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Harri Latvakoski
Utah State University

Marty Mylncak
Utah State University

David Johnson
Utha State University

Rich Cageao
Utah State University

Jason Swasey
Utah State University

Kendall Johnson
Utah State University

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Absolute radiance re-calibration of FIRST

Harri Latvakoski[a], Marty Mylnczak[b], David Johnson[b], Rich Cageao[b], Jason Swasey[a], and Kendall Johnson[a]
[a]Space Dynamics Laboratory, 1695 Research Park Way, N. Logan, UT 84341;
[b]NASA Langley Research Center, Hampton, VA 23681

ABSTRACT

The FIRST (Far-InfraRed Spectroscopy of the Troposphere) instrument is a 10 to 100 micron spectrometer with 0.64 micron resolution designed to measure the complete mid and far-infrared radiance of the Earth's Atmosphere. FIRST has been successfully used to obtain high-quality atmospheric radiance data from the ground and from a high-altitude balloon. A Fourier transform interferometer is used to provide the spectral resolution and two on-board blackbodies are used for calibration. This paper discusses the recent re-calibration of FIRST at Space Dynamics Laboratory for absolute radiance accuracy. The calibration used the LWRICS (Long Wave Infrared Calibration Source) blackbody, which NIST testing shows to be accurate to the ~100 mK level in brightness temperature. There are several challenges to calibrating FIRST, including the large dynamic range, out of phase light, and drift in the interferogram phase. The accuracy goal for FIRST was 0.2 K over most of the 10 to 100 micron range, and results show FIRST meets this goal for a range of target temperatures.

Keywords: FIRST, atmospheric spectra, Fourier transform interferometer, far-infrared spectra, far-infrared blackbody

1. INTRODUCTION

FIRST (Far-IR Spectroscopy of the Troposphere)[1,2] is a high altitude balloon and ground-based instrument to measure the far-infrared spectrum of the atmosphere from 100 to 1000 cm^{-1} (10 to 100 µm) with a spectral resolution of 0.643 cm-1. Build by Space Dynamics Lab (SDL), FIRST has been successfully used since 2005 on multiple campaigns to obtain high-quality radiance data of the atmosphere from both a high altitude balloon and the ground[3,4].

In 2011 FIRST was returned to SDL for absolute radiance recalibration, which is described in this paper. Section 2 is a description of the instrument, section 3 describes the calibration equipment and test, section 4 describes the data processing and section 5 is the absolute calibration results.

2. INSTRUMENT DESCRIPTION

FIRST uses a Fourier transform interferometer with a Germanium-on-Mylar thin film beamsplitter to provide 0.643 cm^{-1} spectral resolution and strong response over a 100 to 1000 cm^{-1} spectral range (with some response from 50 to 2200 cm^{-1}). Data is collected for both directions of interferometer travel and collection time for one 24576-point scan is 11.5 seconds including turnaround. The FIRST aperture is 7 cm and FIRST has 10 silicon bolometer detectors each with a 0.41° field of view. These 10 detectors are at the center and four corners of a sparsely populated array which has a total field of view of 4.4×4.4°. The silicon bolometers are behind Winston cones and are cooled to 4.2 K with liquid helium. Two on-board blackbodies are used for instrument calibration, an ambient blackbody (ABB) and a warm blackbody (WBB) that is heated to ~30 K above ambient. For balloon flights one blackbody can be replaced by a view of space. The FIRST NEDT is <0.1 K @ 310 K from 200 to 1000 cm^{-1} in a single spectrum of a target. The FIRST absolute accuracy goal was 0.2 K at 230 K from 170 to 1000 cm^{-1} and 0.5 K from 100 to 170 cm^{-1}.

FIRST (Figure 1) consists of three sections separated by vacuum windows: a scene select assembly, the interferometer section, and the detector dewar. The vacuum windows are 41-µm thick polypropylene and the detector dewar simply contains the detectors and cryogen tanks. The interferometer section contains the interferometer and the aft-optics that focus the beam from the interferometer onto the detectors. There are no imaging fore-optics. The interferometer section can be cooled to 180 K to demonstrate the interferometer can operate at this temperature, but during most operations, this section is kept under vacuum but at ambient temperature. The scene select assembly contains a rotating mirror that directs the FIRST beam to one of three ports, each of which can connect to an on board blackbody or be left open. The entire scene select assembly can be rotated where it attaches to the interferometer section so that an open port can face up, down, or to the side as needed. Except for the detector amplifiers, the electronics that control and read out FIRST are in a separate container and are entirely commercial-off-the-shelf boards and computers.

