The IR Absolute Radiance Interferometer (ARI) Prototype for CLARREO: New Technologies for On-Orbit Verification and Test (Part-2)

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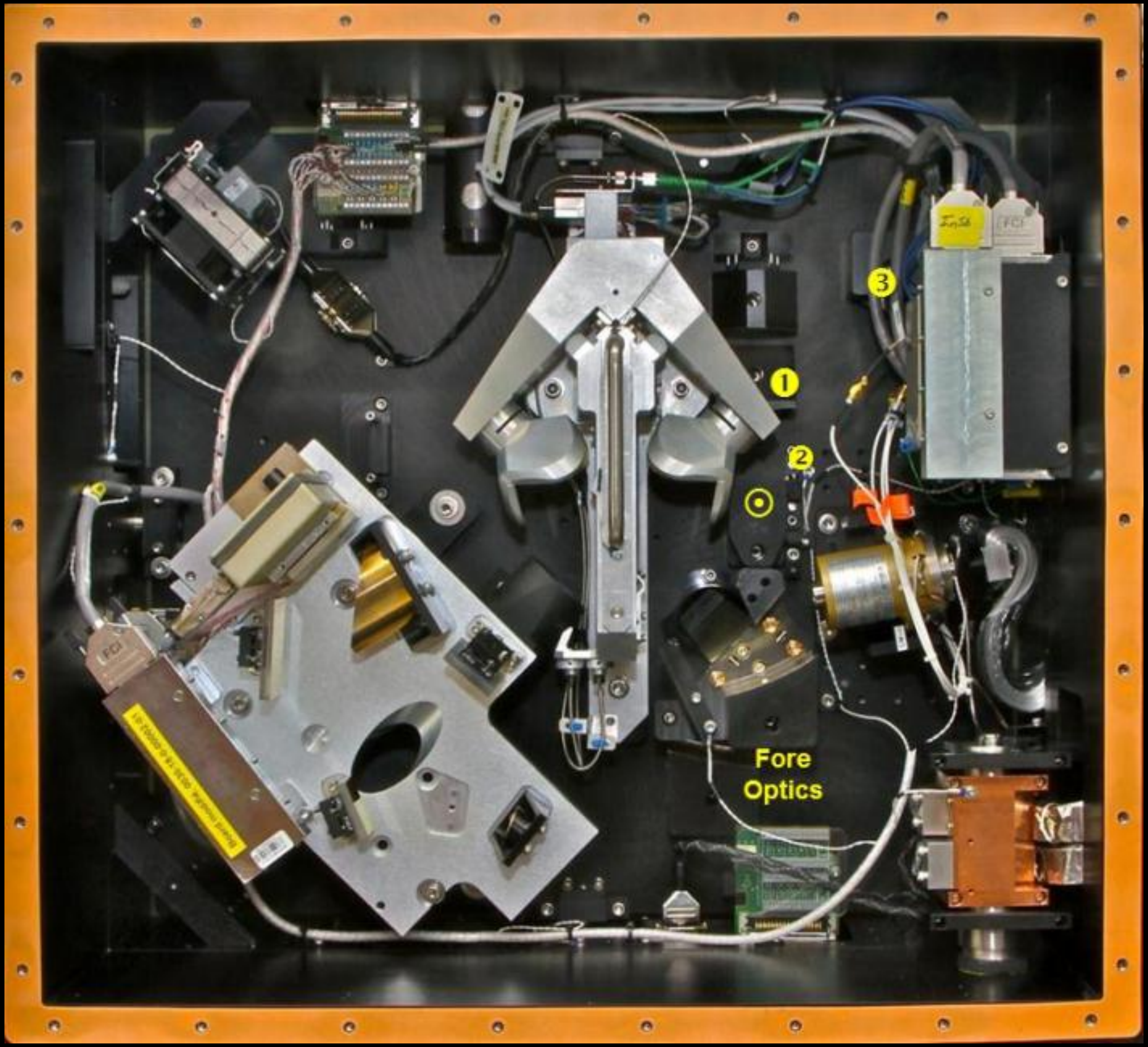
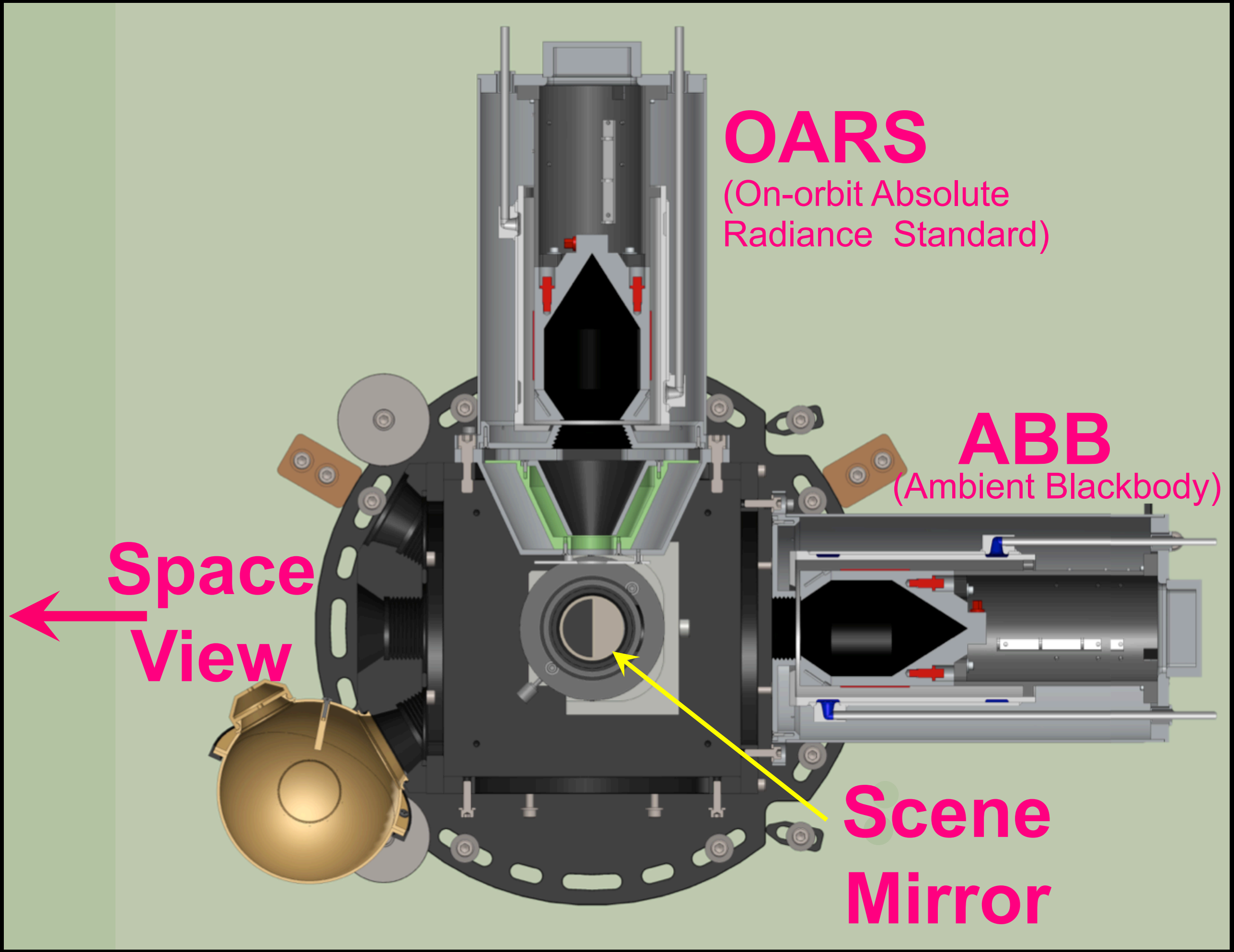
Topics

