CLARREO IR Spectra: Achieving 0.1 K 3-sigma (SI-traceable uncertainty analyses and Post-launch Validation)

Hank Revercomb

University of Wisconsin-Madison,
Space Science and Engineering Center

CLARREO SDT Meeting
NASA LaRC
17-19 May 2011

Other UW SDT Team Members

- **Dave Tobin:** IR Reference Intercalibration
- **Bob Knuteson:** IR RADIANCE BENCHMARK PRODUCT ANALYSES
- **Bill Smith:** RETRIEVAL CLIMATE TREND ANALYSES

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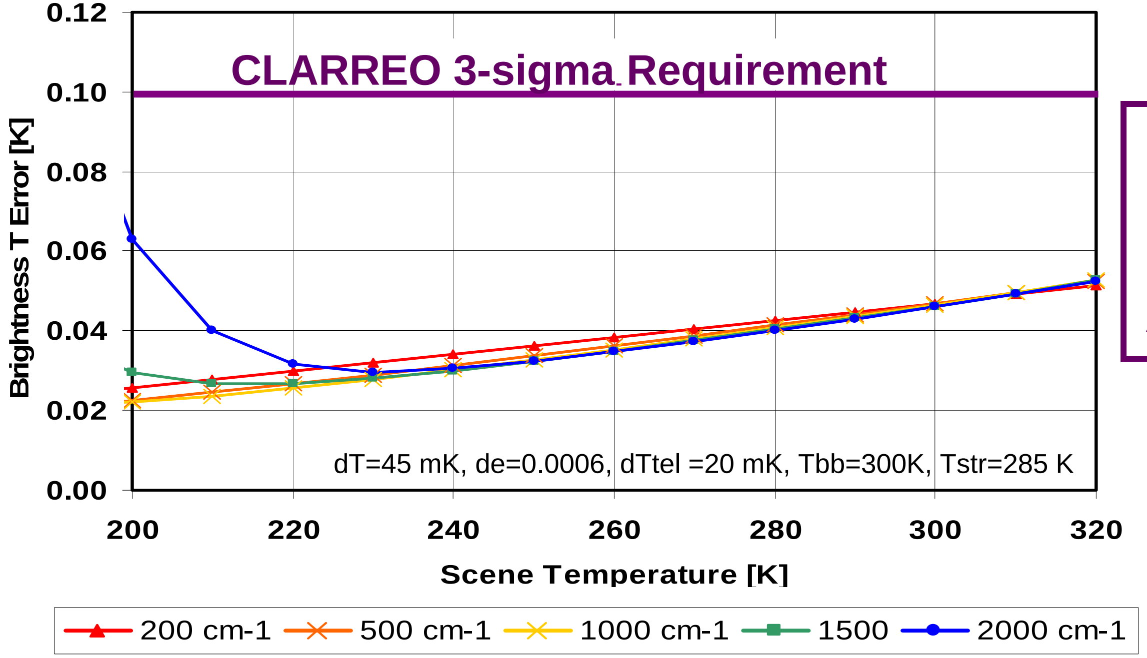
CLARREO IR Accuracy

Radiance Accuracy: <0.1 K 2-sigma brightness T for combined measurement and sampling uncertainty (each <0.1 K 3-sigma) for annual averages of large regions (to approach goal of resolving a climate change signal in the decadal time frame)

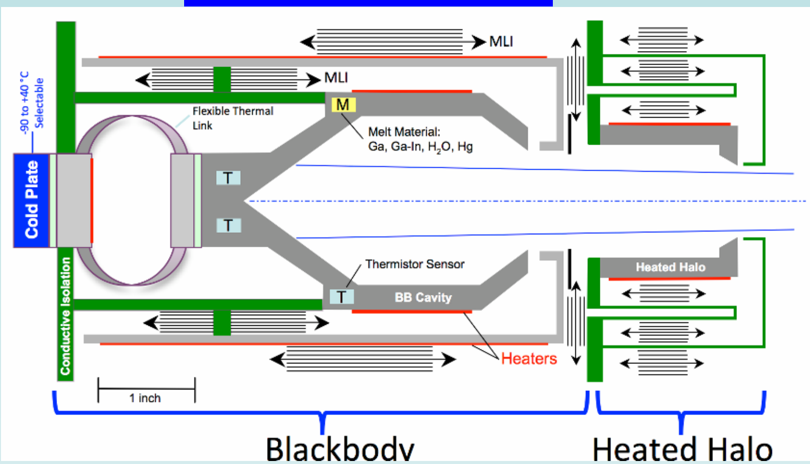


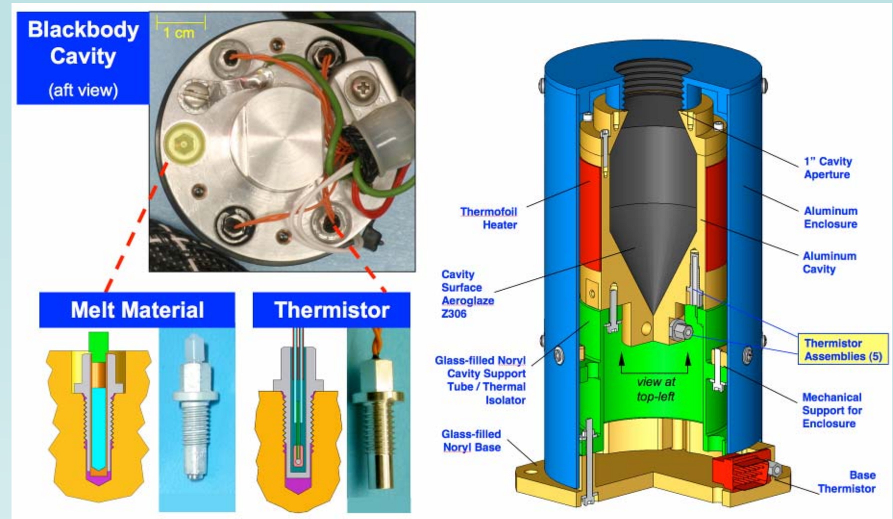
Expected Calibration Accuracy

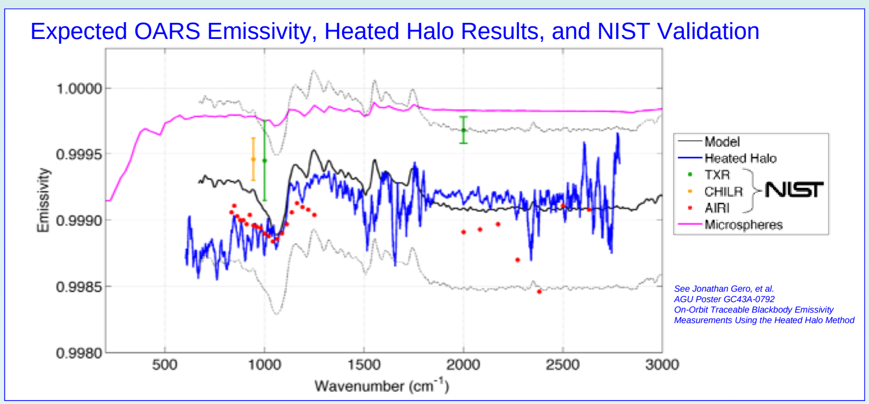
On-Orbit Absolute Radiance Standard

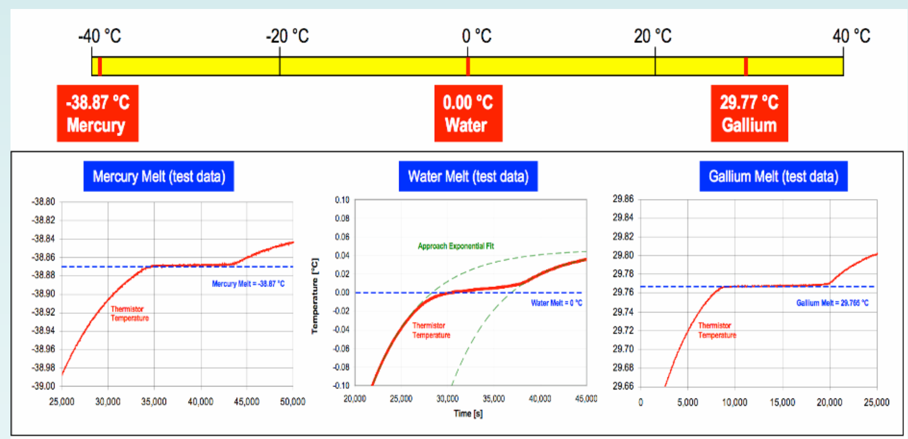
allowing calibration testing throughout mission

OARS









High Emissivity, Measured On-orbit with halo and QCL source

Absolute Temperature Calibration Using Multiple Phase Change Materials

Topics: CLARREO Measurement Science

- Background on IR Accuracy: Calibration and Validation of current sounders supports 0.1 K 3-sigma being achievable for CLARREO
- CLARREO Absolute Radiance Interferometer (ARI) Radiometric Calibration Accuracy
- CLARREO On-orbit Absolute Radiance Standard (OARS) Accuracy

Topics: CLARREO Measurement Science

- **Background on IR Accuracy: Calibration and Validation of current sounders supports 0.1 K 3-sigma being achievable for CLARREO**
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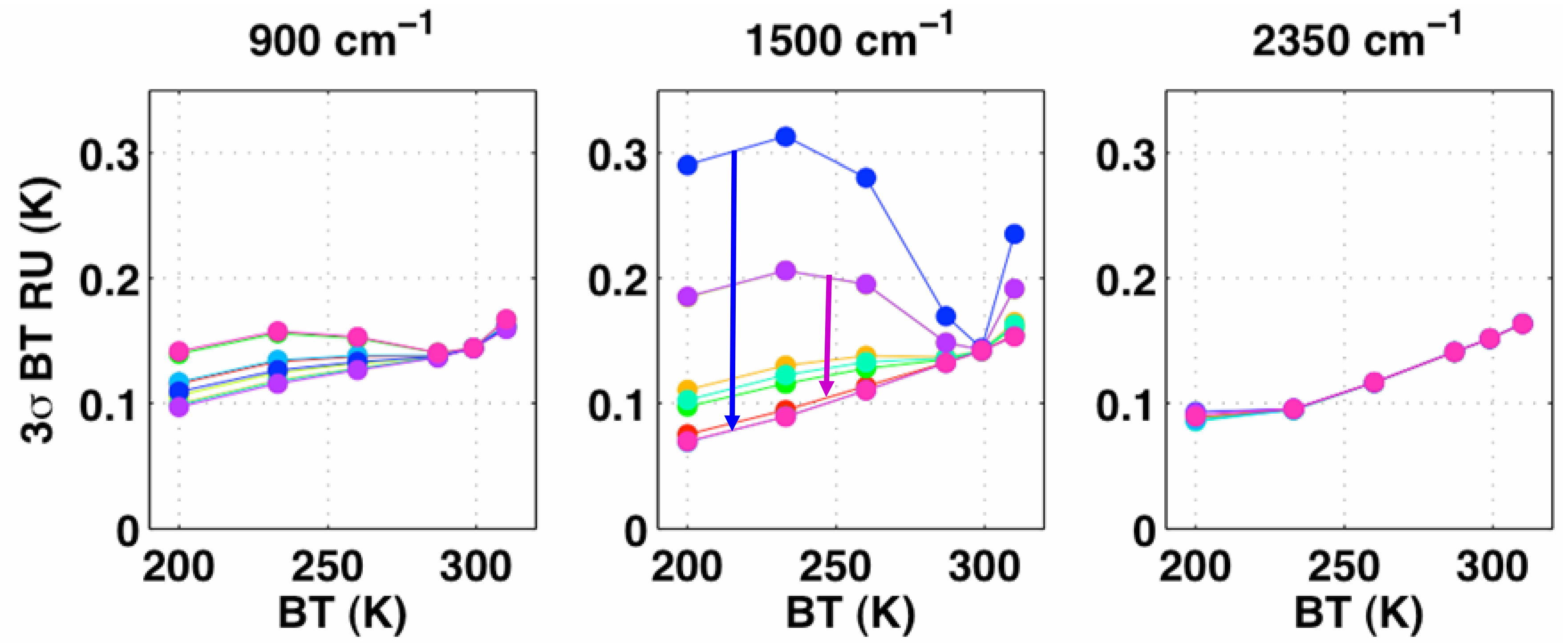
Current System Capabilities