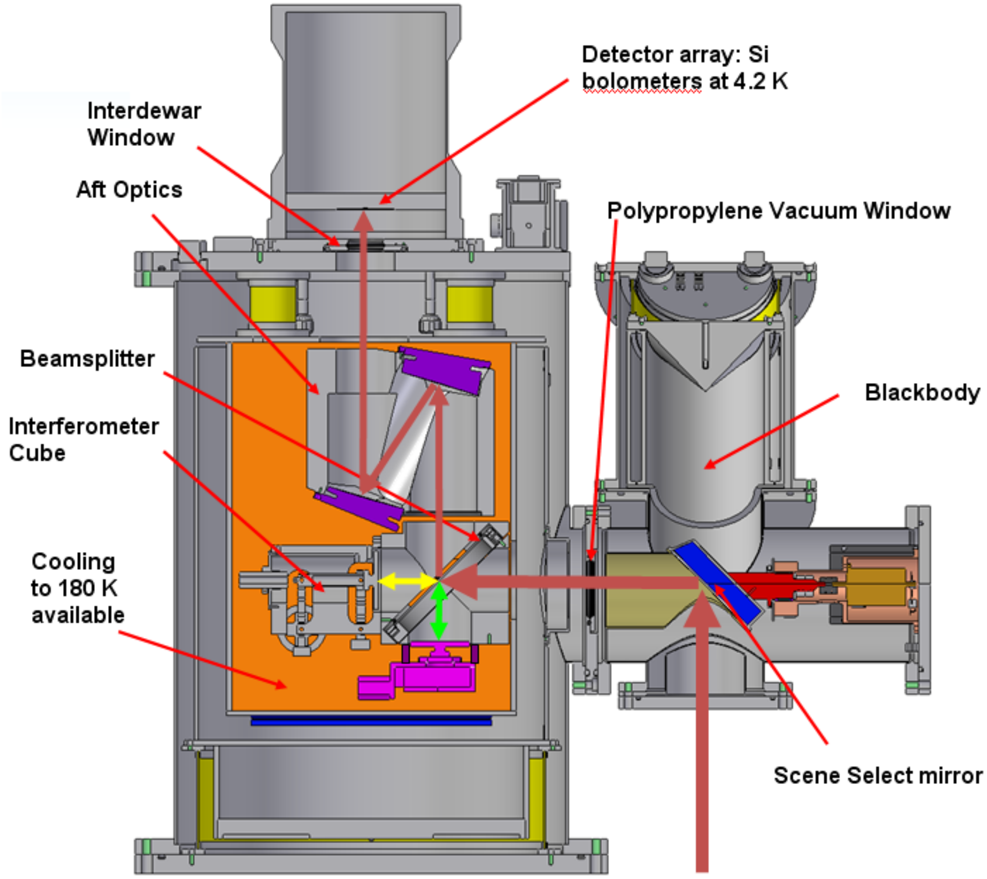


Figure 1: A cutaway view of FIRST with the principle components labeled and the light path shown.

3. ABSOLUTE CALIBRATION TEST

FIRST was calibrated for absolute radiance by attaching the Long Wave Infrared Calibration Source (LWIRCS) blackbody to the third port of the scene select assembly (Figure 2). LWIRCS[5] (Table 1) is a ground calibration blackbody of a similar design to the FIRST on-board blackbodies. This design[6] uses specular Z302 paint and a specular trap cavity to achieve the high emissivity.

Table 1: The LWIRCS performance specifications

Wavelength range	1 to 100 μm
Temperature range	90 to 350 K
Aperture	6.1”
Beam divergence accepted	6° full angle
Emissivity	≥0.9998 (1-35 μm) ≥0.9980 (35-100 μm)
Temperature uncertainty	~130 mK

The output of LWIRCS has been measured with the NIST transfer radiometer (TXR)[7]. The TXR has a 5 µm band and a 10 µm band, each ~1 µm wide, and a brightness temperature scale based on a NIST water bath blackbody. The TXR measurement uncertainty is ~90 mK at 5 µm and ~150 mk at 10 µm. When observed with the TXR, the LWIRCS brightness temperature agreed with the LWIRCS temperature to within 95 mk (maximum deviation) at 5 µm from 210 to 350 K, and to within 186 mK at 10 µm from 180 to 350 K[8]. The agreement is at approximately the TXR measurement uncertainty level. During this test, the emissivity of LWIRCS was measured with the TXR and a heated-halo type test to be 0.99969±0.00003 at 5 µm. This result is consistent with the calculated value of 0.9998 because method used to perform the test reduces the LWIRCS emissivity from the calculated case.

