Absolute Radiance Recalibration of FIRST using a Cold Blackbody

Harri Latvakoski[1], David Johnson[2], Martin Mlynczak[2], and Rich Cageao[2]

[1]Space Dynamics Lab

[2]NASA Langley Research Center

Outline

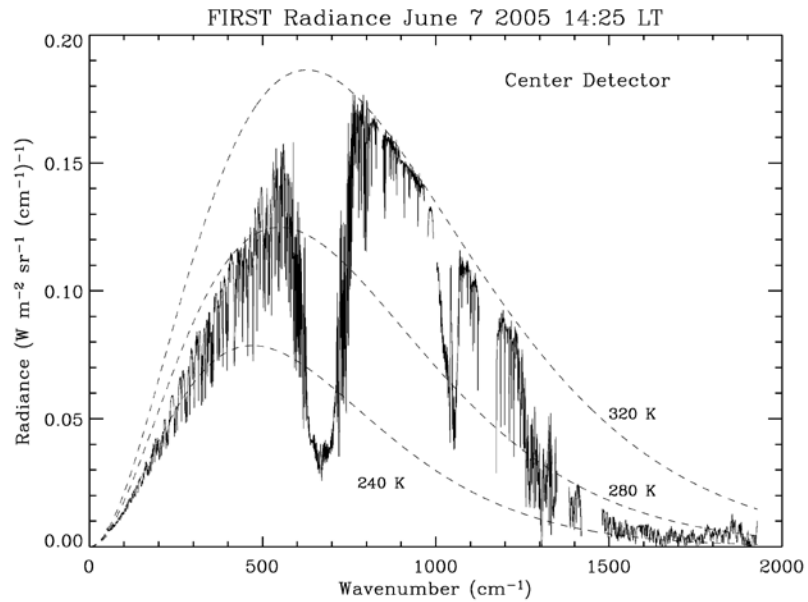
- FIRST
- FIRST calibration
- Previous calibration results
- New absolute radiance response calibration

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})

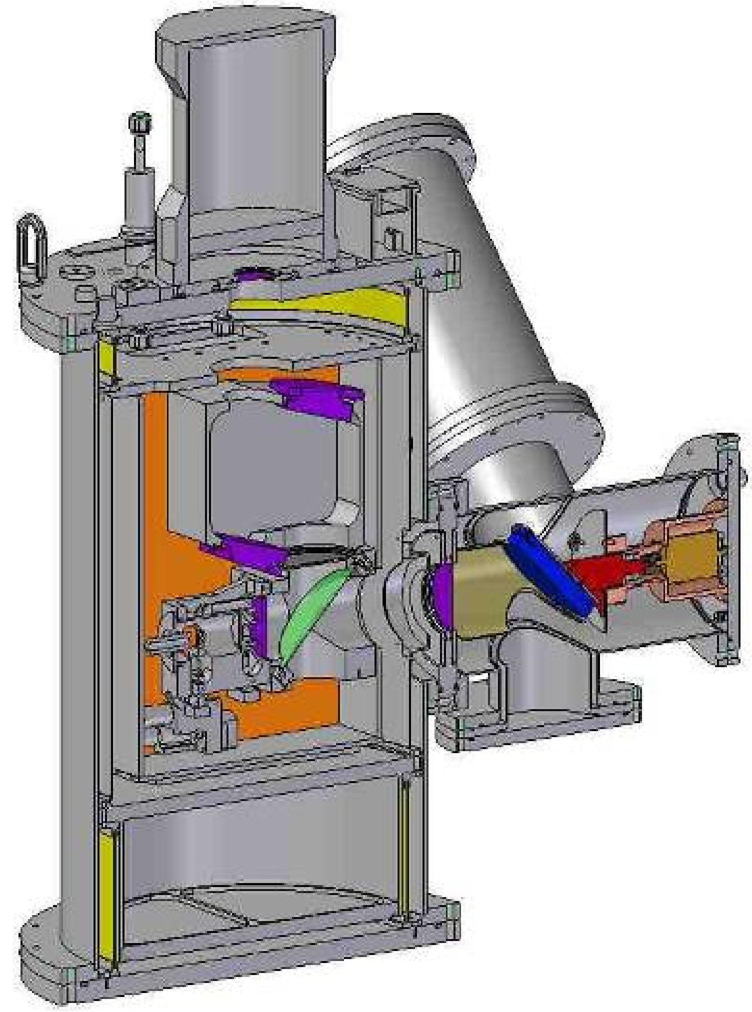
- Contains half of Earth's outgoing long-wave radiation
- Is not well observed spectrally



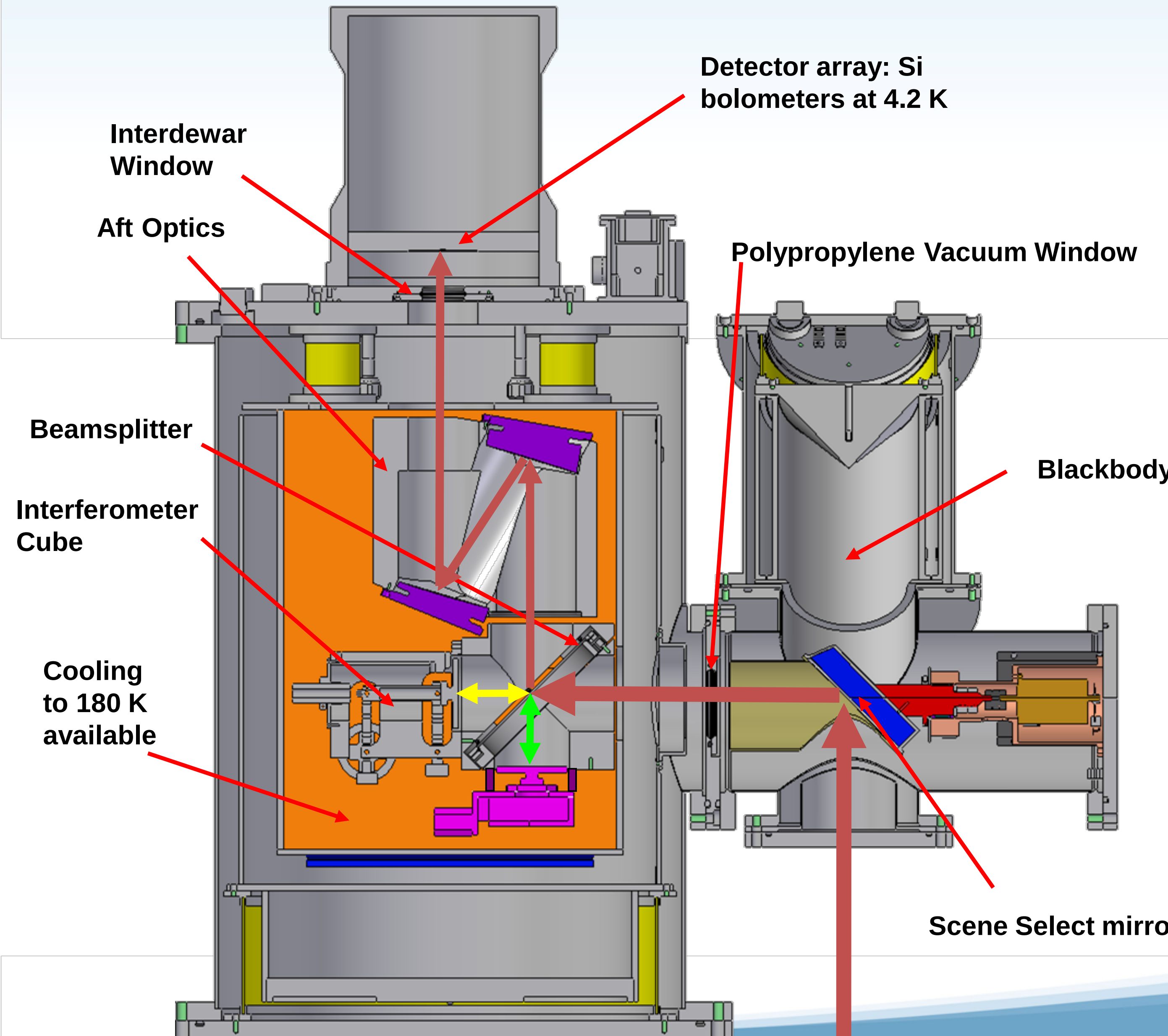
FIRST spectrum from high altitude balloon

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)
- 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 SSA 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

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

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

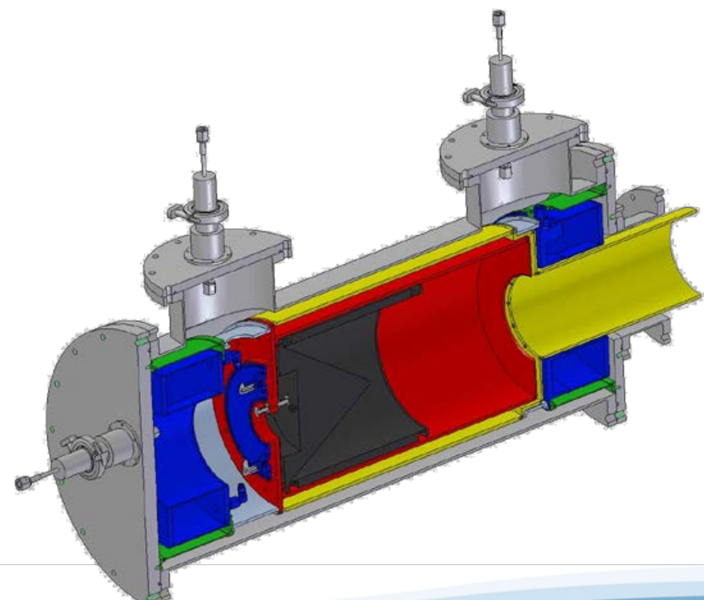
- Used to calculate target radiance
- Warm, Ambient blackbodies used for ground data
- Warm blackbody, space view used for balloon data
- Forward and backward scans are calibrated independently

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)