- **New High Resolution IR Sounders:** AIRS, IASI, CrIS…
  - Tremendous advance in information content & accuracy
  - Huge advance for climate process studies, offering
    - High vertical resolution T and WV profiling
    - Trace gas distributions
    - Cloud and surface properties
  - Provide a solid foundation for CLARREO IR feasibility
  - But, not optimized for unequivocal decadal trending
    - Biased diurnal sampling
    - Inconsistent and incomplete spectral coverage among platforms
    - SI traceability post-launch limited to aircraft inter-comparisons (sounder-to-sounder comparisons useful, but do not have direct, timely connections to International Standards)

CrIS FM1 In-flight Radiometric Uncertainty:

versus scene temperature for all FOVs for ~mid-band spectral channels

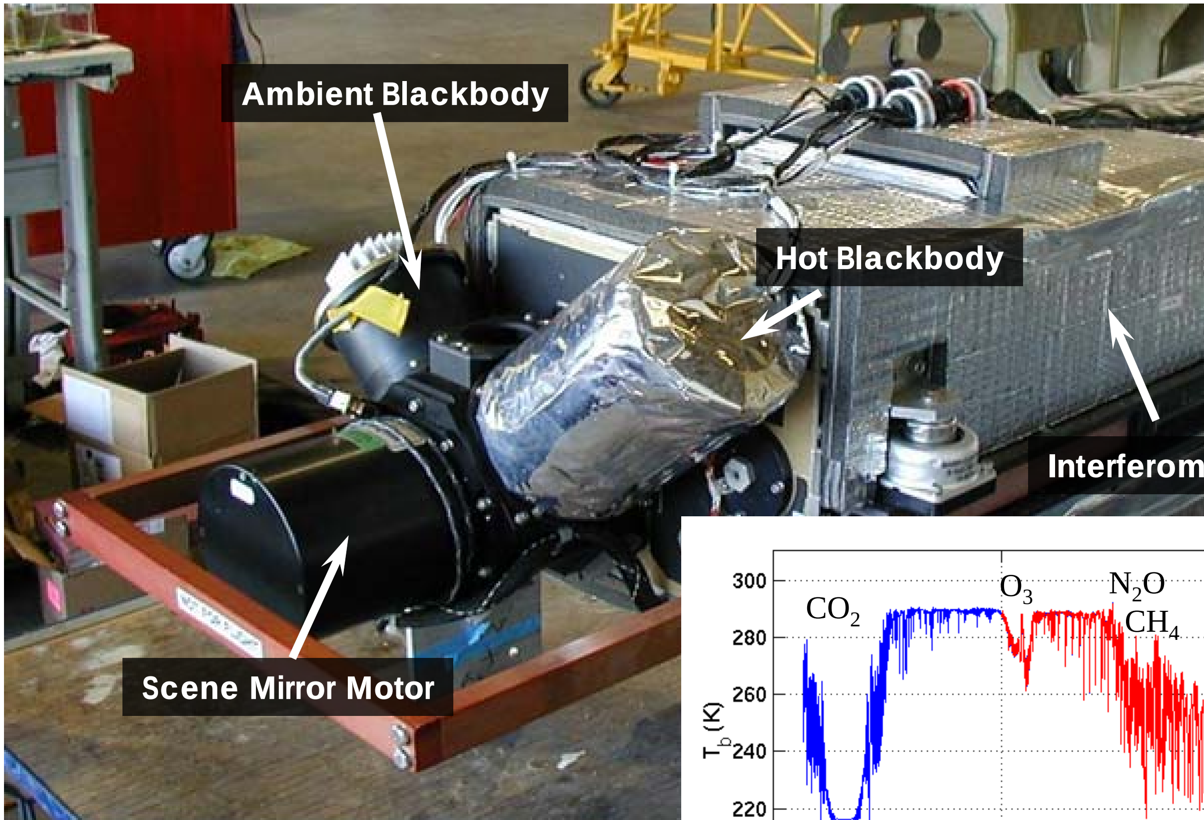
Generally < 0.2 K 3-sigma for all scene temperatures

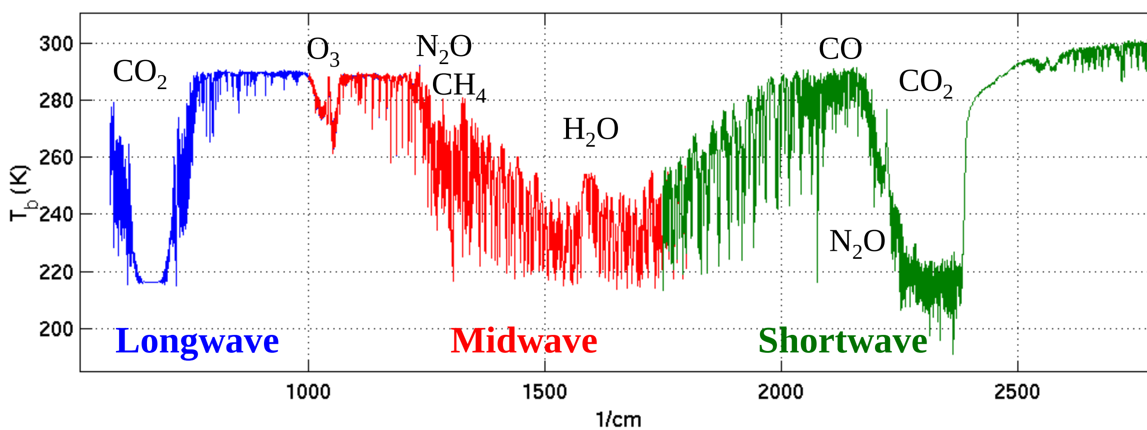


Non-linearity causing prominent FOV dependence (color coded) will be reduced significantly by in-flight FOV inter-comparisons

Scanning HIS Aircraft Instrument:

Inter-comparisons connect high res. sensor calibrations





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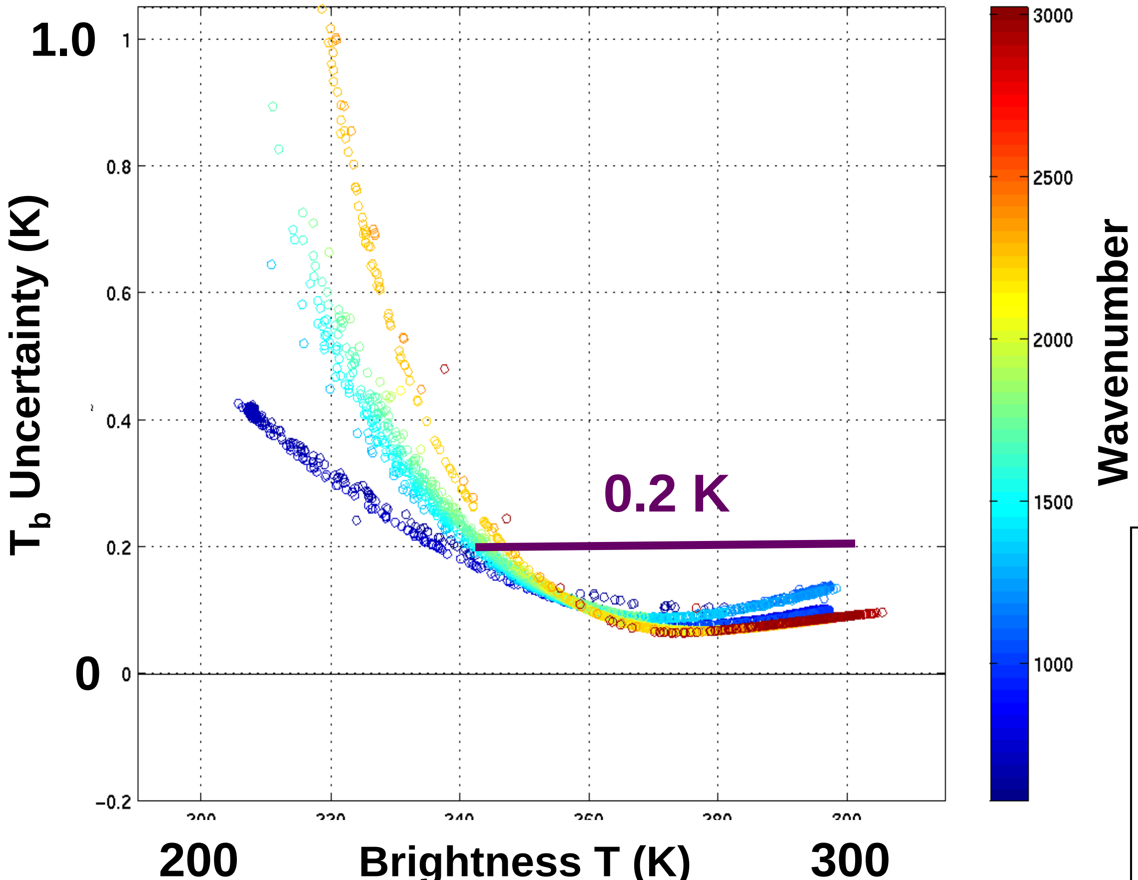
S-HIS Absolute Radiometric Uncertainty