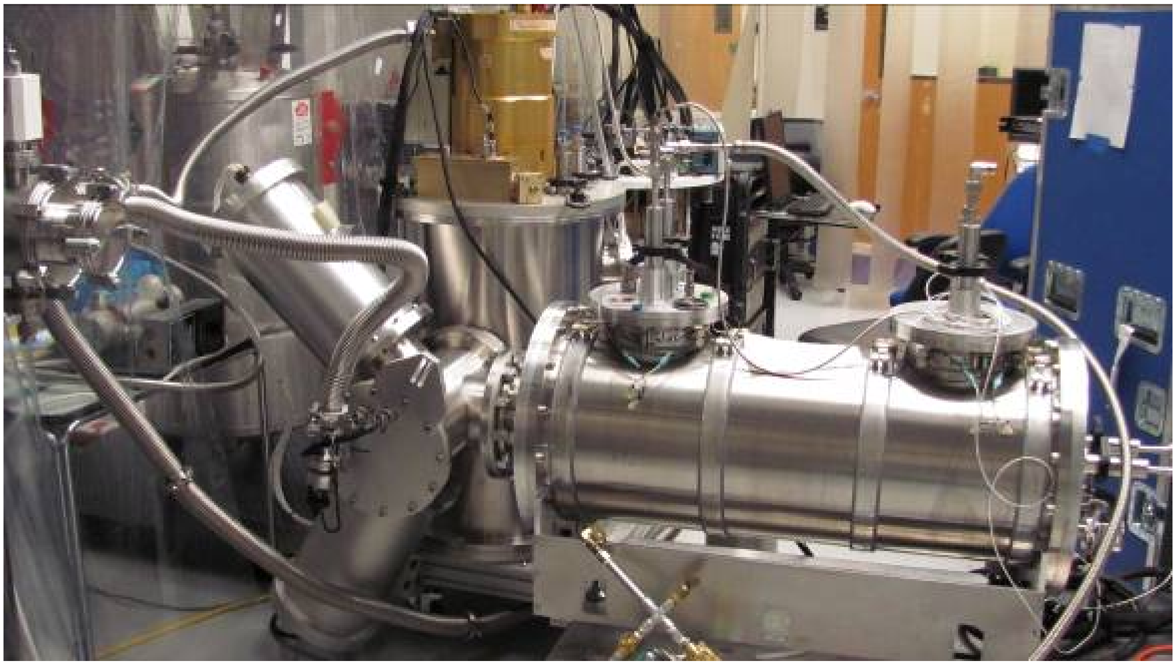


Figure 2: FIRST (at left) attached to the LWRICS blackbody (at right) during ground calibration. The FIRST on-board blackbodies are at left attached to the scene select assembly at an angle.

Absolute radiance data was collected by setting LWIRCS to a variety of temperatures and observing with FIRST. At each LWIRCS temperature a data set was collected by observing the ABB for 4 minutes, LWIRCS for 7 minutes, and the WBB for 4 minutes and then repeating this once. In all cases the ABB was at temperature near 293 K and the WBB was at 324 K.

4. CALIBRATION DATA PROCESSING

To process the FIRST data into spectra follows the general processing of interferograms into spectra, but because of its design, FIRST data also requires combining data from two gain channels per detector, excluding data with large vibration effects, and aligning phases.

To reach the sensitivity levels desired of FIRST requires a 20 bit dynamic range in the interferogram. A commercial 20 bit A/D converter that would meet the needs of FIRST was not available, so instead two sets of data are collected per detector, with one set having 100x higher gain. The data from the gain channels for each detector are combined by using high gain data except where the low gain absolute value is high enough that the high gain data saturates. Before combining, the high gain data is multiplied by a factor and an offset is added match the scale of the low gain data. The factor and offset for each detector were found from this calibration data by comparing simultaneous high and low gain data and fitting a line. The signal levels on the interferogram are such that low gain data is used only within 1000 points of the centerburst (Figure 3).

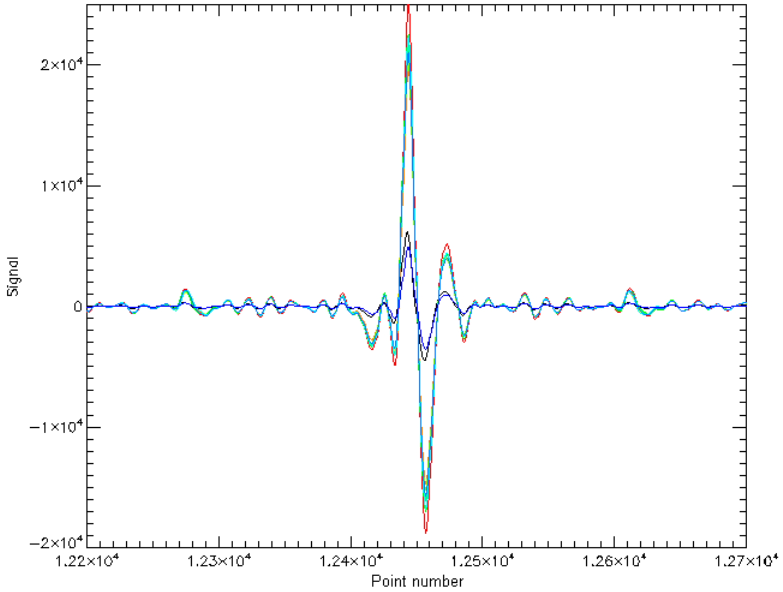
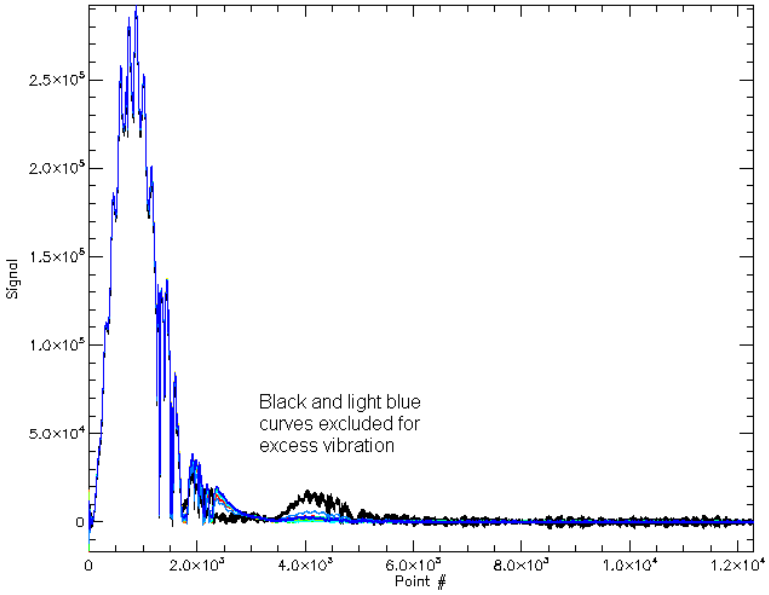


Figure 3: A section of FIRST interferograms from near the centerburst when looking at the ABB. Interferograms from all ten detectors are shown, each in a different color.