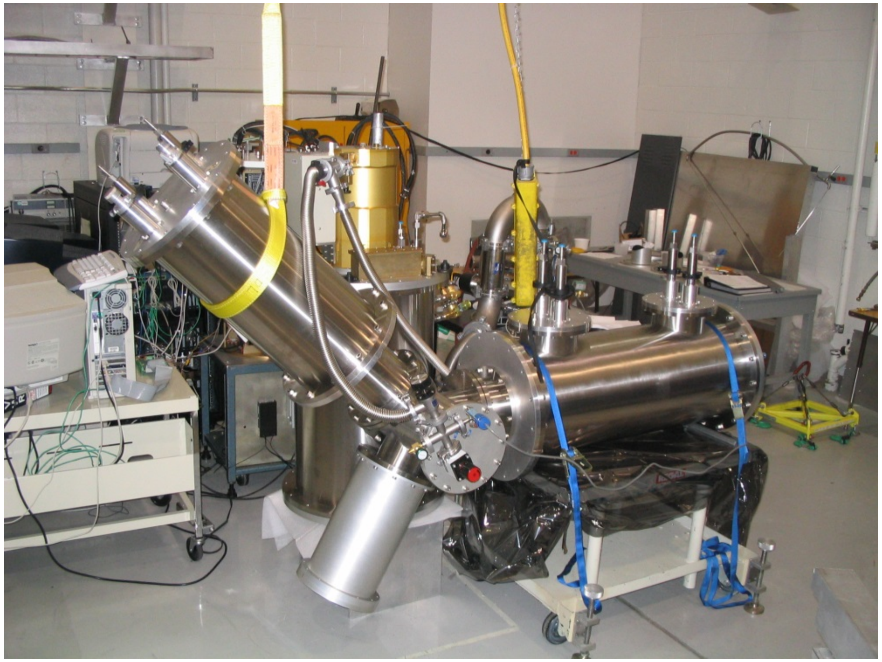


Previous results

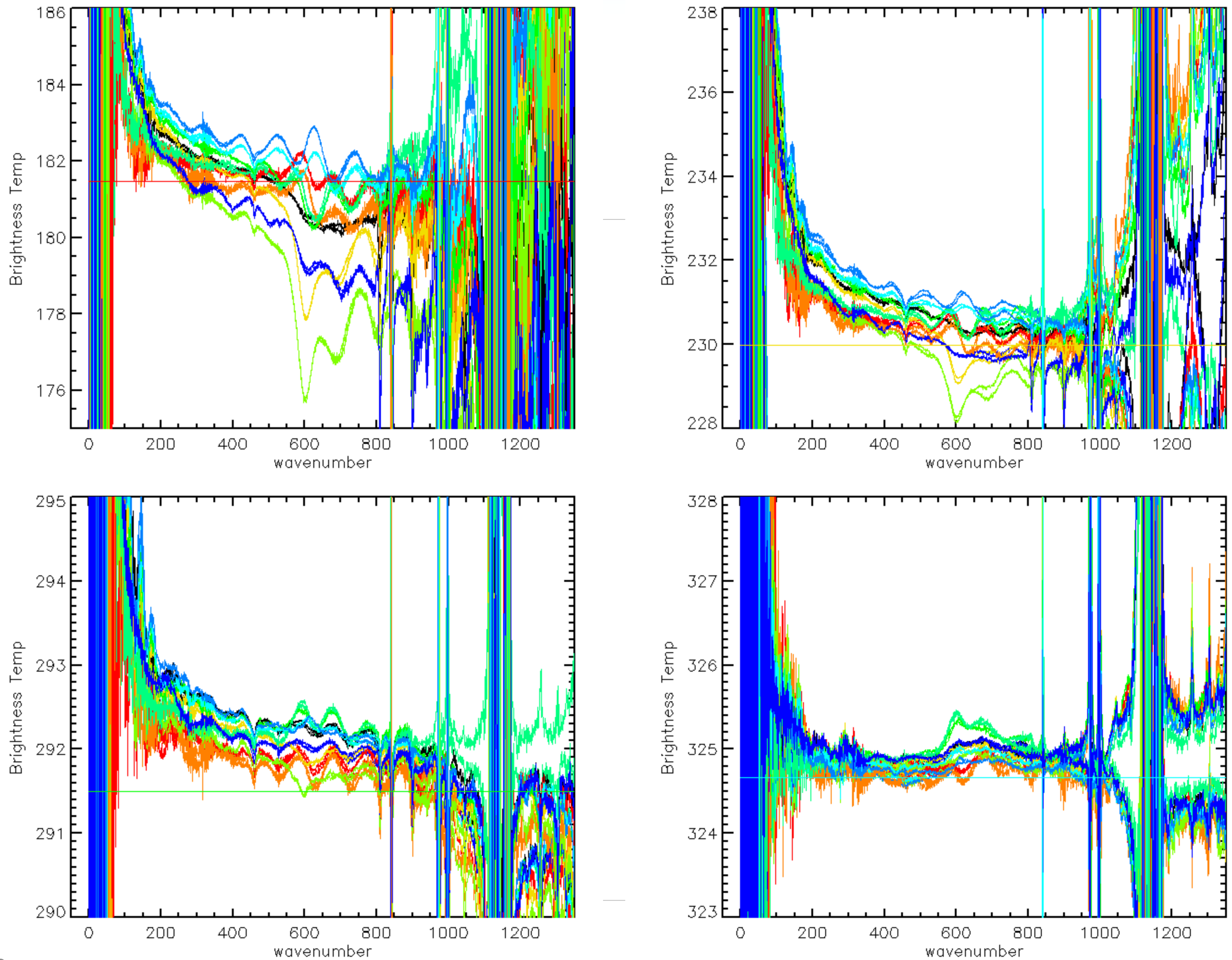
- Calibrated in 2012 using warm and ambient blackbodies over 170 to 320 K range
- Results (presented at last CALCON)
  - Accuracy 1.5 K or better (peak deviation) for T>200 K
  - From 270 to 330 K, accuracy meets design goals of 0.2 K (k=1) 170 to 1000 cm^{-1}
- Conclusions
  - Deviations are due to 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



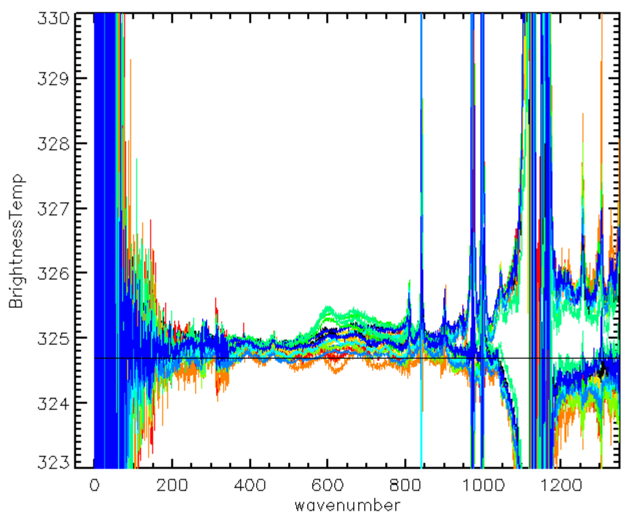
Key: detectors 1-10 are in black, red, orange, yellow, yellow-green, green, blue-green, cyan, light blue, blue.

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

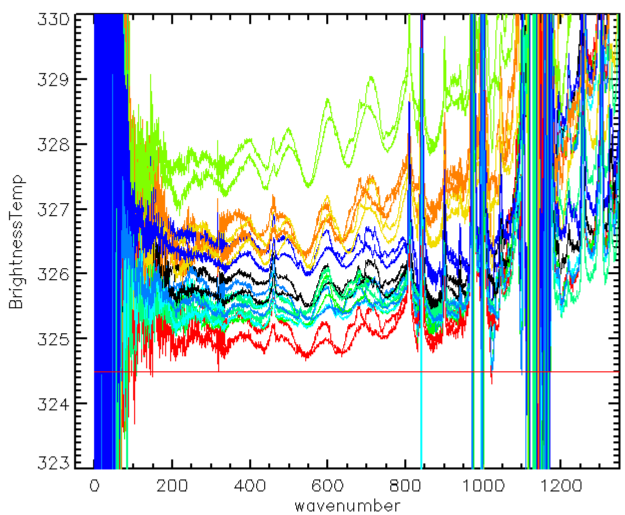
Significant, highly systematic deviations

