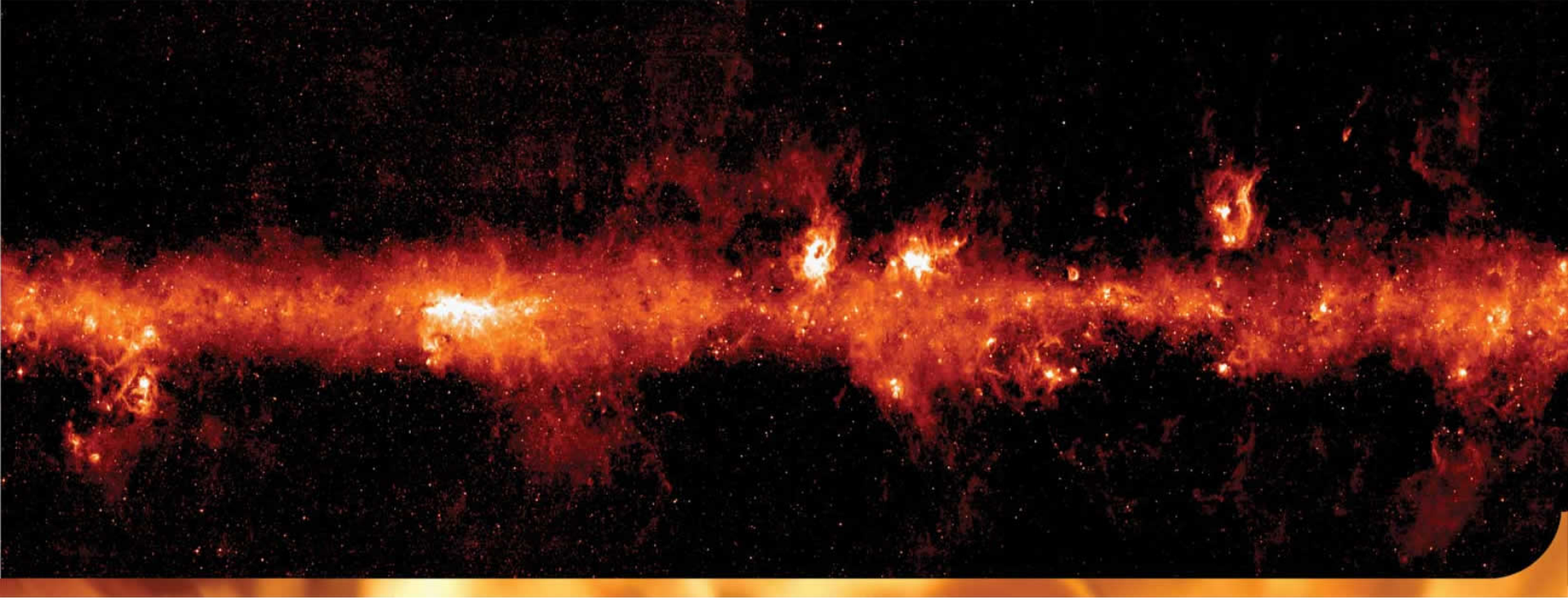

Absolute Radiance Calibration of FIRST

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Space Dynamics Laboratory
Utah State University Research Foundation

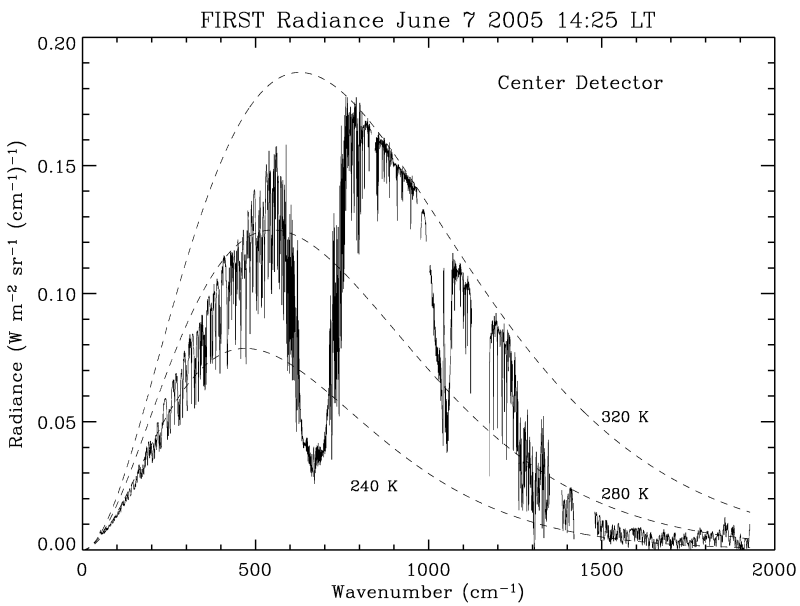
Outline

- FIRST
- FIRST on-board calibration
- Ground calibration equipment
- FIRST calibration data
- Absolute radiance response using an ambient blackbody
- Absolute radiance response using a cold blackbody

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

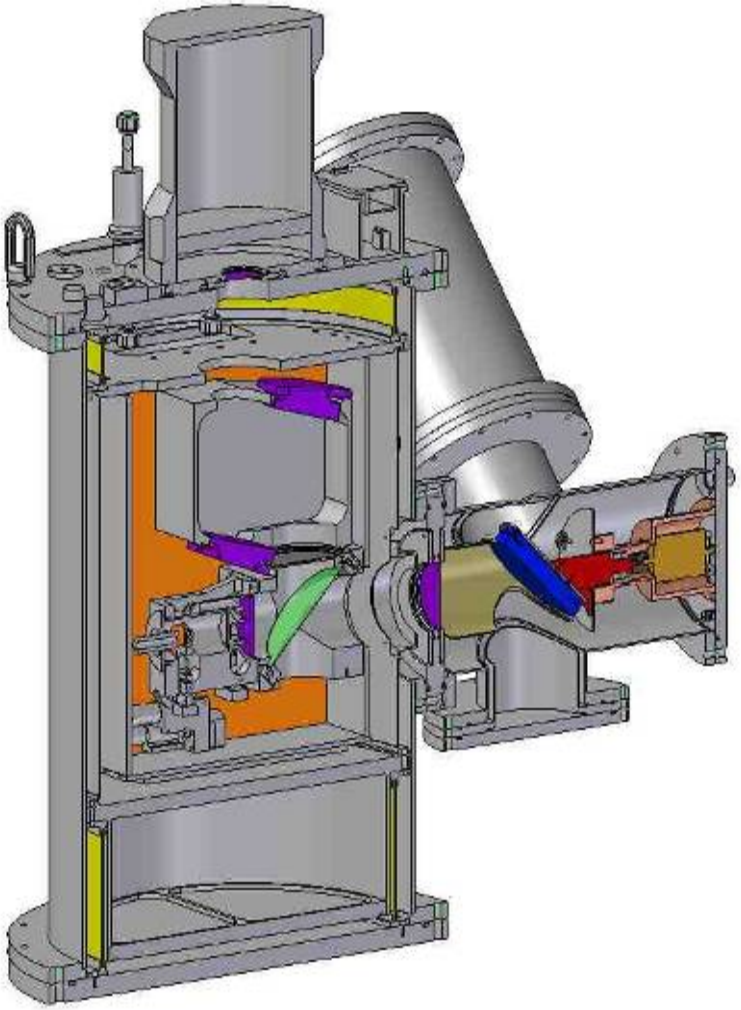
- Far-IR (>15 μm, <667 cm^{-1})
  - Contains half of Earth's outgoing long-wave radiation
  - Is not well observed spectrally



FIRST spectrum from a high altitude balloon

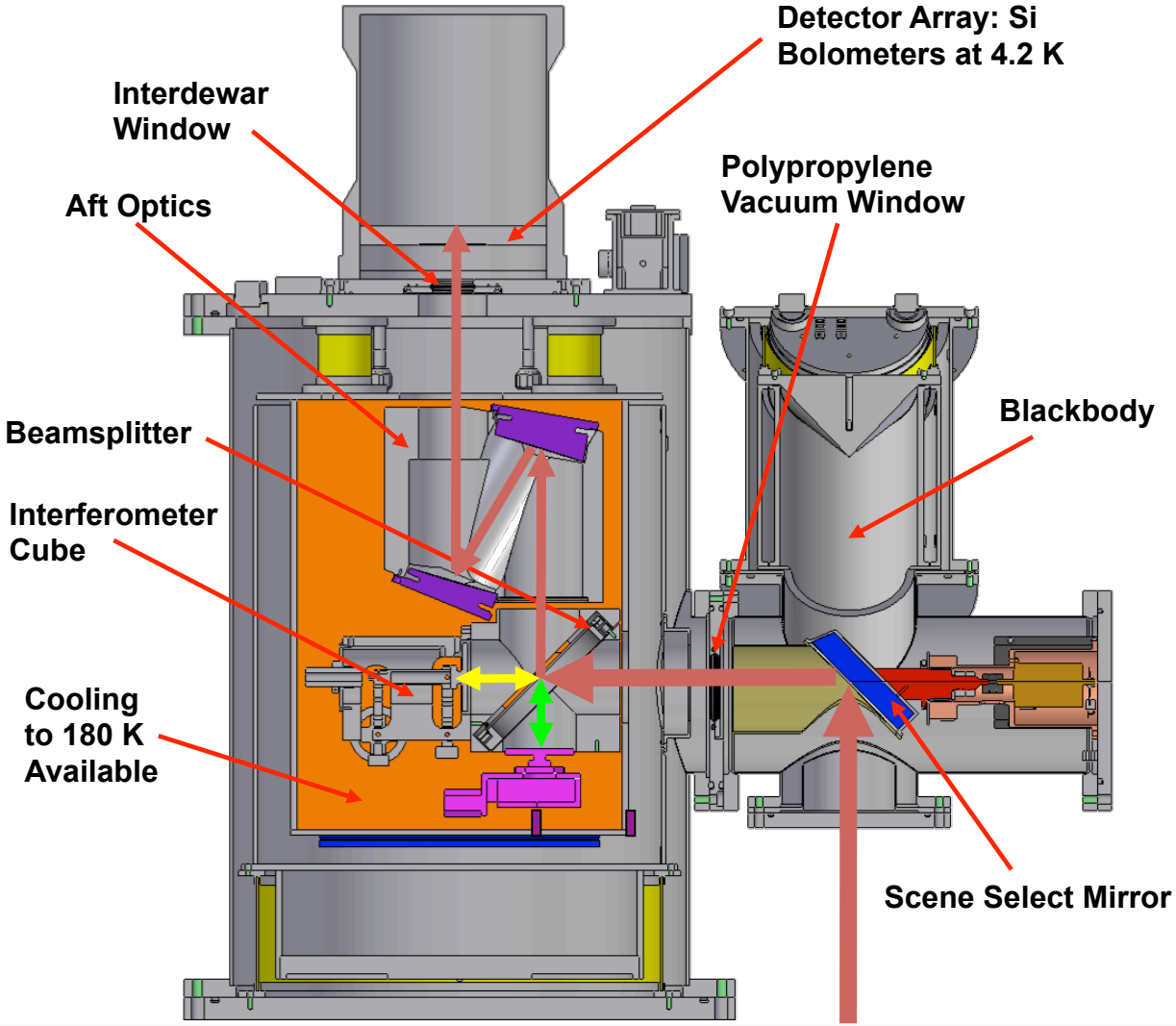
FIRST Specifications

- 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)
- NEΔT 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 NEΔT
- 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 scene select assembly (SSA)
- SSA can be rotated
- COTS electronics



FIRST On-board Calibration

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

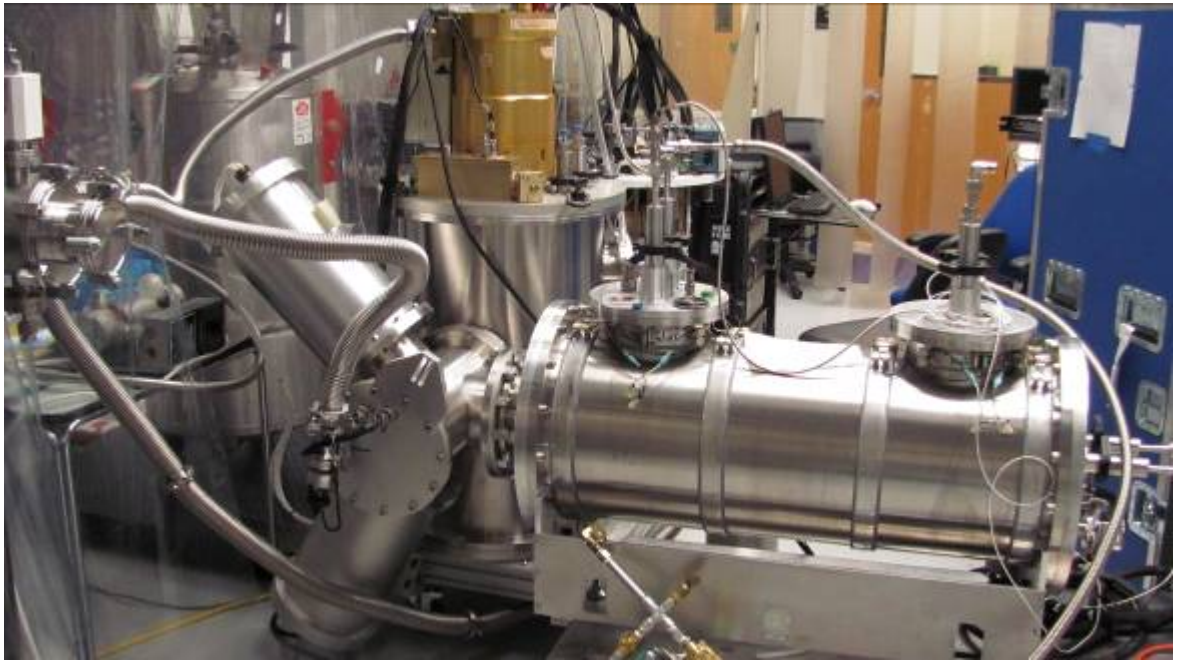
$$R_{Target} = \frac{S_{Target} - S_{CBB}}{\Re} + P(T_{CBB}) \qquad \Re = \frac{S_{WBB} - S_{CBB}}{P(T_{WBB}) - P(T_{CBB})}$$

