Space Dynamics LABORATORY
Utah State University Research Foundation

Absolute Radiance Recalibration of FIRST

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Outline

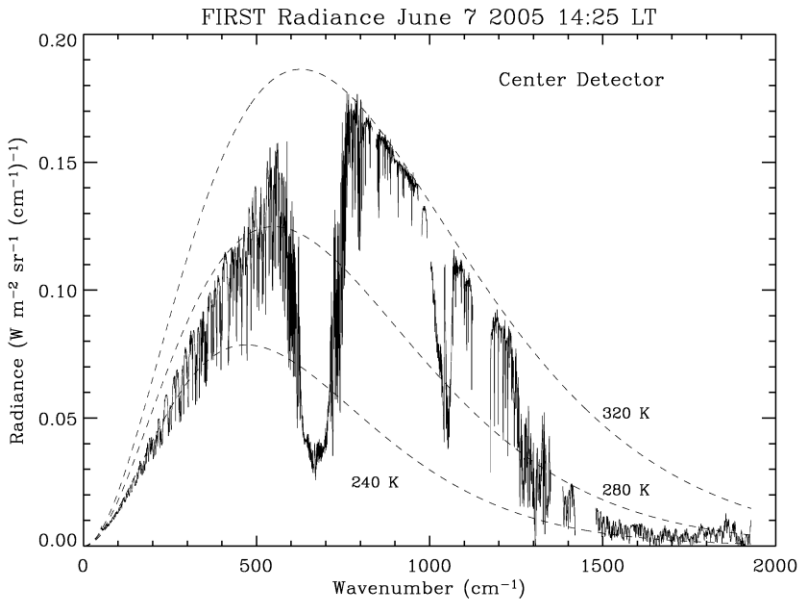
- FIRST
- FIRST on-board calibration
- Ground calibration equipment
- Absolute radiance response calibration
  - Data collection
  - Data processing highlights
  - Non-linearity
  - Results

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})

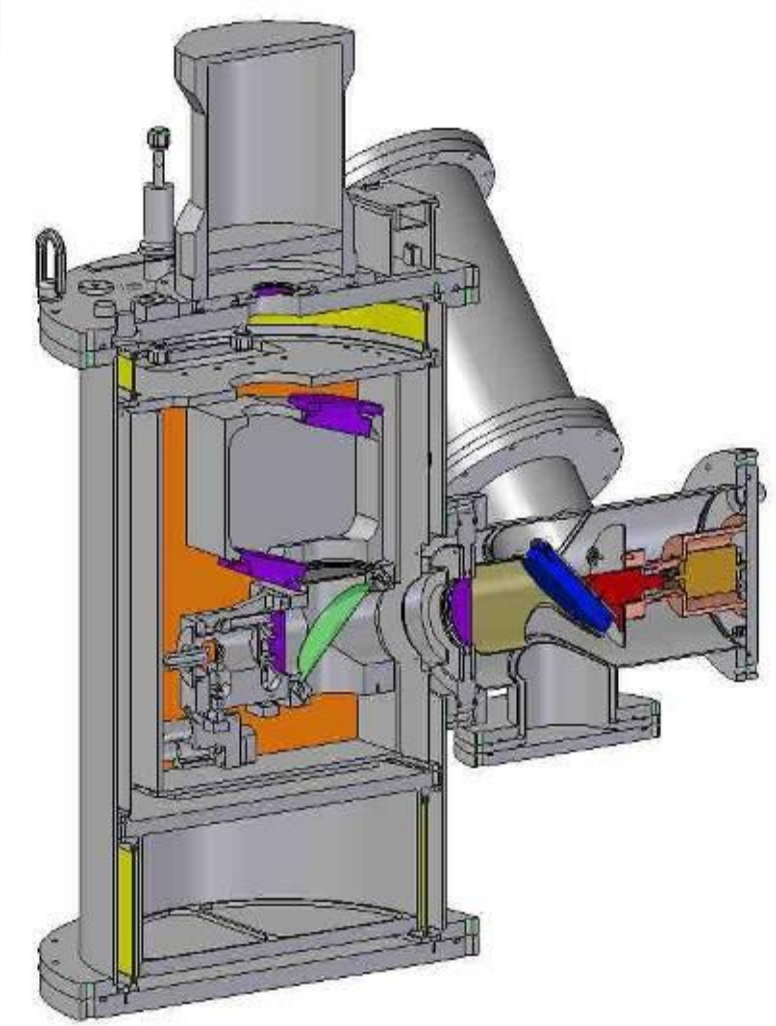
- Contains half of Earth's outgoing long-wave radiation
- Is not well observed spectrally



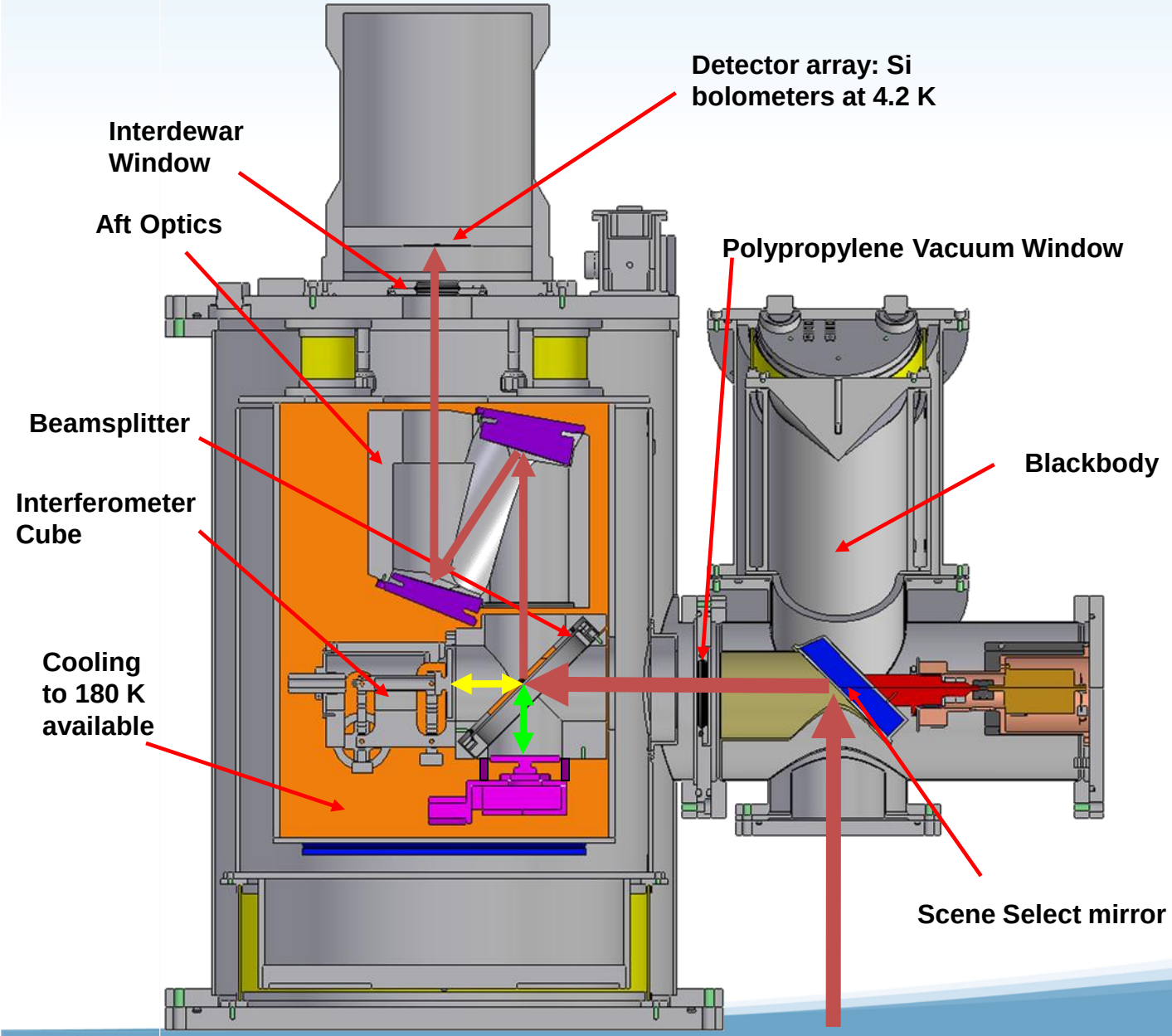
FIRST spectrum from high altitude balloon

