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

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Abstract. We present first light spectra from the new Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument. FIRST is a Fourier Transform Spectrometer developed to measure accurately the far-infrared (15 to 100 μm; 650 to 100 wavenumbers) emission spectrum of the Earth and its atmosphere. The observations presented here were obtained during a high altitude balloon flight from Ft. Sumner, New Mexico on 7 June 2005. The flight data demonstrate the instrument's ability to observe the entire energetically significant infrared emission spectrum (50 to 2000 wavenumbers) 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 of the atmospheric window radiances measured by FIRST and by instruments on the NASA Aqua satellite that overflew FIRST are in excellent agreement. 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.

1. Introduction

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 Fourier Transform Spectrometer (FTS) instrument designed to enable global observations from space of the far-infrared (defined as 15 to 100 μm) portion of the Earth's emission spectrum. The instrument operated at an altitude 27 km for about 5.5 hours and recorded approximately 15,000 interferograms on ten separate detectors.

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*., 1999] instruments presently on the EOS-Aqua satellite record the infrared spectrum between 4 and 15 μm. The Clouds and Earth's Radiant Energy System (CERES) [*Wielicki et al*., 1996] instruments measure the total emission between 4 and 100 μm and the emission in the atmospheric window between 8 and 12 μm, with no further spectral distinction. The far-infrared (to ~ 25 μm) was last 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].

We define the far-infrared to start at 15 μm because of the 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 has been designed to cover 10 to 100 μm to allow overlap with the Aqua (and other mid-infrared) sensors during overflights of the balloon payload, enabling verification of calibration. The FIRST instrument provides a combination of high (0.625 wavenumber) spectral resolution, high (0.2 km from balloon altitude, 10 km from orbit) spatial resolution, with a goal of high (< 1% uncertainty) calibration accuracy. FIRST is also designed to provide global coverage from orbit, which is enabled by a 100-element (10 x 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 quality spectra shown below.

2. The FIRST Instrument

The FIRST instrument consists of a scene select mirror, a Fourier transform spectrometer (FTS), aft optics, a detector assembly, and associated electronics [*Mlynczak et al*., 2005]. The FTS and aft optics are cooled to ~180 K by liquid nitrogen, 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 wavenumbers) 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 an unapodized resolution of 0.625 wavenumber; the scan time varies from 1.4 to 8.5 s, depending on the detector sample interval. 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 x 37.5 mm, large enough for a 10x10 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.

The design of the FIRST beamsplitter is based on the theory described in *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 7 inches, and reduced to a 5-inch 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 is has relatively few absorption features throughout the wavelength span of FIRST compared to other materials. The beamsplitter performances were tested with the Smithsonian Astrophysical Observatory FIRS-2 spectrometer [*Johnson et al*., 1995] to ensure they had the proper wavelength response for FIRST. For optical flatness, the film is evenly stretched over an optically flat ring.

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 wavenumbers) as the spectra indicate the instrument recorded spectra between 2000 and 50 wavenumbers, which corresponds to the entire energetically significant portion of the Earth’s emission spectrum. Comparisons below with measurements from the Aqua satellite indicate a well-calibrated FIRST instrument.

3. FIRST Flight Spectra and Comparisons with Aqua Observations

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 1.5 km on a side. By comparison, the AIRS, CERES, and MODIS footprints are nominally 14 km, 20 km, and 1 km, respectively.

Shown in Figure 1 is an individual spectrum recorded by the FIRST instrument from one of its central detectors at the time of the Aqua satellite overpass. Shown in Figure 2 is an individual spectrum recorded at the same time in a corner detector. The measured interferograms are calibrated, including phase corrections, and then a fast Fourier transform is conducted to produce these spectra. The calibrations are presently based on a reference blackbody carried in flight. These spectra confirm that the FIRST instrument achieved the necessary optical throughput. The spectra also cover the range from approximately 50 to 2000 wavenumbers, 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. We note that *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 wavenumbers at 5 to 10 wavenumber 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].

The spectra in Figures 1 and 2 are plotted with minor gaps at frequencies higher than 1000 wavenumbers. These small regions have purposely not been plotted because of the presence of absorption features in the beamsplitter at these wavenumbers that have not been completely corrected in the calibration process. They will be fully corrected in the near future as the FIRST team does an ever 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. The surface temperature (discussed below) is just under 320 Kelvin, while the far-infrared spectra correspond to an equivalent emission temperature of about 240 to 260 Kelvin. The reduction of the brightness temperature in the far-IR from the surface is a direct indicator of the strong absorption in the far-infrared by water vapor, and hence, of the natural greenhouse effect provided by water vapor.