for typical Earth scene spectrum

****Formal 3-sigma absolute uncertainties, similar to that detailed for AERI in Best et al. CALCON 2003**

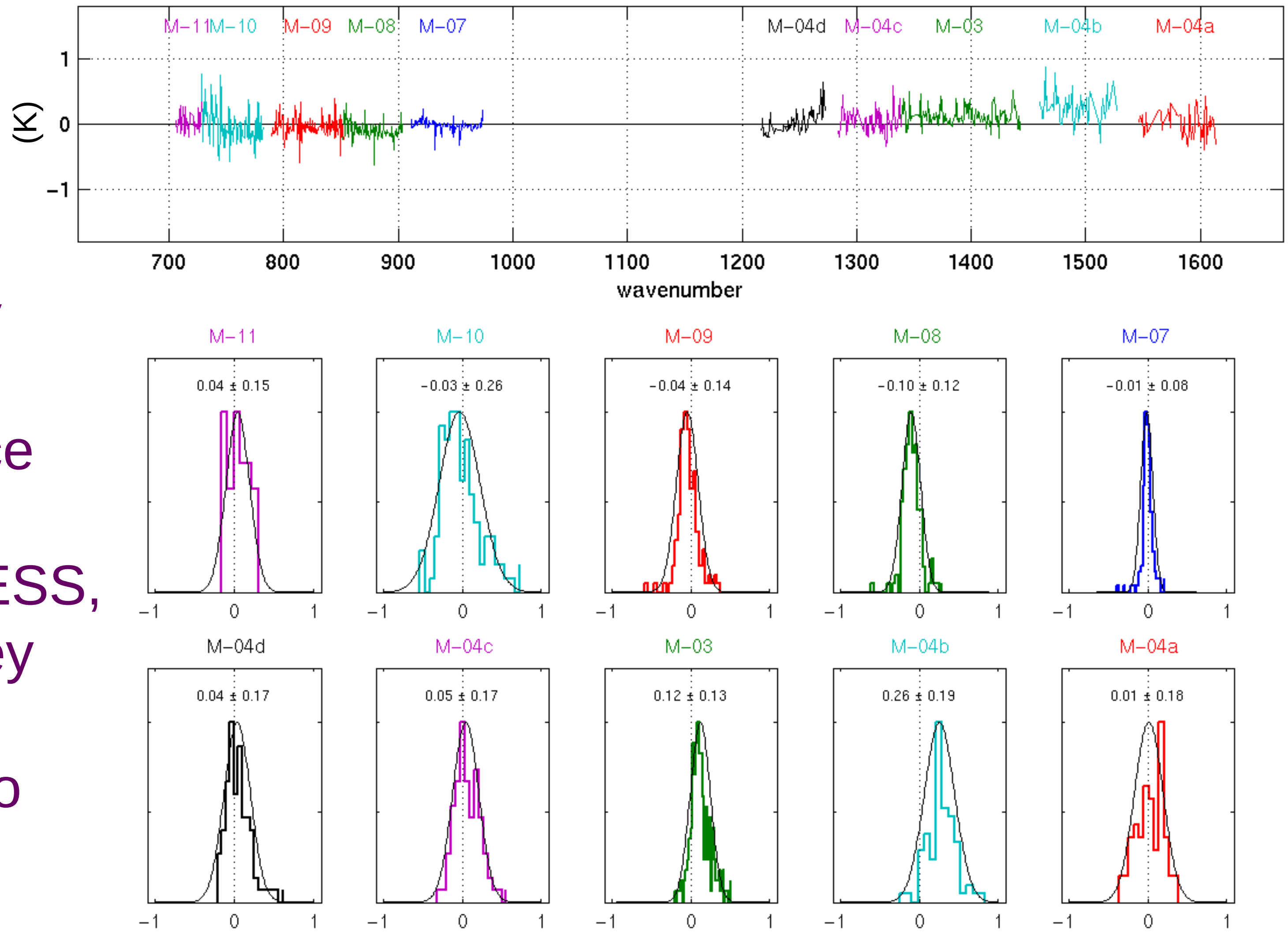


T_{ABB}= 260 K
T_{HBB}= 310 K

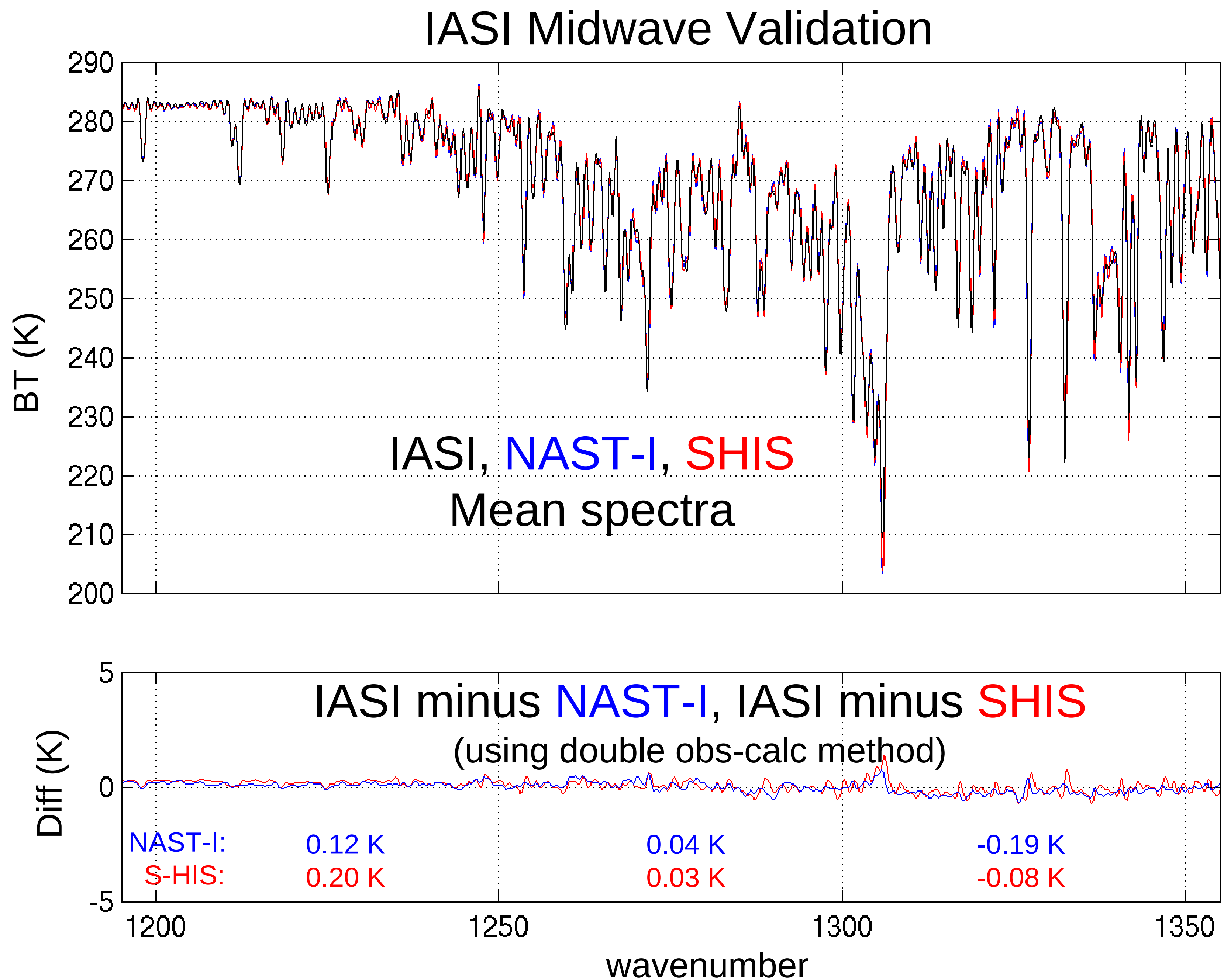
σT_{BB} = 0.10 K
$\sigma \varepsilon_{BB}$ = 0.0010
σT_{refl} = 5 K
10% nonlinearity

Example S-HIS Validation of AIRS

Aircraft is key approach for direct radiance validation of EOS & NPOESS, and will be key to CLARREO validation also



21 November 2002



IASI Midwave Validation
IASI, NAST-I, SHIS
Mean spectra
BT (K)
IASI minus NAST-I, IASI minus SHIS
(using double obs-calc method)
Diff (K)
NAST-I: 0.12 K 0.04 K -0.19 K
S-HIS: 0.20 K 0.03 K -0.08 K
wavenumber

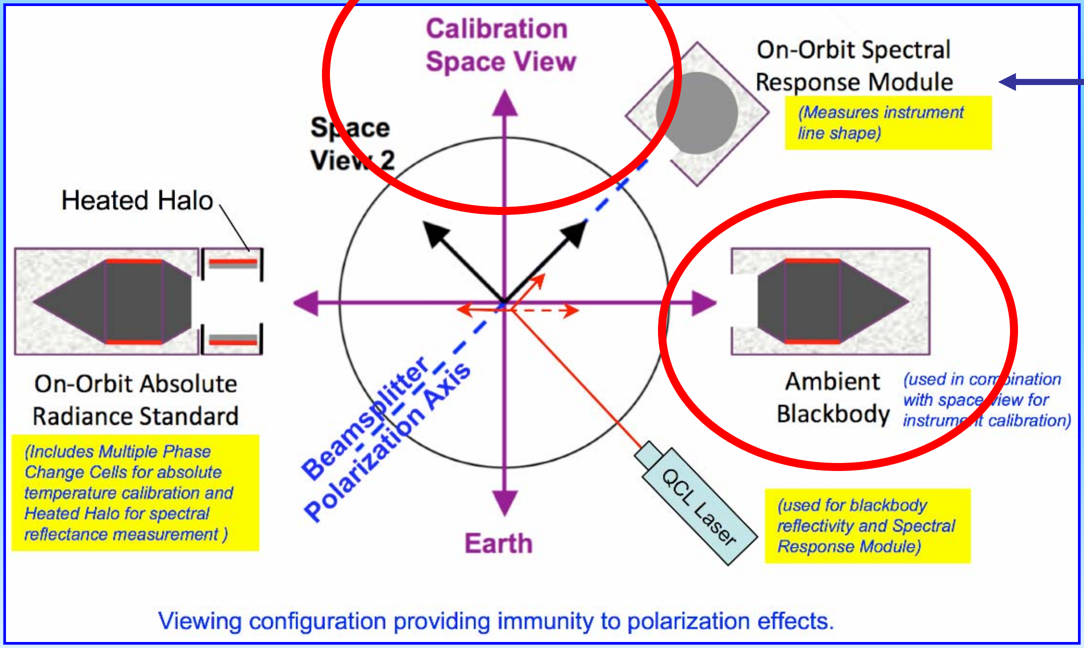
Topics: CLARREO Measurement Science

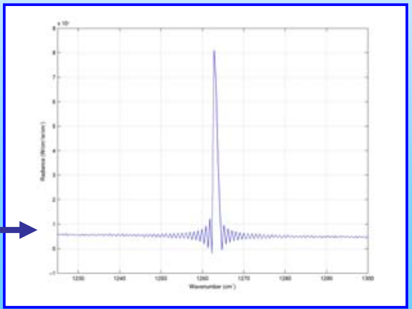
- Background on IR Accuracy: Calibration and Validation of current sounders supports 0.1 K 3-sigma being achievable for CLARREO
- **CLARREO Absolute Radiance Interferometer (ARI) Radiometric Calibration Accuracy**
- CLARREO On-orbit Absolute Radiance Standard (OARS) Accuracy

Absolute Radiance Interferometer (ARI) Calibration

NASA IIP

Basic Radiometric Calibration Established using Views of Ambient Blackbody Reference and Space