FIRST specs

- Fourier Transform spectrometer
  - Michelson interferometer
  - Coverage
    - Goal: 100 to 1000 cm^{-1} (100 to 10 μm)
    - Actual: 50 to 2200 cm^{-1} 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
- 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 rotates
- COTS electronics

FIRST on-board calibration

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

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

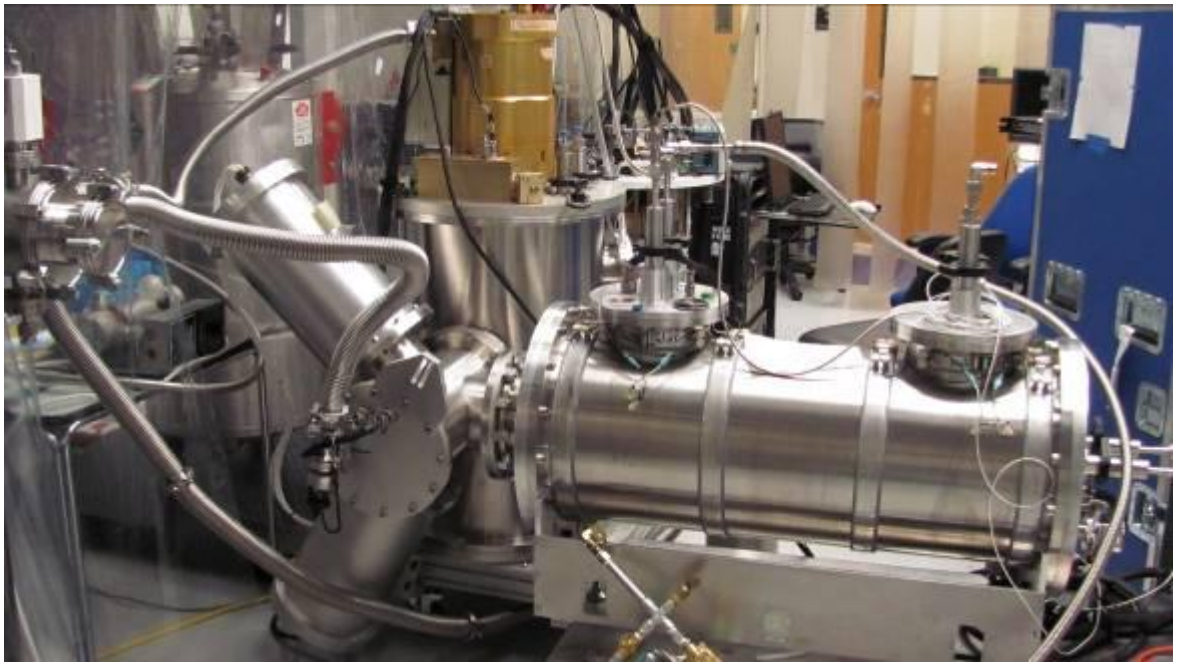
S_{Target}, S_{WBB}, S_{ABB}: Observed signal from target, warm and ambient blackbodies

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 in lab when built in 2005
- Re-calibrated in 2012 for absolute radiance response
  - Calibration data is collected by looking at warm blackbody, ambient blackbody, and LWIRCS (calibrator blackbody)