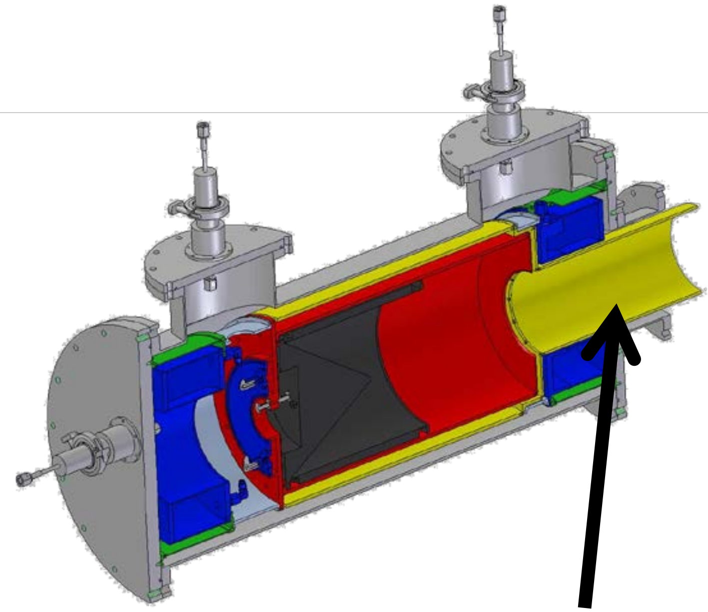
Detector 2 always within 1 K

Stray light



LWIRCS 324.66 K
baffle 321.4 K

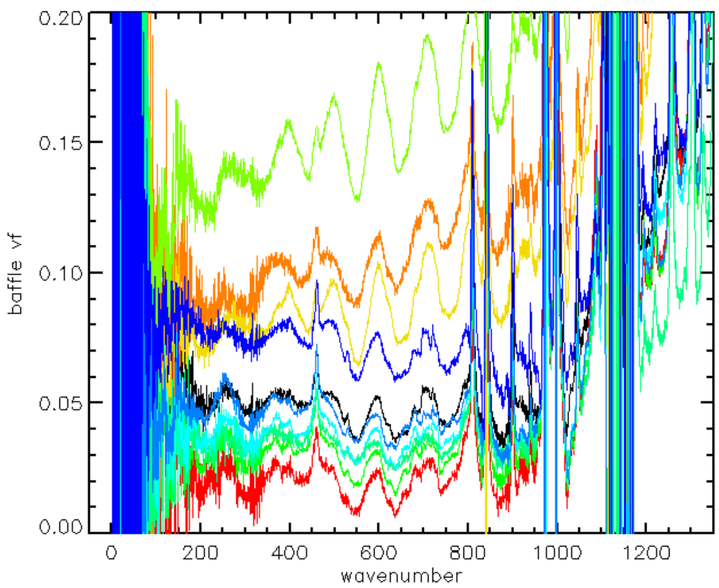




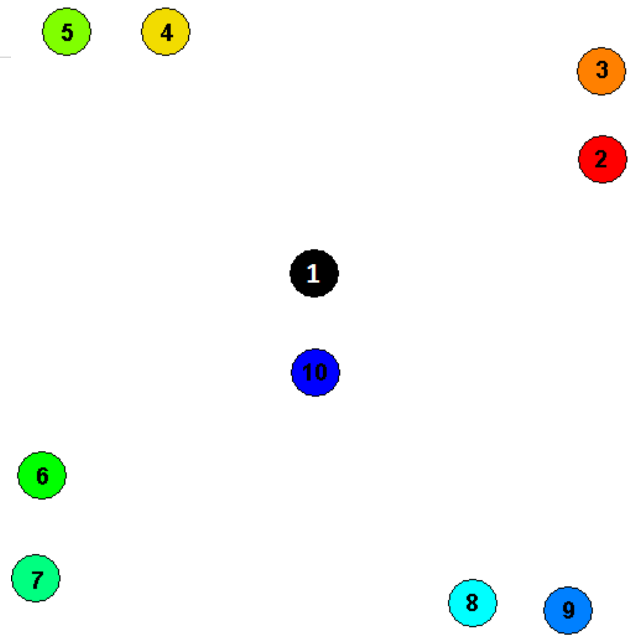
LWIRCS 324.49 K
baffle 341.8 K

Baffle

Baffle view fraction

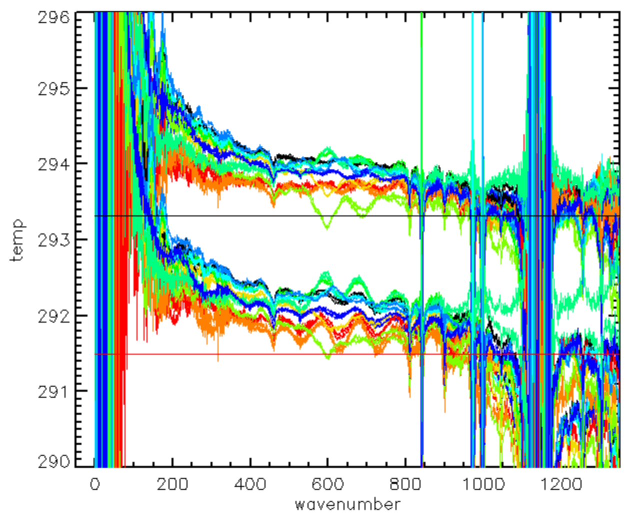


View fraction of baffle by detector

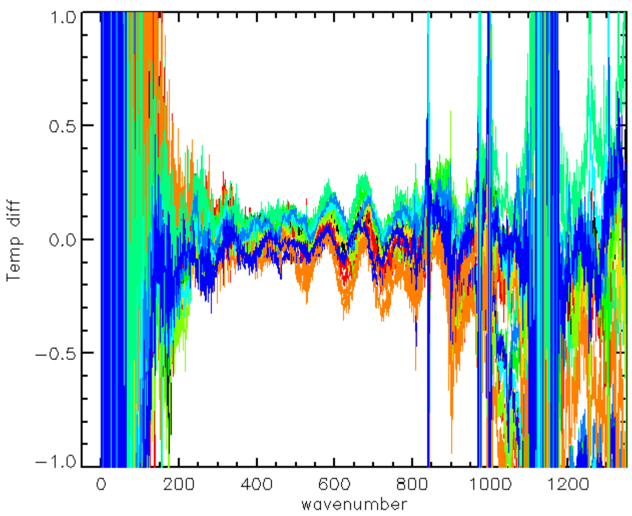


Detector pattern at focal plane

Repeatability



293 K and 292 K data sets
4 days apart



Difference of deviations

Repeatable to 0.2 K
Repeatability always at this level

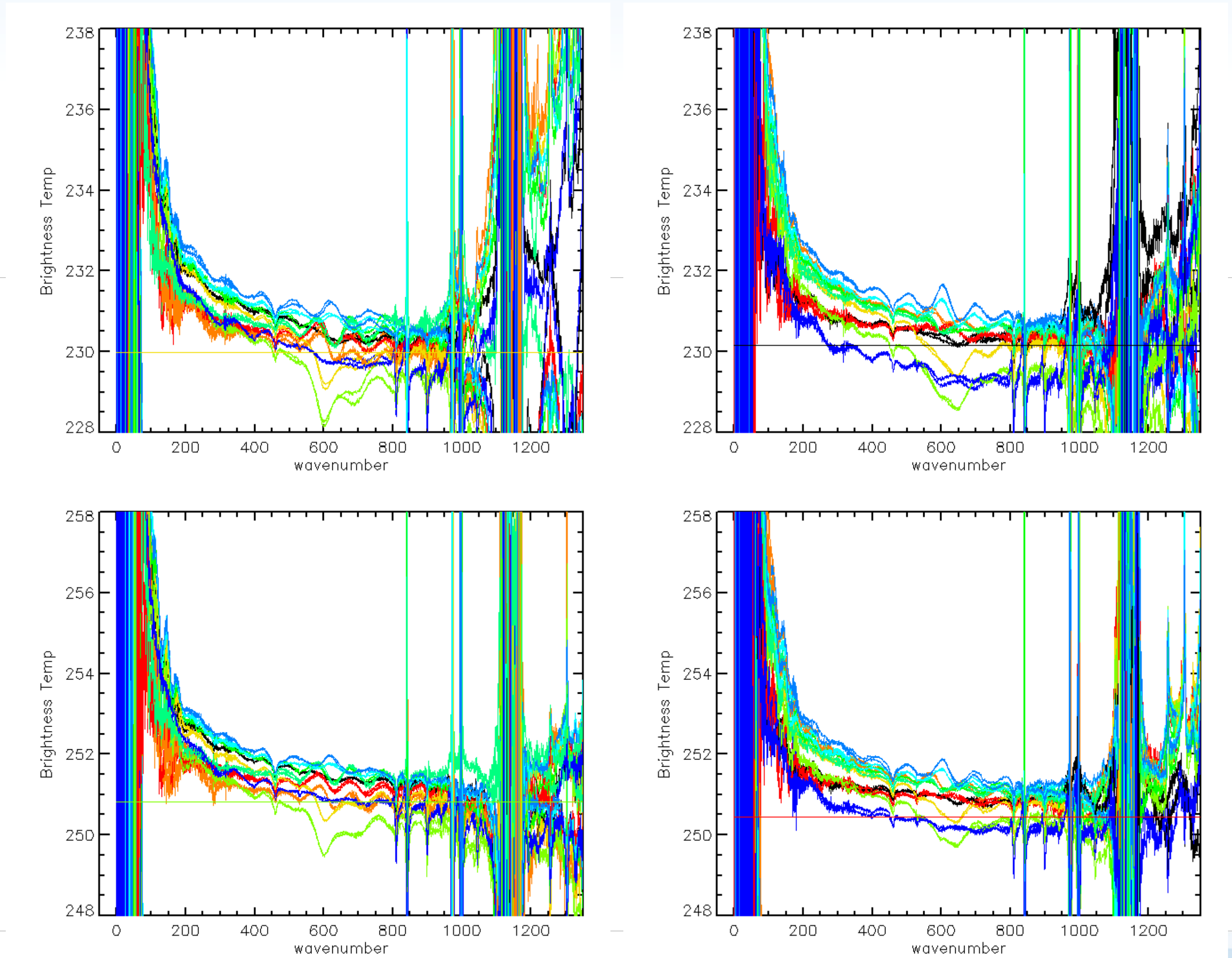
Variation with vacuum cycle confirmed

LWIRCS at ~230, 251 K.

Left: Originals

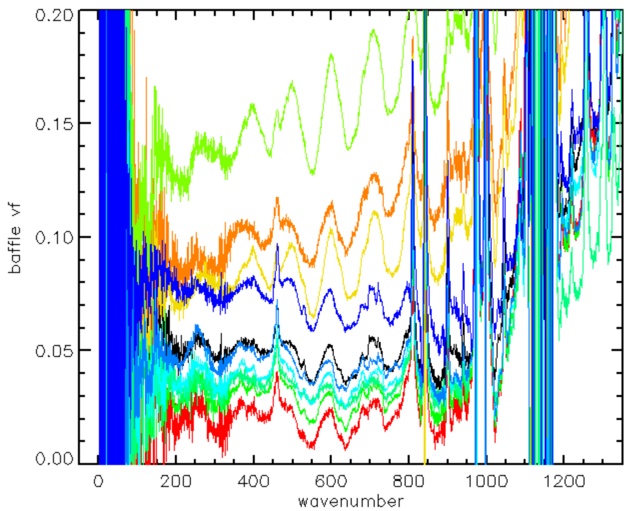
Right: after FIRST at ½ atmosphere for 2 days then re-pumped