We have conducted an initial assessment of the calibration accuracy of the FIRST radiances by looking at the atmospheric window region (800 to 1000 wavenumbers) and comparing these with the measurements recorded by instruments on the Aqua satellite. The FIRST radiance at 900 wavenumbers (cm^{-1}) of 0.15 W m^{-2} sr^{-1} $(cm^{-1})^{-1}$ corresponds to a blackbody surface skin temperature of 318 Kelvin. At first this seems quite high, but the FIRST flight occurred in cloudless skies on a warm day with air temperatures above 32 C or 305 Kelvin.

The radiance recorded by the CERES instrument in its window channel (covering 877 to 1227 wavenumbers, spectrally integrated) was 41.75 W m^{-2} sr. Line by line radiative transfer calculations [e.g., *Kratz et al*., 2005] simulating the CERES measurement and incorporating surface temperatures of 318 K and 297 K with an atmospheric temperature profile from a radiosonde launched at Albuquerque, New Mexico, yielded radiances of 41.83 W m^{-2} sr^{-1}, and 30.76 W m^{-2} sr^{-1}, respectively, confirming the surface temperature of 318 K derived from FIRST and therefore the calibration of FIRST.

A direct comparison of surface skin temperature is available using data from the AIRS instrument. The AIRS database records 4 fields-of-view that are centered 52 km, 46 km, 37 km and 77 km from the location of FIRST. The skin temperatures in the 4 fields are 318.5 K, 314.8 K, 319.0 K, and 311.4 K, respectively. The AIRS observation closest to the FIRST location is within a degree of the FIRST observation. A key point to remember is that the AIRS field of view is about 4900 times larger than the FIRST field of view (14 km diameter vs. 0.2 km diameter.) With these considerations, these results show that FIRST is accurately calibrated, perhaps to better than 1 K.

As the focus of FIRST is on the far-infrared, we show in Figure 3 a FIRST spectrum between the limits of 40 and 600 wavenumbers. Also shown is a spectrum computed with a line-by-line radiative transfer code (at 0.625 wavenumber resolution) using as inputs the coincident profiles temperature and moisture from AIRS. The calculated spectrum is offset by an amount equal to -0.05 radiance units, allowing visual inspection and comparison of the spectral structure of the FIRST measurements against the calculation. The FIRST data are a single measured spectrum, i.e., no averaging of multiple spectra has been done. As is clearly evident, FIRST picks up the fine features in the spectra predicted by radiative transfer theory across the entire far-infrared. The data show remarkable fidelity with theory in the overall magnitude and structure of the far-infrared.

4. Summary and Future Directions

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 dataset 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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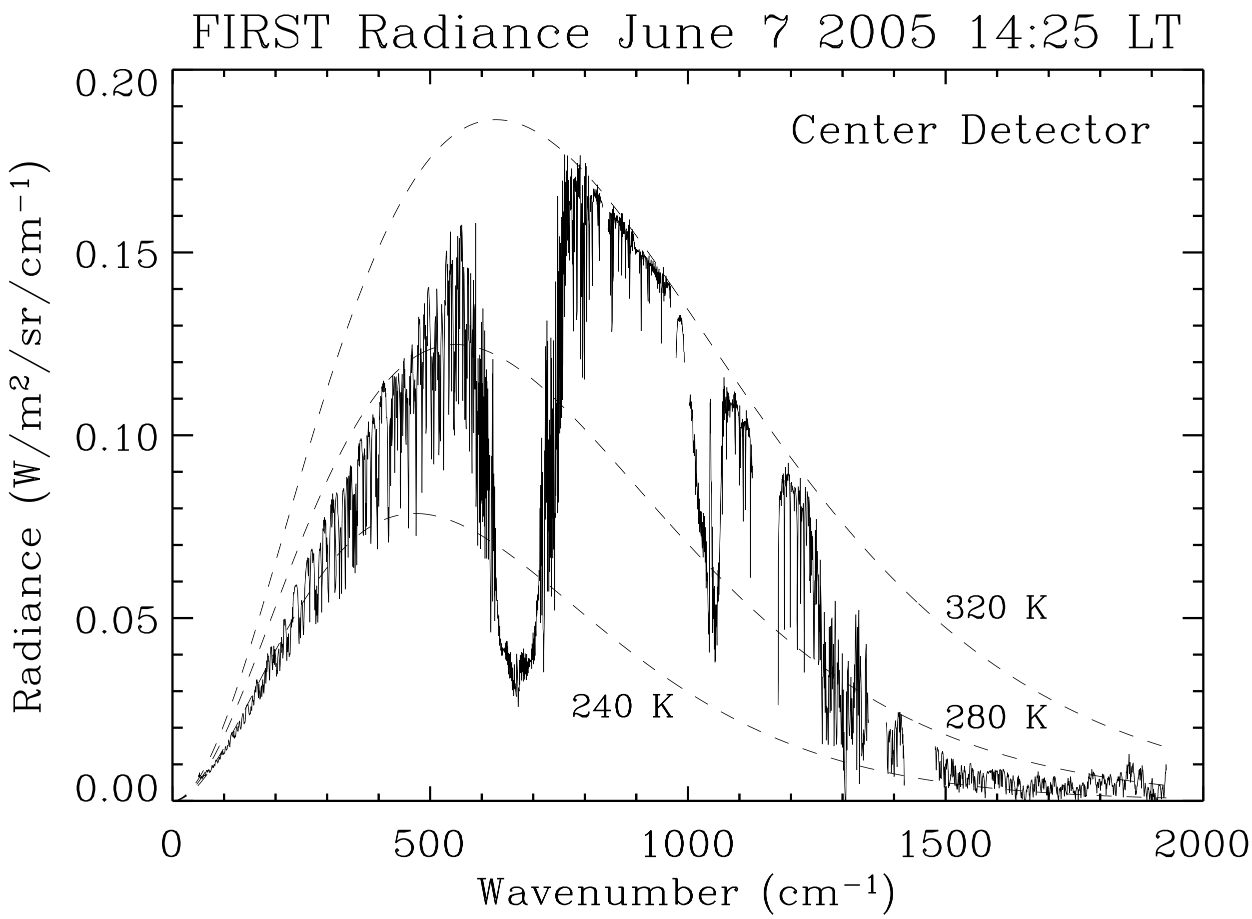