FIRST uses a thin film beamsplitter (Ge on Mylar) in the interferometer which is susceptible to vibration. Vibration effects were observed during the development of FIRST and mitigated by sampling at every fringe of the HeNe laser, which put the Nyquist wavenumber at 7899 cm^{-1} and transferred the major effects of vibration to a region of the spectrum (2500 to 3200 cm^{-1}) with no signal of interest. For most spectra, the remaining effects of vibration are reduced to acceptable levels, but occasionally, outside sources add excessive vibration to some interferograms. Spectra with excessive vibration are excluded by transforming an interferogram from any one detector and screening for excess signal in a broad peak from 2250 to 3215 cm^{-1} (Figure 4).



Black and light blue curves excluded for excess vibration

Figure 4: 10 full-resolution FIRST spectra from detector 3. Excess vibration is present in some spectra and visible as a broad peak around point 4000 (2571 cm^{-1}).

The FIRST beamsplitter does not pass a HeNe laser, and leaving a clear section on it for the laser to pass could have adversely affected the film. Instead, the metrology laser has its own separate beamsplitter and illuminates a polished section on the back side of the moving mirror. This effectively provides position information for the moving mirror; however, thermal expansion can differentially change the optical path of the laser and the infrared beam. This results in a shift of the sampling positions with respect to the peak of the interferogram, which in turn results in the shift of the phase in spectra produced from the interferograms. This phase drift can be enough that it must be accounted for during data processing. To complicate matters, FIRST has out of phase light present, and thus the interferogram phase will differ for targets with a differing radiance. In addition the interferogram peak can be negative for some detectors when viewing a cold target. Figure 5 shows both the variation in spectrum phase with target and the drift in phase at 514 cm^{-1} from a data set with LWIRCS at ~310 K. (The shift in phase produced by differential change in the optical path is a simple linear function of wavenumber so it is sufficient to measure phase over a limited spectral range.) A correction for the drifting phase is found by fitting a line to the WBB and ABB phase data and combining these to give a quadratic phase correction curve (see Figure 5). All spectra are then shifted in phase by the amount of this correction at 514 cm^{-1} with proportional shifting at other wavenumbers. In practice, this aligns the phases to ~0.2°, below which phase errors are not significant.

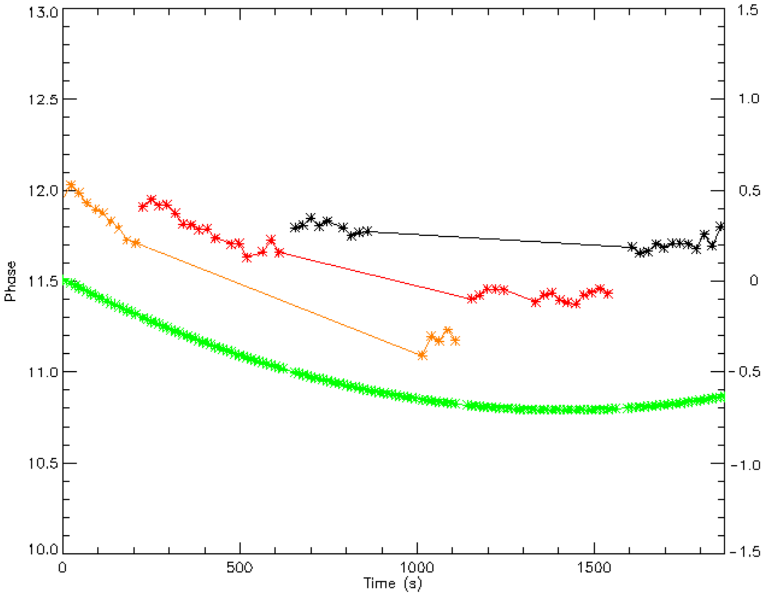


Figure 5: The phase (left axis) for all good spectra in the forward direction for detector 3 at 514 cm^{-1} averaged over 15 cm^{-1} for the data set where LWIRCS was at ~310 K. Orange is the ABB data, red is LWIRCS data, and black is the WBB data. The green curve (right axis) is the phase correction function at 514 cm^{-1}, which shows the amount subtracted from all forward direction phases to correct for the drift.