Deviations change

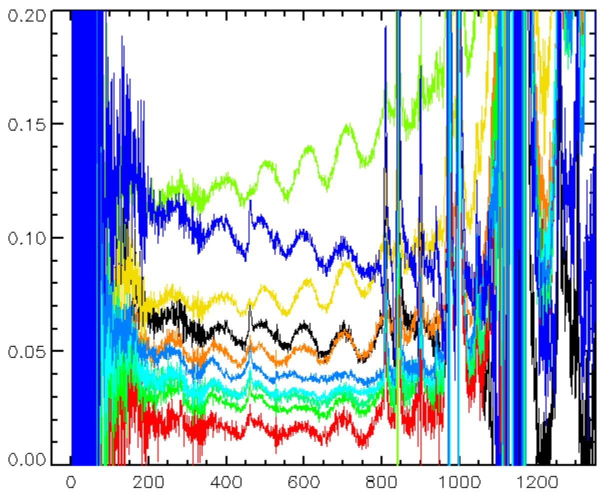


Window effects

- Baffle view fraction changes too



Original from a few slides back



After vacuum cycled

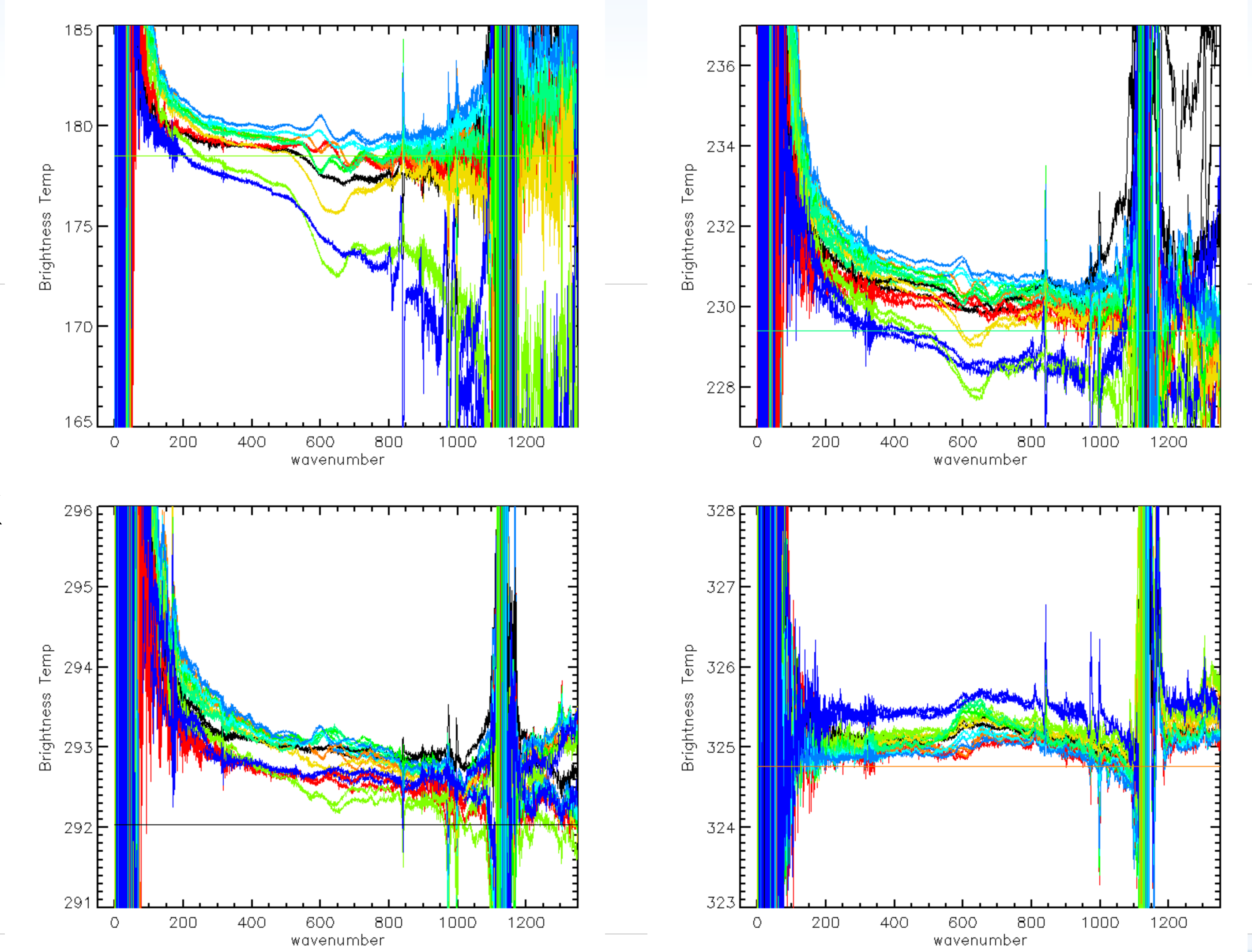
- Window changes shape with each vacuum cycle and window shape directs beam

Windowless data

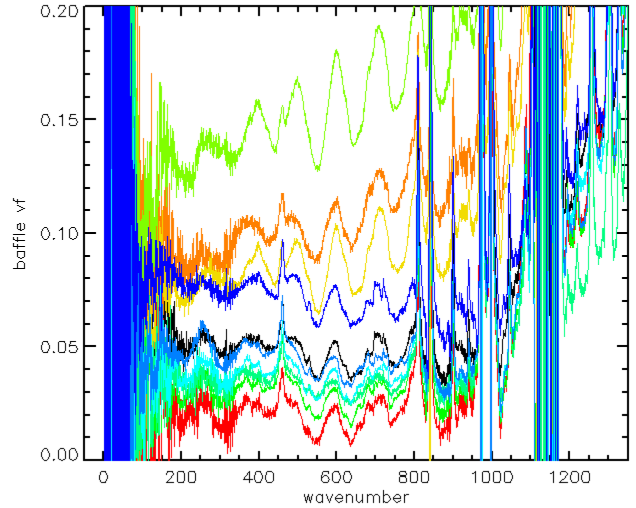
Still have significant systematic deviations

Fewer wiggles

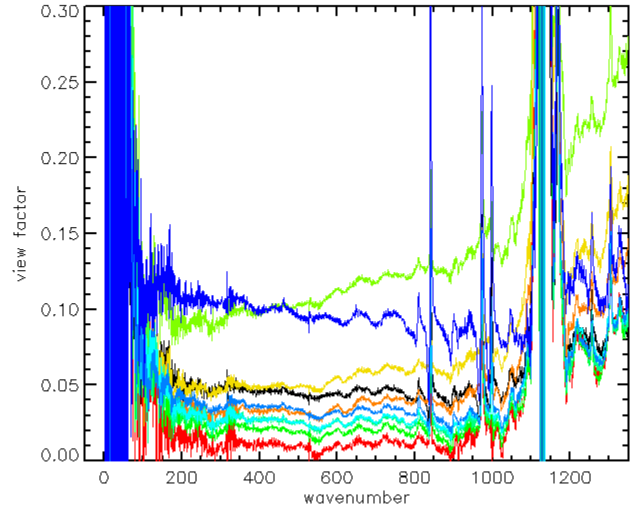
Detector 2 still within 1 K



Windowless baffle view fraction



Original from several slides back



Without window

- 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

$$(1 - f_L)P_L + f_L R_L = x\big((1 - f_W)P_W + f_W R_W - (1 - f_C)P_C - f_C R_C\big) + (1 - f_C)P_C + f_C R_C \qquad x \stackrel{\text{def}}{=} \frac{S_L - S_C}{S_W - S_C}$$

Re-arrange

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

$$R_1 = \frac{1}{1 - f_L}\big((f_L - f_W)P_W + f_W R_W - (f_L - f_C)P_C - f_C R_C\big) \qquad R_2 = \frac{1}{1 - f_L}\big((f_L - f_C)P_C + f_C R_C - f_L R_L\big)$$

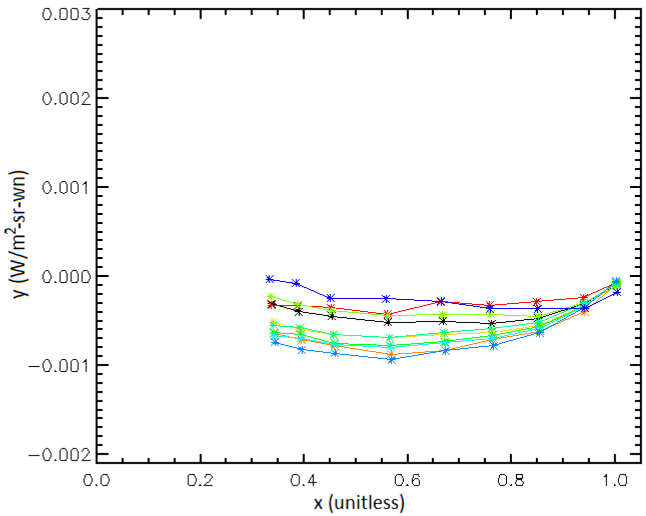
R_1 and R_2 are constant

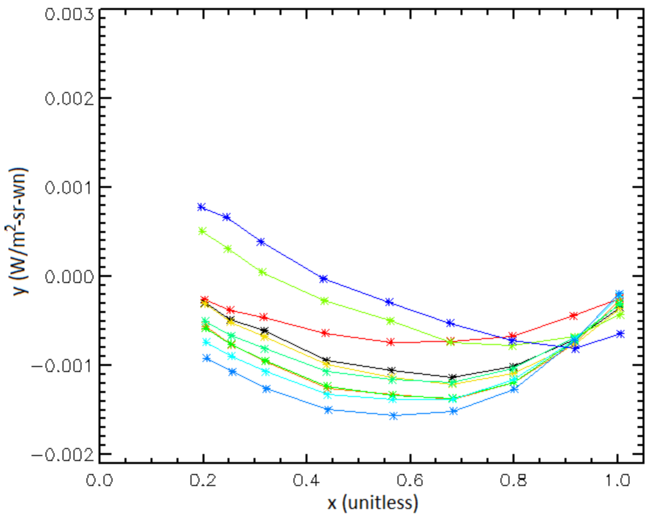
$$P_L - P_C - x(P_W - P_C) \stackrel{\text{def}}{=} y = xR_1 + R_2$$