S_{Target}, S_{WBB}, S_{ABB}: Observed signal from target, warm, and ambient blackbodies
T_{WBB}, T_{CBB}: Temperature of warm and cool 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

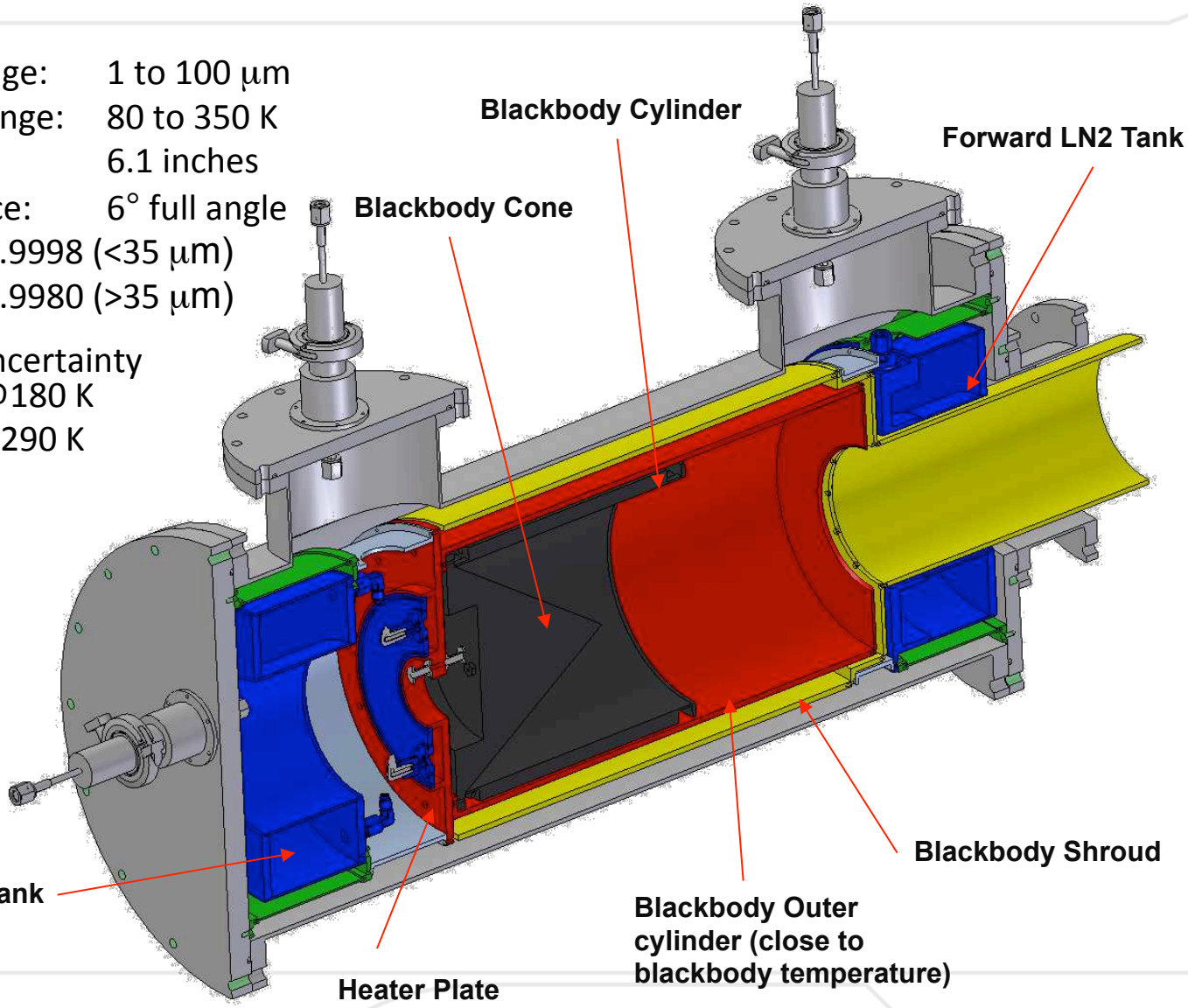
- Calibration data is collected by looking at the warm blackbody, ambient blackbody (or space view simulator), and the LWIRCS (calibrator blackbody)
- FIRST was calibrated in the lab when built in 2005
- Calibrated in 2011 using an ambient blackbody
- Calibrated in 2013 using a space view simulator



LWIRCS – Long Wave Infrared Calibration Source

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

NIST TXR confirms performance to ~150 mK level at 5 and 10 μm

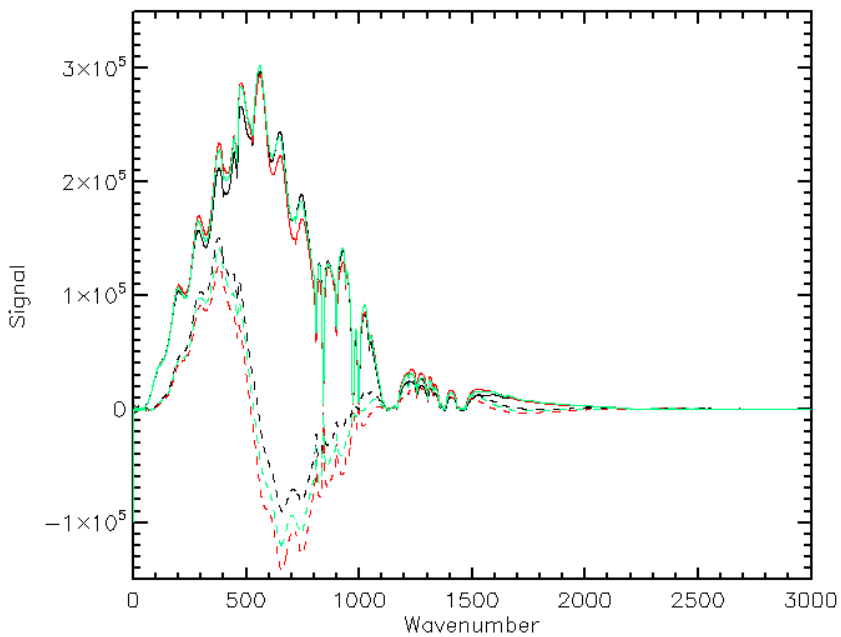


FIRST Response Calibration Data

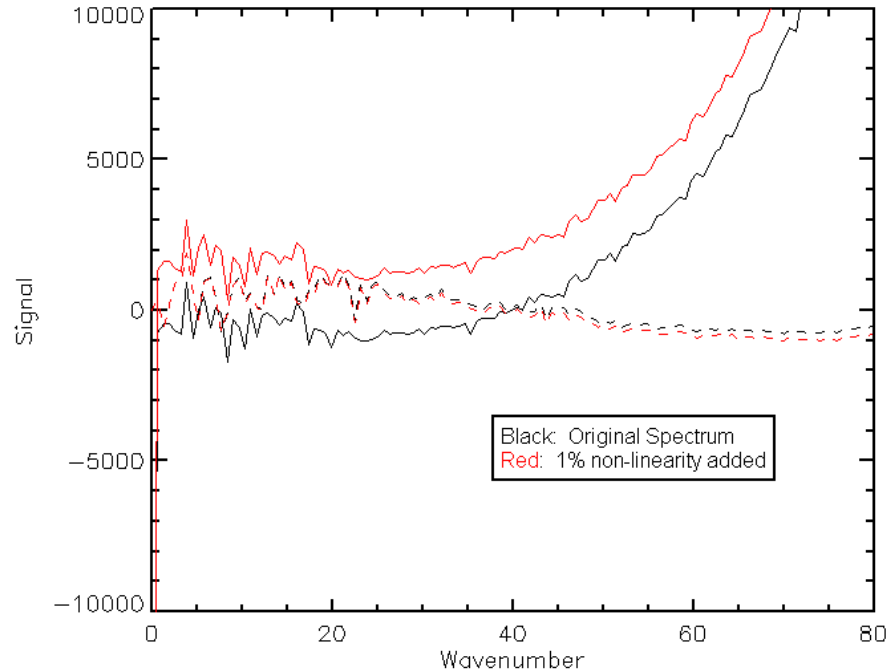
- Collect LWIRCS data at a range of temperatures from 169 to 324 K and compare the LWIRCS temperature to the brightness temperature measured by FIRST
  - Warm BB at ~324.5 K, ambient BB at ~294 K, or SVS at ~77 K
- Process the data from interferograms to spectra, average the spectra by target and scan direction, and finally calibrate the spectra using calibration equation
- Unusual FIRST data processing required for:
  - Hi and low gain channels (needed for 20 bit dynamic range)
  - Vibration effects
  - Phase drift

Non-linearity

- Spectra are complex numbers

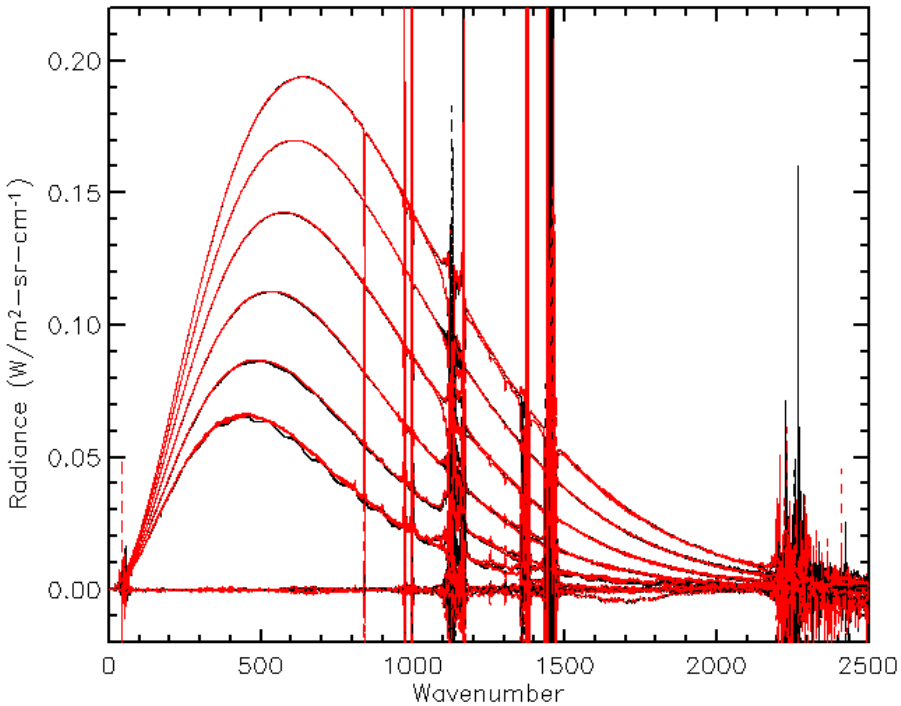


Three average spectra of the WBB in the forward direction from detector 3. The real part is shown by the solid line and the imaginary part is indicated by the dashed line



- Non-linearity is visible at low wavenumber end if present
- Non-linearity no more than ~0.3% in the inteferogram

Calibration with Ambient Blackbody

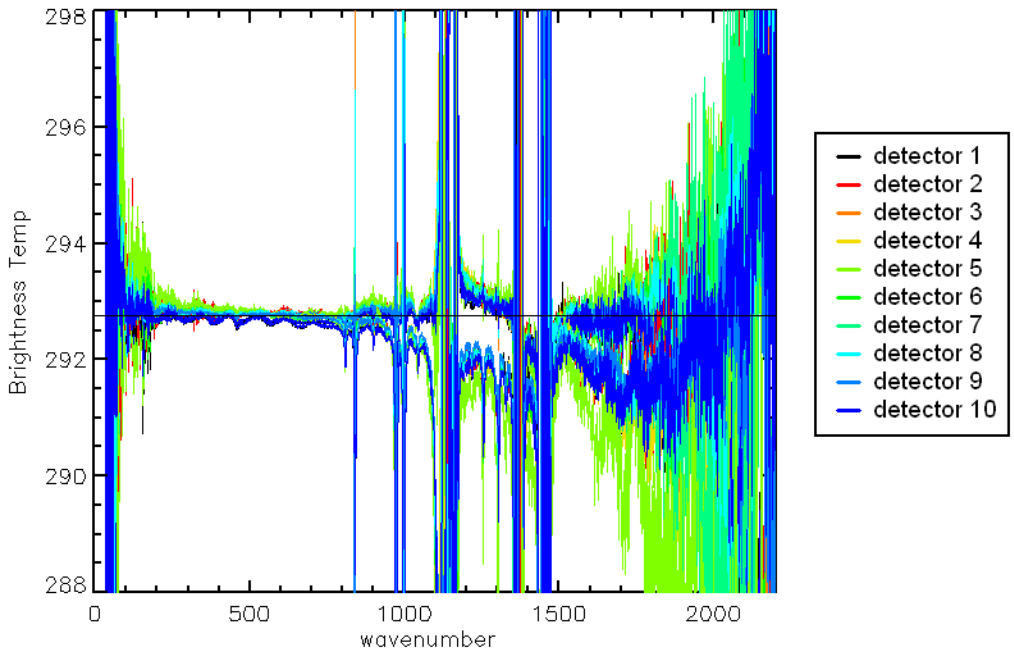


LWIRCS radiance from detectors 1 and 2 for LWRICS at 324, 310, 293, 271, and 225 K

- Calibrated LWIRCS spectra as seen by FIRST
- Look like Planck functions on this scale