- Instrument Overview and Top-Level Measurement Uncertainty
- Highlights of the On-Orbit Absolute Radiance Standard (OARS), a key component of the OVTS (On-Orbit Verification & Test System)
  - Temperature Calibration
  - Emissivity Measurement
- End-to-end Performance Results
- QCL for Measuring Blackbody Emissivity & Instrument Line Shape
- Concept of Operations
- Summary

ARI Calibrated FTS



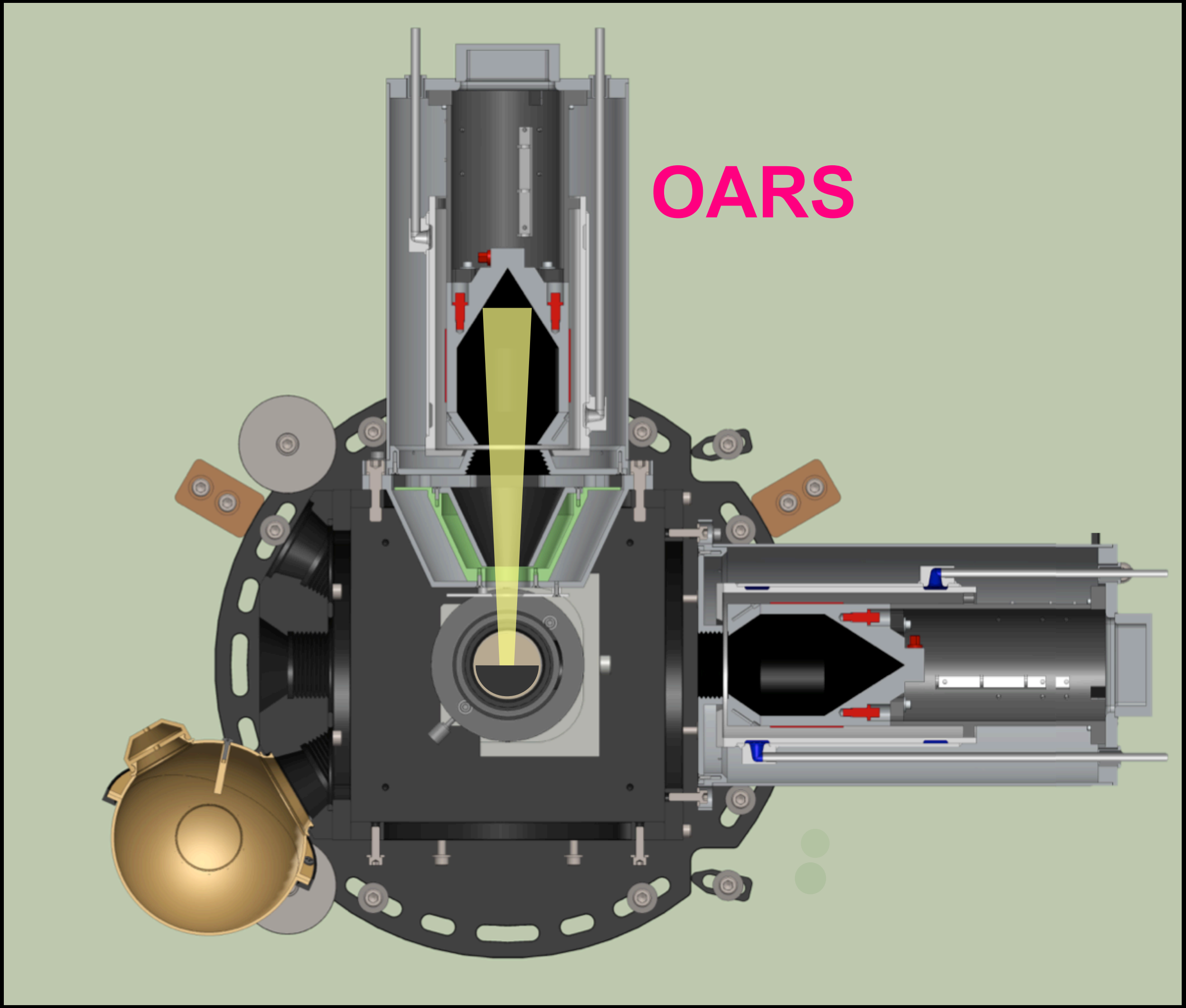
ARI Front-End Key Elements



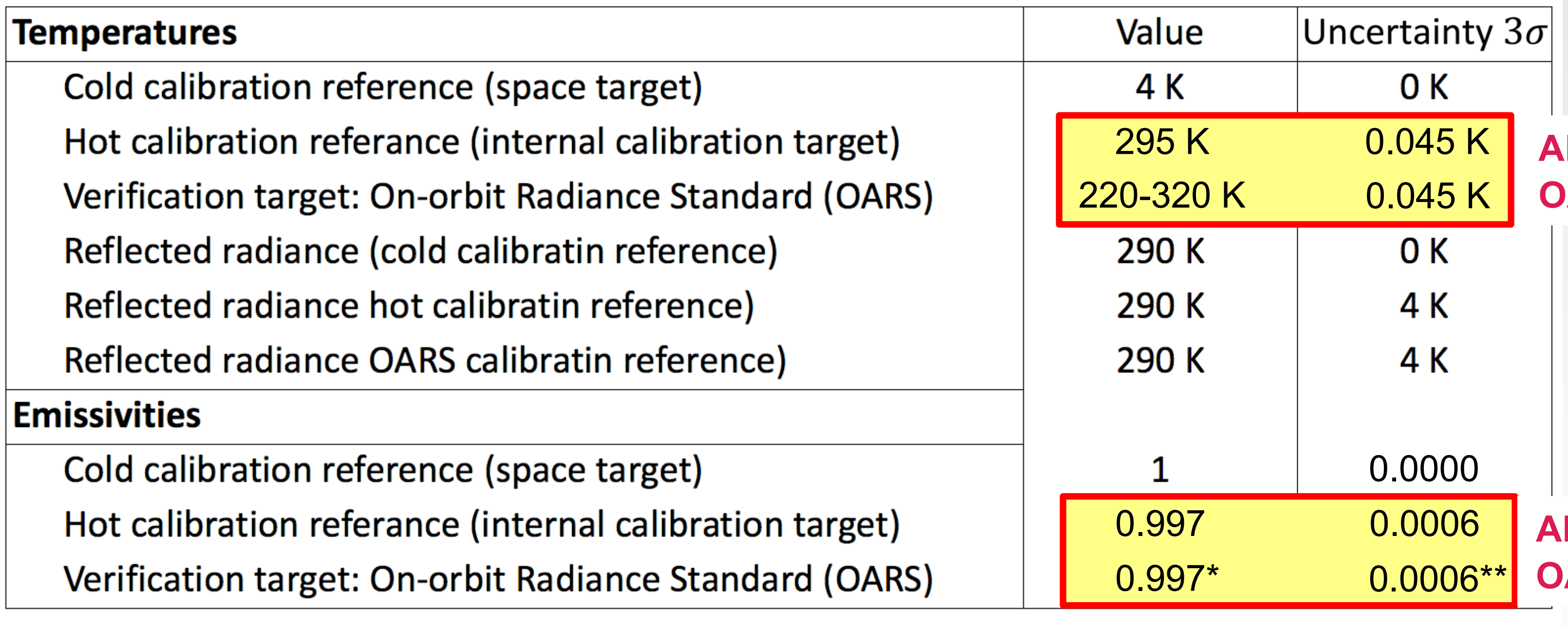
FTS is Calibrated by positioning Scene Mirror to get views of ABB & Space

On-Orbit Absolute Radiance Standard (OARS)

Provides On-Orbit End-to-End Verification of CFTS