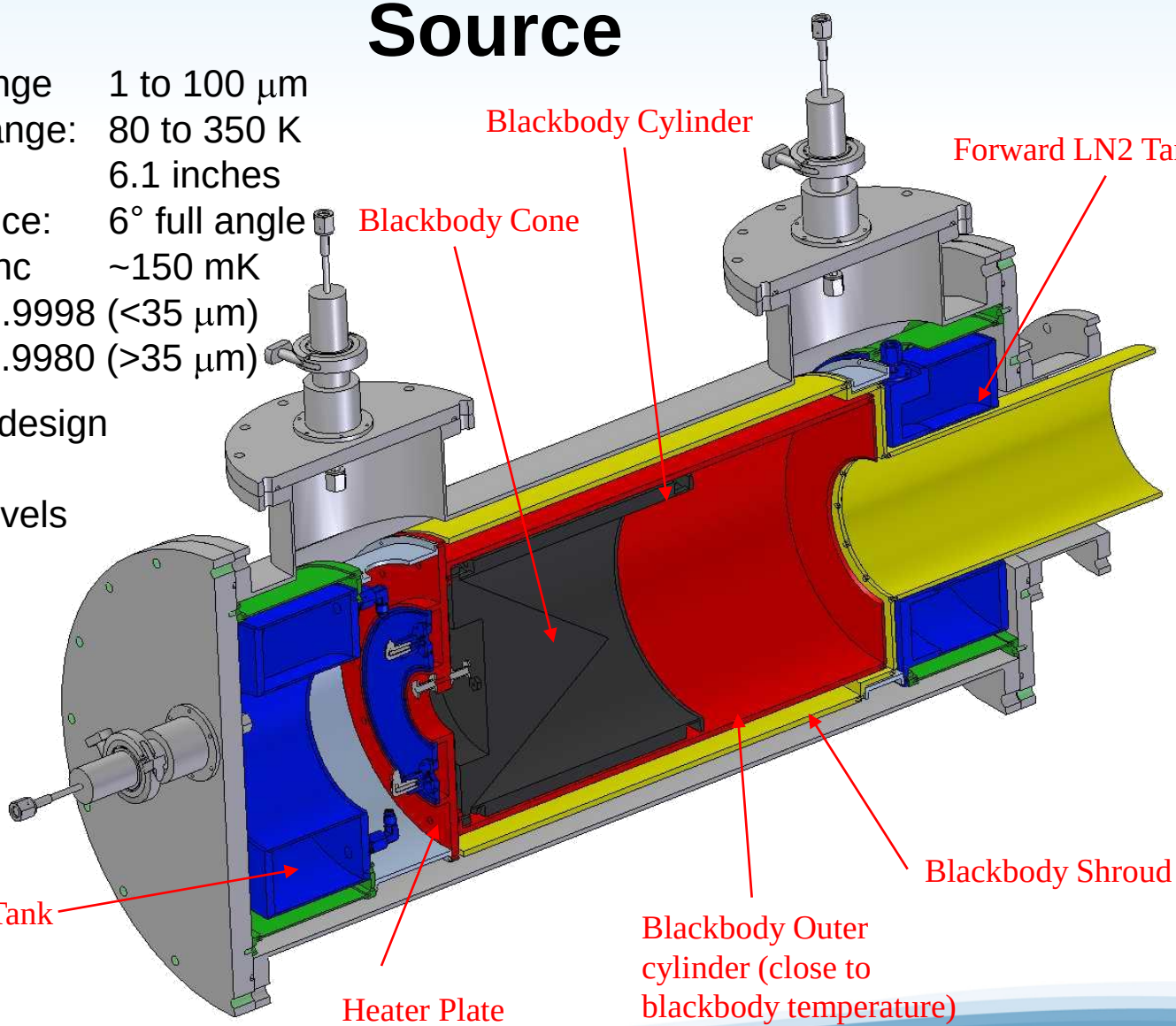


LWIRCS – Long Wave Infrared Calibration Source

- Wavelength range 1 to 100 μm
- Temperature range: 80 to 350 K
- Aperture: 6.1 inches
- Beam divergence: 6° full angle
- Temperature unc ~150 mK
- Emissivity ≥0.9998 (<35 μm)
  ≥0.9980 (>35 μm)

- Specular trap design
- Z302 paint
- Two cooling levels

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

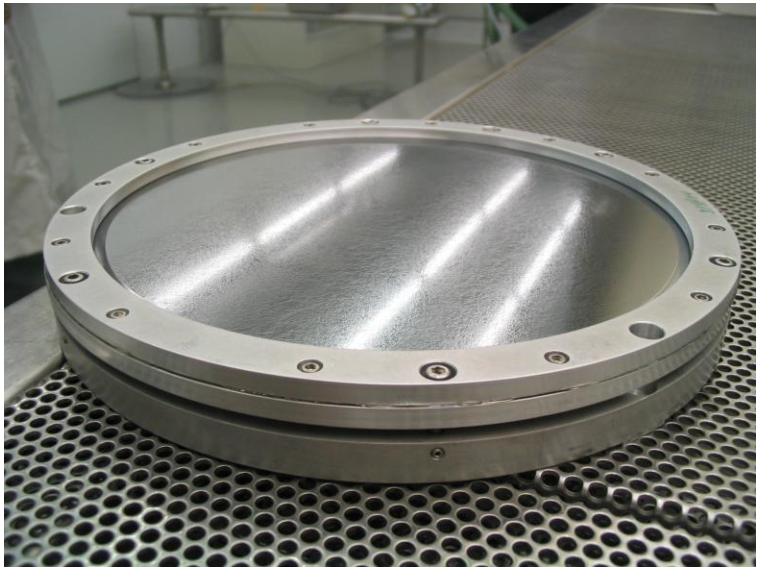


FIRST Response Calibration Data Details

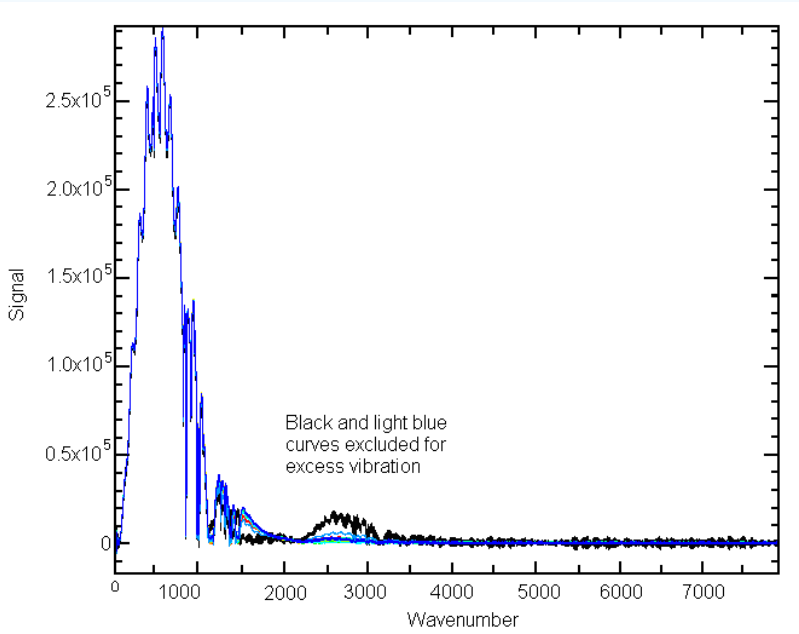
- Collect data of LWIRCS at a range of temperatures from 169 to 324 K, compare LWIRCS temperature to brightness temperature measured by FIRST
  - 30 min per set
  - Warm BB at ~324.5 K, ambient BB at ~294 K
- Data processed from interferograms to spectra, spectra averaged by target and scan direction, then spectra calibrated by calibration equation
- Unusual FIRST data processing
  - Hi and low gain channels
    - Need 20 bit dynamic range
  - Vibration effects
  - Phase drift