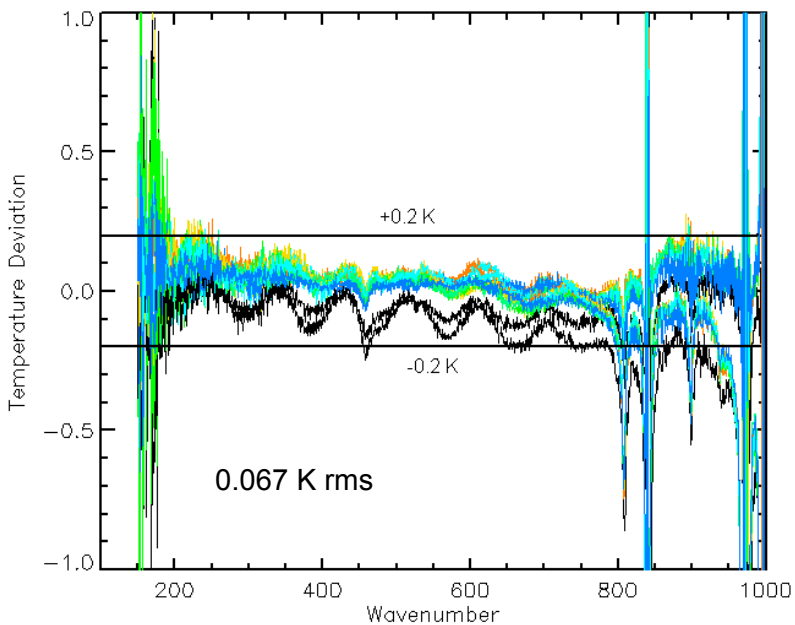
Calibration Results at 292.76 K

- LWIRCS at room temperature
  - Directly compares LWIRCS, ABB temp sensors
- Brightness temperature within 0.2 K of LWIRCS sensors 200 to 1000 cm^{-1}



LWIRCS brightness temperature at 292.76 K

- Vibration noise above 900 cm^{-1}
  - Different for two scan directions
  - Same for all detectors
- ABB, LWIRCS temp sensors within 0.1 K of each other

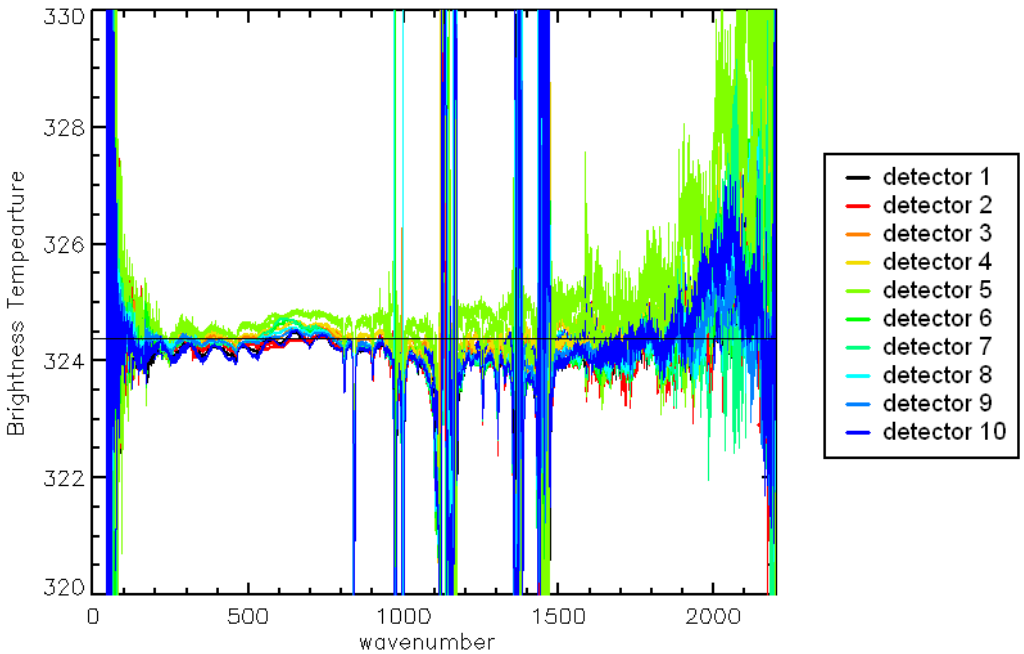


LWIRCS temperature deviation excluding detectors 2, 5 and 10

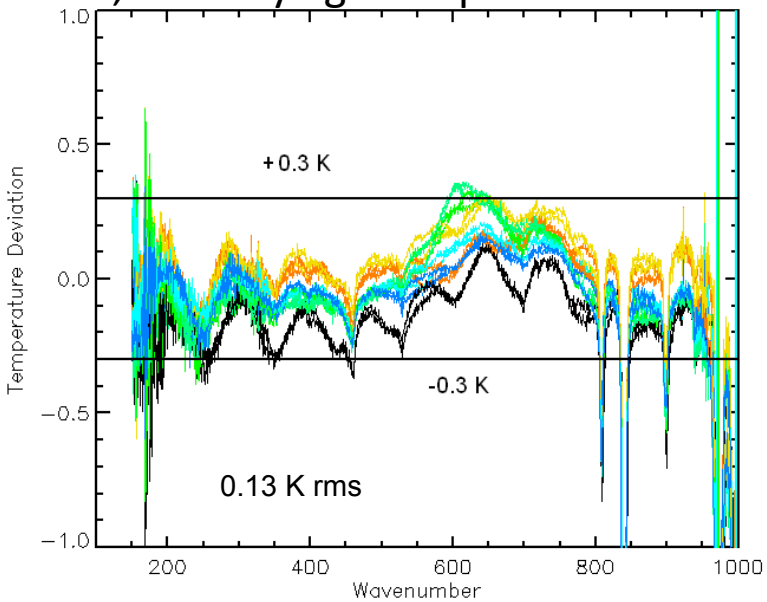
Calibration Results at 324.38 K

- LWIRCS at WBB temperature
- Brightness temperature within 0.3 K of LWIRCS sensors
- LWIRCS and WBB agree to within 0.1 K

- Noise mainly systematic
  - Same in both scan directions
  - Less vibration here
- Exclude detectors 2, 5, 10
  - 2,10 some excess noise
  - 5, 10 stray light response



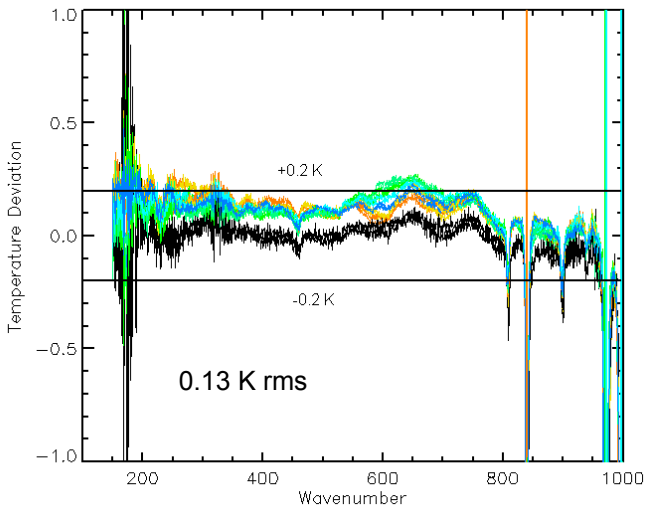
LWIRCS brightness temperature at 324.38 K

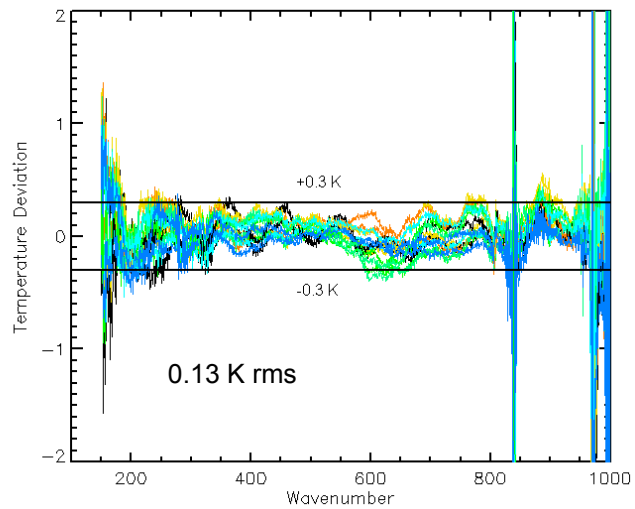


LWIRCS temperature deviation excluding detectors 2, 5, and 10

More Calibration Results

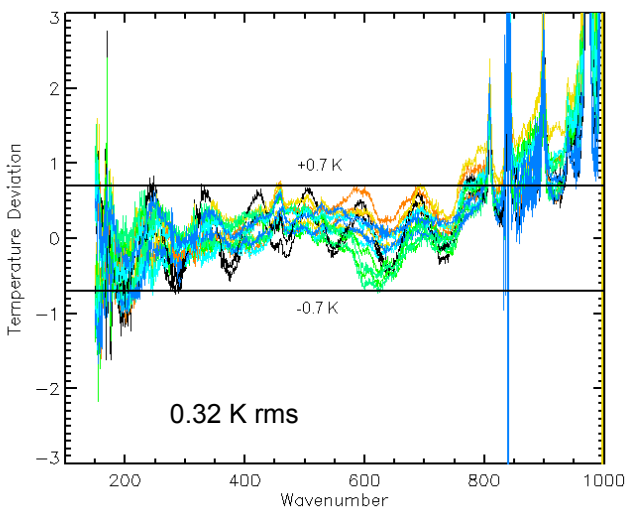
LWIRCS temperature deviation 310.34 K

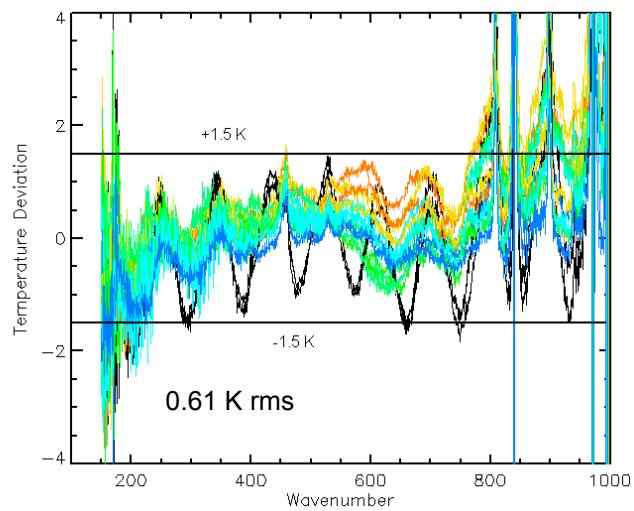




LWIRCS temperature deviation 270.55 K

LWIRCS temperature deviation 247.42 K

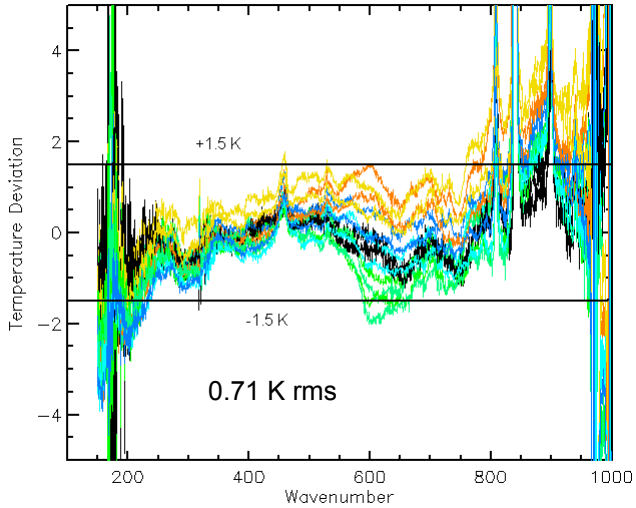


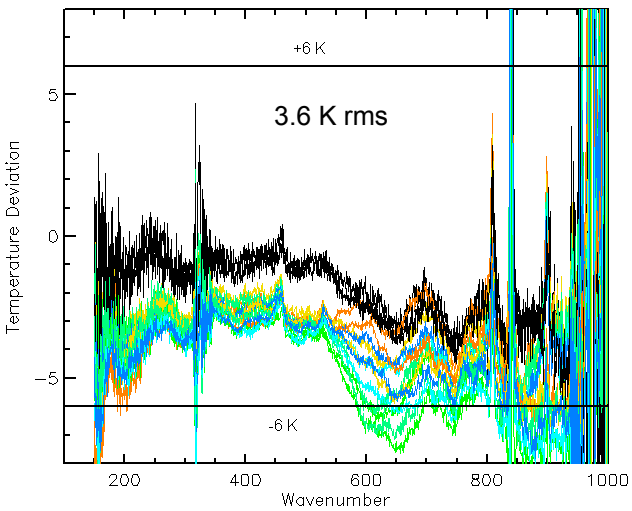


LWIRCS temperature deviation 225.18 K

More Calibration Results

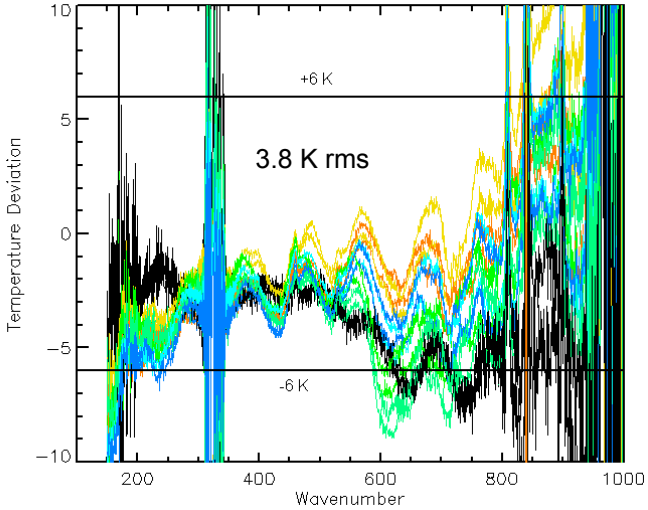
LWIRCS temperature deviation 209.41 K





LWIRCS temperature deviation 189.33 K

LWIRCS temperature deviation 169.06 K



- Noise increases with falling temperature, reduces high end of range
- Deviations larger below 200 K
- Deviations mainly systematic

Error Propagation Effects

- Error from ABB, WBB spectra propagate into errors in target spectra
  - Amount rises significantly with temperature