ARI Calibration and Verification Key Parameter Assumptions

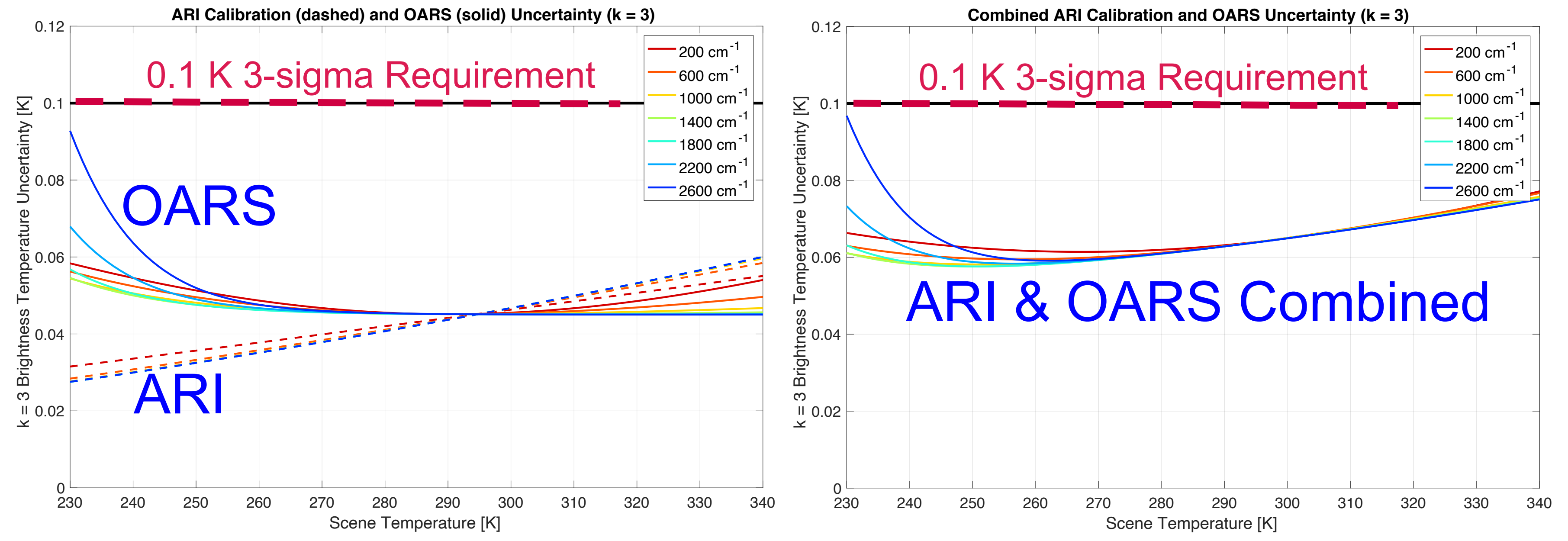


Temperatures	Value	Uncertainty 3σ	
Cold calibration reference (space target)	4 K	0 K	
Hot calibration referance (internal calibration target)	295 K	0.045 K	ABB
Verification target: On-orbit Radiance Standard (OARS)	220-320 K	0.045 K	OARS
Reflected radiance (cold calibratin reference)	290 K	0 K	
Reflected radiance hot calibratin reference)	290 K	4 K	
Reflected radiance OARS calibratin reference)	290 K	4 K	
Emissivities			
Cold calibration reference (space target)	1	0.0000	
Hot calibration referance (internal calibration target)	0.997	0.0006	ABB
Verification target: On-orbit Radiance Standard (OARS)	0.997*	0.0006**	OARS