Figure 1. Infrared spectrum recorded by FIRST on 7 June 2005, on the central detector, covering 50 to 2000 wavenumbers, demonstrating achievement of broad spectral bandpass in one beamsplitter and focal plane combination.

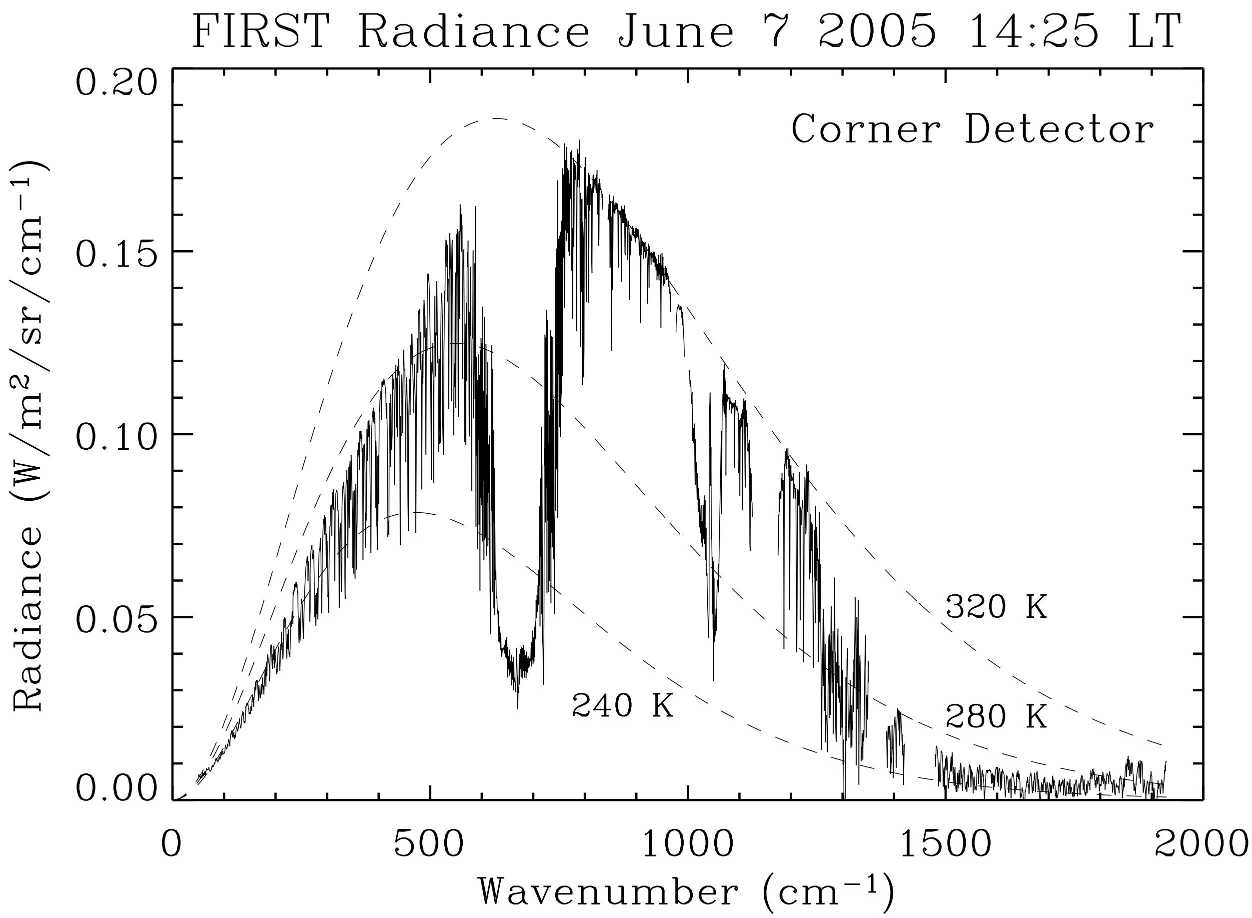

Figure 2. Infrared spectrum recorded by FIRST on 7 June 2005, on a corner detector, demonstrating achievement of the high throughput requirement.