Target Temp	200 cm^{-1}	500 cm^{-1}	800 cm^{-1}
225 K	0.9 K	1.1 K	1.4 K
169 K	1.7 K	2.7 K	5.4 K

Propagated error in target assuming
324.5 K WBB with 0.3 K error
293 K ABB with 0.2 K error

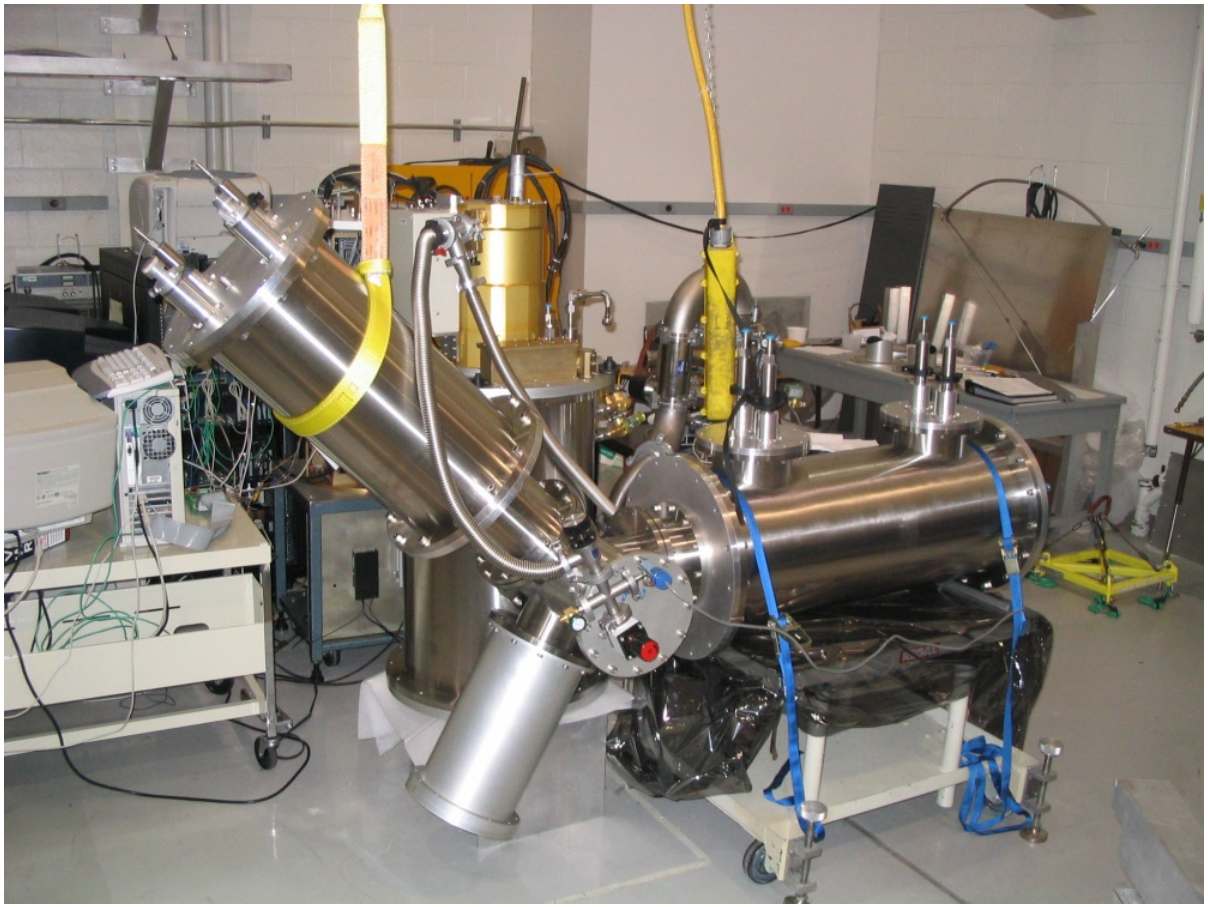
- Increased low temperature deviation is an effect of error propagation when extrapolating calibration outside of blackbody temperatures

Calibration Results with Ambient Blackbody

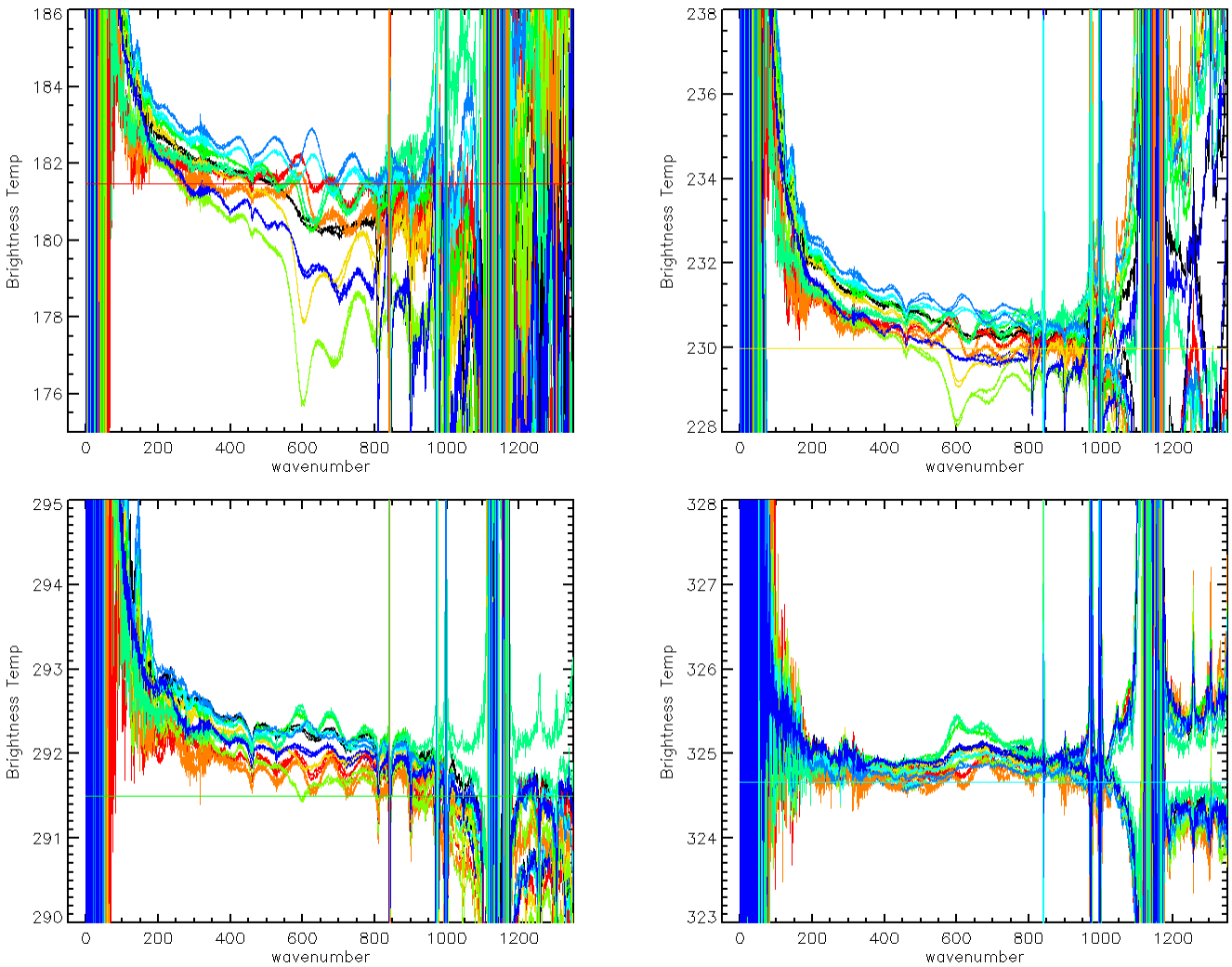
- FIRST absolute accuracy: 1.5 K or better (peak deviation) for temperatures >200 K from 200 to 800 cm^{-1}
- From 270 to 330 K (near ABB, WBB temperatures), FIRST meets design accuracy goals
  - 0.2 K (k=1) 170 to 1000 cm^{-1}
- No additional corrections to calibration equation
  - ABB, WBB consistent with LWIRCS
  - No clear non-linearity observed here
- Observed deviations are systematic
  - Stray light found to be an error source
  - Some evidence stray light varies with vacuum cycle
- Error propagation increases uncertainty away from blackbody temperatures

2013 Calibration

- Calibrate using warm blackbody (324.5 K) and space view simulator (77 K)



Some Temperature Deviations

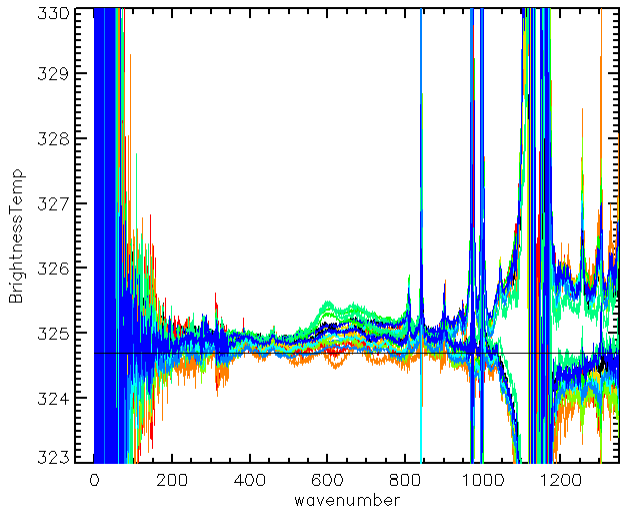


Significant, highly systematic deviations

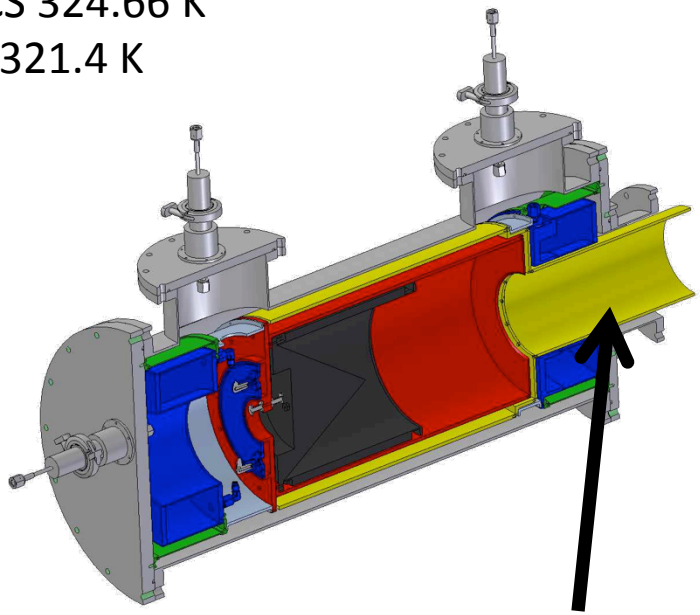
Detector 2 always within 1K

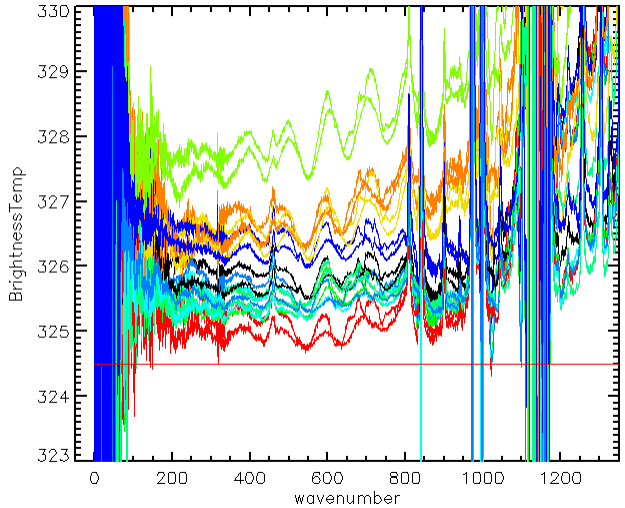
Results repeatable to 0.2K (peak deviation) after days

Stray Light



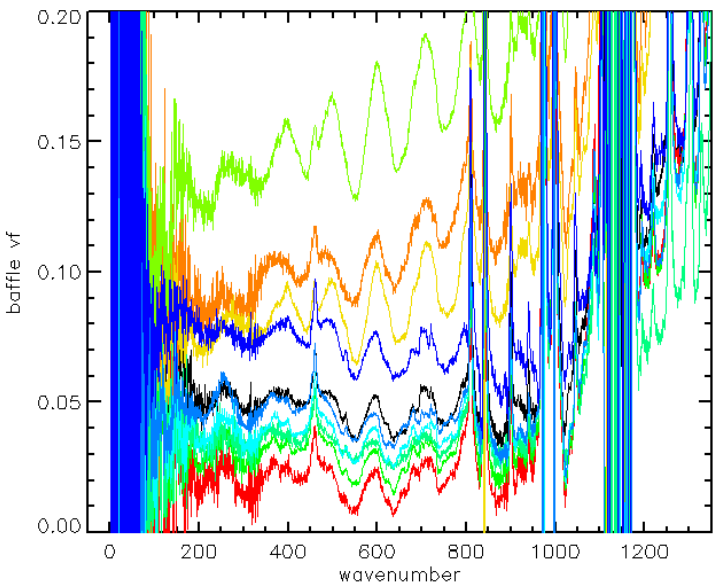
LWIRCS 324.66 K
baffle 321.4 K



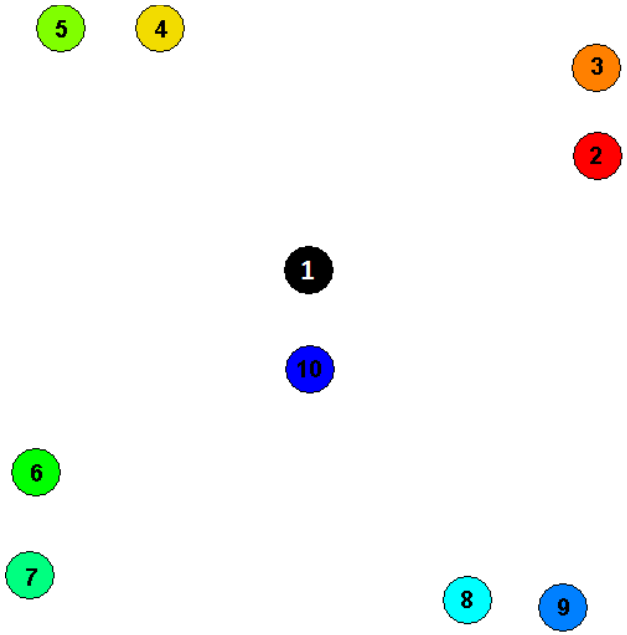


LWIRCS 324.49 K
baffle 341.8 K

Baffle View Fraction



View fraction of baffle by detector



Detector pattern at focal plane

- The LWIRCS baffle is normally kept at LWIRCS temperature for data collections, but stray light will affect the view of other blackbodies