*Worst case assumption

**For the Verification Target it has been assumed that the OARS emissivity and associated uncertainty is determined from pre-launch TVAC testing with a very high emissivity source, providing emissivity uncertainties of: 0.0006 at 200 cm-1; 0.0004 at 800 cm-1; 0.0002 at 1400 cm-1; 0.0001 at 2000 cm-1; and 0.000075 at 2600 cm-1.

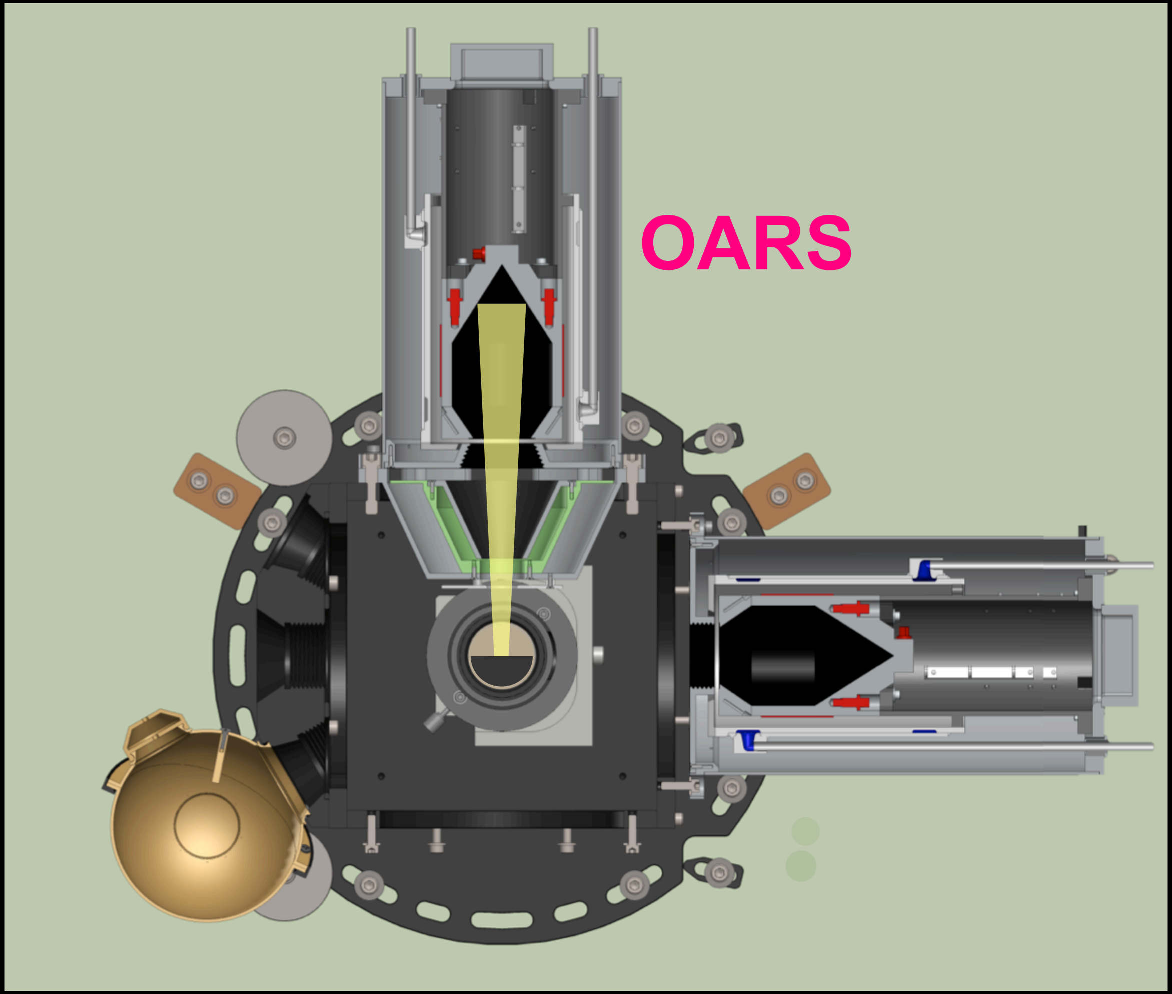
OARS Verification of ARI: Uncertainty On-Orbit