Vibration issues

- Beamsplitter is a stretched thin film
  - Ge on polypropylene
  - Can become a drumhead
- Vibration effects much reduced by sampling every HeNe laser fringe



FIRST Beamsplitter



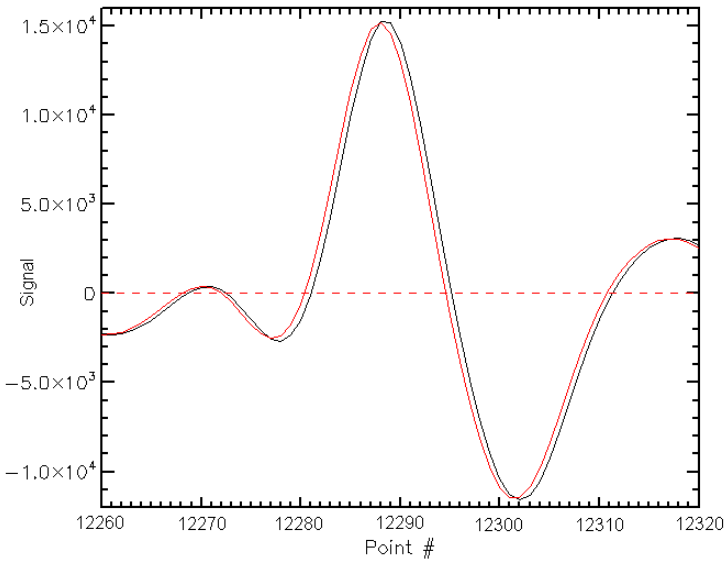
10 spectra from detector 3

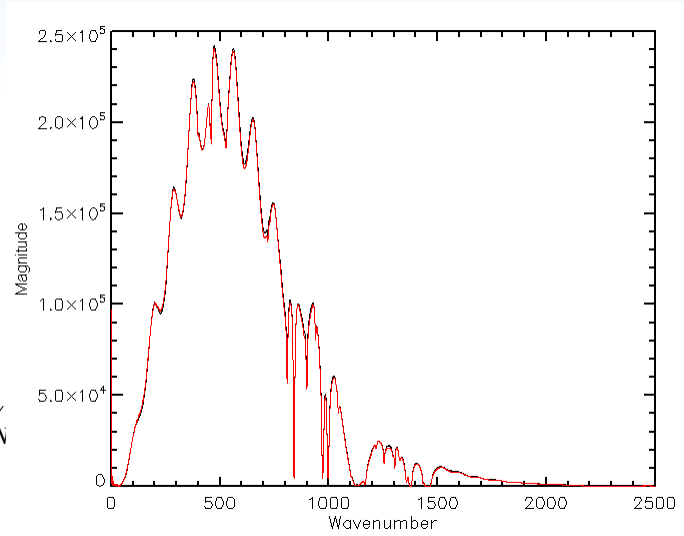
- Vibration effects appear around 2800 cm^{-1}
- Occasional noisy spectrum excluded

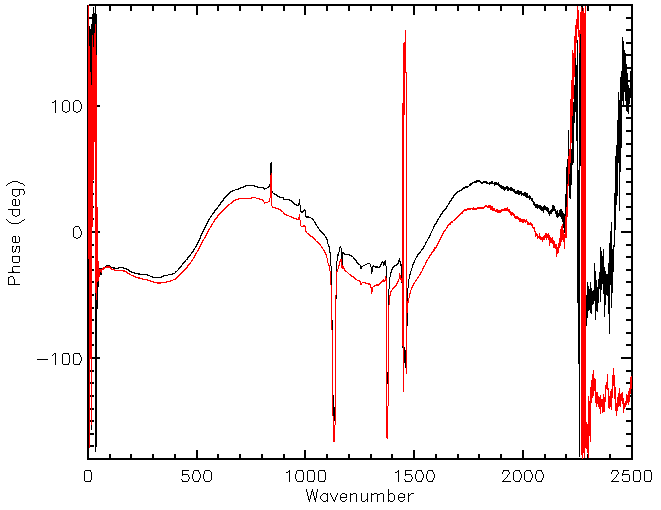
Phase shifting

- FIRST metrology laser does not pass through beamsplitter, uses backside of moving interferometer mirror
- Thermal expansion changes optical paths differently, results in a shift in the phase of the spectrum

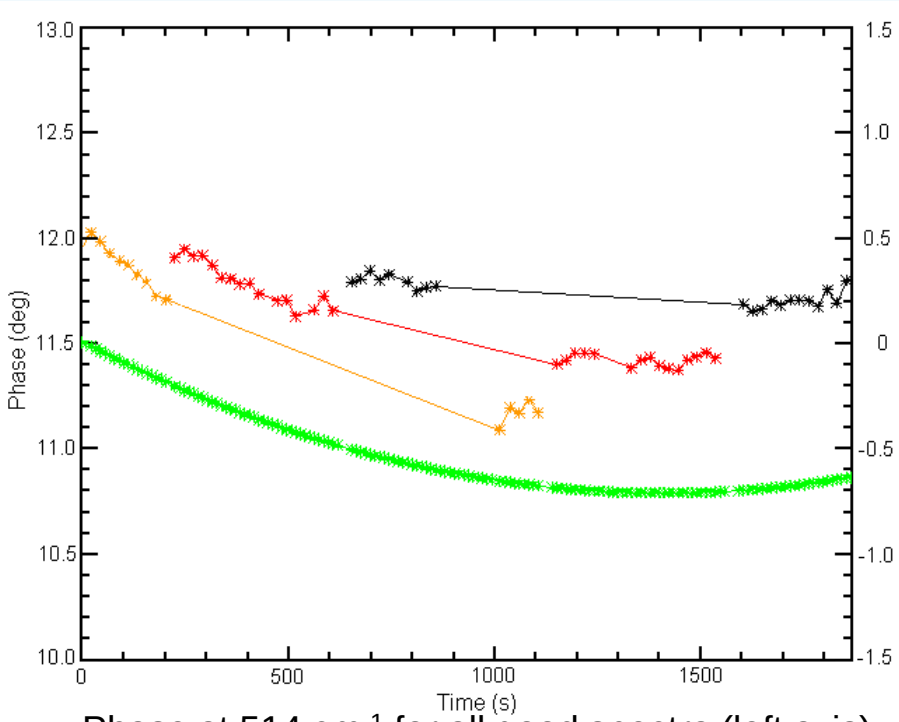
$$f_m = \sum_{n=0}^{N-1} F_n e^{i2\pi mn/N}$$