After processing from interferograms to spectra, all good spectra were averaged for each target with separate averages kept for each scan direction. To assess the FIRST absolute calibration, these spectra were used to calculate a measured radiance from LWIRCS using the calibration equation:

$$R_{target} = \frac{S_{Target} - S_{ABB}}{\mathfrak{R}} + P(T_{ABB}) \;;\; \mathfrak{R} = \frac{S_{WBB} - S_{ABB}}{P(T_{WBB}) - P(T_{ABB})} \tag{1}$$

S_{ABB} and S_{WBB} are the measured spectra of the ABB and WBB, S_{Target} is the measured spectra of LWIRCS, P is the Planck function and T_{ABB} and T_{WBB} are the blackbody temperatures. The FIRST responsivity is $\mathfrak{R}$ and R_{Target} is the measured LWIRCS radiance, which was then used to calculate a brightness temperature using the inverse Planck function. The measured spectra and the responsivity are complex numbers. If the spectral phases are properly aligned and FIRST does not change between views of each blackbody the imaginary component of the LWIRCS radiance will show only noise. This was the case for all calibration data. A correction for detector non-linearity was not applied as additional processing of this data indicates the FIRST detector response is linear to ~0.3%.

5. ABSOLUTE RADIANCE CALIBRATION RESULTS

The FIRST absolute calibration was assessed by comparing the LWIRCS brightness temperature as measured by FIRST with the temperature from the LWIRCS temperature sensors. Figure 6 shows the brightness temperature measured when LWIRCS is at 292.76 K. Between 200 and ~1000 cm^{-1}, excluding the narrow regions of low response, the brightness temperature agrees with the LWRICS temperature to within 0.2 K. The brightness temperatures for the two directions trace each other closely but not exactly and the difference between the two is indicative a random noise component in the spectra. Above ~900 cm^{-1} the backward and forward results diverge, which is indicative of significant noise. As data sets for other LWIRCS temperature data sets do not consistently show this amount of noise, the cause is probably beamsplitter vibration.

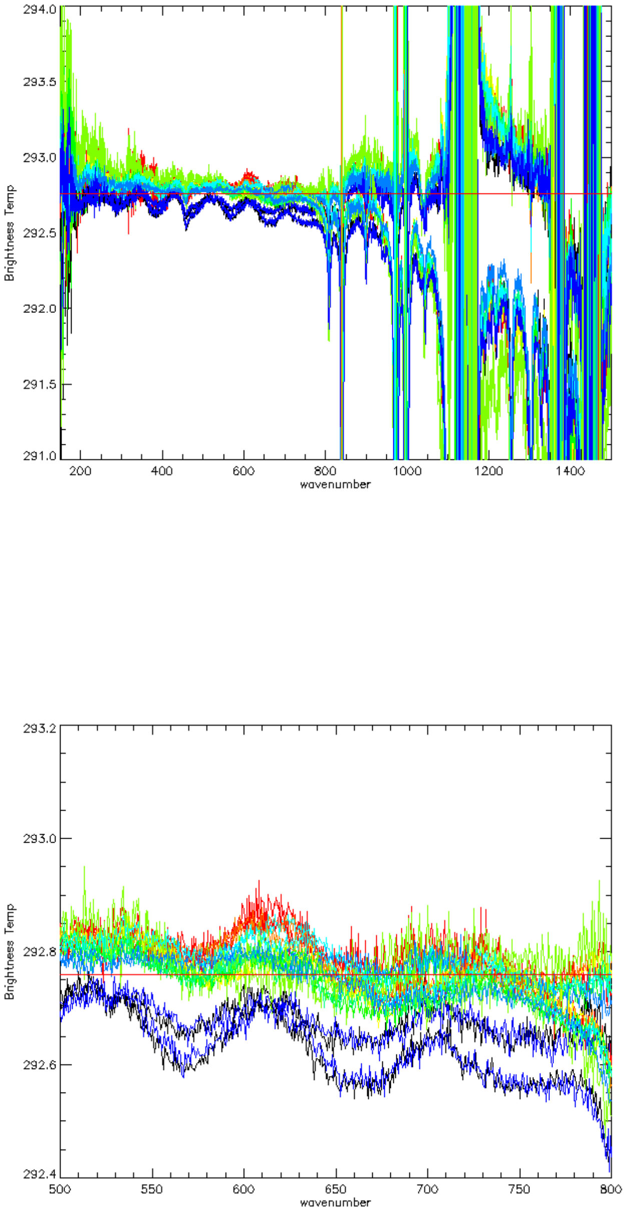


Figure 6: The brightness temperature for LWIRCS at 292.76 K as measured by each detector (the color order for detectors 1-10 is black, red, orange, yellow, yellow-green, green, blue-green, cyan, sky-blue, and blue). Both scan directions are shown in the same color. The plot at right is a close up on the plot at left. The red line in each plot is 293.76 K. The spectral resolution is 0.6428 cm^{-1}.

