Absolute Radiance Recalibration of FIRST using a Cold Blackbody

Harri Latvakoski¹, David Johnson², Martin Mlynczak², and Rich Cageao²

¹Space Dynamics Lab
²NASA Langley Research Center
Outline

- FIRST
- FIRST calibration
- Previous calibration results
- New absolute radiance response calibration
FIRST (Far-IR Spectroscopy of the Troposphere)

- FIRST is an instrument that measures the Earth’s atmospheric radiance in the FAR-IR
- Has been successfully used since 2005 from high altitude balloons and from the ground
- FIRST developed under an Instrument Incubator Program
  - Goal of developing technology needed to attain daily global coverage, from low-earth orbit, of the Earth’s far-infrared spectrum
  - Technology to be demonstrated with a prototype instrument in a space like environment

Far-IR (>15 μm, <667 cm⁻¹)
- Contains half of Earth’s outgoing long-wave radiation
- Is not well observed spectrally

FIRST spectrum from high altitude balloon
FIRST specs

- Fourier Transform spectrometer
  - Michelson interferometer
  - Coverage
    - Goal: 100 to 1000 cm$^{-1}$ (100 to 10 µm)
    - Actual: 50 to 2200 cm$^{-1}$ (200 to 4.5 µm) with breaks
- Spectral Resolution: 0.643 cm$^{-1}$ (unapodized)
- NE$\Delta$T goals
  - 0.2 K (k=1) 170 to 1000 cm$^{-1}$ @ 230 K
  - 0.5 K (k=1) 100 to 170 cm$^{-1}$ @ 230 K
- Accuracy goal: equal to NE$\Delta$T
- Two on-board blackbodies or blackbody and space view for calibration
- 7 cm aperture
- Ability to have 4.4° FOV (~100 km from orbit)
  - 10 detectors in sparsely populated array
- Liquid He cooled Si bolometers
- 0.41° IFOV (~10 km from orbit)
- 24576 points per interferogram
- 11.5 sec collection time
FIRST

Simple optics
3 sections
3 port SSA scene select assembly (SSA)
SSA can be rotated
COTS electronics

Interferometer Cube
Aft Optics
Beamsplitter
Detector array: Si bolometers at 4.2 K
Polypropylene Vacuum Window
Blackbody
Scene Select mirror
Interdewar Window
Cooling to 180 K available
FIRST on-board calibration

- FIRST views both on-board calibration sources during data collection
- Calibration equation

\[ R_{\text{Target}} = \frac{S_{\text{Target}} - S_{\text{ABB}}}{\Re} + P(T_{\text{ABB}}) \]

\[ \Re = \frac{S_{\text{WBB}} - S_{\text{ABB}}}{P(T_{\text{WBB}}) - P(T_{\text{ABB}})} \]

- \( S_{\text{Target}}, S_{\text{WBB}}, S_{\text{ABB}} \): Observed signal from target, warm and ambient blackbodies
- \( T_{\text{WBB}}, T_{\text{ABB}} \): Temperature of warm and ambient blackbodies

- Used to calculate target radiance
- Warm, Ambient blackbodies used for ground data
- Warm blackbody, space view used for balloon data
- Forward and backward scans are calibrated independently
FIRST ground calibration

- FIRST calibrated for absolute response on ground by observing on-board blackbodies and LWIRCS (calibrator blackbody) on the open port.
- Observe LWIRCS at a set of temperatures, compare observed brightness temperature to LWIRCS temperature

**LWIRCS**
- Wavelength range: 1 to 100 µm
- Temperature range: 80 to 350 K
- Aperture: 6.1 inches
- Beam divergence: 6° full angle
- Temperature unc: 130 mK 180 K
  - 60 mK 290 K
- Emissivity: ≥0.9998 (<35 µm)
  - ≥0.9980 (>35 µm)
Previous results

- Calibrated in 2012 using warm and ambient blackbodies over 170 to 320 K range

- Results (presented at last CALCON)
  - Accuracy 1.5 K or better (peak deviation) for T>200 K
  - From 270 to 330 K, accuracy meets design goals of 0.2 K (k=1) 170 to 1000 cm$^{-1}$

- Conclusions
  - Deviations are due to small systematic effects combined with large increase in error from extrapolating from blackbodies
  - Stray light confirmed as an error source
  - Window variation with vacuum cycle suspected as error source
2013 Calibration

- Repeated calibration using warm blackbody (324.5 K) and space view simulator (77 K)
Some temperature deviations

Key: detectors 1-10 are in black, red, orange, yellow, yellow-green, green, blue-green, cyan, light blue, blue.