This should be just a line. Can fit for R_1 and R_2 and use to correct data

X vs. Y w/o window

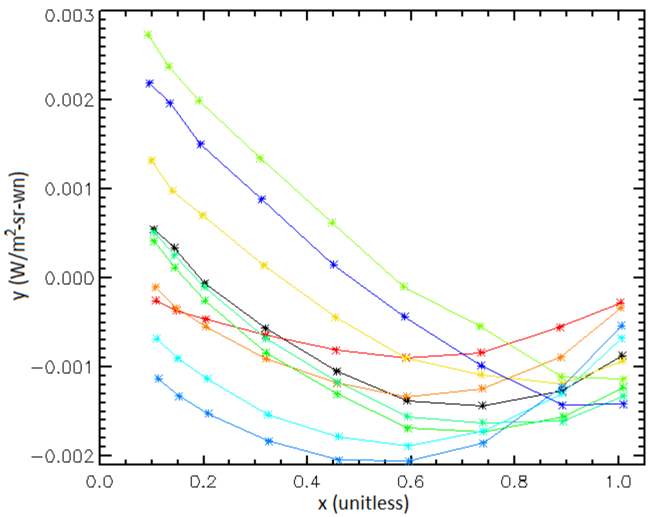
200 cm^{-1}





400 cm^{-1}

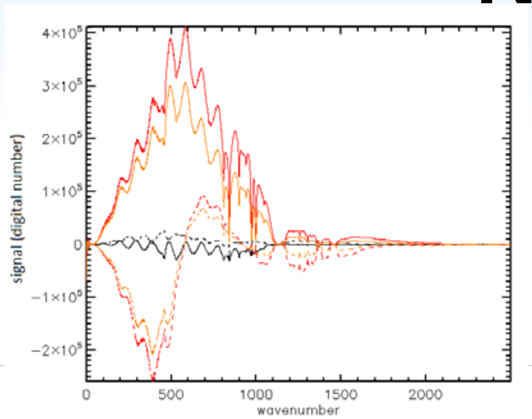
600 cm^{-1}



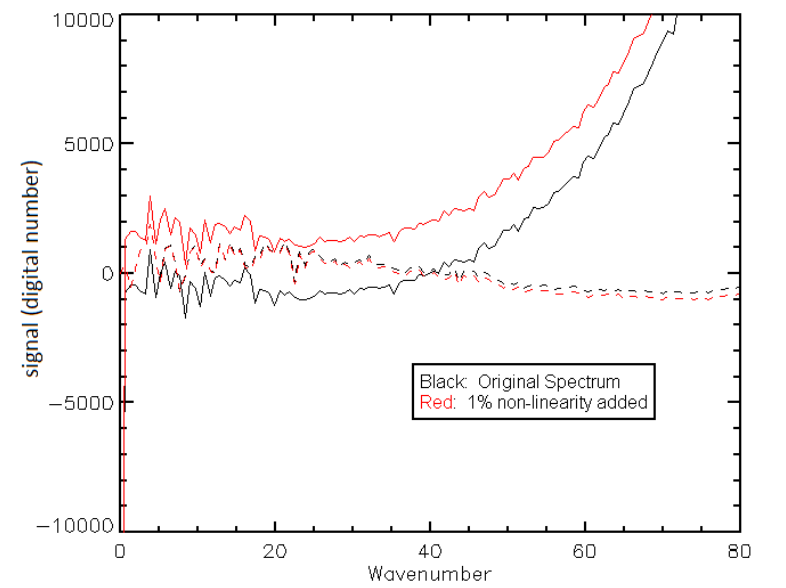
These are not lines

Looks like non-linearity

Non linearity?



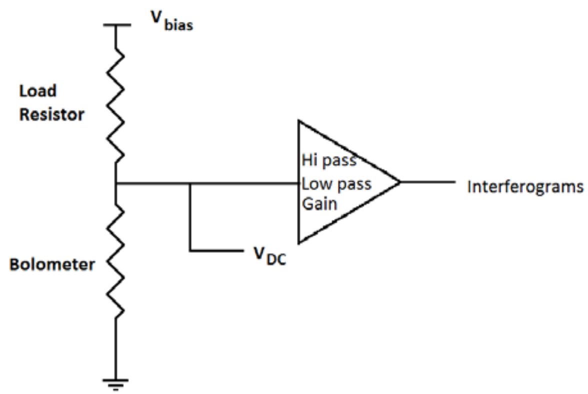
Three example spectra
dashed lines are imaginary component

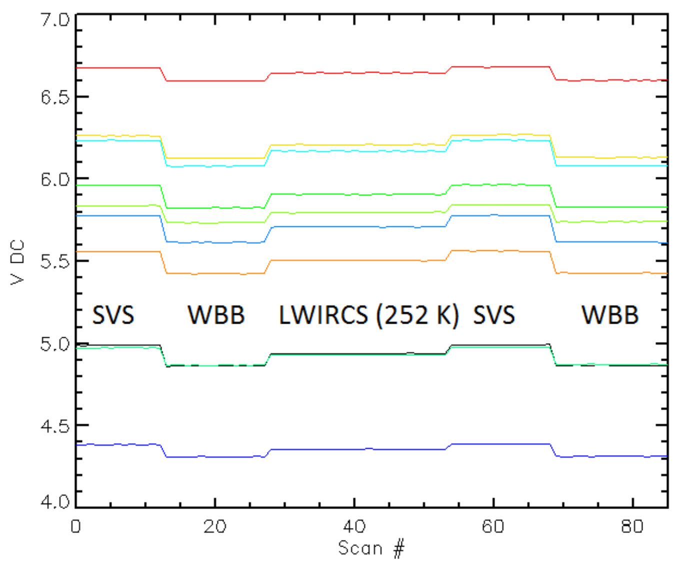


Spectra show interferograms are linear to better than ~0.3% here

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 $\propto V_{DC}$

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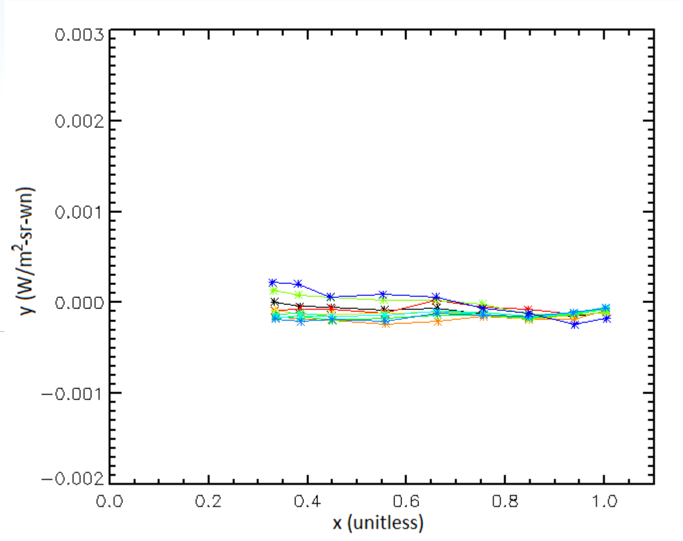
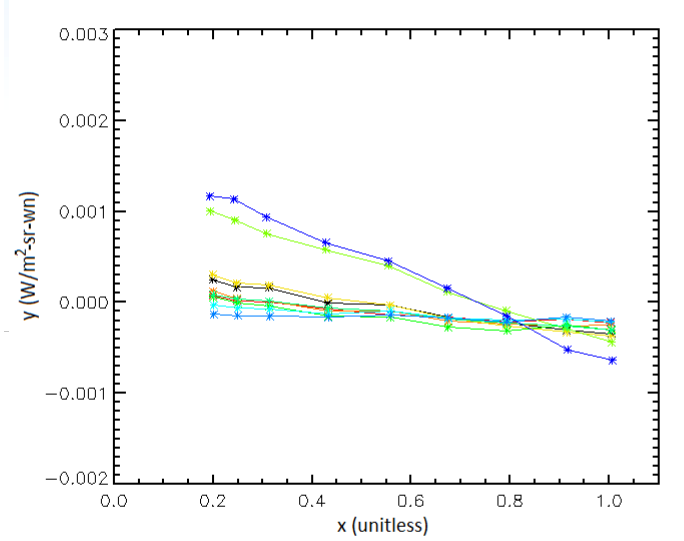
X vs. Y with correction

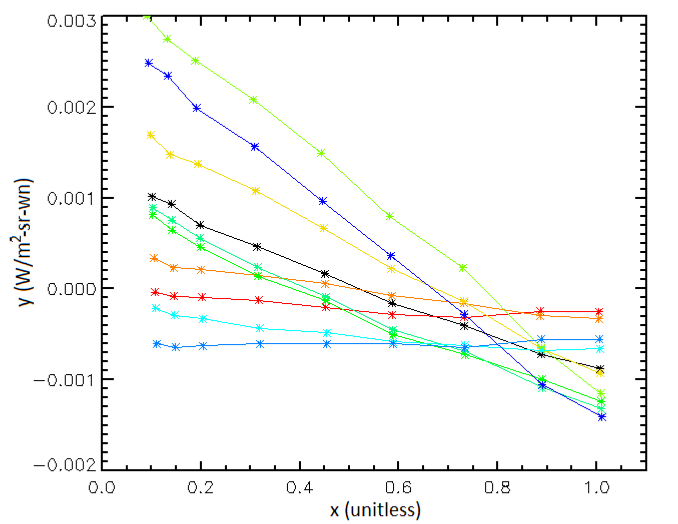
200 cm^{-1}





400 cm^{-1}

600 cm^{-1}



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

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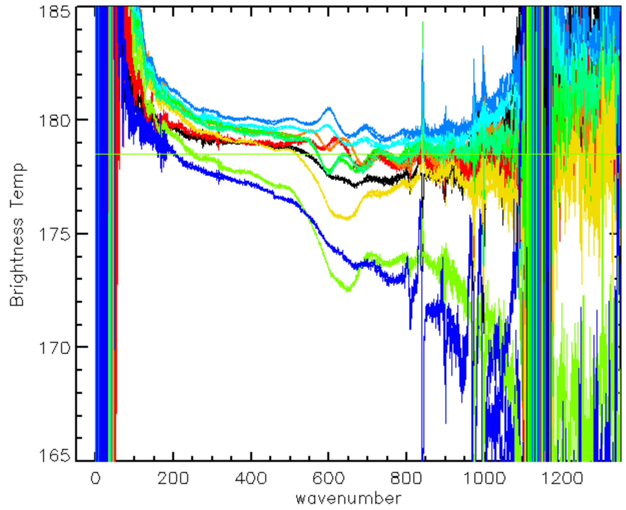
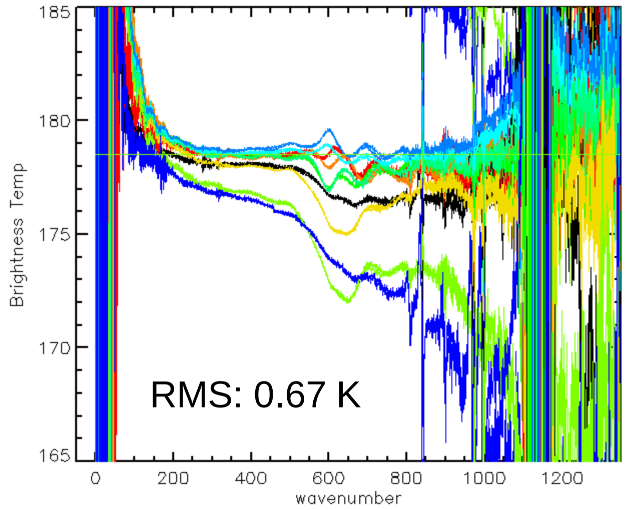
179 K windowless data set