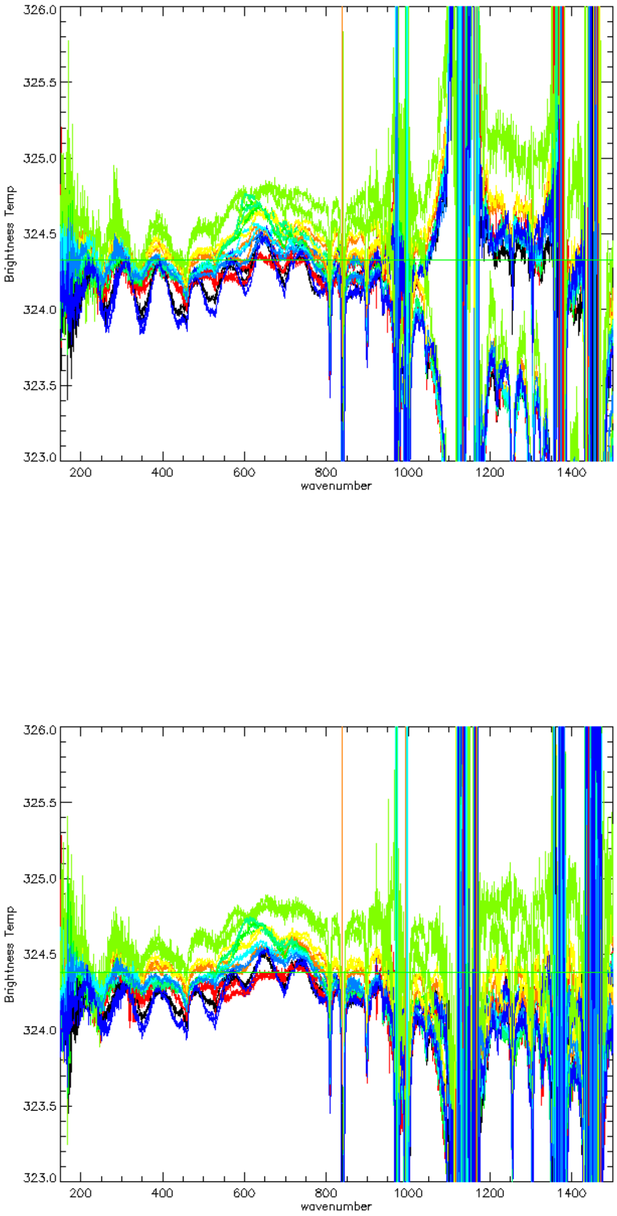


Figure 7: The brightness temperature for LWIRCS at 324.33 K (left) and 324.38 (right).

For the data set with LWRICS at 292.76 K, the ABB was at 293.66 K. By Equation 1, this data set is essentially a comparison of the ABB with LWIRCS, and because both are at room temperature, it reduces to a comparison of the temperature sensors. Given the result shown in Figure 6, the blackbody temperature sensors must agree to within 0.1 K, which is at the level of the estimated uncertainty in these sensors.

Figure 7 show the measured brightness temperature with LWIRCS at ~324 K. Two separate data sets were taken to show the repeatability. The 324.38 K set clearly shows less noise than the 324.34 K especially above 1000 cm^{-1}. Below 800 cm^{-1} both sets are very similar and the brightness temperature deviation from the LWRICS temperature is dominated by systematic effects, such as the oscillations in the curves for detector 1 (black) and 10 (blue). For all detectors the brightness temperature is within 0.5 K of the LWRICS temperature, but if 1, 5 (yellow-green), and 10 are excluded the brightness temperature is within 0.3 K. Other data taken during this calibration suggests that detector 5 is affected by light from outside the blackbodies, and the oscillations in brightness temperature deviation seen for detectors 1 and 10 may be an effect of stray light from outside the blackbodies with the amount varying with wavenumber.

LWRICS at 324.38 K is very close to the WBB at 324.60 K so this set is a comparison of LWIRCS with the warm blackbody. To achieve the agreement seen in Figure 7, the brightness temperature of each blackbody must agree to ~0.1 K, which is again the uncertainty in the temperature sensors.

Figure 8 to Figure 11 shows the LWIRCS brightness temperature at several other temperatures from 169 to 310 K. At 310.43 K, the brightness temperature is within 0.2 K of the LWIRCS temperature with the exception of detector 10 which shows high noise here. For 270.55, 247.42 and 225.18 K, detector 5 reads notably high and the oscillations in 1 and 10 increase, and detector 2 becomes increasingly noisy. Excluding these three detectors, the brightness temperature deviations are within 0.3, 0.5 and 1 K, respectively.