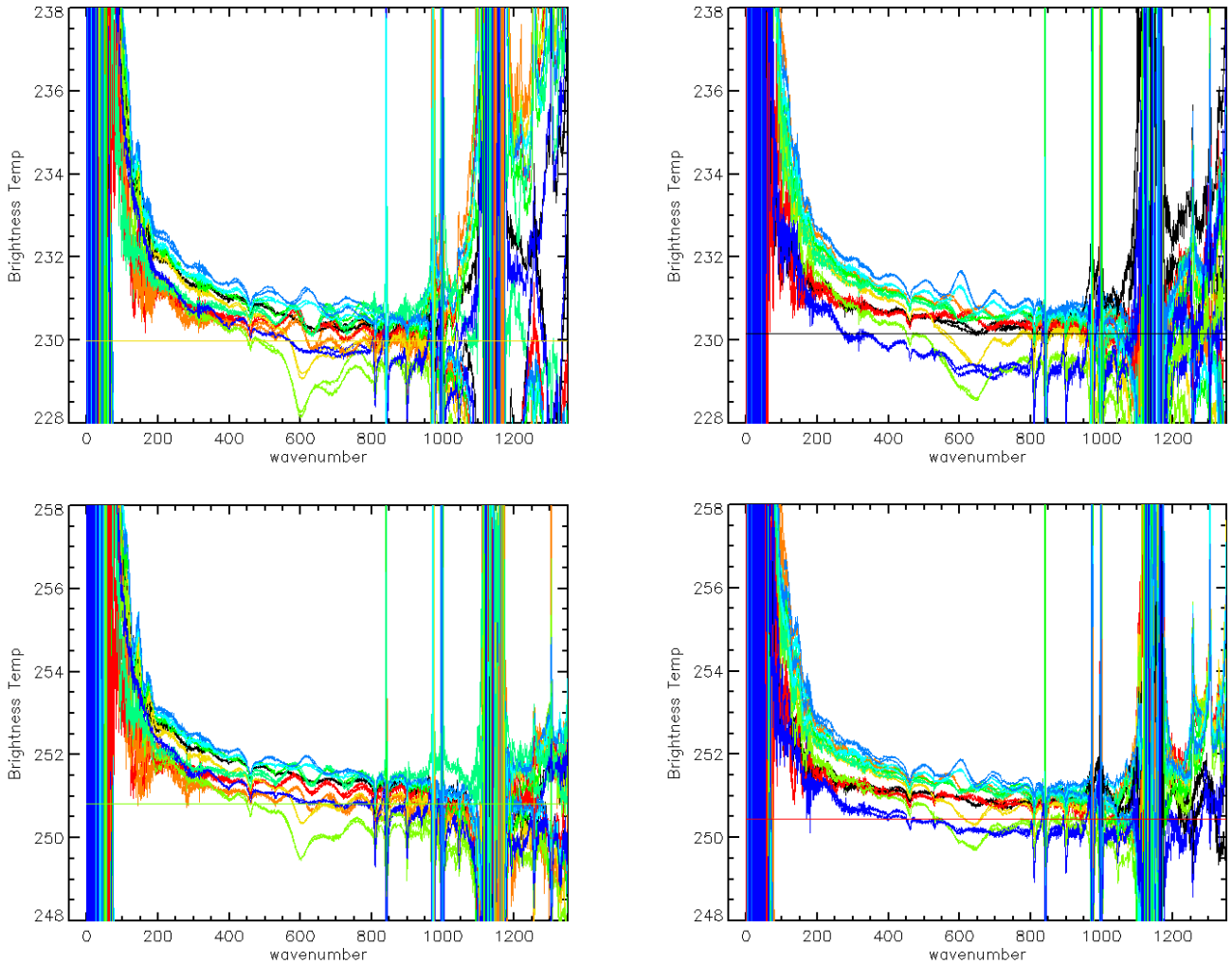
Variation with Vacuum Cycle Confirmed

LWIRCS at ~230, 251 K

Left: Originals

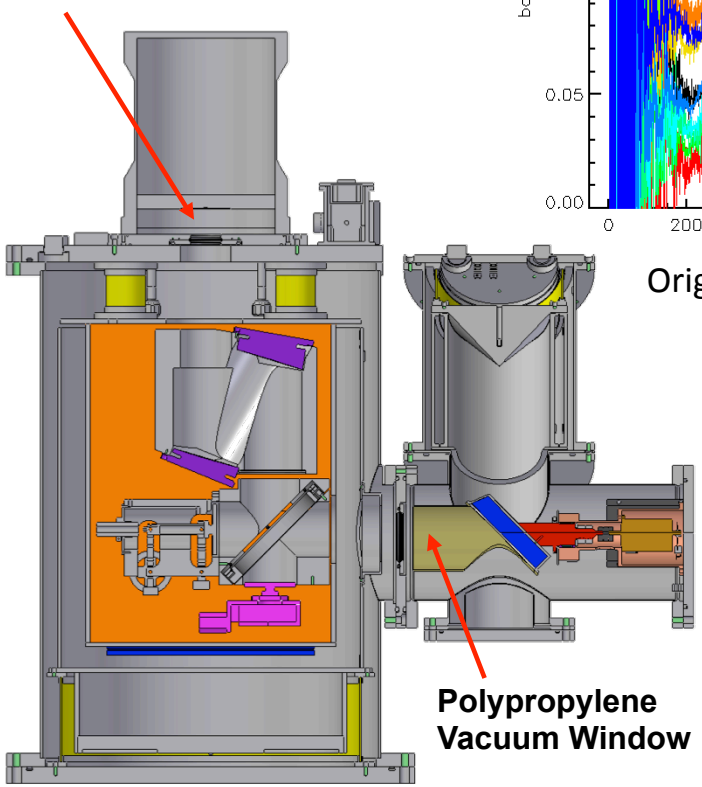
Right: After FIRST at ½ atmosphere for 2 days then re-pumped

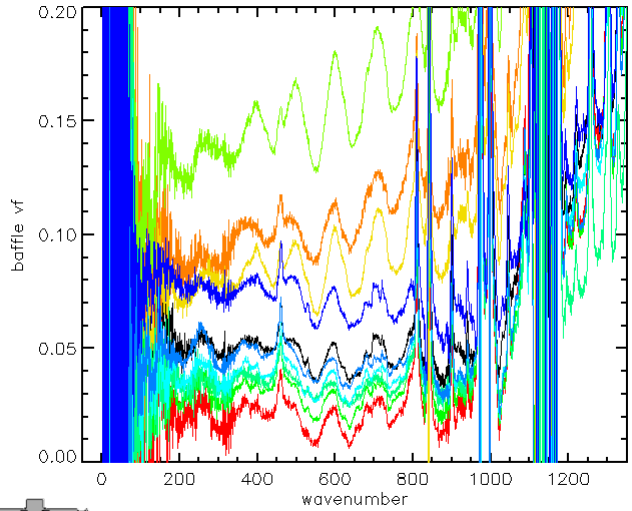
Deviations change



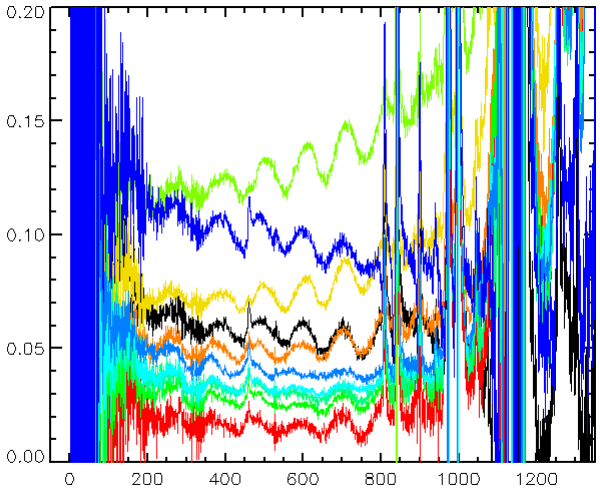
Window Effects

- Baffle view fractions changes





Original (from previous slide)

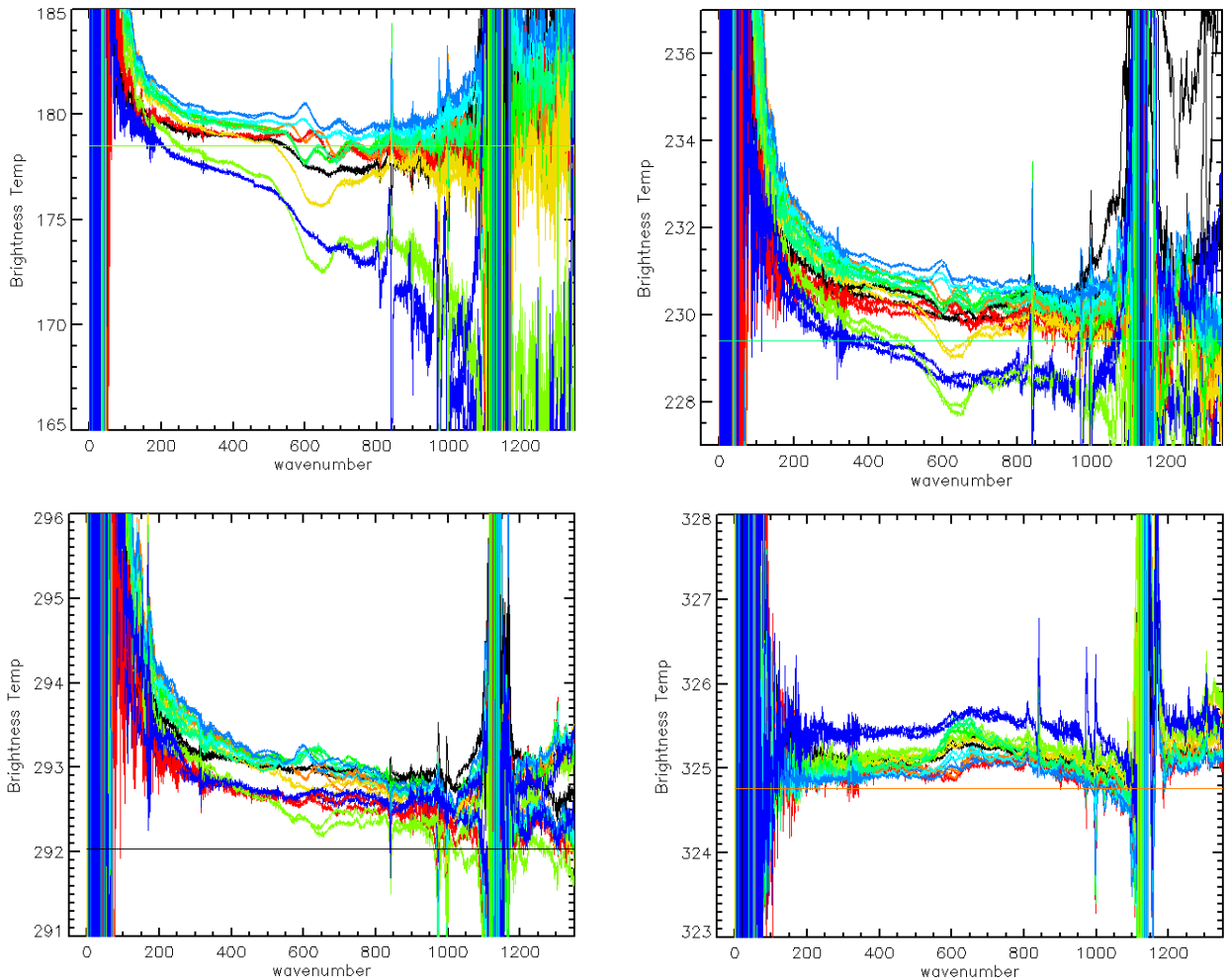


After vacuum cycled

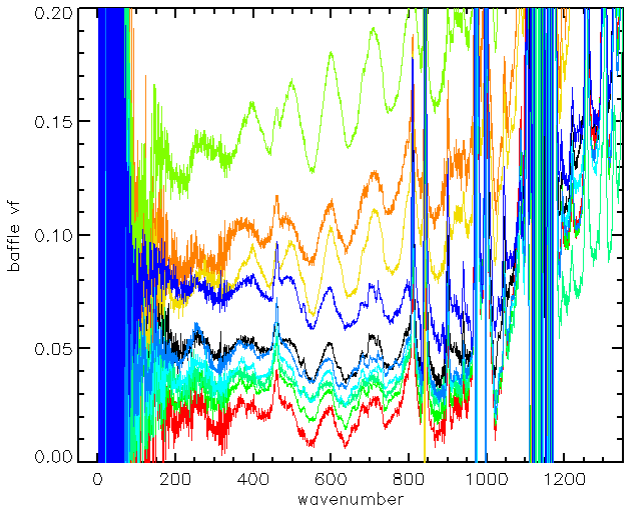
- Window changes shape with each vacuum cycle and window shape directs beam

Windowless Data

- Removed vacuum window between interferometer and SSA
- Still have significant systematic deviations
- Fewer wiggles
- Detector 2 still within 1 K