Data from the each scan direction for each detector are the same color

Significant, highly systematic deviations

Detector 2 always within 1 K
Stray light

LWIRCS 324.66 K
baffle 321.4 K

LWIRCS 324.49 K
baffle 341.8 K
Baffle view fraction

View fraction of baffle by detector

Detector pattern at focal plane
Repeatability

293 K and 292 K data sets
4 days apart

Repeatable to 0.2 K
Repeatability always at this level

Difference of deviations
Variation with vacuum cycle confirmed

LWIRCS at ~230, 251 K.

Left: Originals

Right: after FIRST at ½ atmosphere for 2 days then re-pumped

Deviations change
Window effects

- Baffle view fraction changes too

Original from a few slides back

After vacuum cycled

- Window changes shape with each vacuum cycle and window shape directs beam
Windowless data

Still have significant systematic deviations

Fewer wiggles

Detector 2 still within 1 K
Windowless baffle view fraction

- Baffle view fraction improves without window, but still have stray light
- If FIRST beam can miss LWIRCS, it can also miss WBB, SVS
FIRST cal equation with stray light

Ideal cal equation, P’s are BB radiances, S’s are measured spectra

\[ P_L = \frac{S_L - S_C}{S_W - S_C} (P_W - P_C) + P_C \]

With view factor of f of contaminating radiance, R, for each blackbody

\[(1 - f_L)P_L + f_L R_L = x( (1 - f_W)P_W + f_W R_W - (1 - f_C)P_C - f_C R_C ) + (1 - f_C)P_C + f_C R_C \]

\[ x \overset{\text{def}}{=} \frac{S_L - S_C}{S_W - S_C} \]

Re-arrange

\[ P_L = x(P_W - P_C + R_1) + P_C + R_2 \]

\[ R_1 = \frac{1}{1 - f_L}((f_L - f_W)P_W + f_W R_W - (f_L - f_C)P_C - f_C R_C) \]

\[ R_2 = \frac{1}{1 - f_L}((f_L - f_C)P_C + f_C R_C - f_L R_L) \]

R₁ and R₂ are constant

\[ P_L - P_C - x(P_W - P_C) \overset{\text{def}}{=} y = xR_1 + R_2 \]

This should be just a line. Can fit for R₁ and R₂ and use to correct data
X vs. Y w/o window

200 cm\(^{-1}\)

These are not lines
Looks like non-linearity

400 cm\(^{-1}\)

600 cm\(^{-1}\)
Non linearity?

Three example spectra dashed lines are imaginary component

Spectra show interferograms are linear to better than ~0.3% here

To reproduce observed effect requires several % non linearity
Another type of non-linearity

Detector DC voltage level varies with target

Detector Response $\propto R_{Det} \propto V_{DC}$

Another type of non-linearity:
Interferogram linear but $\propto V_{DC}$
X vs. Y with correction

- Applied correction from response $\propto V_{DC}$
  - No free parameters
- These are lines
  - Near zero for good detectors
179 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too

Linearity correction alone significantly improves deviation

RMS is from 200 to 800 cm\(^{-1}\) for detectors 2,3,6,7,8,9 (left), all but 5 and 10 (right)

RMS: 0.67 K
RMS: 0.59 K
191 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too
205 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too
229 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too
253 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too
273 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too

RMS: 0.40 K
RMS: 0.14 K
292 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too

RMS: 0.47 K
RMS: 0.13 K
311 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too

RMS: 0.45 K
RMS: 0.17 K
325 K windowless data set

Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too

RMS: 0.45 K
RMS: 0.22 K
RMS deviation vs. temperature all detectors except 5 and 10. No window, non-linearity and stray light corrections applied.
Conclusions

- FIRST requires an unusual non-linearity correction
- FIRST has stray light
  - Windows cause some but not all of it
  - Some detectors worse than others
  - Stray light probably still limits accuracy
- FIRST is highly accurate
  - Some detectors not affected strongly by stray light
  - Stray light can be fixed