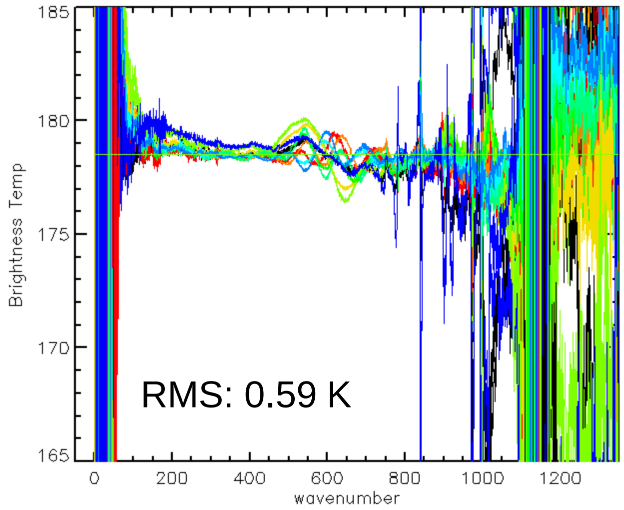


Left: without linearity correction
Bottom left: with non-linearity correction
Bottom right: with stray light correction too

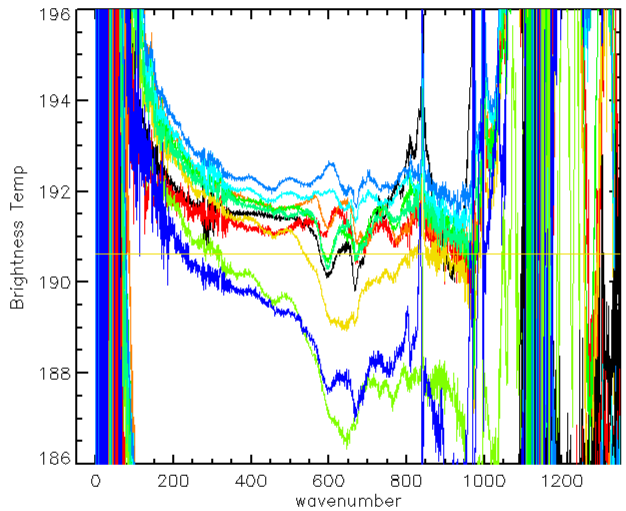
Linearity correction alone significantly improves deviation

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





191 K windowless data set



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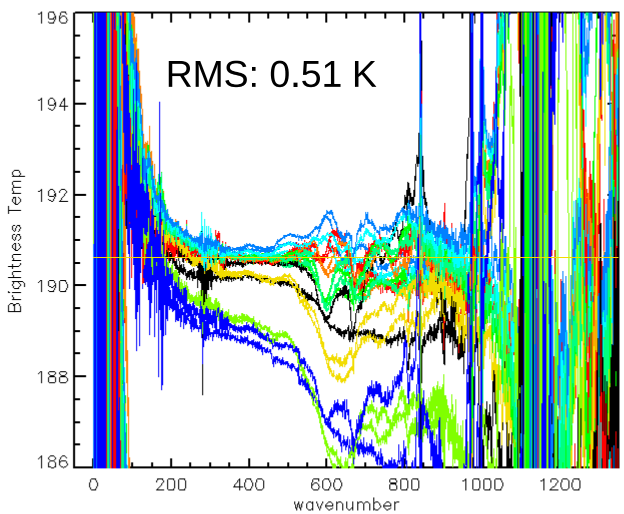
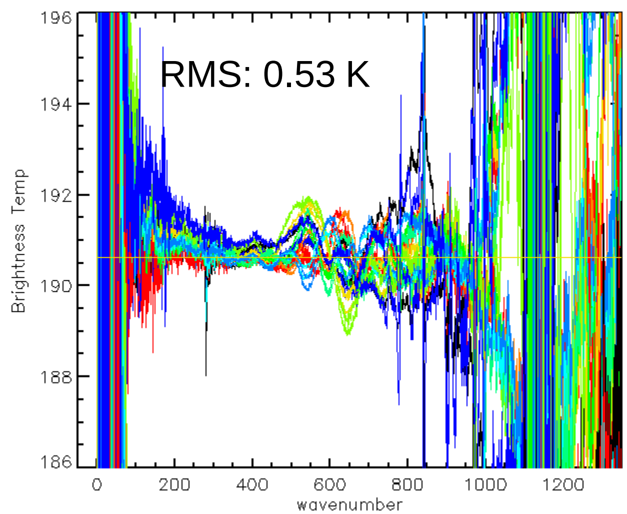
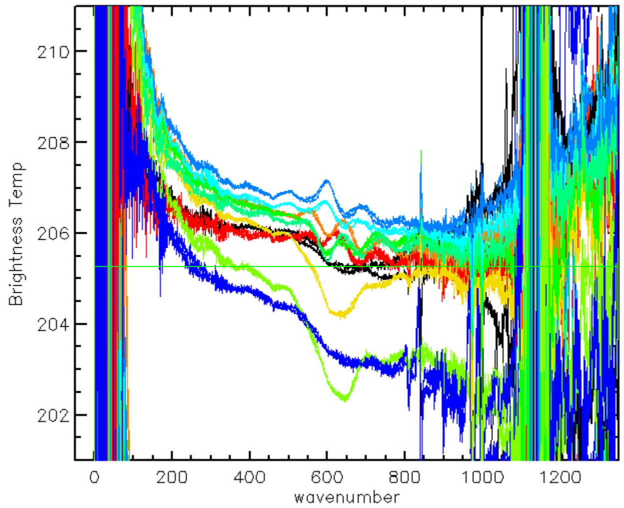




205 K windowless data set



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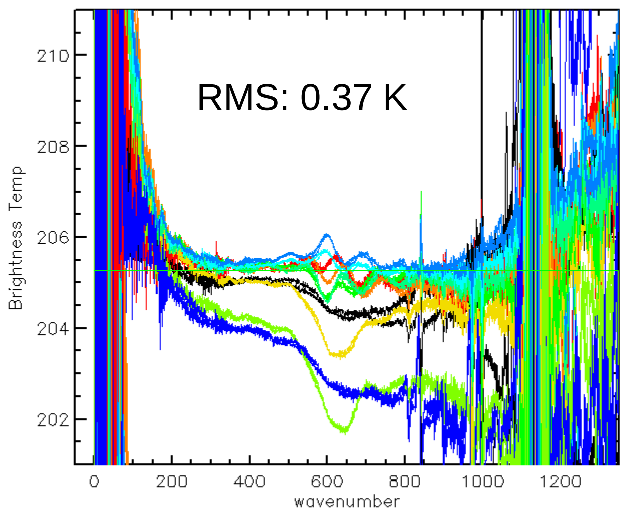
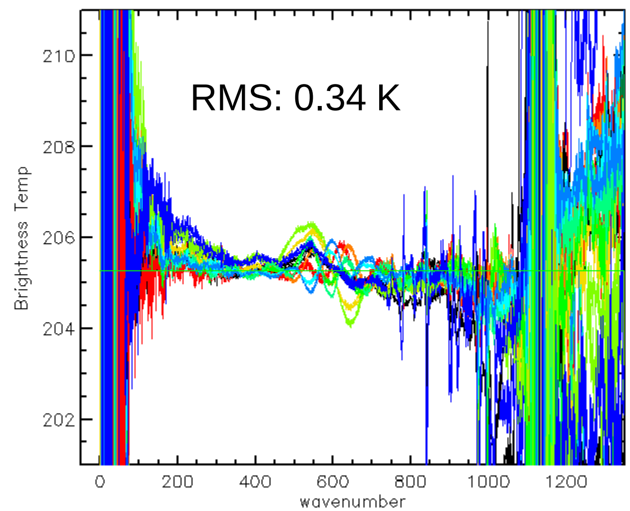
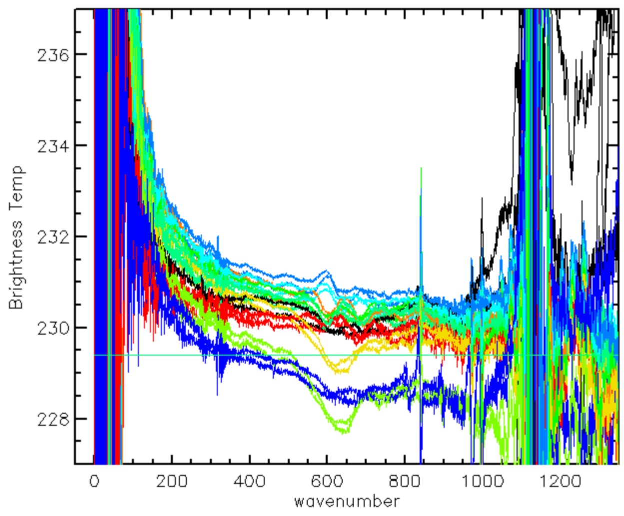