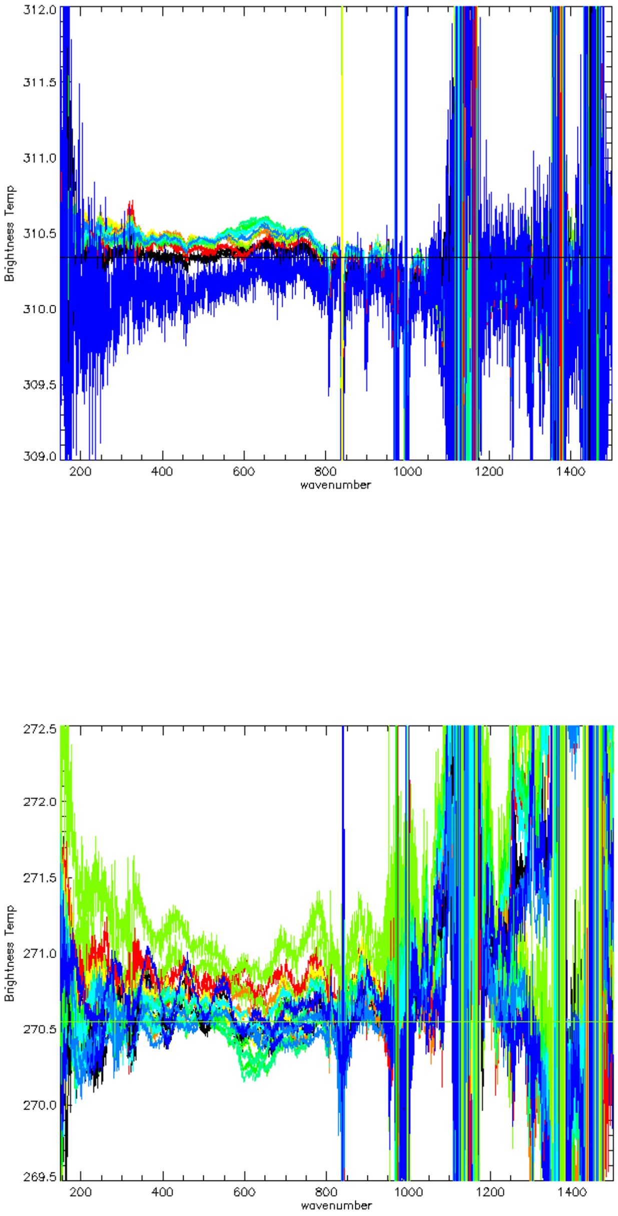


Figure 8: The brightness temperature for LWIRCS at 310.43 K (left) and 270.55 K (right).

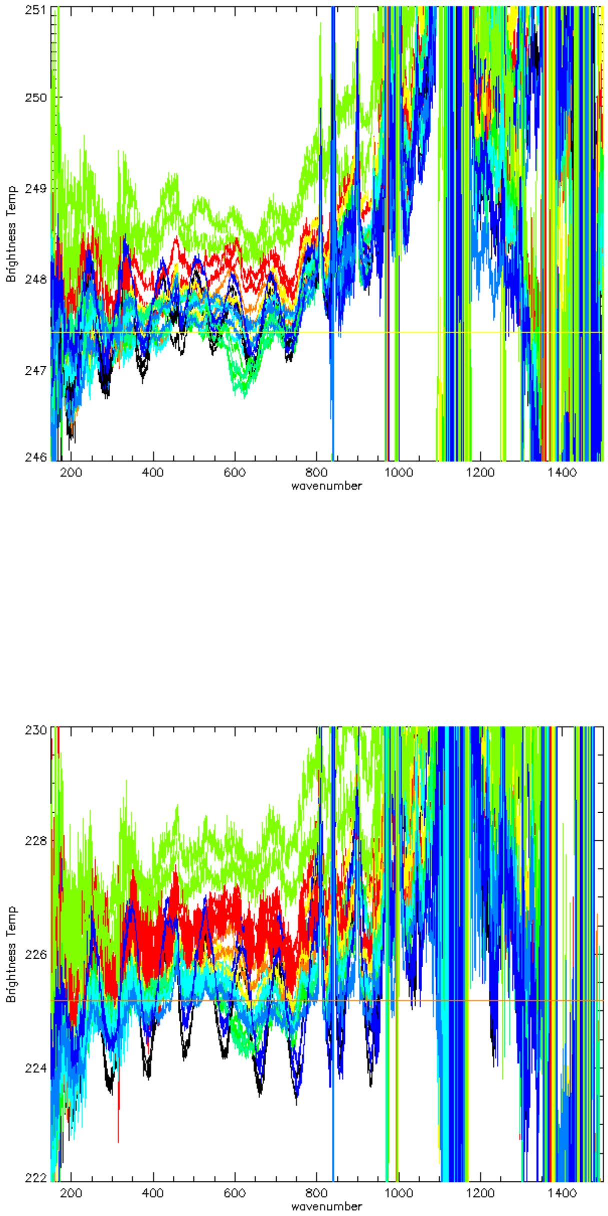


Figure 9: The brightness temperature for LWIRCS at 247.42 K (left) and 225.18 K (right).