Phase alignment

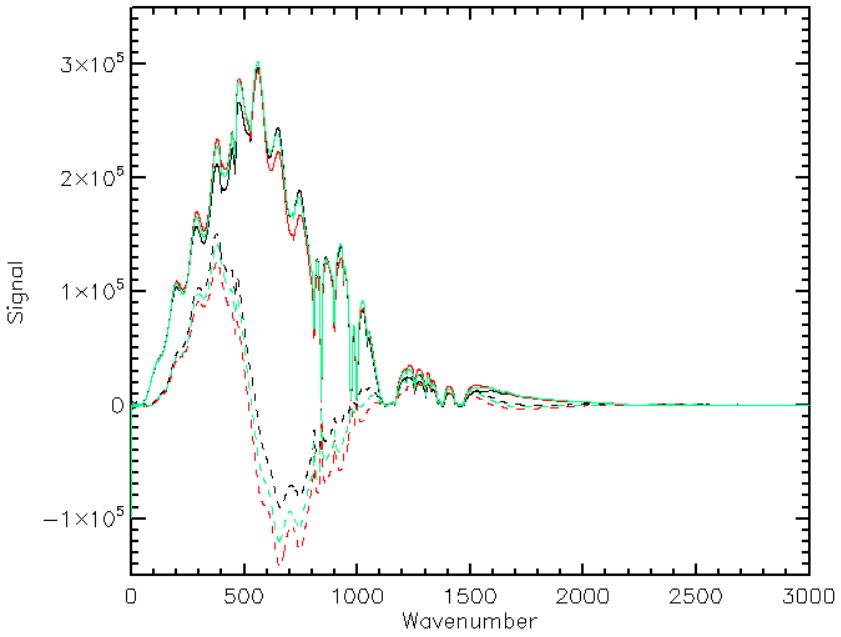


Phase at 514 cm^{-1} for all good spectra (left axis) for detector 3 in the forward direction of ABB (orange), LWIRCS (red) and WBB (black). Green curve is the phase drift curve (right axis)

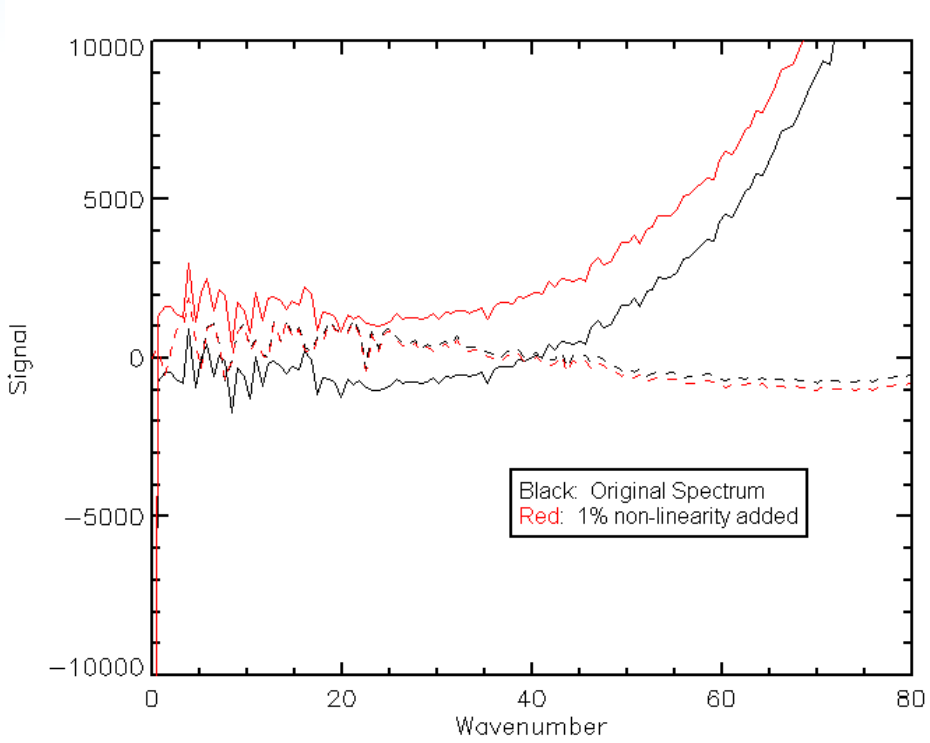
- FIRST has out of phase light, CANNOT phase correct each spectrum individually
- Adjust phase by fitting observed drift in WBB, ABB phase and adjusting phase of all spectra by amount of drift curve
- After this step, average all spectra by target and direction

Non-linearity

- Spectra are complex numbers



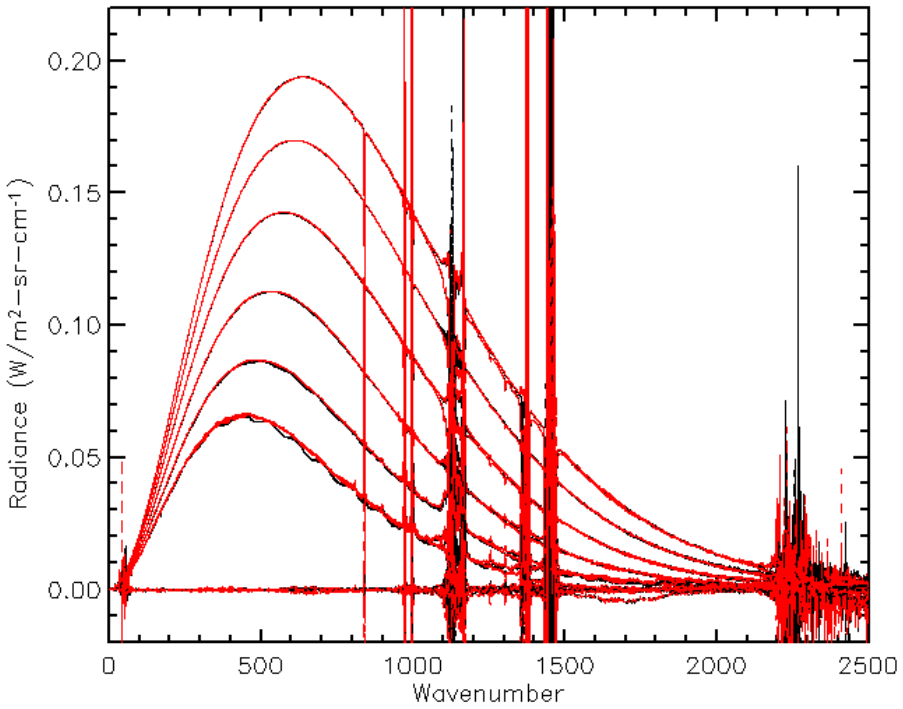
Three average spectra of the WBB in the forward direction from detector 3. Real part is solid line, imaginary part is dashed