229 K windowless data set



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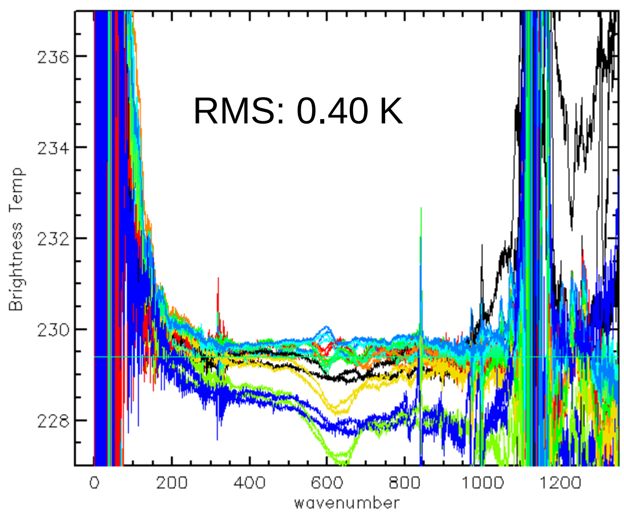
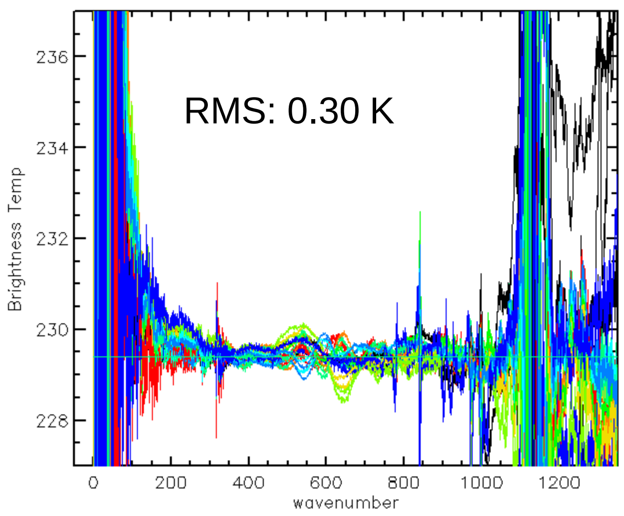
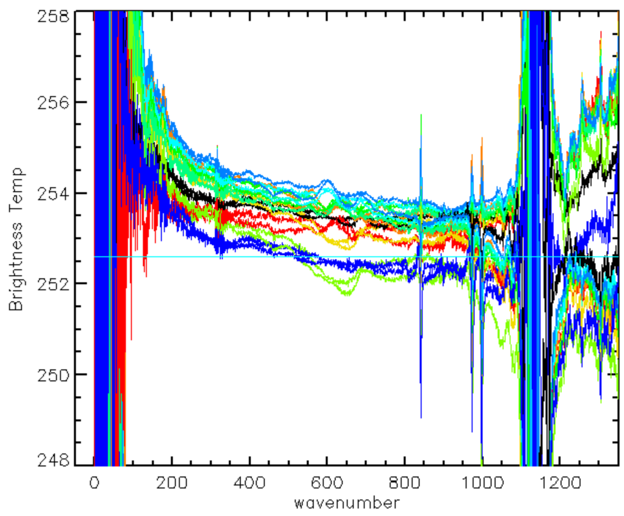




253 K windowless data set



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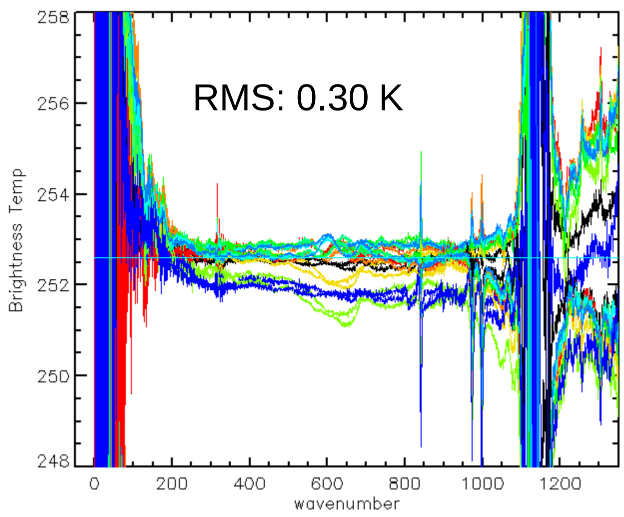
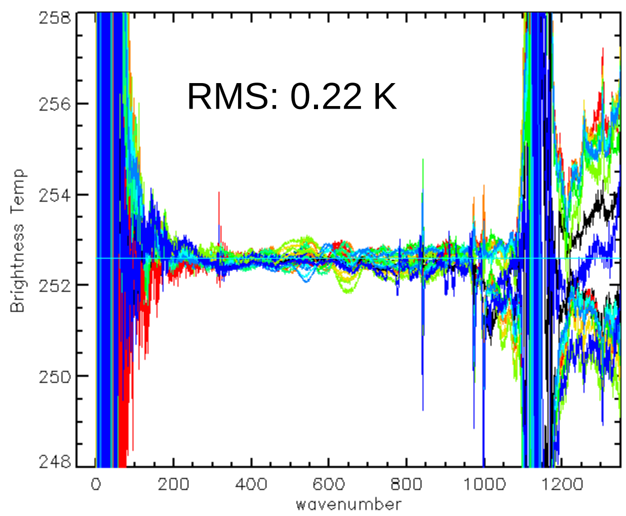
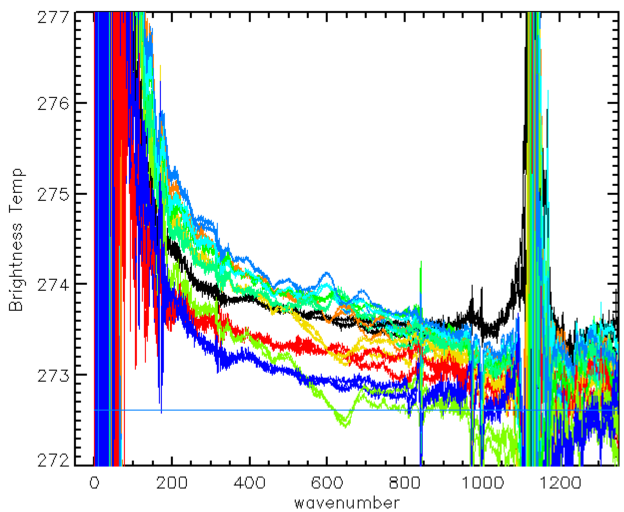




273 K windowless data set



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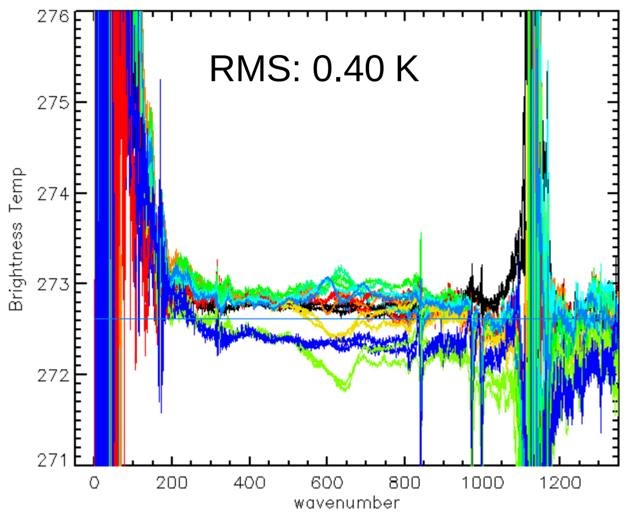
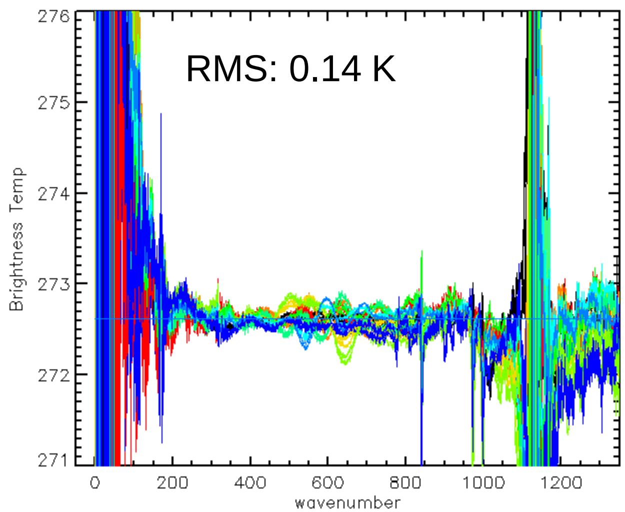
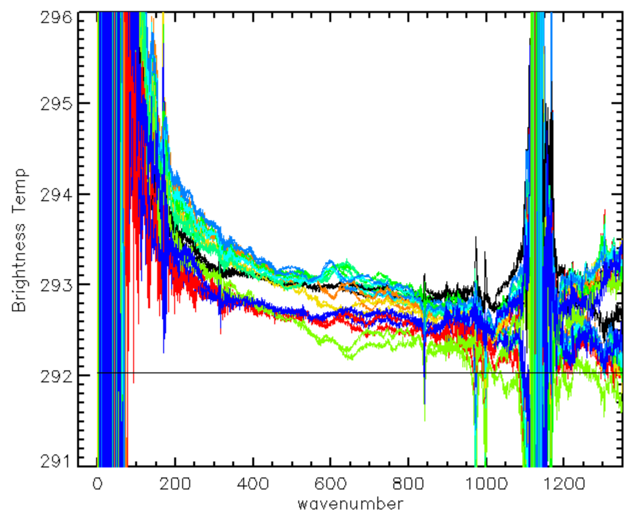