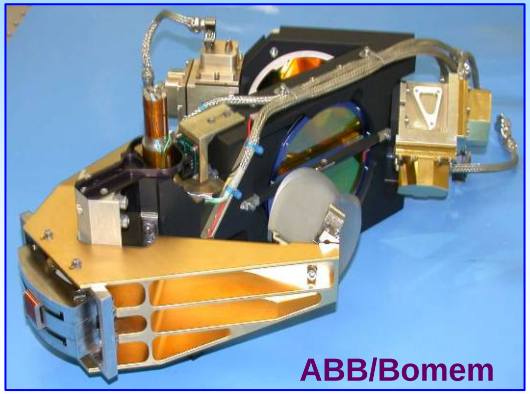




Spectral line shape from QC Laser source

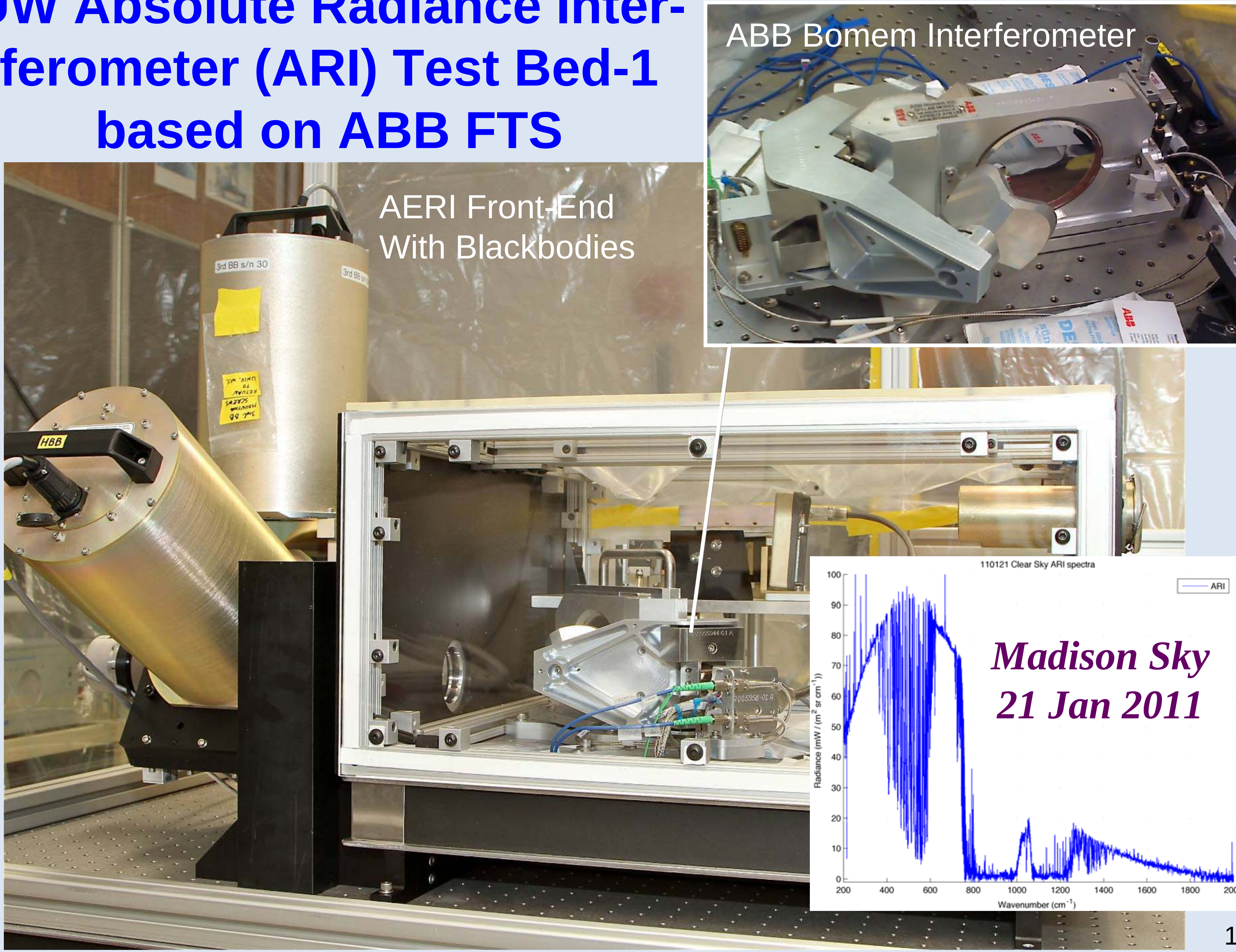
Pulse-tube detector cooler

Lack of requirement for cross-track coverage and high noise performance allows calibration biases to be minimized



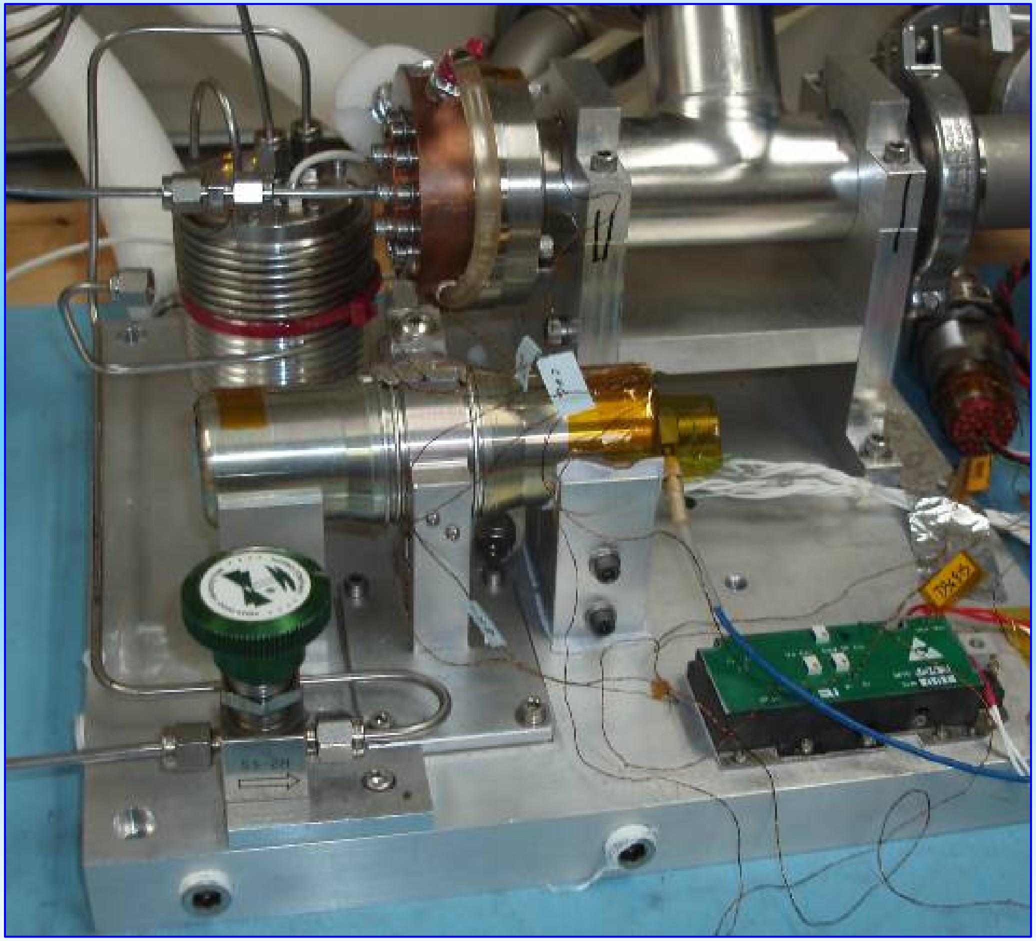
High Performance FTS

UW Absolute Radiance Interferometer (ARI) Test Bed-1 based on ABB FTS



CLARREO Candidate Detector Cooler

NGST Pulse Tube Microcooler



Calibration: Blackbody Contributors

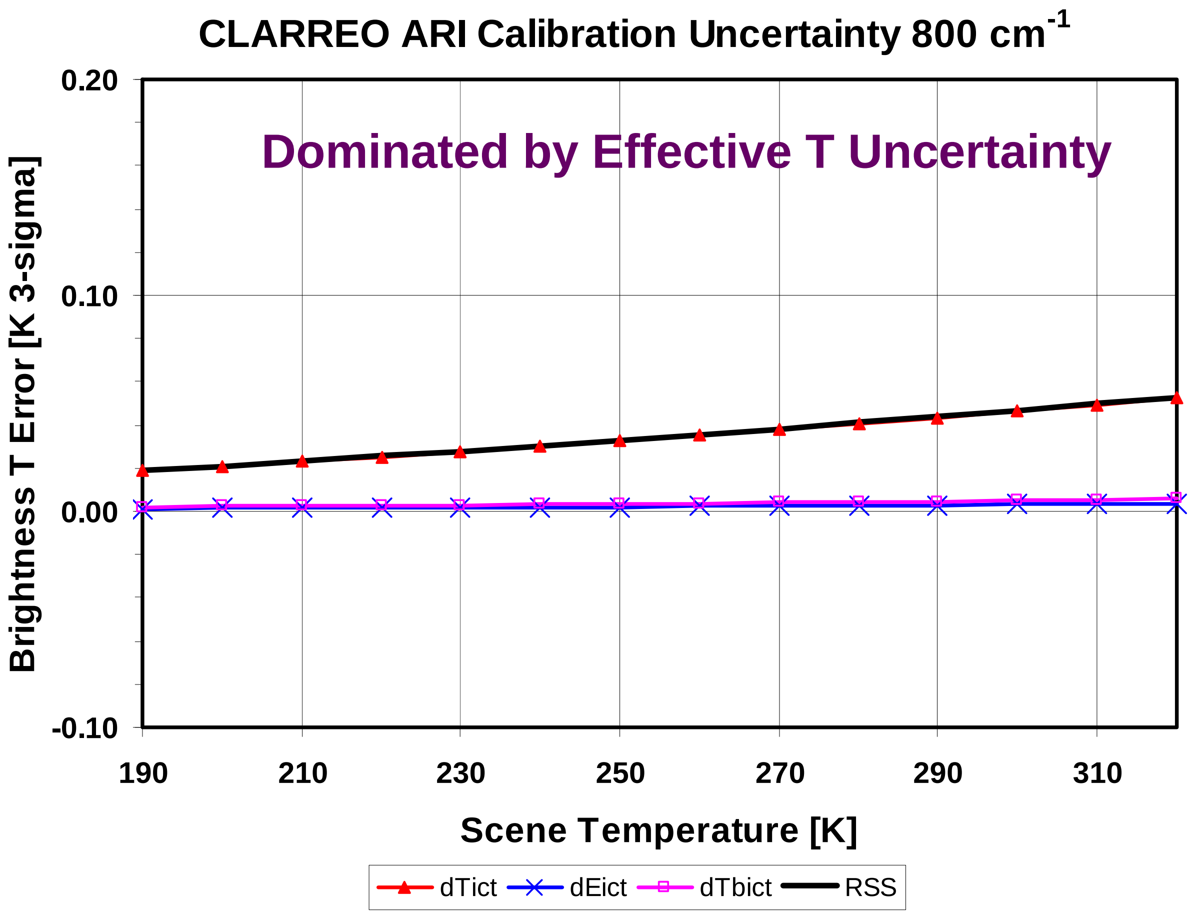
Parameter ± 3-sigma

Blackbody T:
295 ± 0.047 K

Background T:
290 ± 5 K

Emissivity:
0.999 ± 0.0006*

*** Gero et al.**



Blackbody Effective Temperature

Temperature Uncertainty	3 sigma error [K]	RSS [K]
Temperature Calibration Standard (Thermometrics SP60 Probe with Hart Scientific 2560 Thermistor Module)	0.005	
		0.005
Blackbody Readout Electronics Uncertainty		
Readout Electronics Uncertainty (at delivery)	0.005	
		0.005
Blackbody Thermistor Temperature Transfer Uncertainty		
Gradient Between Temperature Standard and Cavity Thermistors	0.010	
Calibration Fitting Equation Residual Error	0.001	
		0.010
Cavity Temperature Uniformity Uncertainty *(based on GIFTS)*		
Cavity to Thermistor Gradient Uncertainty	0.025	
Thermistor Wire Heat Leak Temperature Bias Uncertainty	0.008	
Paint Gradient	0.018	
		0.032
Long-term Stability *(assuming transfer from OARS)*		
Blackbody Thermistor	0.010	
Blackbody Controller Readout Electronics		
		0.010
Effective Radiometric Temperature Weighting Factor Uncertainty		
Monte Carlo Ray Trace Model Uncertainty in Determining Teff	0.030	
(1/3 of total max expected gradient)		0.030
		0.047