- Non-linearity visible at low wavenumber end if present
- Non-linearity less then ~0.3% here

LWIRCS radiance

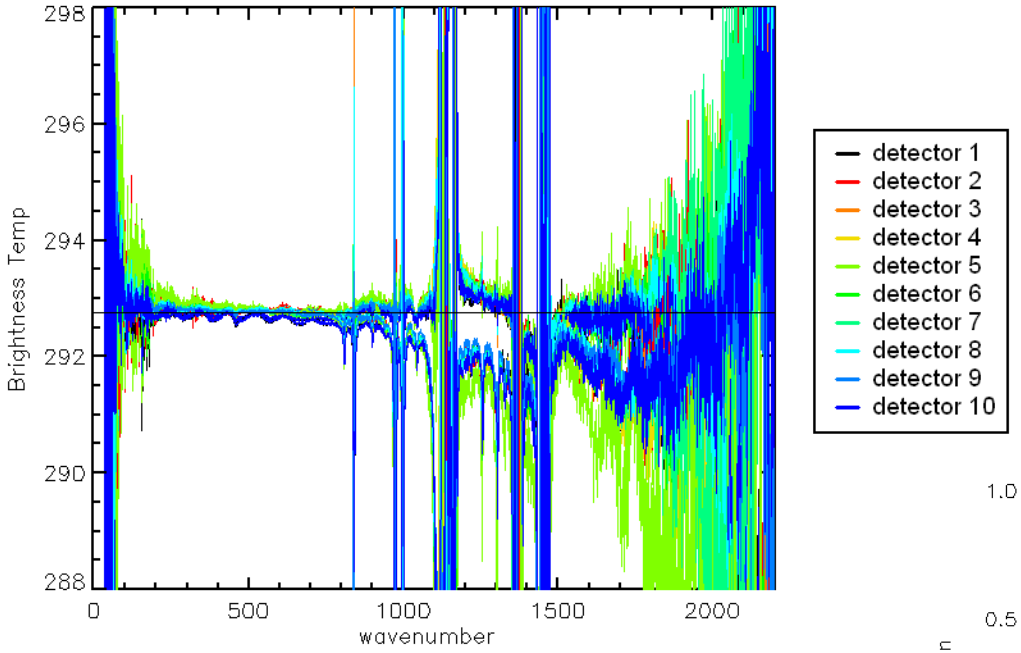
- Calibrated LWIRCS spectra
  - Imaginary part zero in calibrated spectra



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

- Radiances from other detectors overlap these
- Look like Planck functions on this scale

Calibration results at 292.76 K

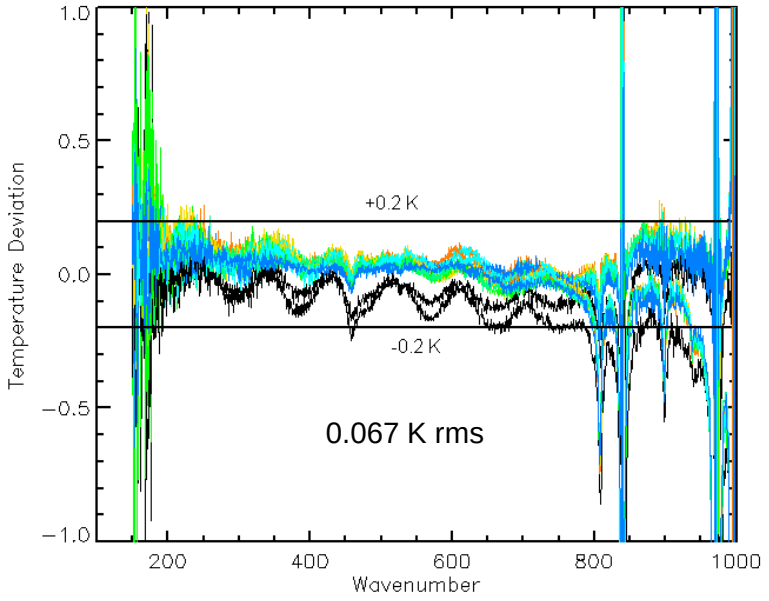


LWIRCS brightness temperature at 292.76 K

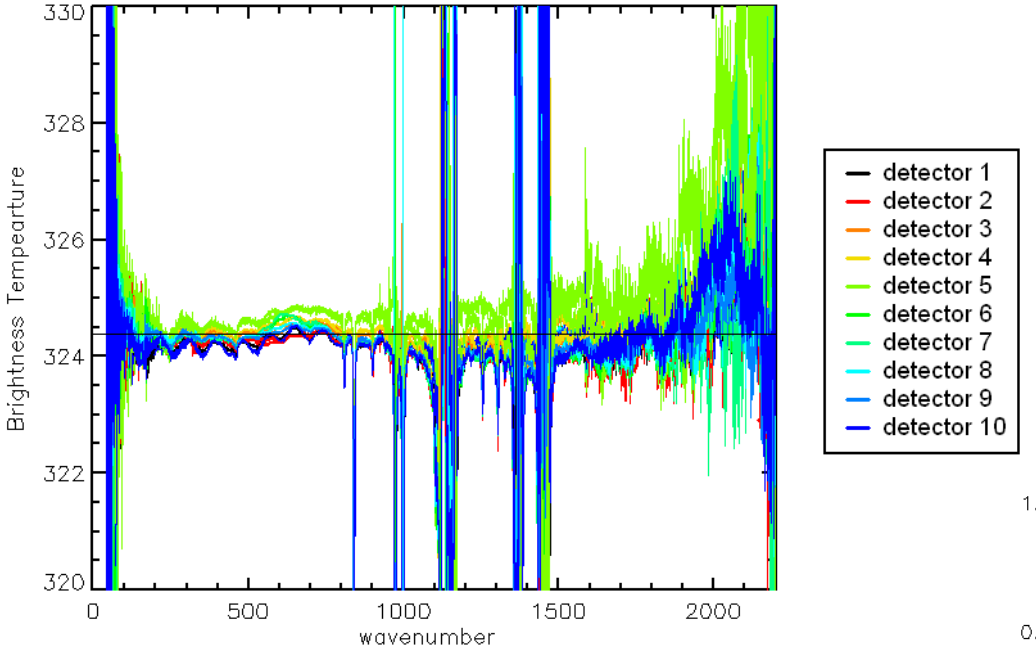
- Brightness temperature within 0.2 K of LWIRCS sensors 200 to 1000 cm^{-1}
- Vibration noise above 900 cm^{-1}
  - Different for two scan directions
  - Same for all detectors