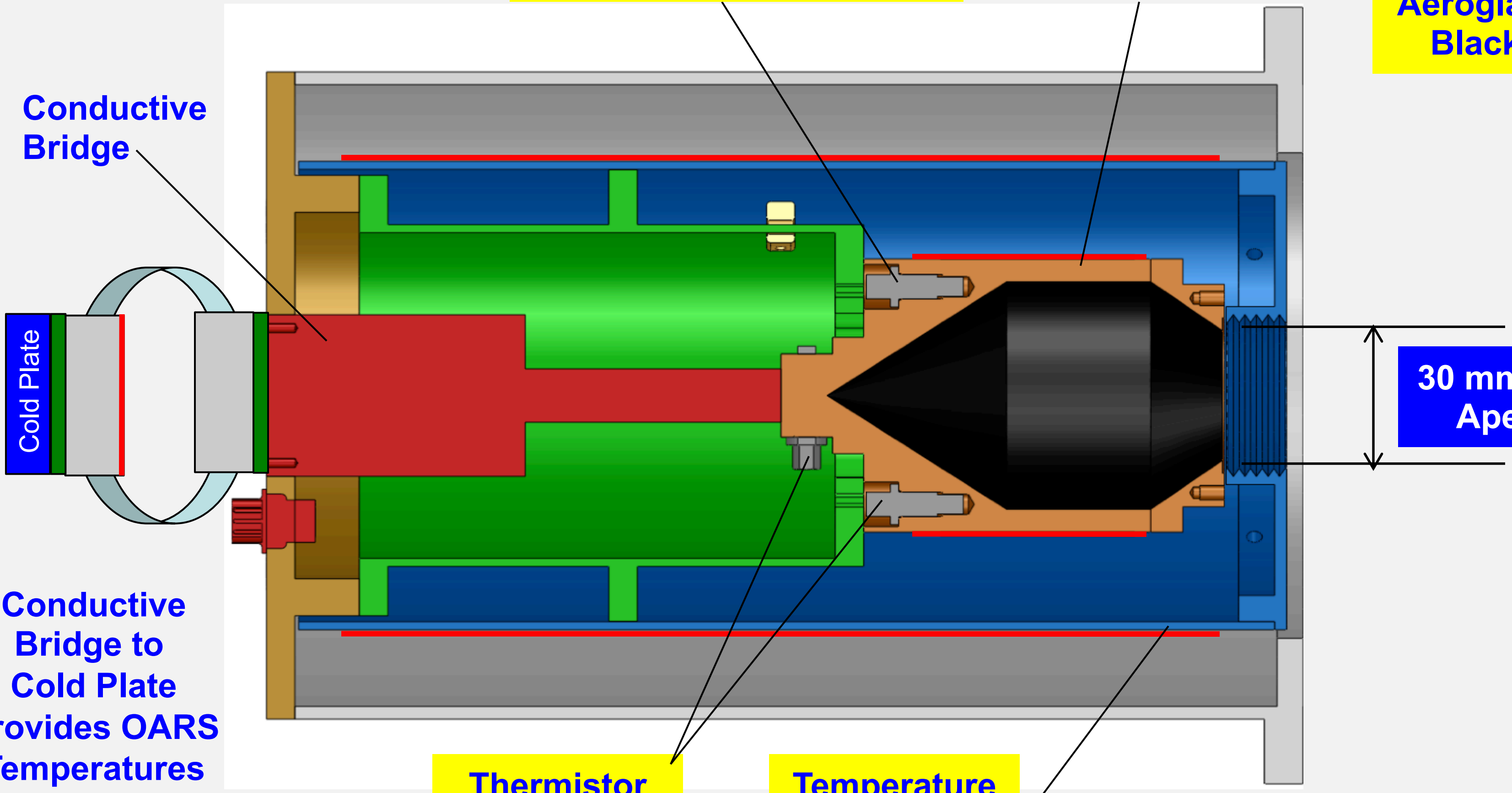
- The plot on the **left** shows the brightness temperature error for the ARI instrument (dashed lines) calibrated with its internal ambient blackbody and a space view, and the OARS verification source (solid lines), for on-orbit conditions at several wavenumbers.
- The plot on the **right** is the combination of the errors shown at left, and represents the level of ARI instrument verification that can be provided by the OARS on-orbit.

On-Orbit Absolute Radiance Standard (OARS)

On-Orbit Absolute Radiance Standard



Key Elements of the OARS



Miniature Phase Change Cells (three cells, one each with Ga, H_2O, & Hg)

