We note that despite the scientific relevance of the far-infrared to the Earth's climate, it has been measured extensively and directly on every planet with an atmosphere in the solar system except Earth and Pluto [*Hanel et al.*, 2003].

[11] The spectra in Figures 1 and 2 are plotted with minor gaps at frequencies higher than 1000 cm^{-1}. These small regions have purposely not been plotted because of the presence of absorption features in the beamsplitter at these frequencies that significantly reduce the calibration accuracy. They will be fully corrected in the near future as the FIRST team does more in-depth calibration and analysis of the measurements. Also, overlaid on each spectrum are blackbody curves (dashed) at various temperatures labeled in each figure, allowing the brightness temperatures of the spectral features to be estimated. The surface skin temperature is observed to be 320 Kelvin based on the radiances near 900 cm^{-1}, while the far-infrared spectra correspond to equivalent emission temperatures ranging from 220 to 270 Kelvin.

[12] FIRST was designed to provide a single-scan precision of 0.2 K from 170–1000 cm^{-1} and 0.5 K from 100–170 cm^{-1} at a nominal brightness temperature of 230 K. During laboratory testing of the FIRST spectrometer and detectors, excess noise was discovered entering the signal path between the preamplifier and the data acquisition system. The result is that noise in the spectra has a very small amplitude uncorrelated component superimposed on a larger correlated noise component. We calculated the noise-equivalent temperature difference (NETD) in two ways in order to estimate the magnitude of both the total noise and the uncorrelated component. First we estimated the total noise equivalent temperature difference (NETD) by calculating the mean and standard deviation about the mean from 74 calibrated nadir-view spectra recorded during the balloon flight over a period of 15 minutes. The NETD for both center and corner detectors is less than 1.1 K from 250 to 800 cm^{-1}, gradually increasing to 3 K at 150 and 1000 cm^{-1}. Next we estimated the uncorrelated component by calculating the mean and standard deviation about the mean for the difference between adjacent detector pairs for the same set of 74 spectra. The uncorrelated NETD is less than 0.05K from 250 to 800 cm^{-1}, gradually increasing to 0.28K and 0.15 K at 100 and 1000 cm^{-1}, respectively, more than meeting our original performance goal. We believe that once we have reduced the excess noise the system performance will approach the limit suggested by the uncorrelated noise component.

[13] We have conducted an initial assessment of the calibration of the FIRST radiances by looking at the atmospheric window region and comparing against observations recorded by instruments on the Aqua satellite which overflew the FIRST instrument at approximately 2:25 p.m. local time. FIRST was located at 34° 54′ N latitude and 105° 2′ W longitude at the time of the Aqua overpass. Figure 3 shows spectra recorded by FIRST (blue curve) and by AIRS (red curve) between 800 and 950 cm^{-1}. Figure 3 indicates remarkable agreement between AIRS and FIRST, demonstrating the calibration accuracy of the FIRST instrument. The broad spectral feature in the FIRST spectrum near 840 cm^{-1} is primarily a consequence of absorption features in the FIRST beamsplitter that have not yet been fully corrected. Otherwise the spectral features and overall radiance levels are in excellent agreement. The surface skin temperature (320 K) is also in agreement with that observed by MODIS and is consistent with the window channel radiance observed by CERES.

[14] As the focus of FIRST is on the far-infrared, we show in Figure 4 a FIRST spectrum between the limits of 20 and 600 cm^{-1}. This is a single spectrum recorded by the interferometer. The rich structure of the far-infrared is readily obvious in the measured spectrum. Also shown in Figure 4 is the difference between the measured spectrum and a spectrum computed using AIRS temperature and moisture profiles from the overflight as inputs to a line-by-line (LbL) code [*Kratz et al.*, 2005]. Figure 4 shows

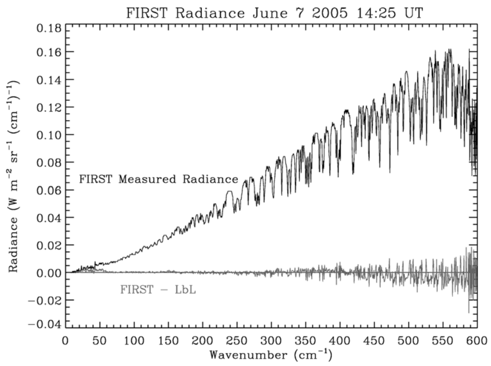

Figure 4. Far-infrared spectrum (20 to 600 cm^{-1}) measured by FIRST and the difference between this spectrum and that computed with a line-by-line (LbL) radiative transfer code using an AIRS temperature and moisture profile.

excellent agreement between the observed and computed spectra at this "first light" stage of the analysis of the instrument.

4. Summary and Future Directions

[15] We have developed and flown a new instrument designed to measure the far-infrared emission spectrum of the Earth. A high throughput, broad bandpass Michelson FTS has been successfully demonstrated during a high altitude balloon flight. The instrument has sensitivity over the entire range of energetically-relevant infrared wavelengths. It shows excellent spectral fidelity in the far-infrared compared with theoretical calculations. The instrument calibration appears to be quite good. The FIRST instrument is now at NASA Langley where it will undergo more testing and a comprehensive evaluation of the calibration measurements made before flight. The entire flight data set will be reduced and made available to the community for science studies pending the more comprehensive calibration of the flight data. These calibrations and detailed comparisons with theory will be presented in future publications. The FIRST team anticipates future deployments of the payload in both flight and ground-based campaigns in order to study many aspects of Earth's climate including water vapor feedbacks, cirrus radiative properties (in the mid- and far-infrared simultaneously), and the natural greenhouse effect of the planet.

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G. Bingham, H. Latvakoski, M. Watson, and S. J. Wellard, Space Dynamics Laboratory, Logan, UT 84341, USA.

C. R. Hyde, D. G. Johnson, D. P. Kratz, X. Liu, and M. G. Mlynczak, NASA Langley Research Center, Hampton, VA 23681, USA. (m.g.mlynczak@nasa.gov)

K. Jucks, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA.

W. A. Traub, Jet Propulsion Laboratory, Pasadena, CA 91109, USA.