- LWIRCS at room temperature
  - Directly compares LWIRCS, ABB temp sensors
  - Temp sensors within 0.1 K of each other

LWIRCS temperature deviation excluding detectors 2, 5 and 10



Calibration results at 324.38 K

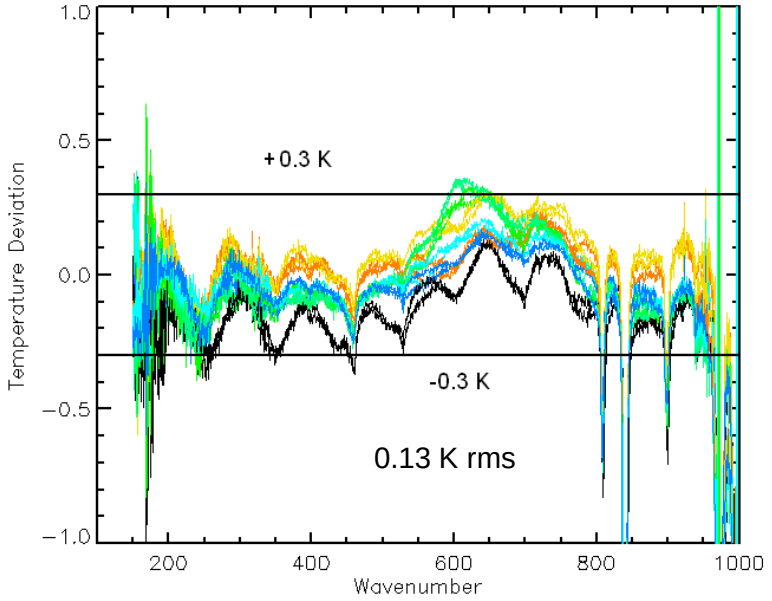


LWIRCS brightness temperature at 324.38 K

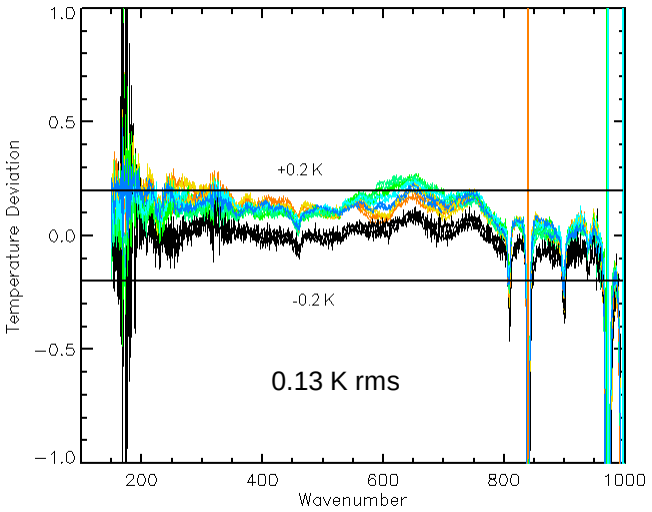
- Brightness temperature within 0.3 K of LWIRCS
- Exclude detectors 2, 5, 10
  - 2, 10 excess noise in some cases
  - 5, 10 stray light response

- LWIRCS at WBB temperature
  - LWIRCS and WBB agree to within 0.1 K
- Noise mainly systematic
  - Same in both scan directions
  - Less vibration here

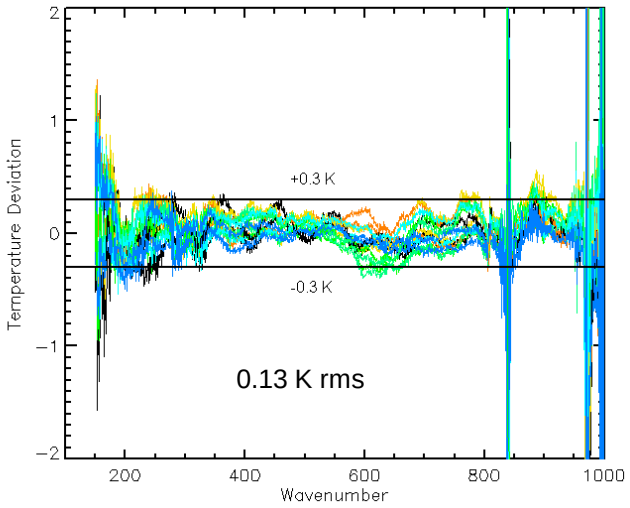
LWIRCS temperature deviation excluding detectors 2, 5 and 10