- Lab Cal Standard
- Transfer to cavity
- T Sensor to Paint Surface
- Uncertainty of OARS transfer
- Effect of surface T gradients

Calibration: Wavenumber Dependence

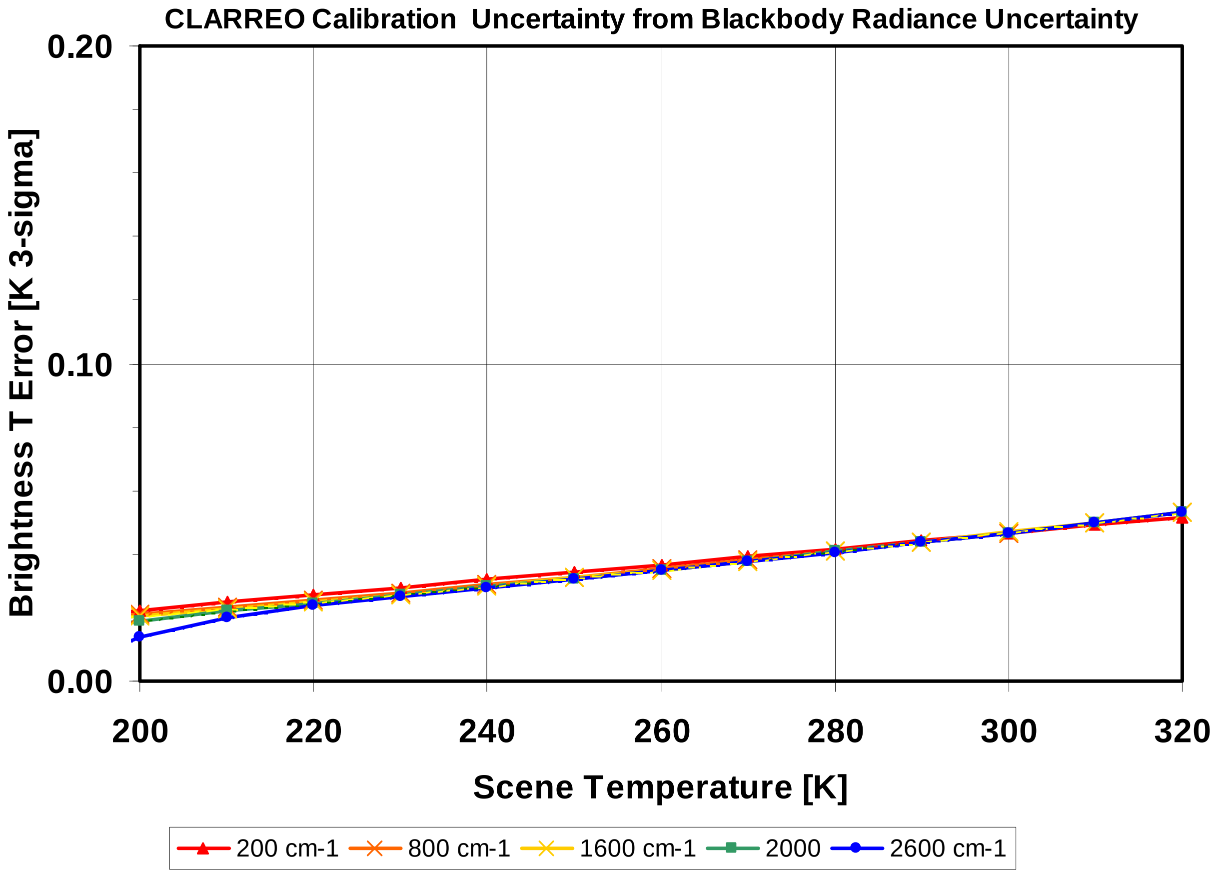
Parameter ± 3-sigma

Blackbody T:
295 ± 0.047 K

Background T:
290 ± 5 K

Emissivity:
0.999 ± 0.0006*

*** Gero et al.**



Non-linearity

- **Keep small by design:** Pyroelectric and SW semiconductor detectors (InSb or PV MCT) are extemely linear for earth scenes
- **Characterization:** (thermal vacuum testing and on-orbit)
  - (1) viewing accurate blackbody sources over a wide range of temperatures,
  - (2) using out-of-band harmonic signatures for the PV HgCdTe detectors as was demonstrated to be very effective during thermal vacuum testing of CrIS (originally demonstrated by UW for PC HgCdTe detectors on the AERI ground-based and Scanning HIS and NAST-I aircraft instruments), and
  - (3) spectral comparisons in the overlap region with the FAR IR detectors, which are known to have zero effective non-linearity for the dynamic range of ARI observations (Theochaourous *App. Opt.* **47** (21) p3731 2008).

Calibration: Non-linearity

Parameter ± 3-sigma

Blackbody T:
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Background T:
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Emissivity:
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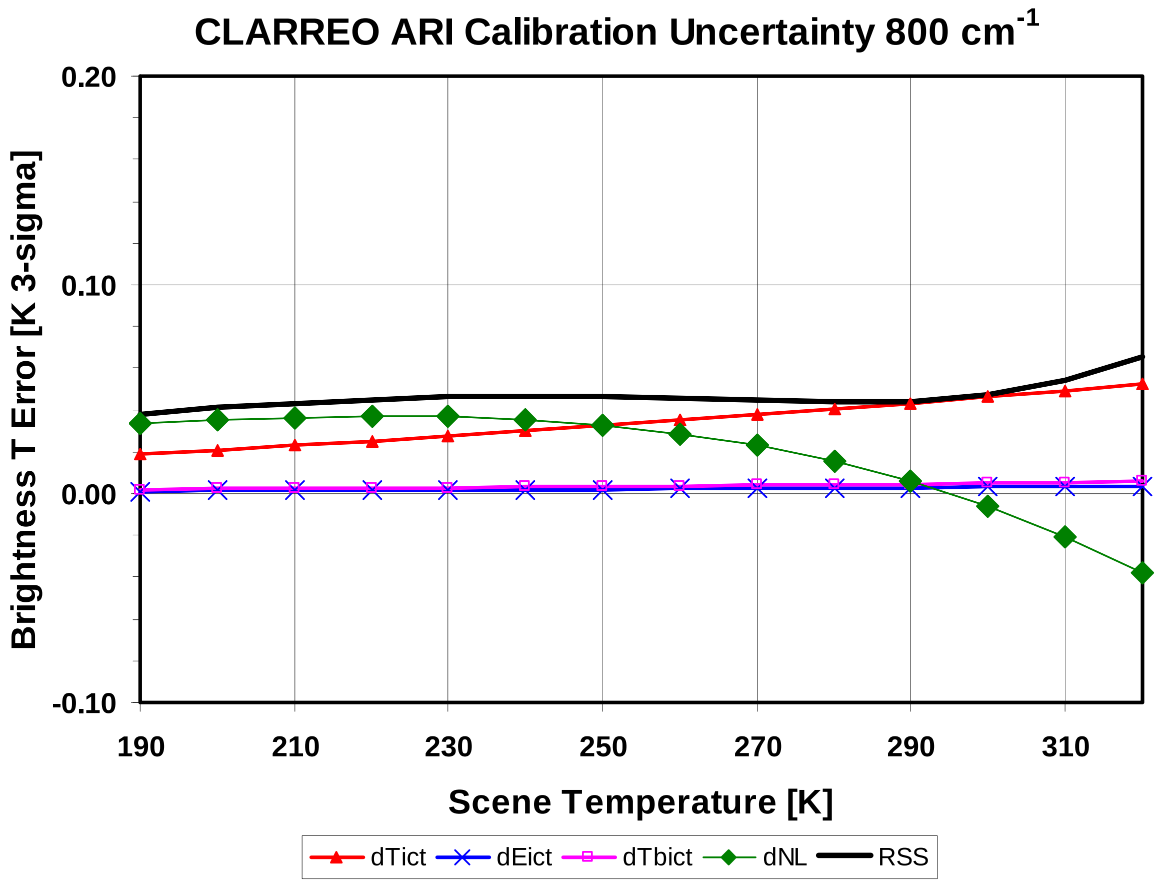

Non-Linearity <0.03%

(Non-linearity ≡ maximum departure from linearity at half of the calibration blackbody radiance, expressed as a percent of the calibration blackbody radiance)

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Other Important Factors

- Polarization
  - Scene selection mirror is used at 45° for all sources and is gold plated to assure that the induced polarization is very small (polarization at 45° degrees is less than about 0.5% for gold with no over-coating)
  - It is possible to arrange all calibration views to have the same polarization sensitivity as the earth view (with no cross-track scanning, all can be placed at ±90° or 180° from the earth view)
  - A second space view at a significantly different angle will be used to demonstrate that the polarization-null design is maintained on-orbit
- Stray Radiation
  - It is expected that calibration uncertainty from stray radiation can be made negligible by careful optical design, control and placement of stops, selection of low-scatter optics, and by matched aperture viewing to earth and calibration sources
  - Stray radiation will also be tested on the ground and in orbit using heated viewing apertures
- Thermal Stability
  - The effects of thermal changes between calibrations will be controlled to negligible levels using frequent calibration viewing and by effectively interpolating calibration view data and housekeeping temperature data to the times of each earth view