Windowless Baffle View Fraction



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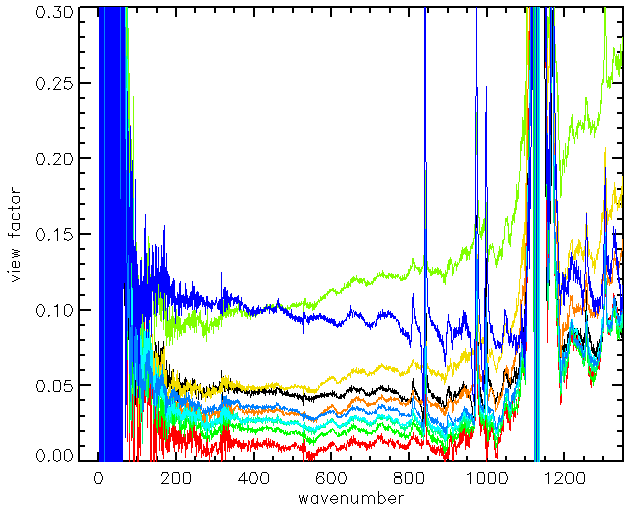


Without window

- The baffle view fraction improves without the window, but will still allow stray light

FIRST Calibration Equation with Stray Light

- Correcting for stray light

Ideal calibration equation, P's are BB radiances, S's are measured spectra

$$P_L = S_L - S_C / S_W - S_C \; (P_W - P_C) + P_C$$

With a view factor of $f_?$ of contaminating radiance $R_?$ for each blackbody

$$x \stackrel{\text{def}}{=} S_L - S_C / S_W$$

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

Re-arrange

$$P_L = x(P_W - P_C + R_1) + P_C + R_2$$

$$R_1 = 1/1 - f_L \; ((f_L - f_W) P_W + f_W R_W - (f_L - f_C) P_C - f_C R_C)$$

$$R_2 = 1/1 - f_L \; ((f_L - f_C) P_C + f_C R_C - f_L R_L)$$

R_1 and R_2 are constant

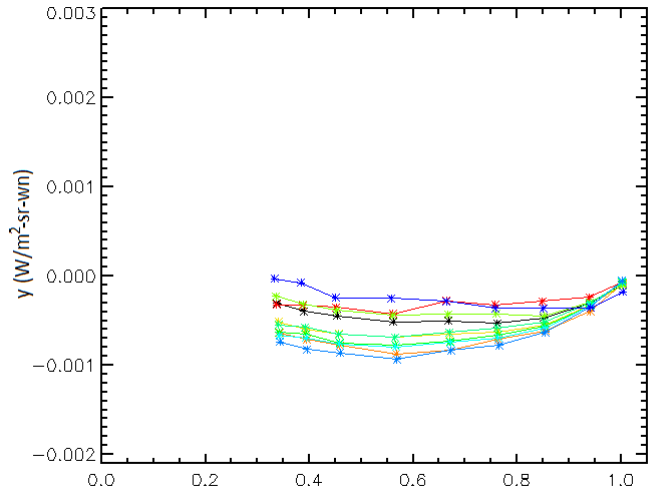
$$P_L - P_C - x(P_W - P_C) \stackrel{\text{def}}{=} y = x R_1 + R_2$$

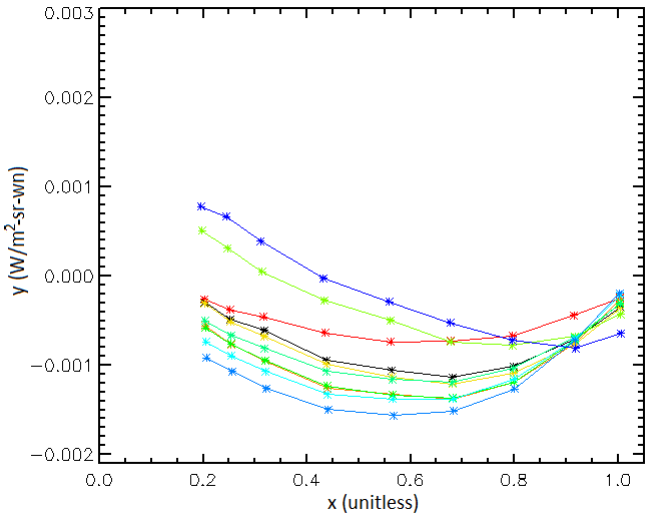
This should be a line that can be fit for R_1 and R_2

R_1 and R_2 can then be used to correct the data

X vs. Y without Window

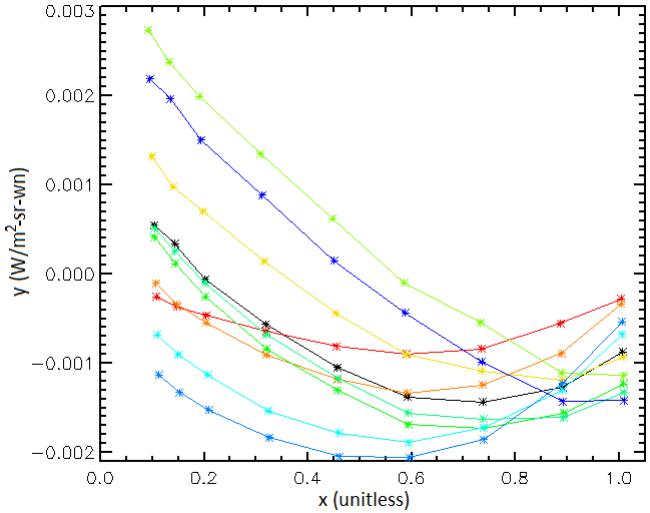
200 cm^{-1}





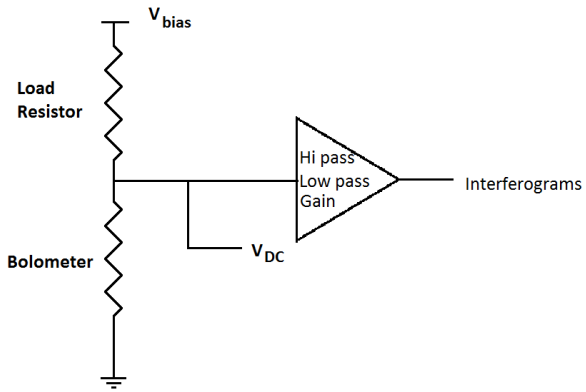
400 cm^{-1}

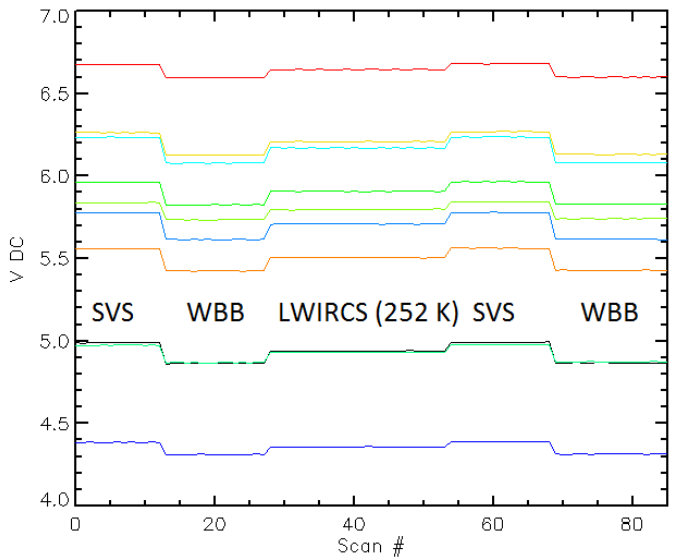
600 cm^{-1}



- These are not lines
- The curvature looks like non-linearity, but to produce the observed curvature requires several % non-linearity in the interferograms and this was not observed

Another Type of Non-linearity

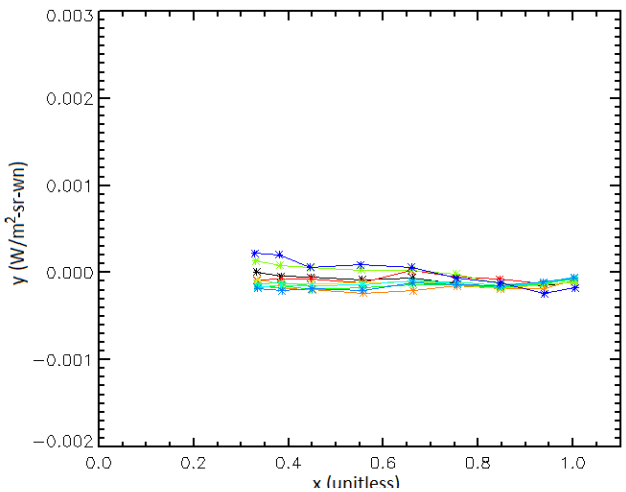


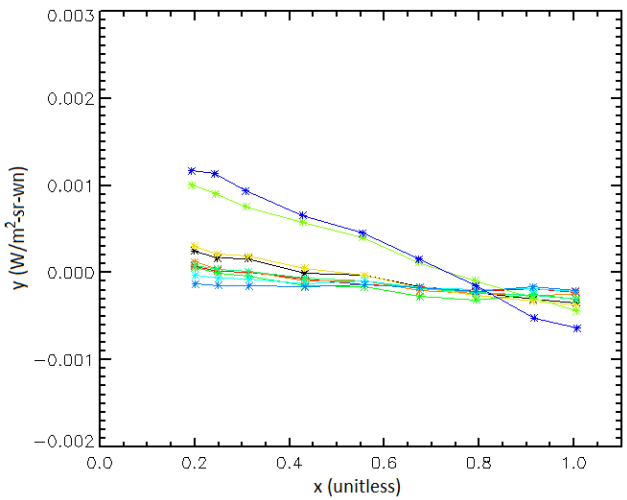


- The detector DC voltage level varies with the target
- Detector response: $\propto R_{Det} \propto V_{DC}$
- Unusual non-linearity: The interferogram is linear but the gain is $\propto V_{DC}$

X vs. Y with Correction

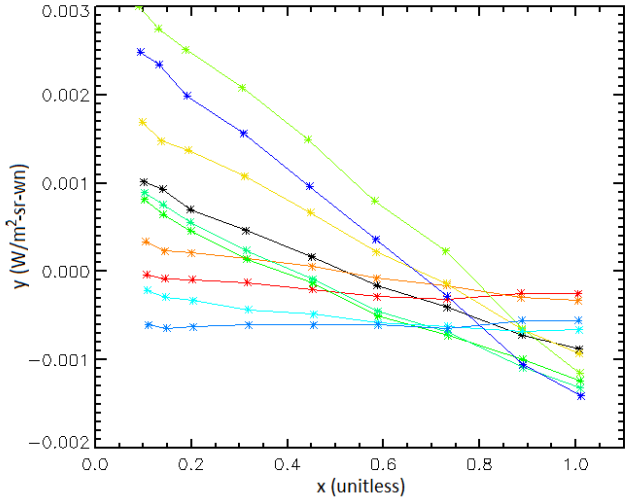
200 cm^{-1}





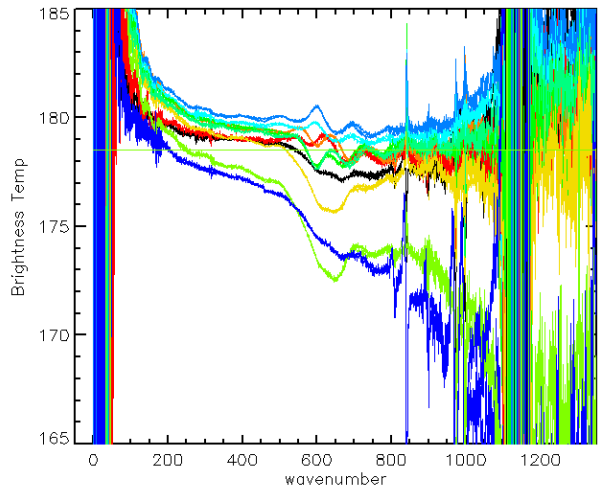
400 cm^{-1}

600 cm^{-1}



- Applied correction from response $\propto V_{DC}$
  - No free parameters
- These are lines
  - Near zero for detectors with little stray light

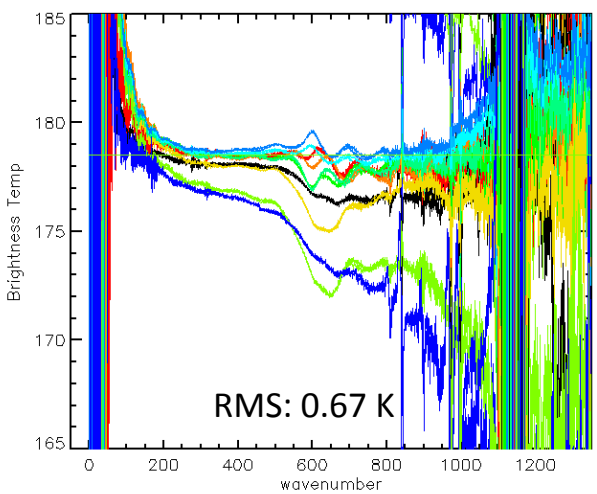
179 K Windowless Data Set

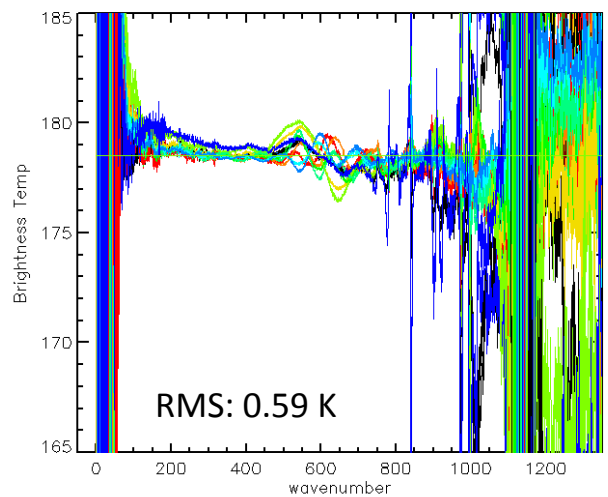


Left: Without non-linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

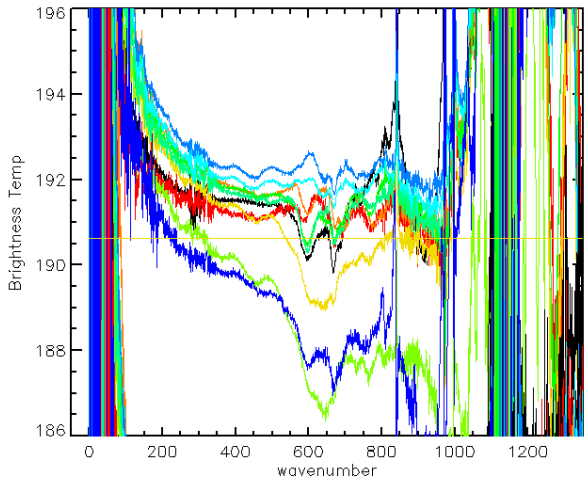
Linearity correction alone significantly improves deviation