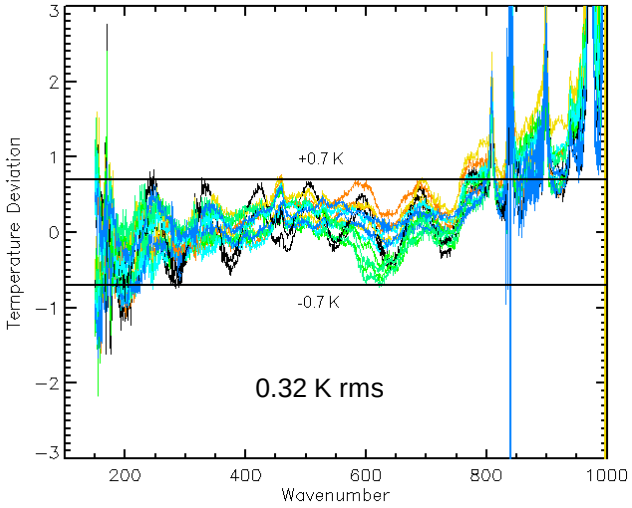
More Calibration Results



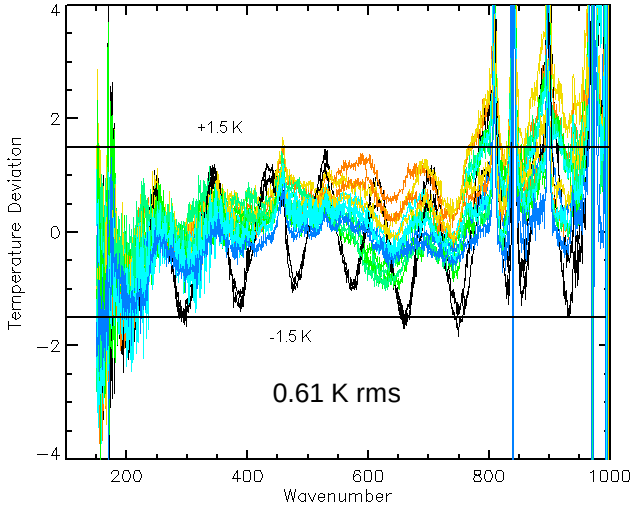
LWIRCS temperature deviation 310.34 K



LWIRCS temperature deviation 270.55 K

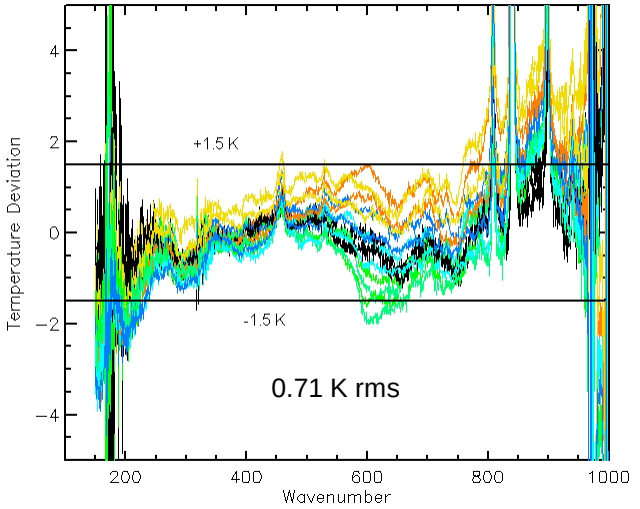


LWIRCS temperature deviation 247.42 K

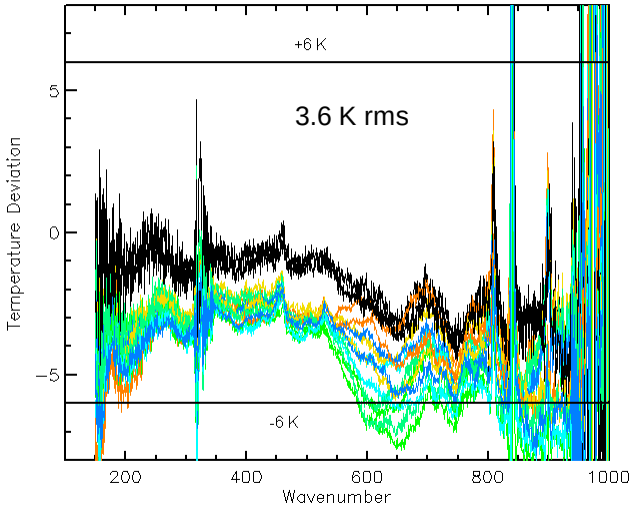


LWIRCS temperature deviation 225.18 K

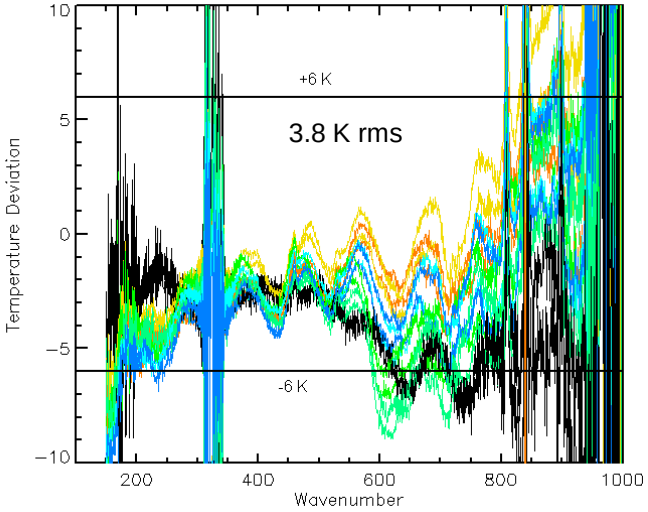
More Calibration results



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

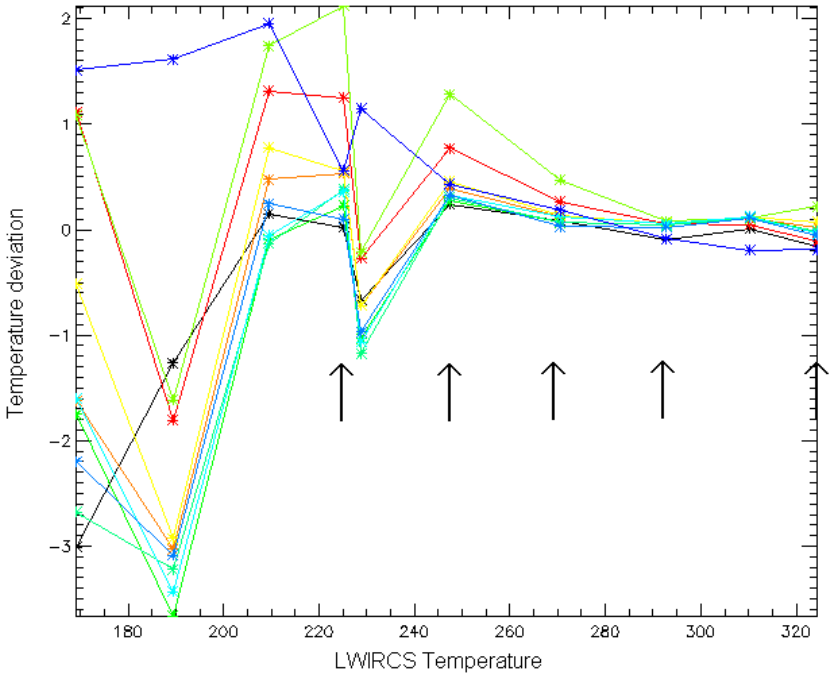
- Error from ABB, WBB spectra propagate into errors in target spectra
  - Amount rises significantly with temperature

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

- Some of increased low temperature deviation is simply an effect of error propagation

More Calibration Results



LWIRCS temperature deviation (average from 459.6 to 559.9 cm^{-1}) forward direction only. Data taken during two vacuum cycles, arrows show data from one cycle

- Deviation at low temperatures shows no consistent trend with temperature
- Source probably systematic effect that varies over time combined with error propagation
- Deviation at low temperature may vary with vacuum cycle

Conclusions

- 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 needed in calibration equation
  - No significant non-linearity
  - ABB, WBB consistent with LWIRCS
- Observed deviations probably due to small systematic effect that changes over time combined with error propagation