Topics: CLARREO Measurement Science

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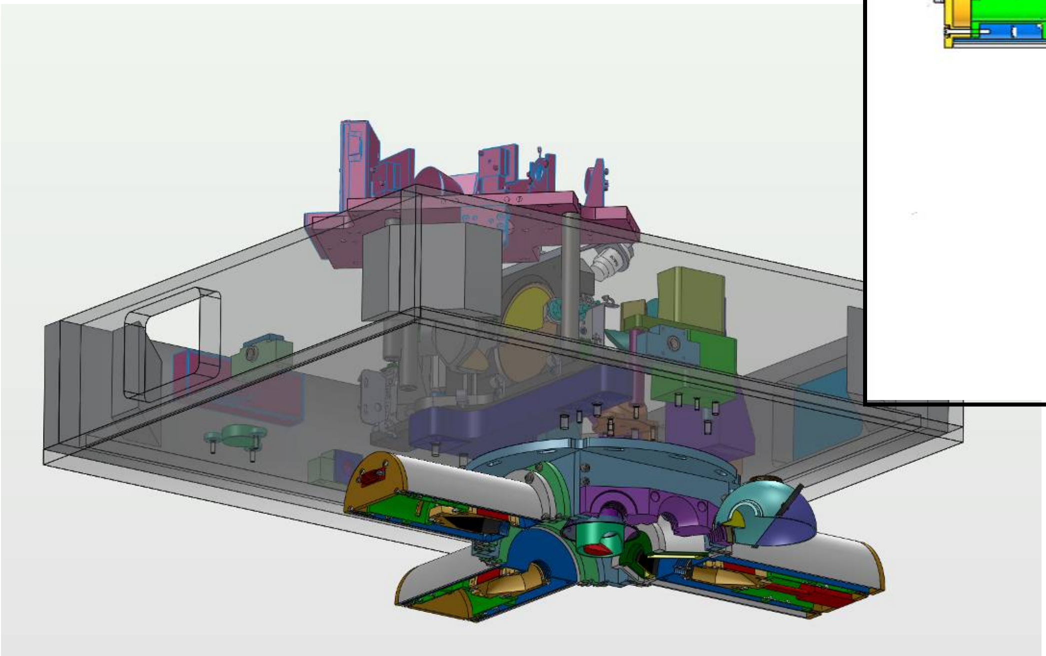
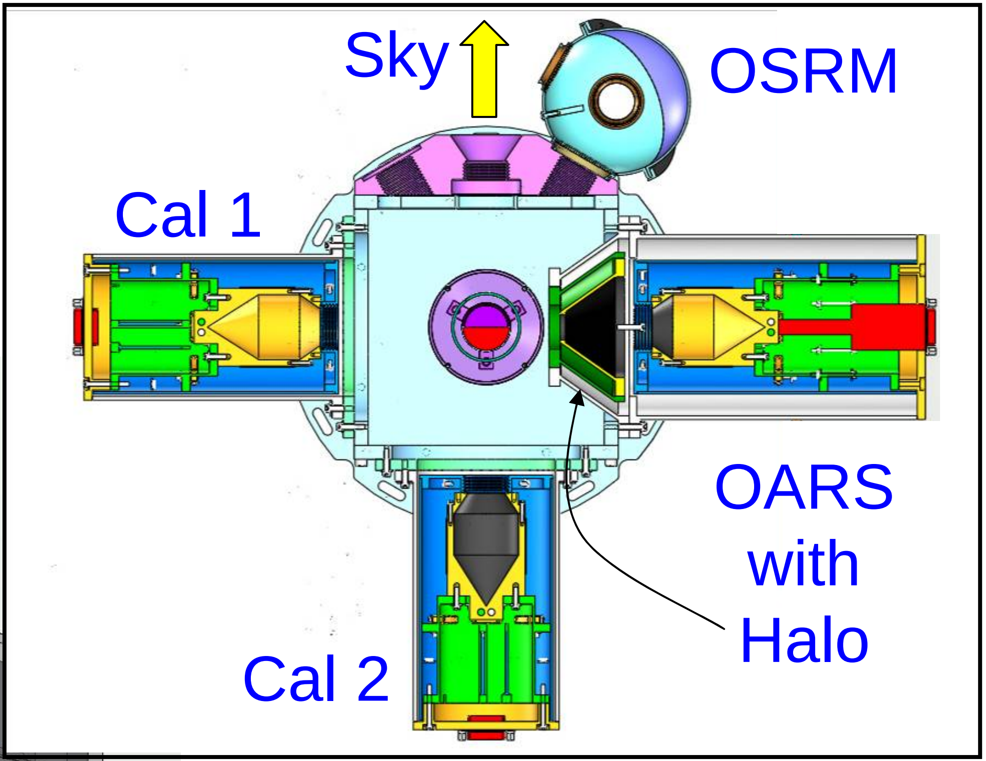
- **CLARREO On-orbit Absolute Radiance Standard (OARS) Accuracy**

Breadboard 2: Flight-like Configuration

3 cm aperture Sources

45° Gold Scene Mirror selects source

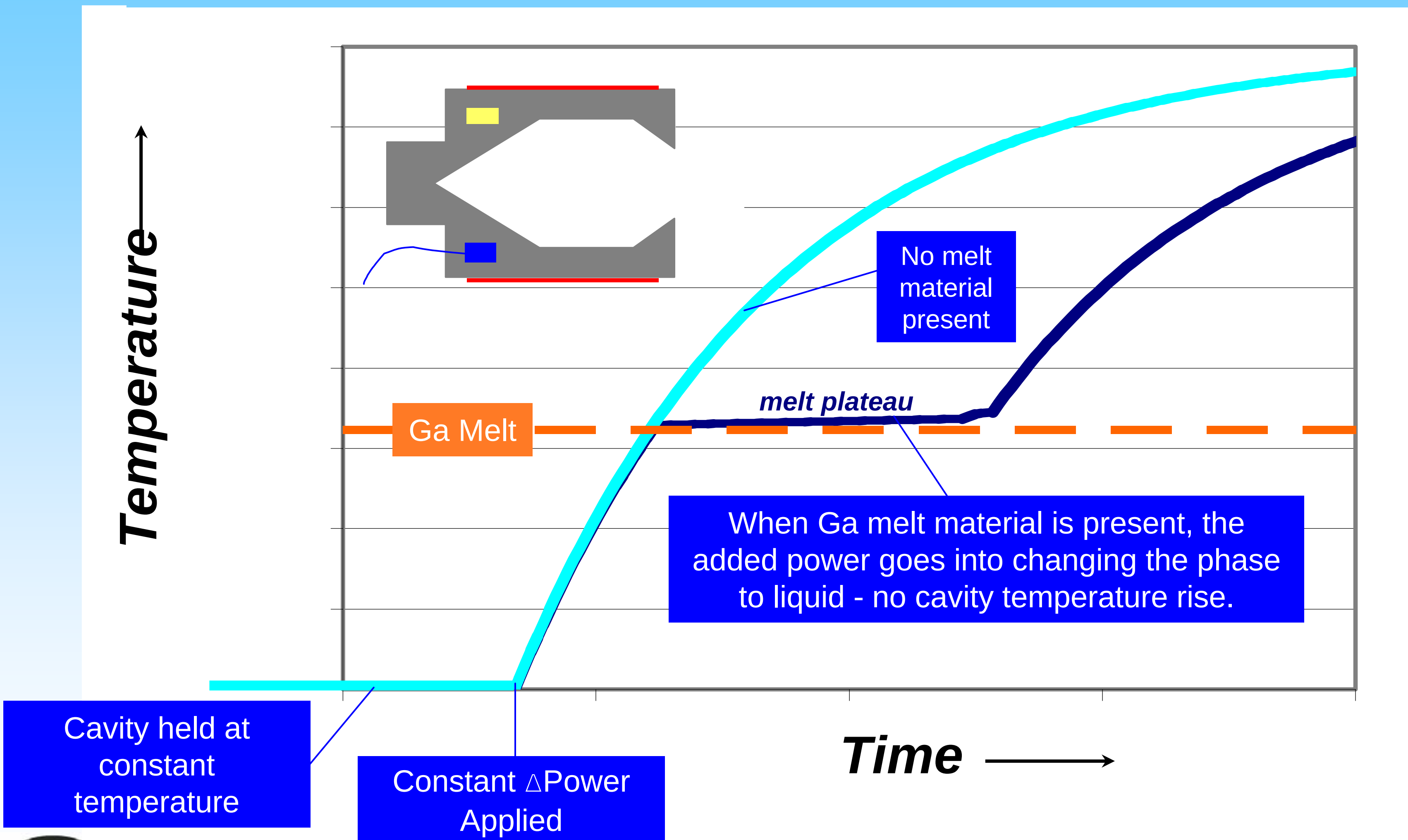




OARS: On-orbit Absolute Radiance Standard

OSRM: On-orbit Spectral Response Module

New concept for on-orbit phase change temperature calibration: Anatomy of a Melt Signature

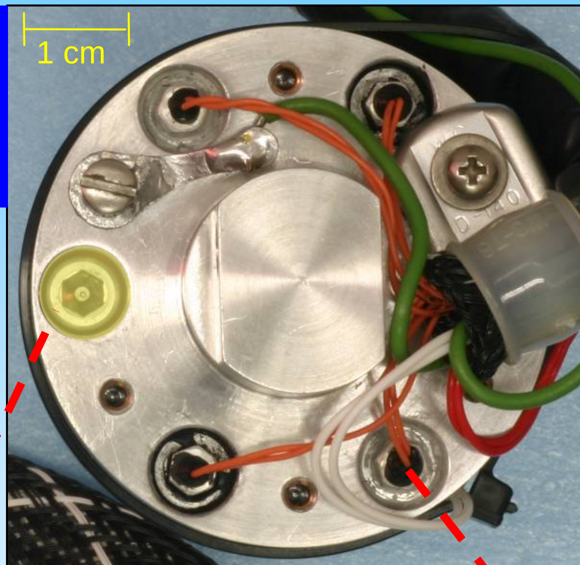


SSEC GIFTS-type Cavity

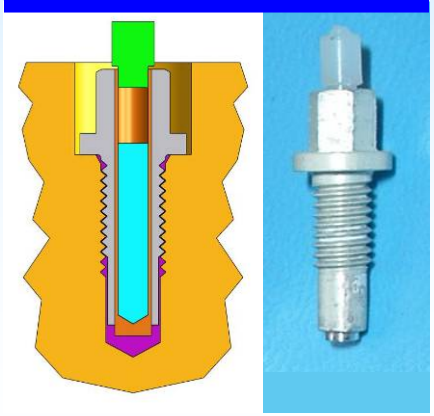
(configured for melt signature tests)

Blackbody Cavity

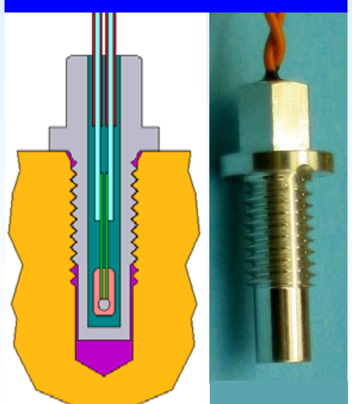
(aft view)