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

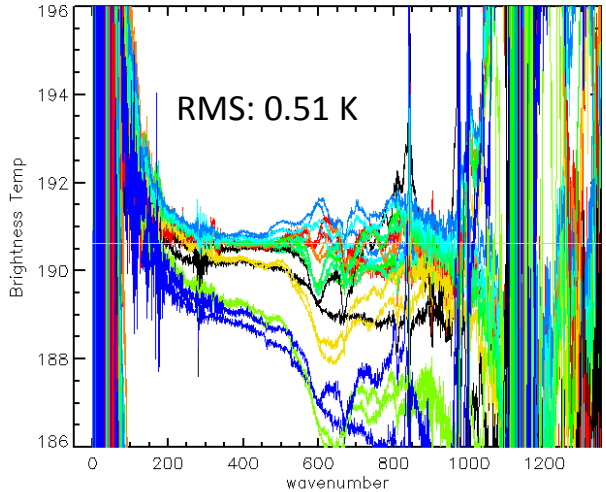


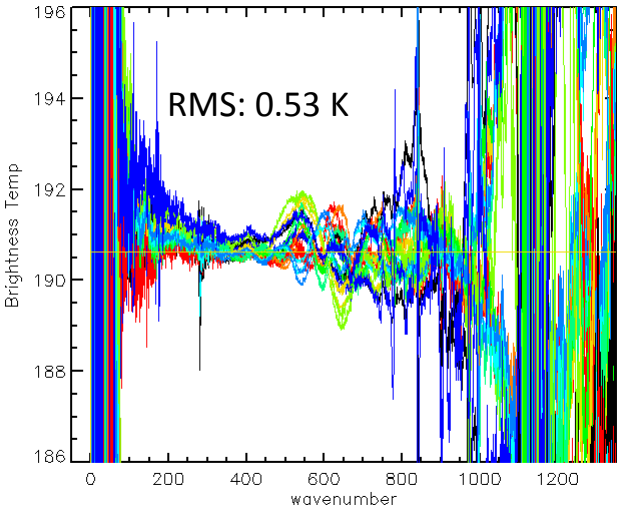


191 K Windowless Data Set

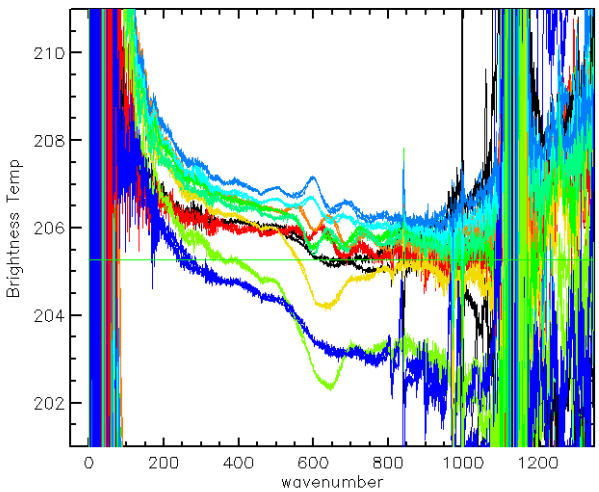


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

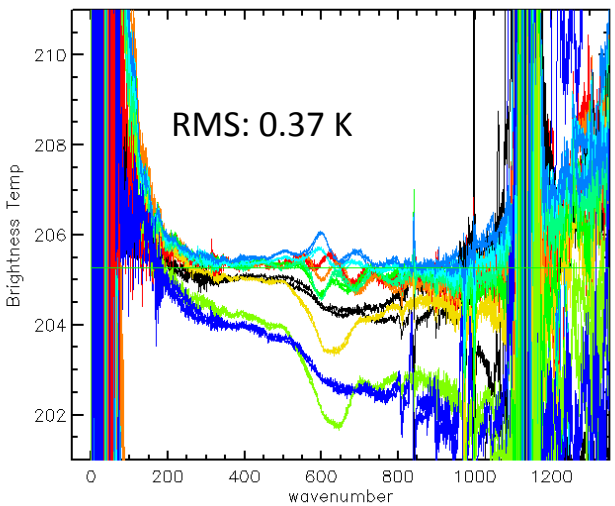


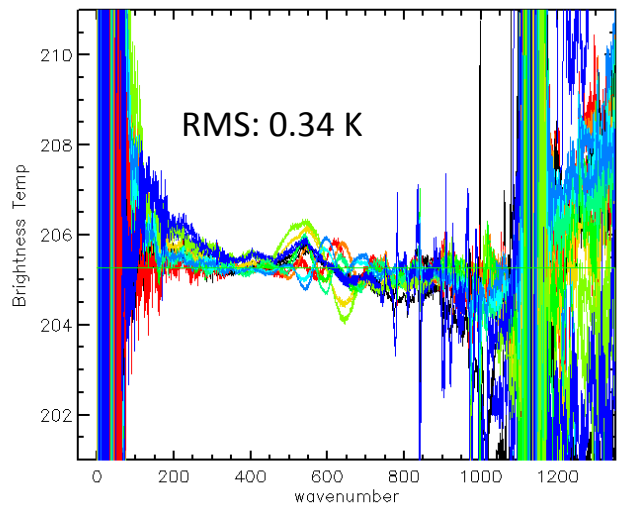


205 K Windowless Data Set

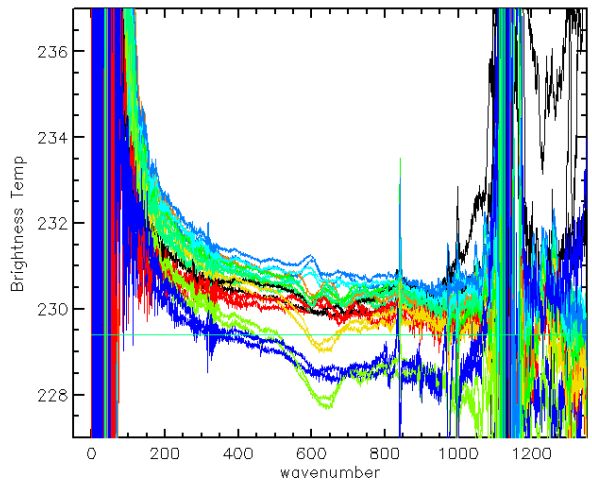


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

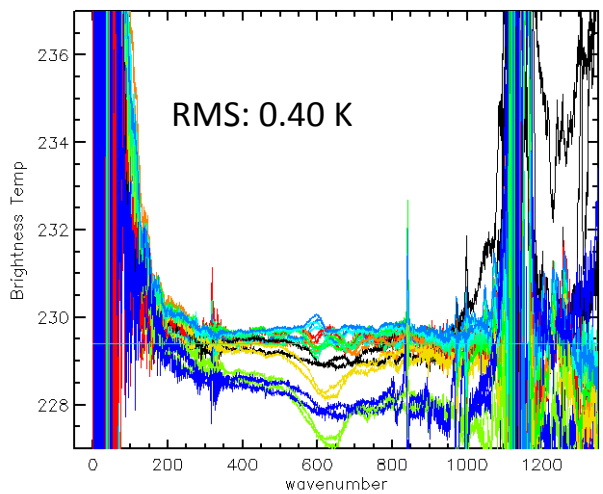


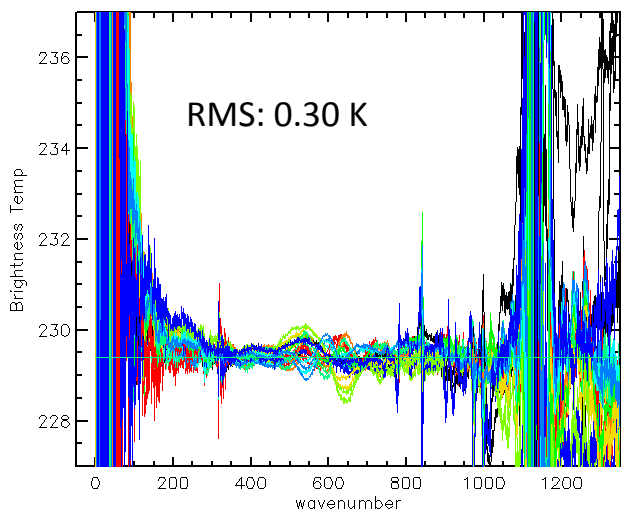


229 K Windowless Data Set

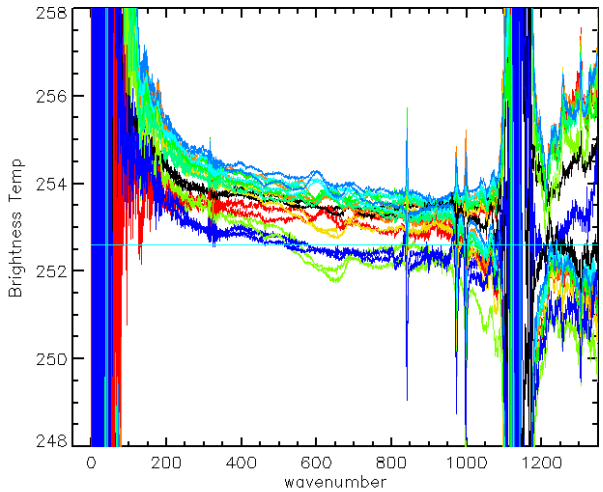


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

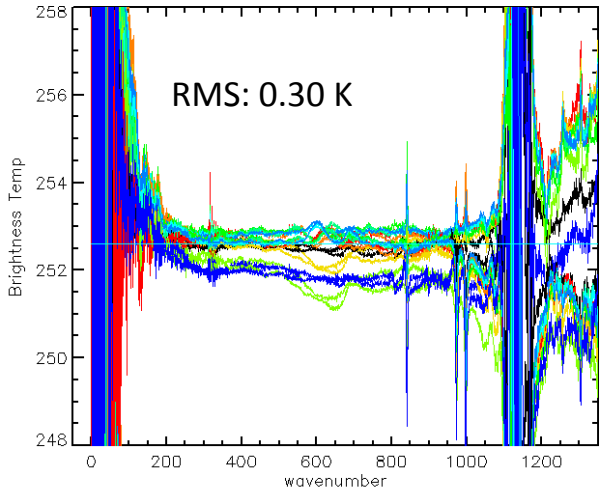


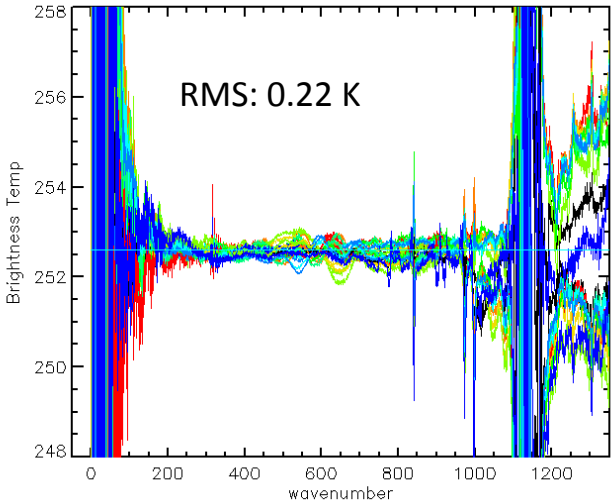


253 K Windowless Data Set

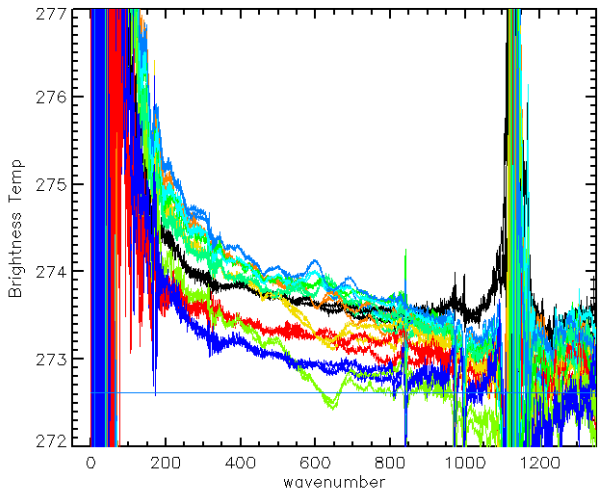


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

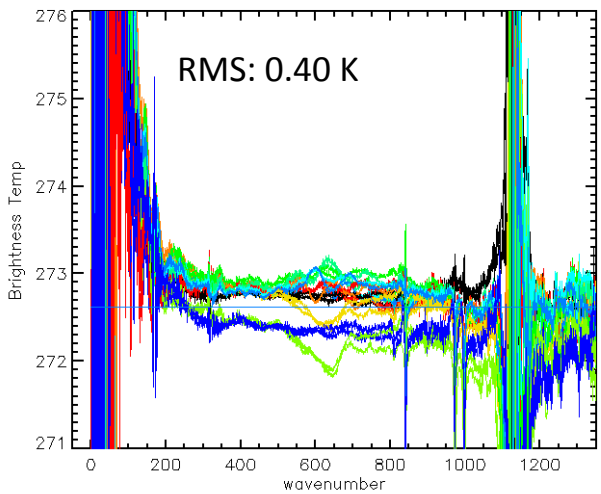


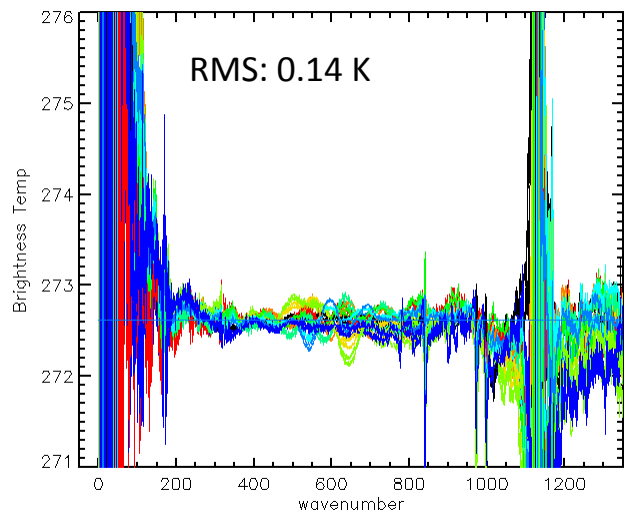


273 K Windowless Data Set

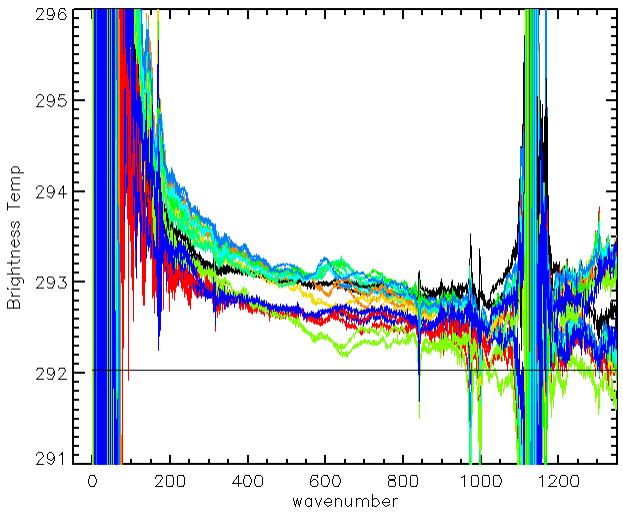


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

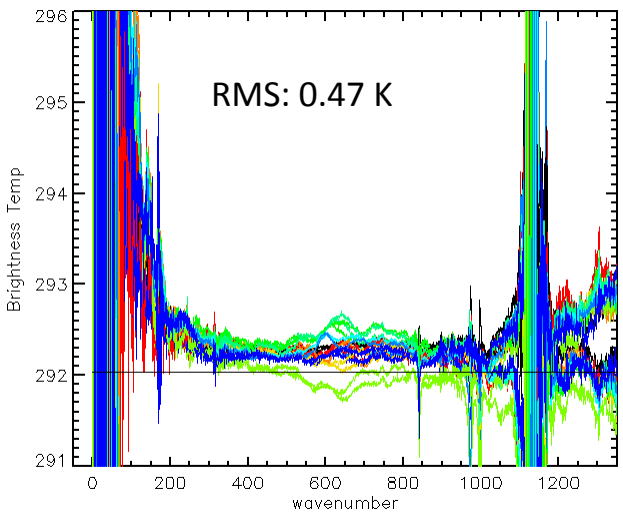


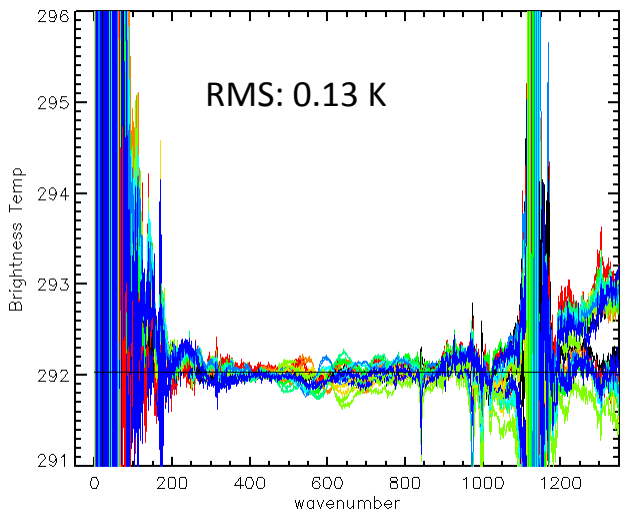


292 K Windowless Data Set

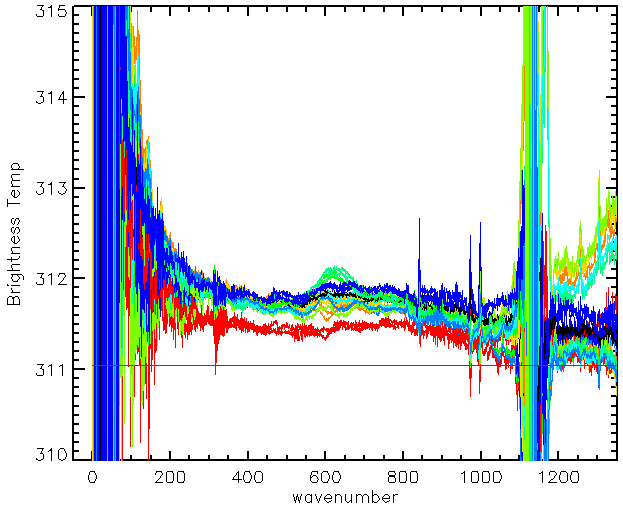


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

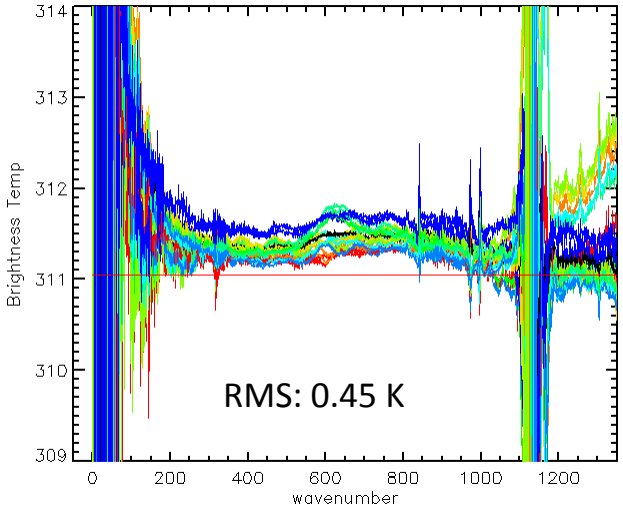