Temperature Controlled High Emissivity (0.999) Blackbody cavity

Aeroglaze Z306 Black Paint

Conductive Bridge

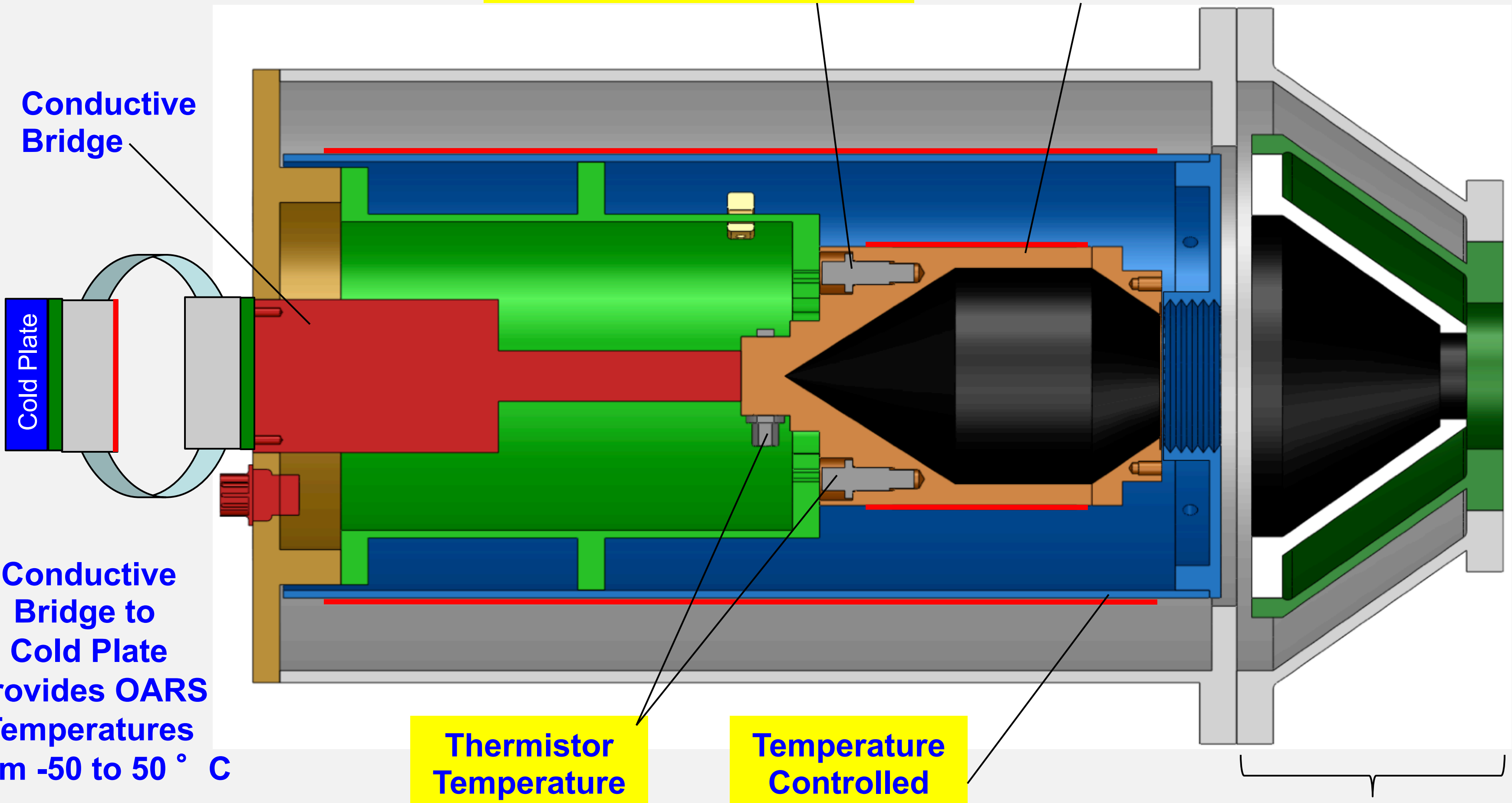
30 mm Cavity Aperture

Conductive Bridge to Cold Plate Provides OARS Temperatures From -50 to 50 ° C

Thermistor Temperature Sensors

Temperature Controlled Shield

Key Elements of the OARS



Miniature Phase Change Cells (three cells, one each with Ga, H_2O, & Hg)

Temperature Controlled High Emissivity Blackbody cavity

Conductive Bridge

Conductive Bridge to Cold Plate Provides OARS Temperatures From -50 to 50 ° C

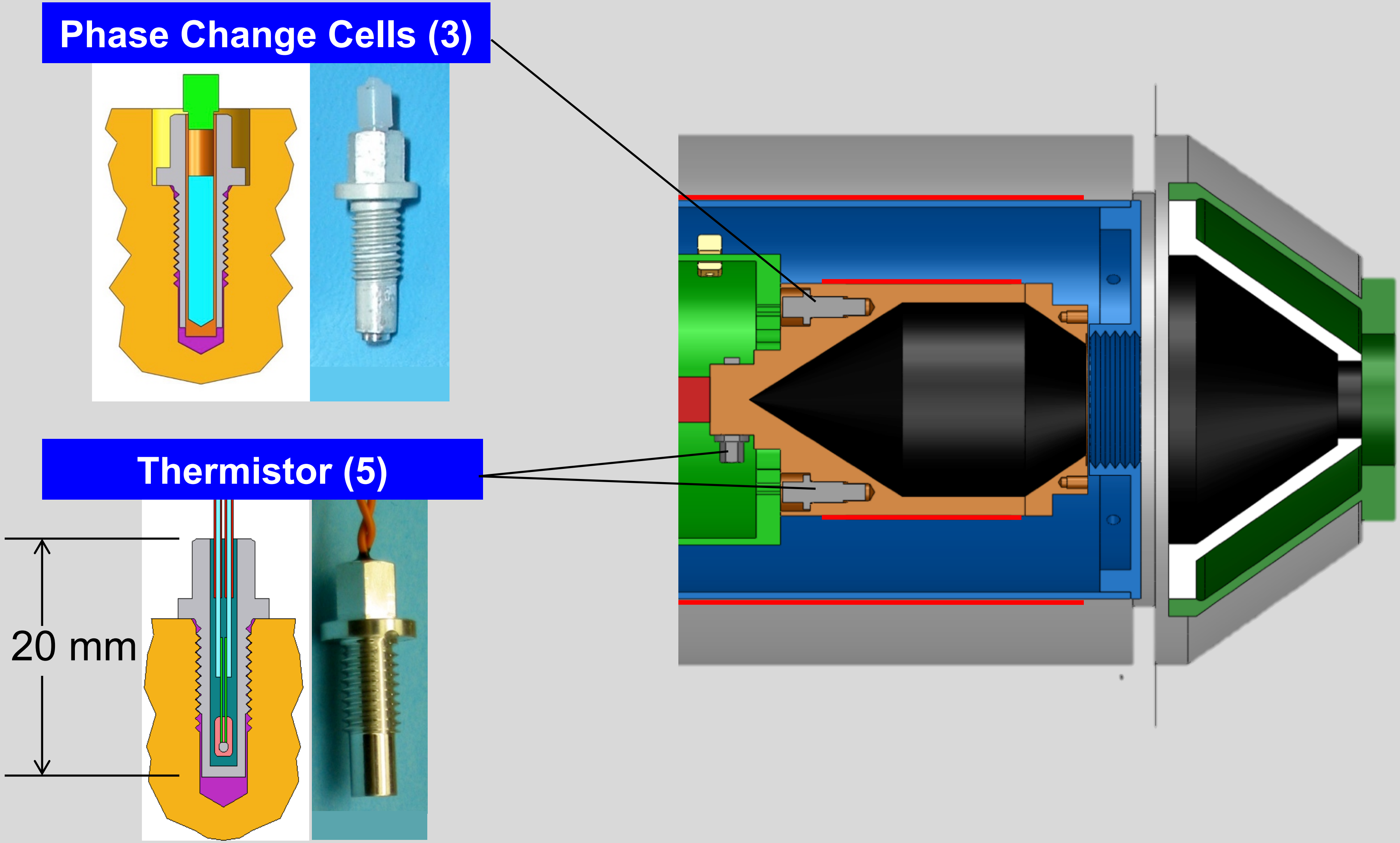
Thermistor Temperature Sensors

Temperature Controlled Shield

Heated Halo

Key Elements of the OARS

Phase Change Cells and Thermistors Imbedded in Cavity



Phase Change Cells (3)

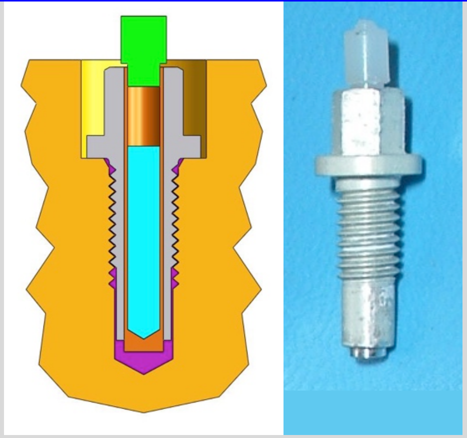
Thermistor (5)