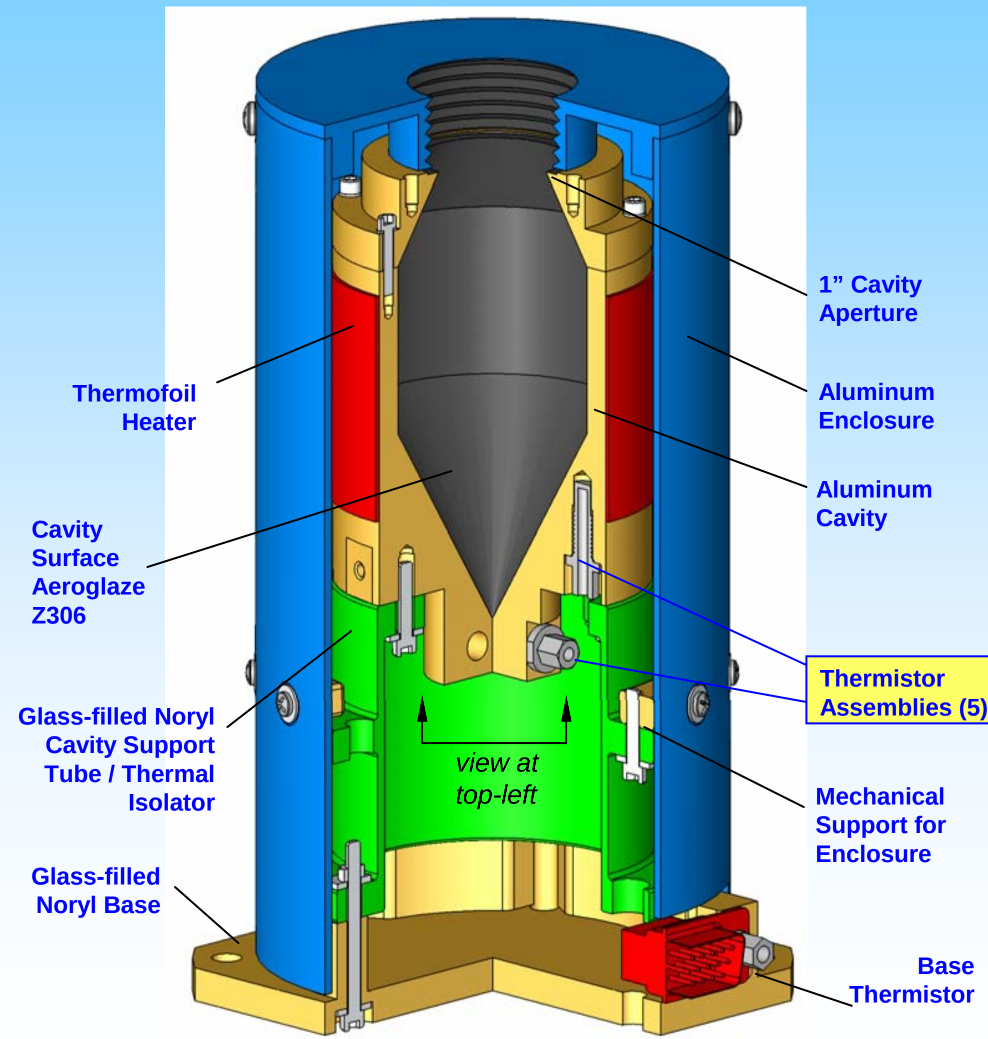


Melt Material

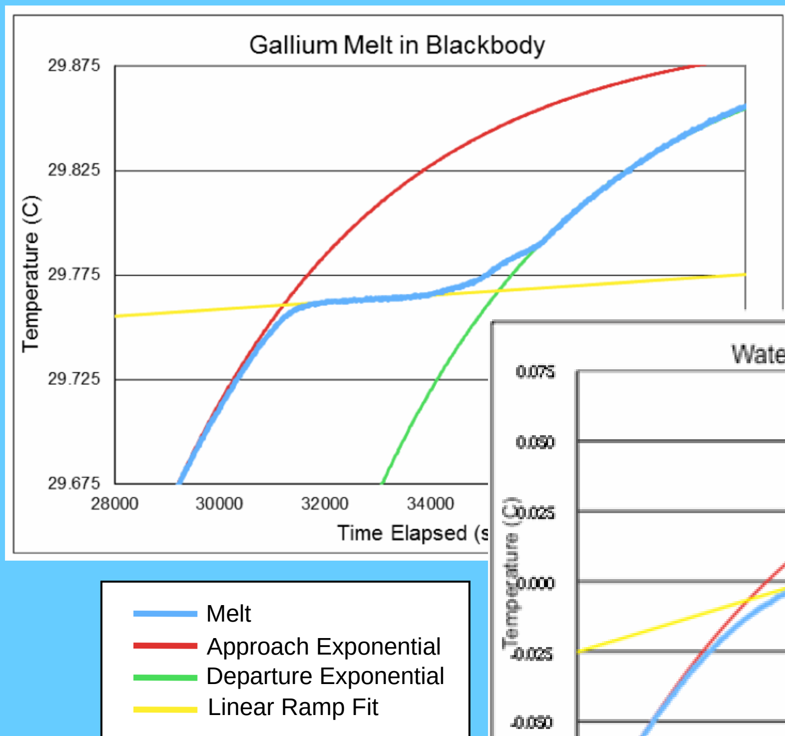


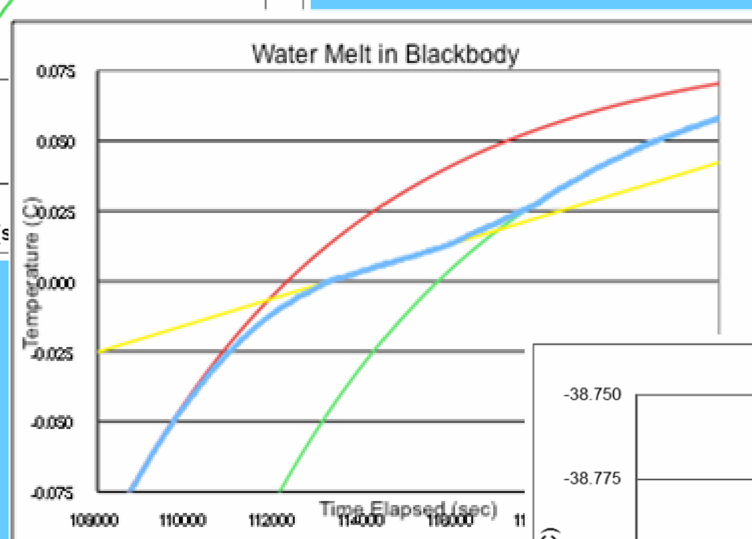
Thermistor

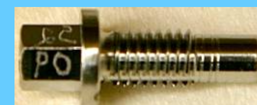


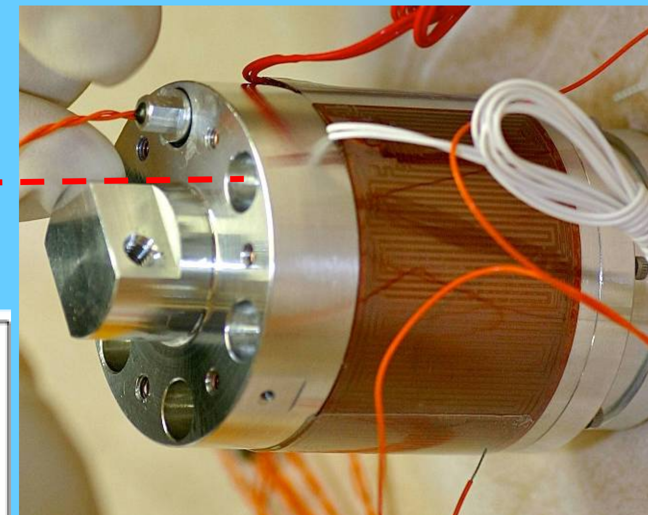


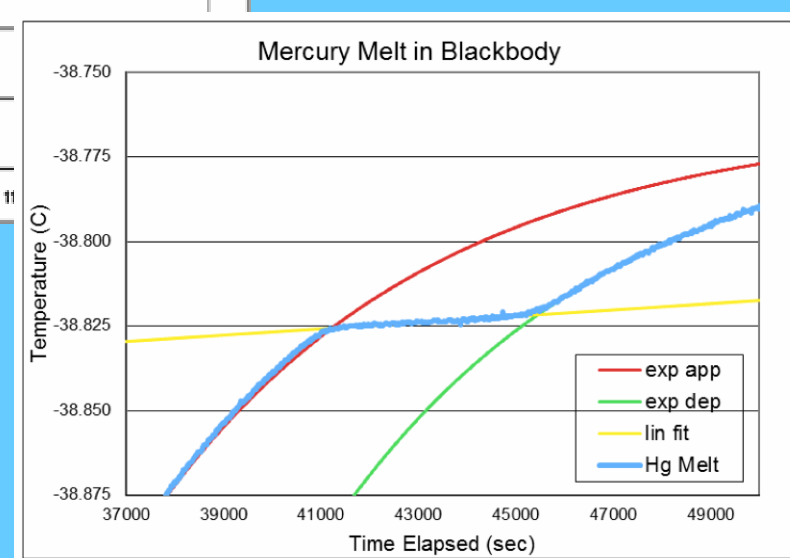
Signatures in Blackbody
demonstrate better than ±5mK accuracy