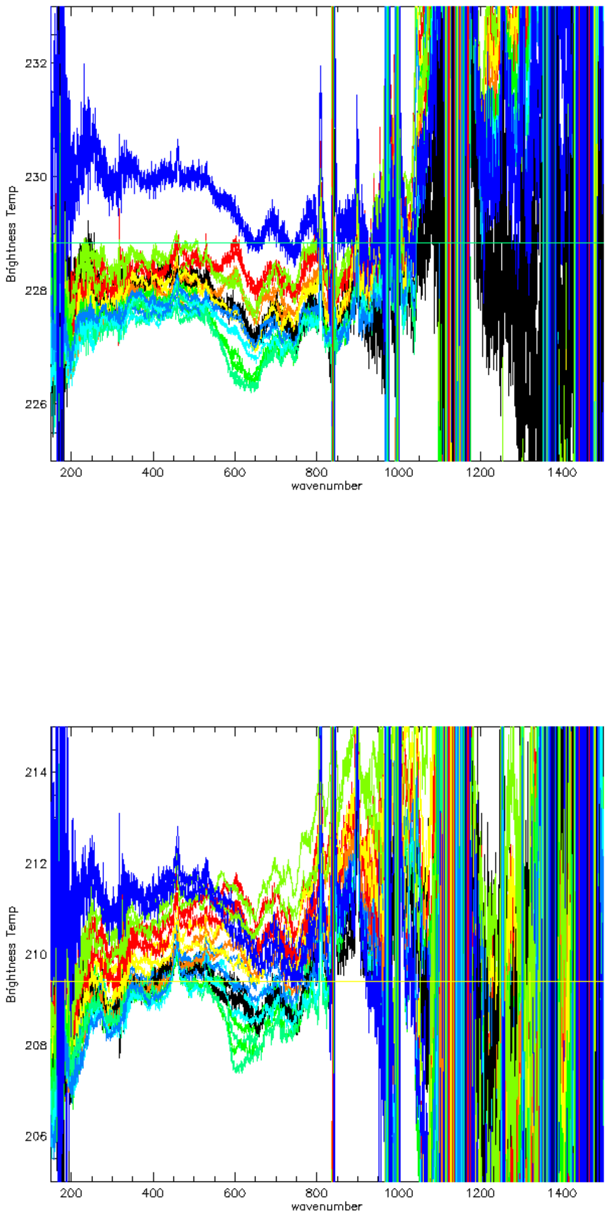


Figure 10: Brightness temperatures with LWRICS at 228.84 K (left) and 209.41 K (right).

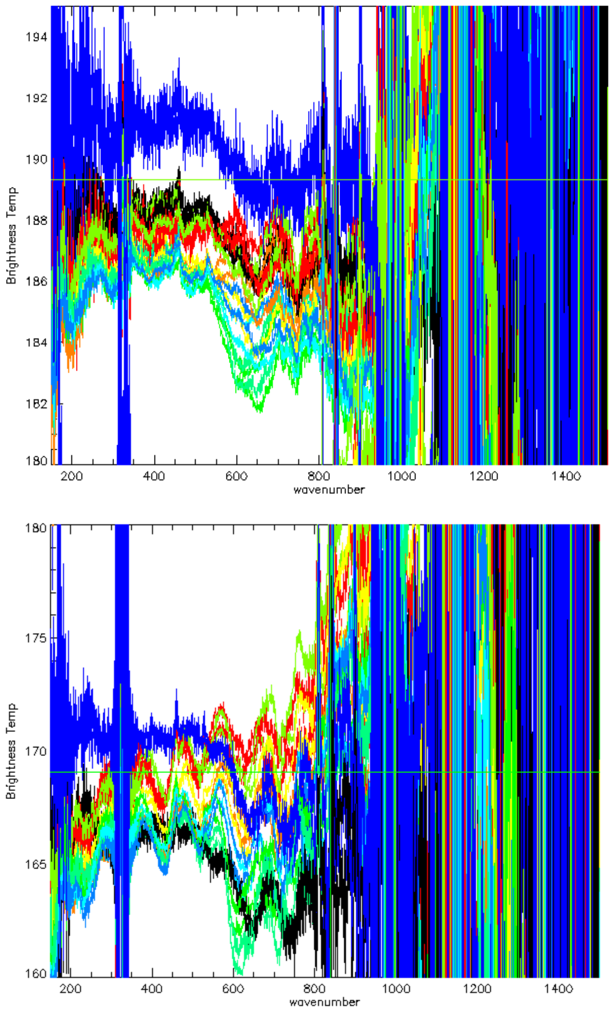


Figure 11: Brightness temperatures with LWIRCS at 189.33 K (left) and 169.06 K (right).

For the data at 310, 229, 209, 189, and 169 K , the large oscillations in the detector 1 and 10 brightness temperatures are not present, the temperature from detector 5 is not unusually high, nor is 2 noisy. These sets were collected during a different vacuum cycle of FIRST, and the changes to the detector 5, 1 and 10 behaviors suggest the amount of stray light may change with cold cycle. This is possible since the FIRST windows do not return to the same shape after each pumpdown and this may direct the light.

At 228 K the brightness temperature deviations from the LWRICS temperature are within ~1 K, while at 209 K the deviations are within 2K, but at 189 K and 169 K the deviation can be up to 5 K. For these lower temperature sets, the wavenumber range where temperatures are accurate is reduced because of decreasing signal with temperature at the higher wavenumbers. Noise is increasingly significant at colder temperatures because a given amount of noise in the radiance is a larger change in temperature at a lower temperature, and because noise in the WBB and ABB spectra add increasing noise to the measurement as the LWIRCS temperature gets farther from the WBB and ABB temperatures.

The reduced accuracy in the brightness temperature at low temperatures is clearly dominated by systematic effects that seem to lack a clear trend with temperature.

6. CONCLUSIONS

The results of the FIRST recalibration shows that, for detectors 2, 3, 4, 6, 7, 8, and 9, the absolute calibration is better than 1 K (peak deviation) from 200 to 800 cm^{-1} for temperatures above 209 K, and the result is likely as good for detectors 1, 5, and 10 but stray light size issues complicate direct measurement. For temperatures in between or close to the WBB and ABB temperatures, FIRST meets the design goal of 0.2 K absolute accuracy. The WBB and ABB spectra agree with the well calibrated and NIST tested LWIRCS spectra to within 0.1 K for the on-board blackbody temperatures used during this calibration. Because of this and the lack of any observed non-linearity in the FIRST detectors, FIRST data can be calibrated using the calibration equation and the on-board blackbody temperatures with no additional corrections.

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