Key Elements of the OARS

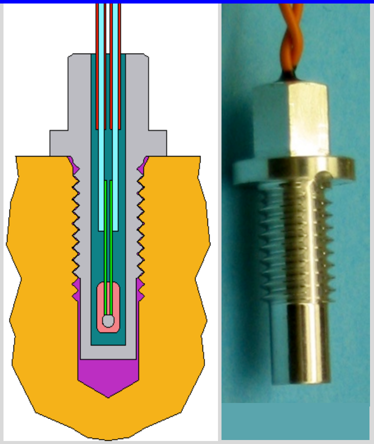
Phase Change Cells and Thermistors Imbedded in Cavity

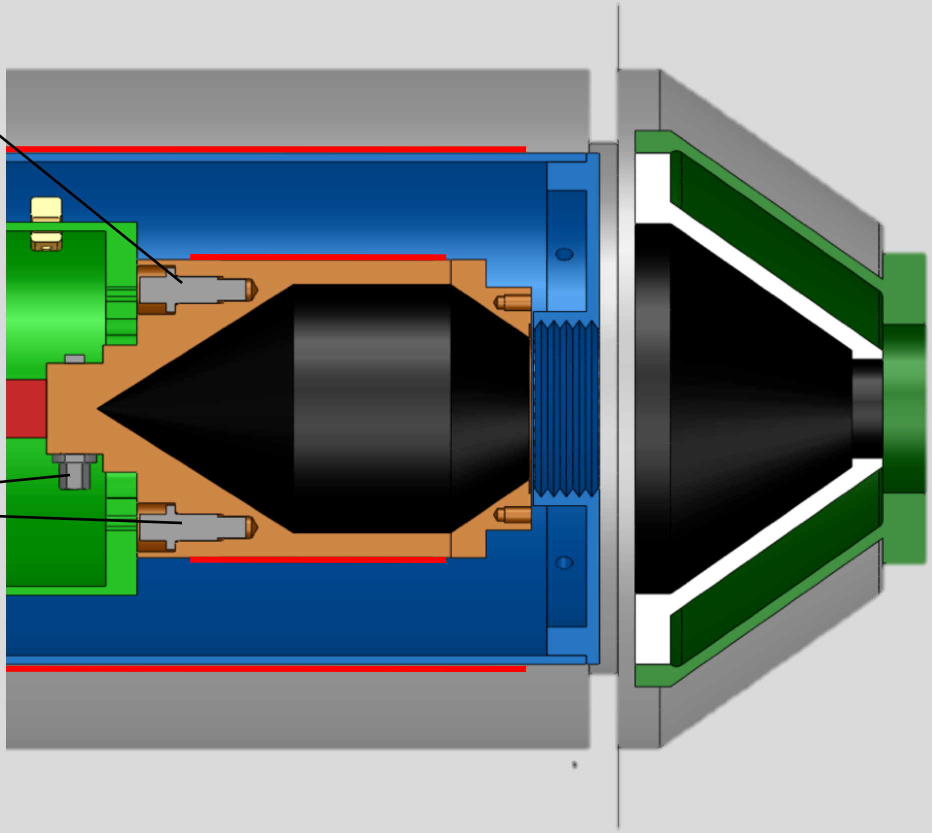
Only a fraction of a gram of phase change material is used

Phase Change Cells (3)



Thermistor (5)