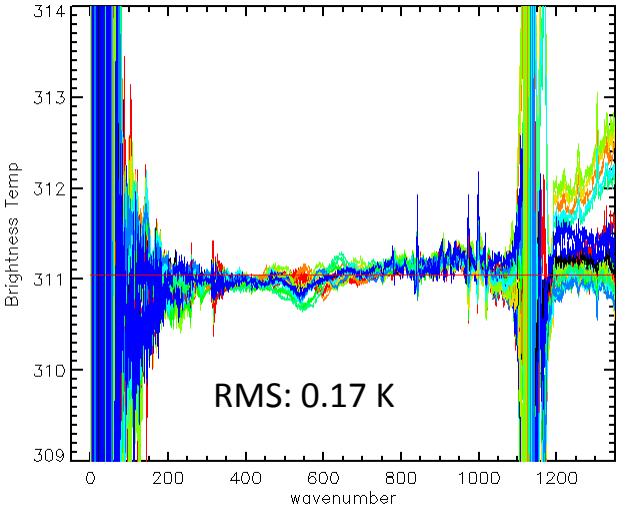


311 K Windowless Data Set

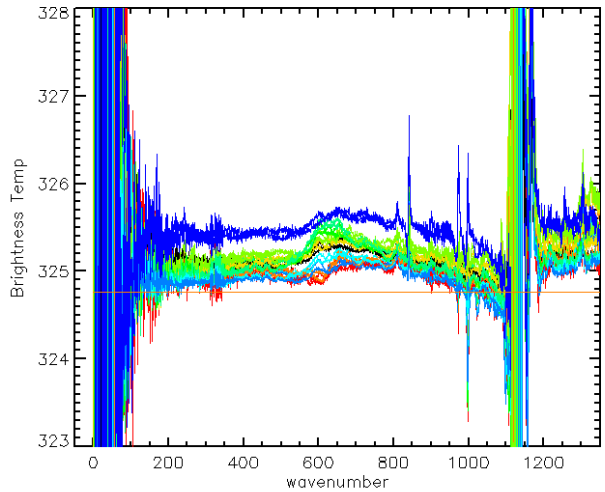


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction

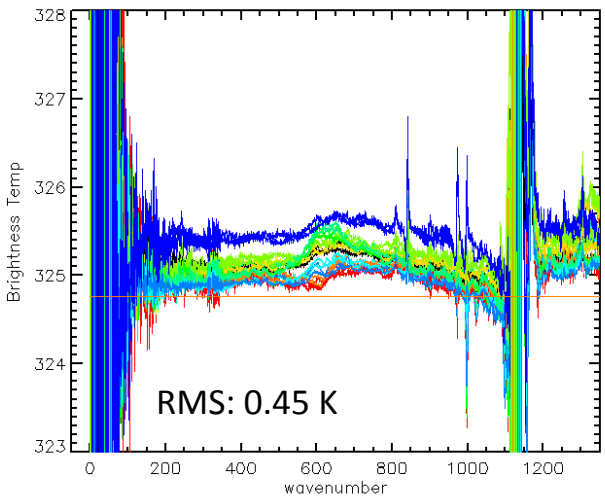


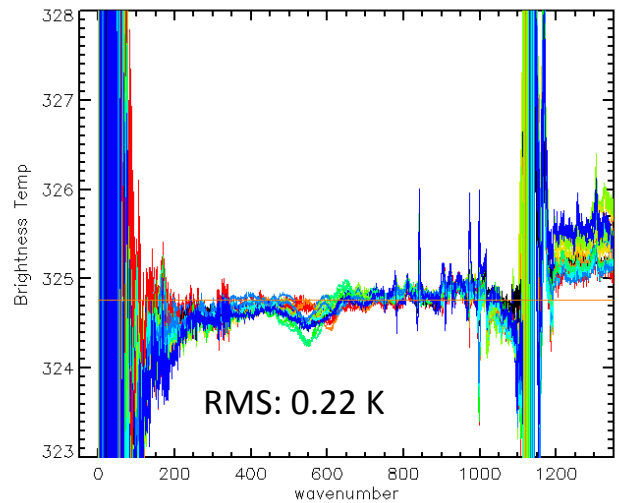


325 K Windowless Data Set

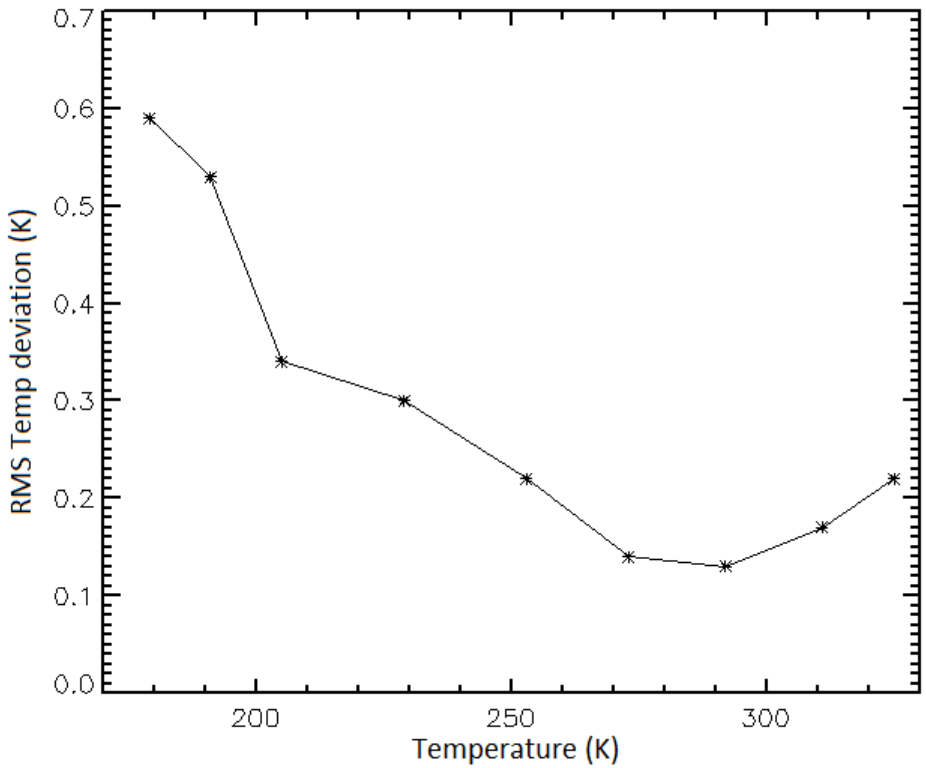


Left: Without linearity correction
Bottom left: With non-linearity correction
Bottom right: With stray light and non-linearity correction





RMS Deviation vs. Temperature



- RMS deviation vs. temperature for all detectors except 5 and 10
- No window, non-linearity, and stray light corrections applied

Conclusions

- FIRST is highly accurate
  - Ground-up mode: 0.1 to 0.7 K (rms) for T>200 K, 200 to 800 cm^{-1}
  - Balloon mode: 0.3 K to 0.7 K for T>180 K, 200 to 800 cm^{-1}
  - If stray light is fixed, the expected accuracy will improve
- FIRST has stray light
  - Limits accuracy, even with stray light correction
  - Some detectors are better than others
  - Windows are a cause
  - Stray light can be fixed
- FIRST requires a non-linearity correction
  - Apparent in calibration using a cold blackbody due to the large radiance difference between blackbodies
  - Gain varies with interferogram DC level
  - Can show from the bolometer response equation that it is possible to have gain $\propto$ DC level with little non-linearity in the FIRST interferogram