292 K windowless data set



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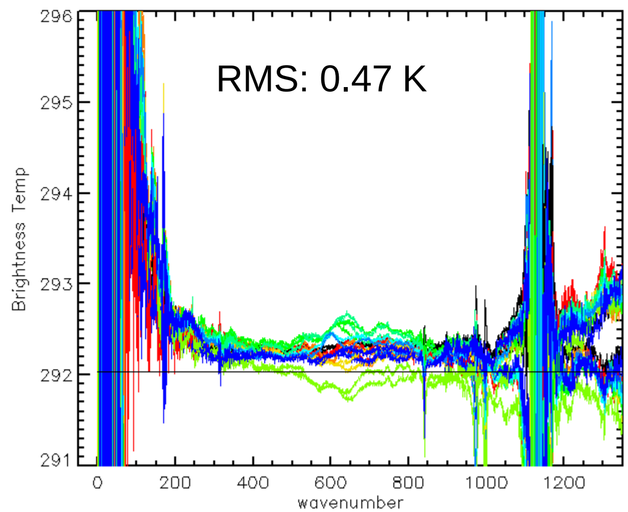
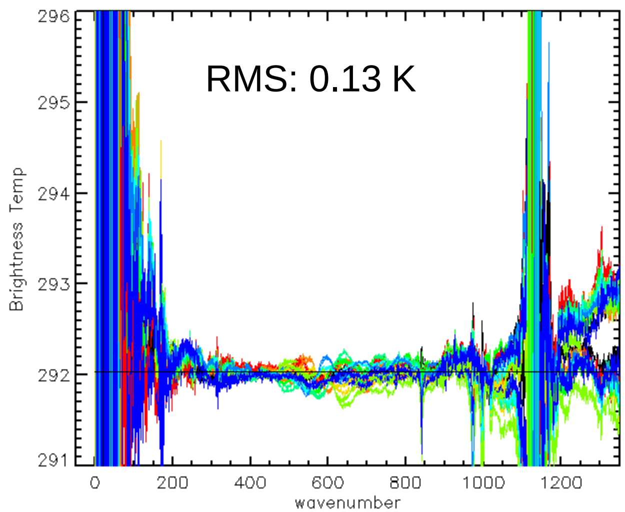
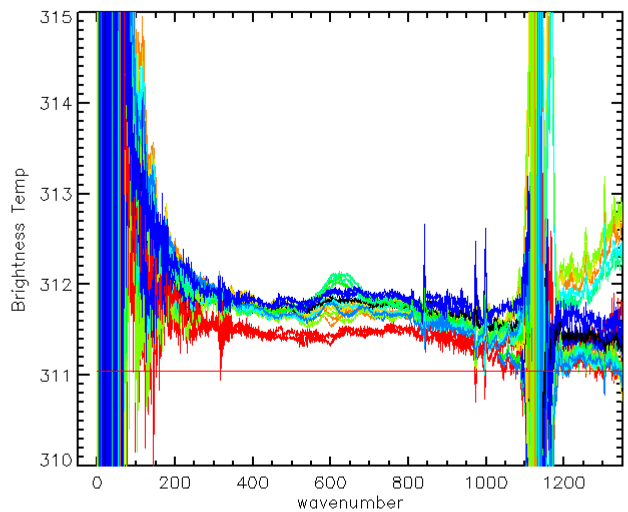




311 K windowless data set



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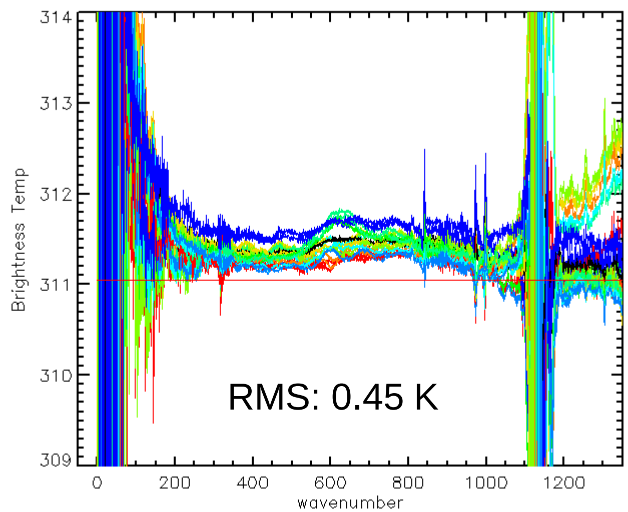
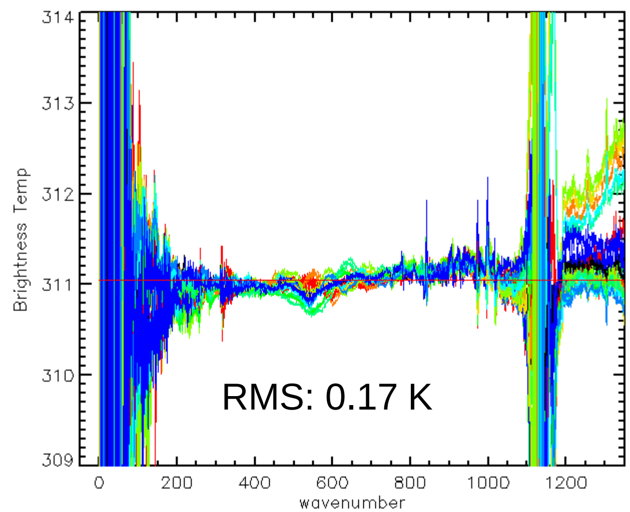
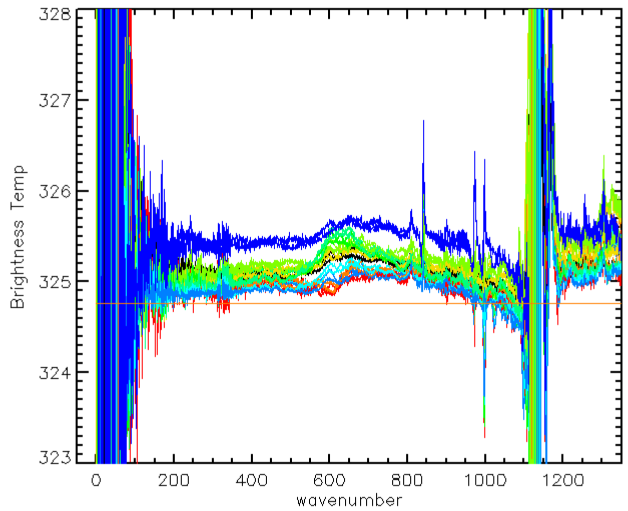




325 K windowless data set



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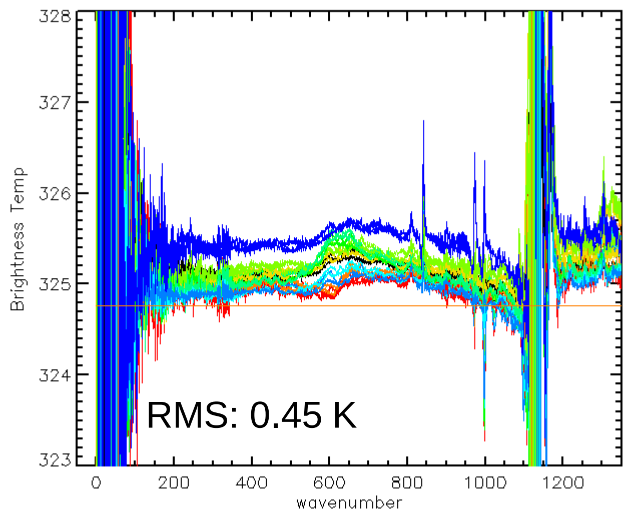
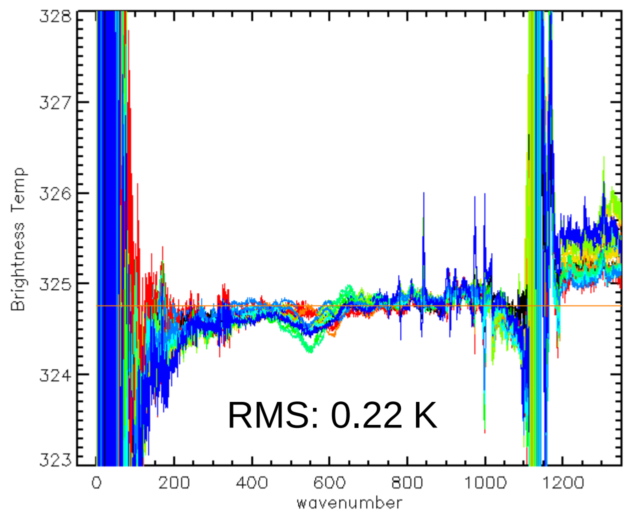
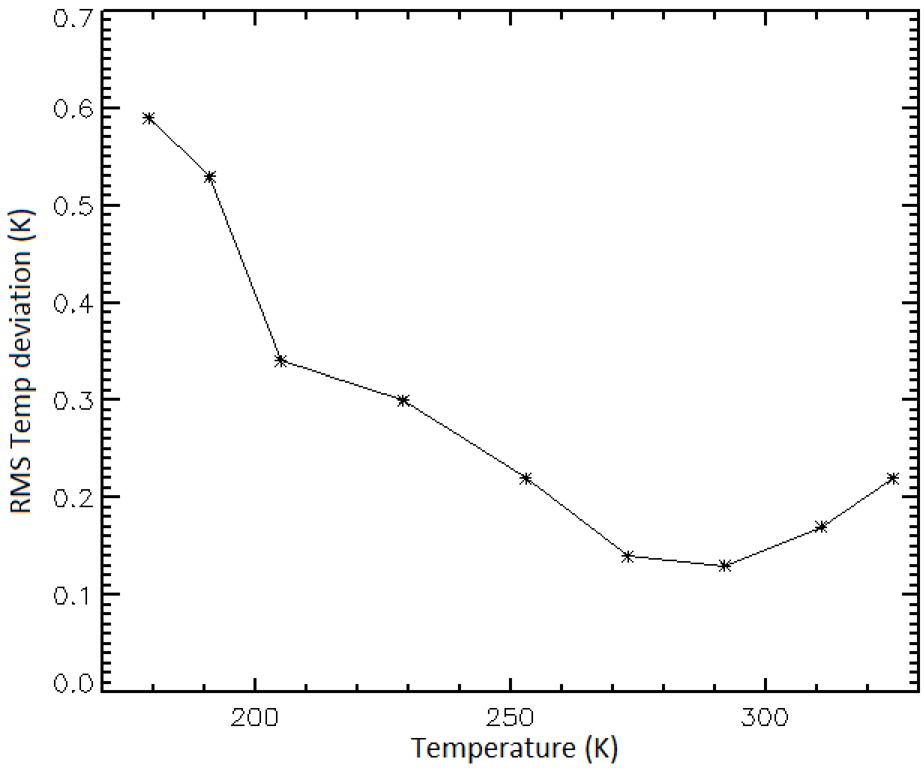
Bottom right: with stray light correction too





RMS deviation vs. temperature



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