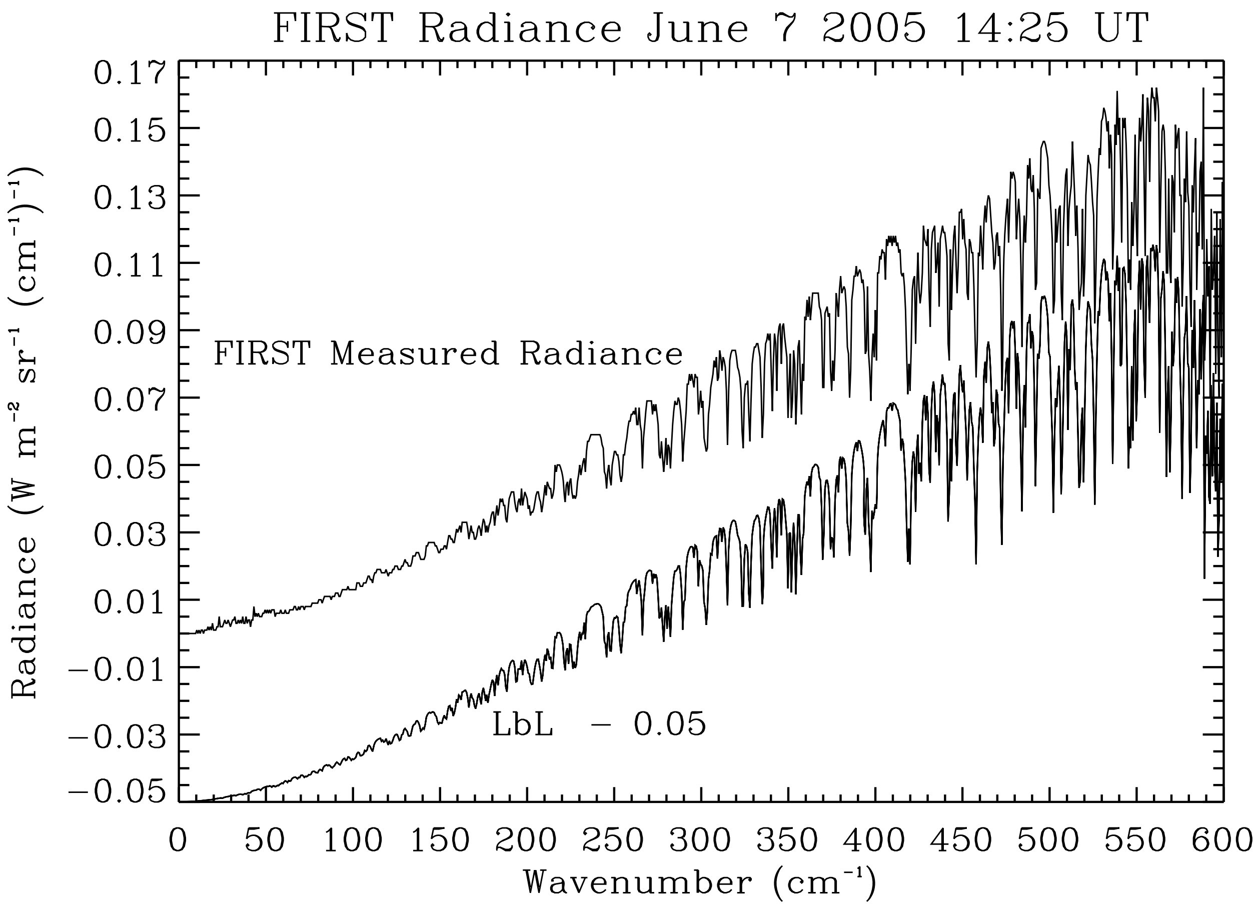

Figure 3. Far-infrared spectrum (80 to 600 wavenumbers) measured by FIRST (top curve) and line-by-line radiative transfer calculation based on AIRS soundings (bottom curve, offset by -0.05 radiance units), demonstrating spectral fidelity of the FIRST measurement relative to theory.