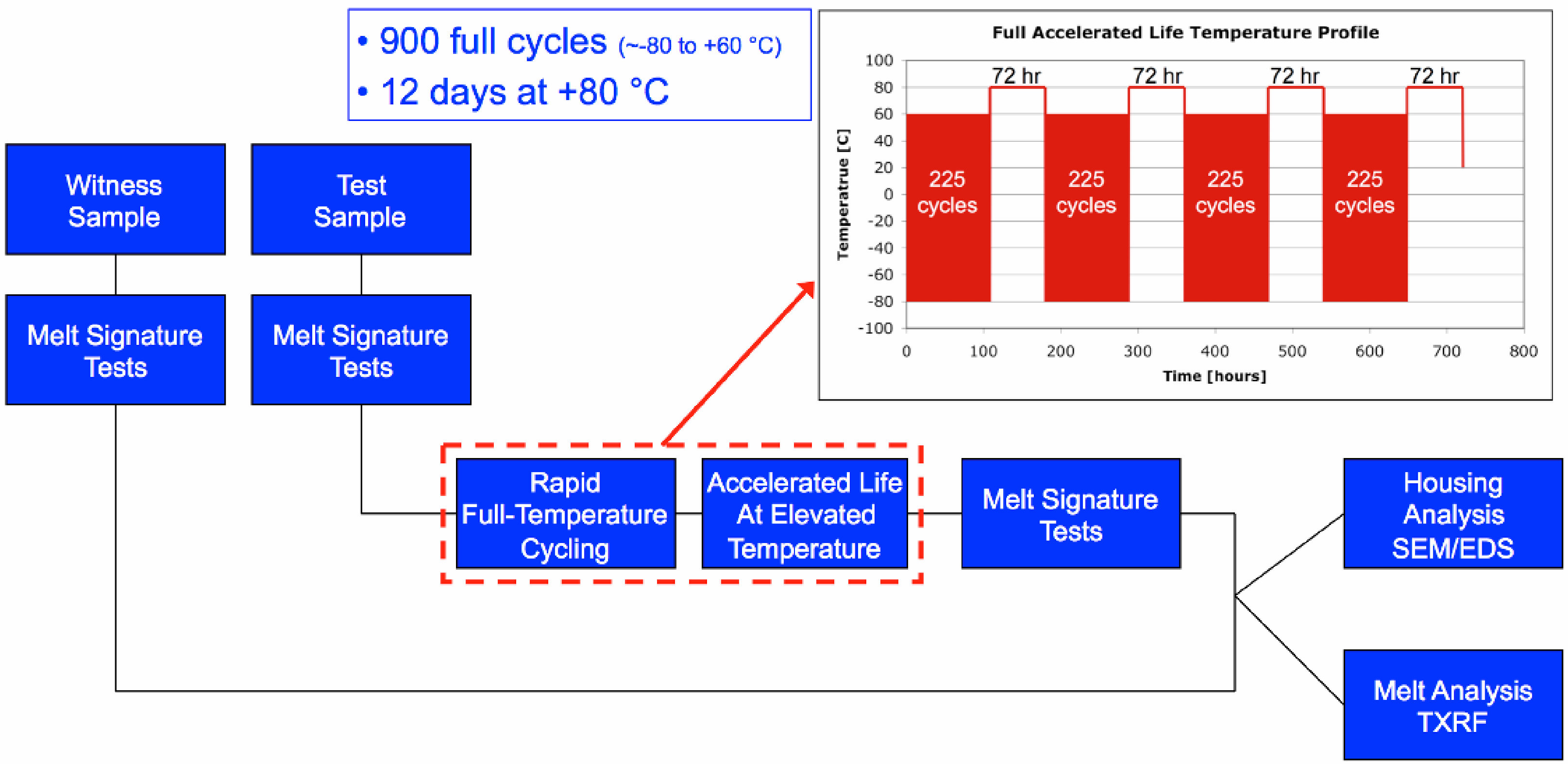






Miniature Phase Change Cells Integrated Into Blackbody and Signatures Obtained

Conducted Full Accelerated Life Test For Ga, H2O, and Hg Packaged in Welded Housings



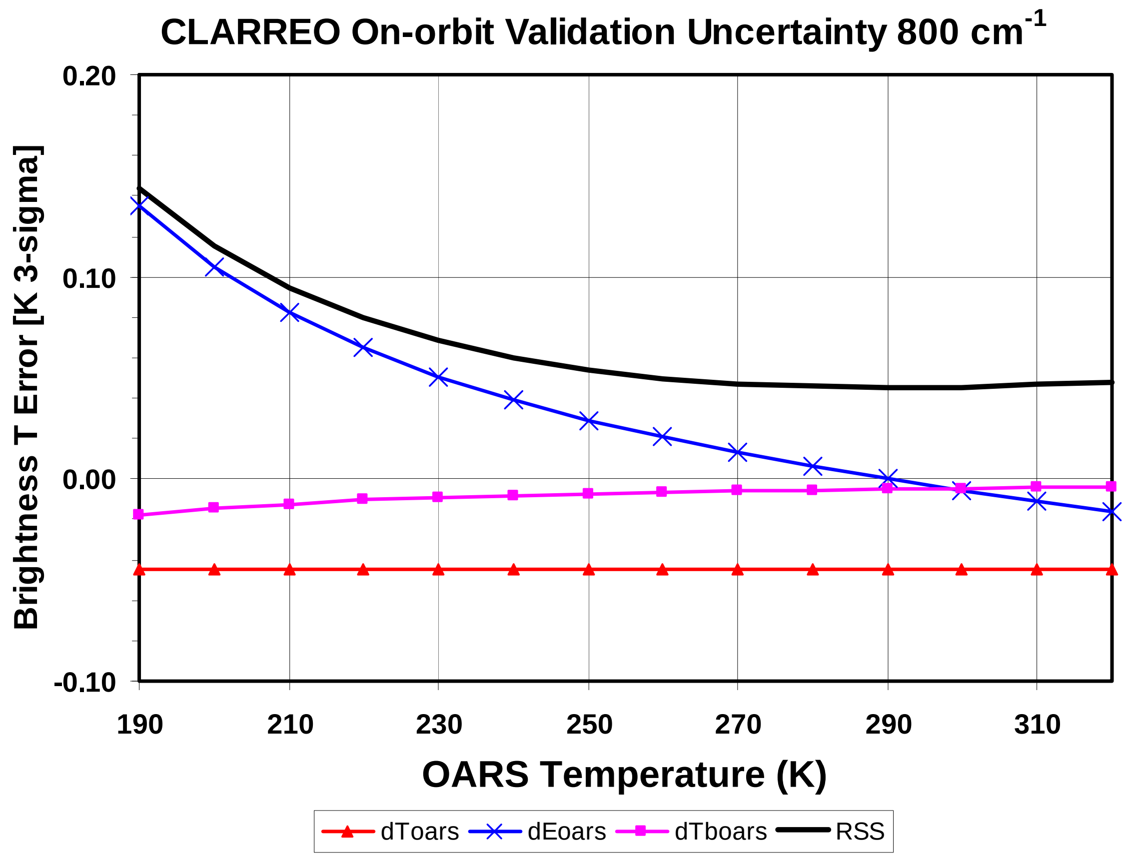
Uncertainty of On-orbit Absolute Radiance Standard (OARS)

Parameter ± 3-sigma

<u>OARS T</u>:
OARS T ± 0.046 K

<u>Background T</u>:
290 ± 5 K

<u>OARS Emissivity</u>:
0.999 ± 0.0006*



*** Gero et al.**

Note the strong effects of even very small emissivity uncertainty for cold atmospheric temperatures

OARS Effective Temperature

Temperature Uncertainty		3 sigma error [K]	RSS [K]
	Temperature Calibration Standard *(Ga, H2O, and Hg melt signatures)* (melt signature temperature uncertainty)	0.010	
			0.010
Blackbody Readout Electronics Uncertainty			
	(Included in phase change calibration)	0.000	
			0.000
Blackbody Thermistor Temperature Transfer Uncertainty			
	Gradient Between Temperature Standard and Cavity Thermistors	0.002	
	Calibration Fitting Equation Residual Error Between Calibration Temps.	0.010	
			0.010
Cavity Temperature Uniformity Uncertainty *(based on GIFTS)*			
	Cavity to Thermistor Gradient Uncertainty	0.025	
	Thermistor Wire Heat Leak Temperature Bias Uncertainty	0.008	
	Paint Gradient	0.018	
			0.032
Long-term Stability *(eliminated using periodic melt signatures on-orbit)*			
	Blackbody Thermistor		
	Blackbody Controller Readout Electronics	0.000	
			0.000
Effective Radiometric Temperature Weighting Factor Uncertainty			
	Monte Carlo Ray Trace Model Uncertainty in Determining Teff	0.030	
	(1/3 of total max expected gradient)		0.030
			0.046

- **Phase Change Cell Melt Signature**
- **Steinhart-Hart Interpolation**
- **T Sensor to Paint Surface**
- **Eliminated by Periodic Melts**
- **Effect of surface T gradients**

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OARS Radiance Uncertainty compared to ARI Uncertainty

Parameter ± 3-sigma

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OARS T ± 0.046 K

Background T:
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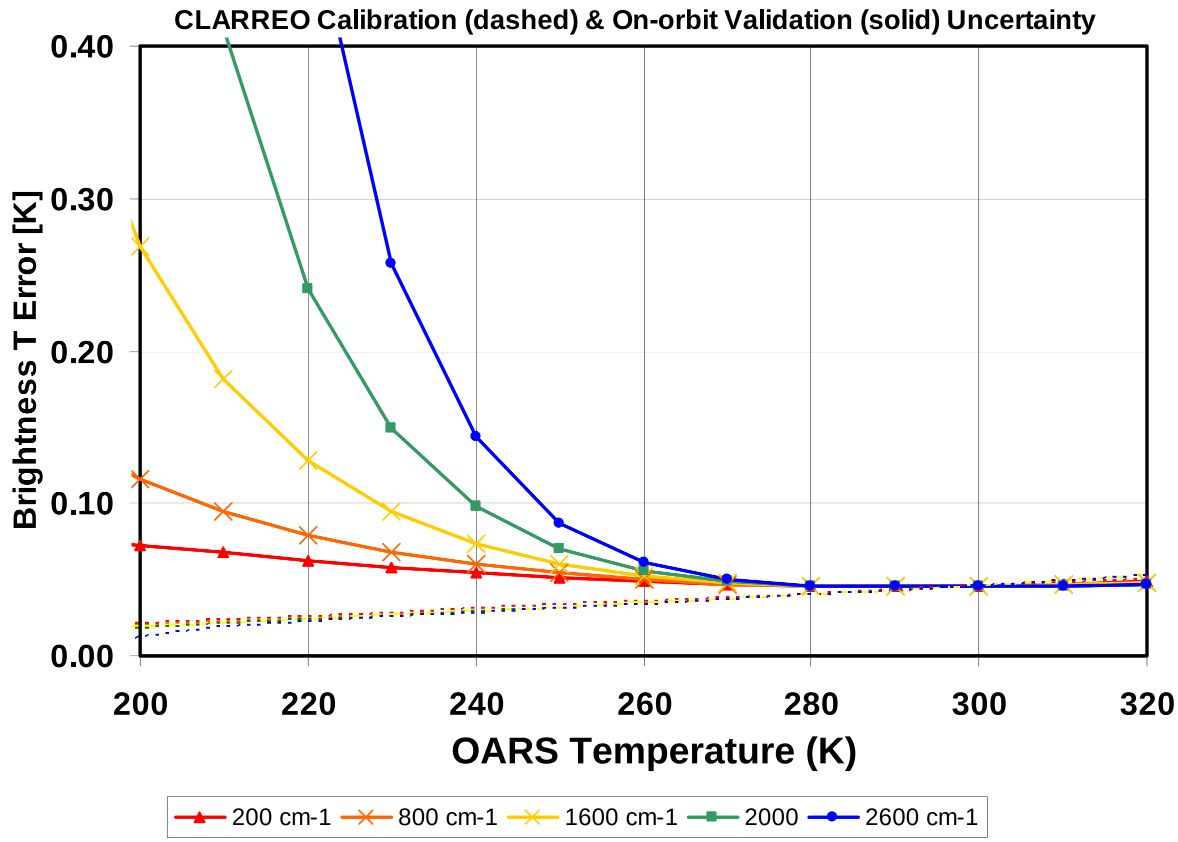
OARS Emissivity:
0.999 ± 0.0006*

*** Gero et al.**



Cold Scene Temperature Test Approaches

- **On-orbit testing to identify the source of ARI differences from the OARS:**
  - The scene temperature and wavelength dependence of the emissivity is unique and will be identifiable from planned on-orbit tests of CLARREO.
  - The approach is to identify the expected signature of an OARS emissivity uncertainty from ARI – OARS radiance residuals, and to make a post-launch adjustment to the assumed OARS emissivity.
  - ARI-OARS residuals will then form a tight bound on any ARI properties that might change in ways that could effect the calibration for cold temperatures over the life of the mission.
- **Flying two instruments** to directly verify agreement would also be very attractive for establishing confidence that the accuracy requirement is being met.

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Summary

- **Accuracy estimates for Absolute Radiance Interferometer (ARI) sensors and On-orbit Absolute Radiance Standard (OARS) based on detailed uncertainty assessments are essential elements of CLARREO science**

- **Existing validation approaches with aircraft, ground-based, and spaceflight instruments are important tools for establishing CLARREO credibility**