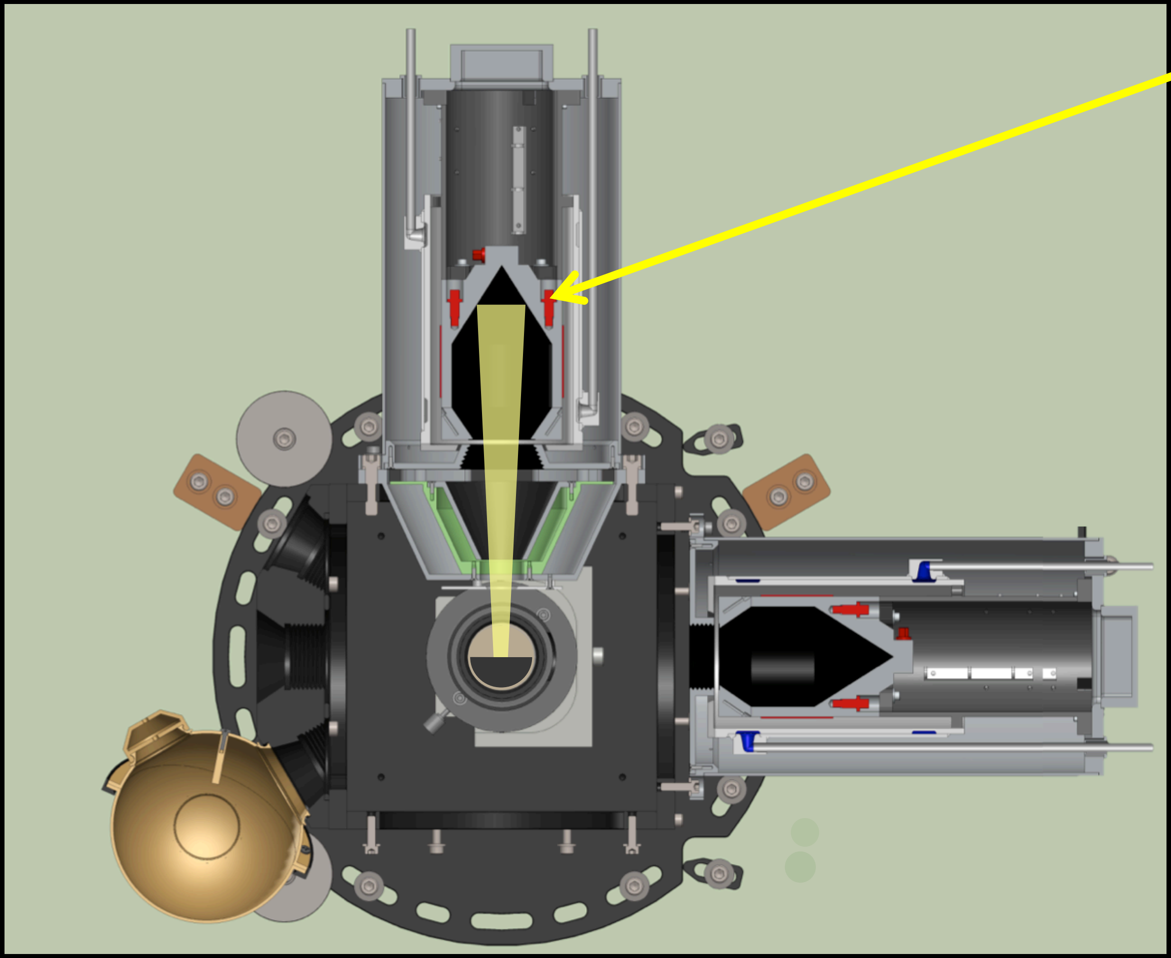




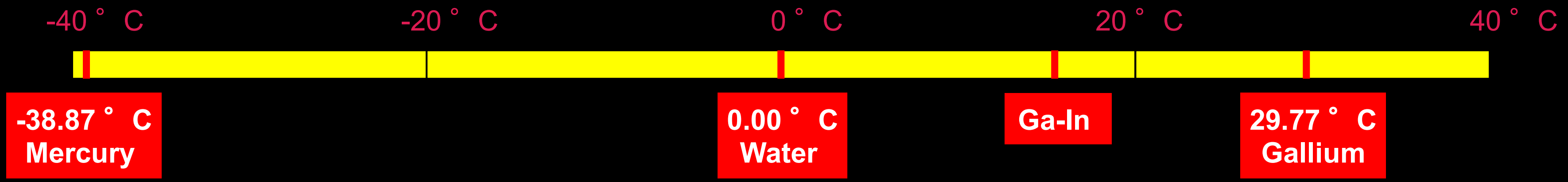
Temperature Calibration Using Miniature Phase Transition Cells

OARS: Thermistor Temperature Calibration

Establishing a temperature scale on orbit



The OARS has miniature phase change cells containing Ga, H_2O, and Hg, used for periodic temperature calibration of interleaved thermistors at 30, 0, and -38 ° C



-40 ° C
-20 ° C
0 ° C
20 ° C
40 ° C

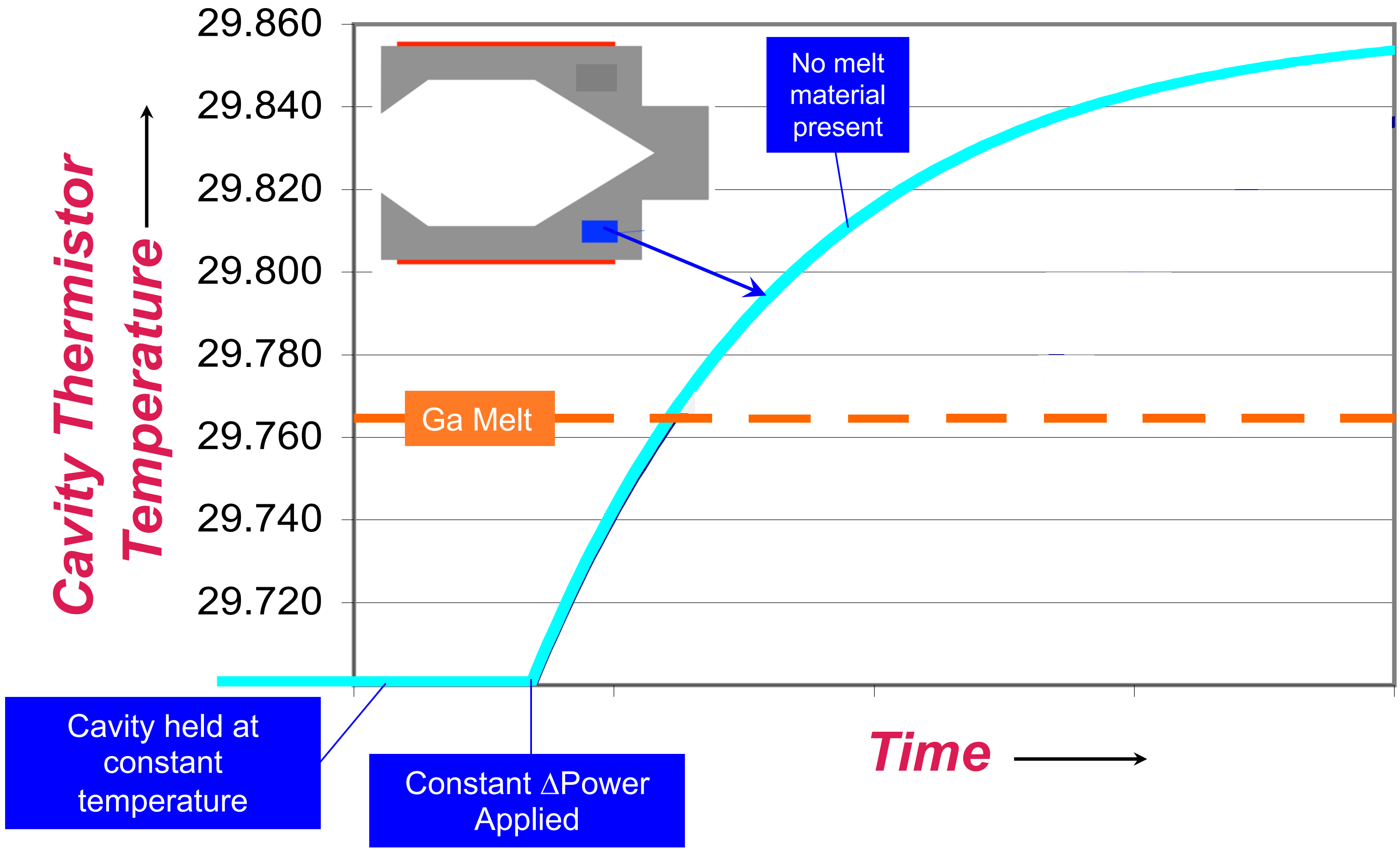
-38.87 ° C
Mercury

0.00 ° C
Water

Ga-In

29.77 ° C
Gallium

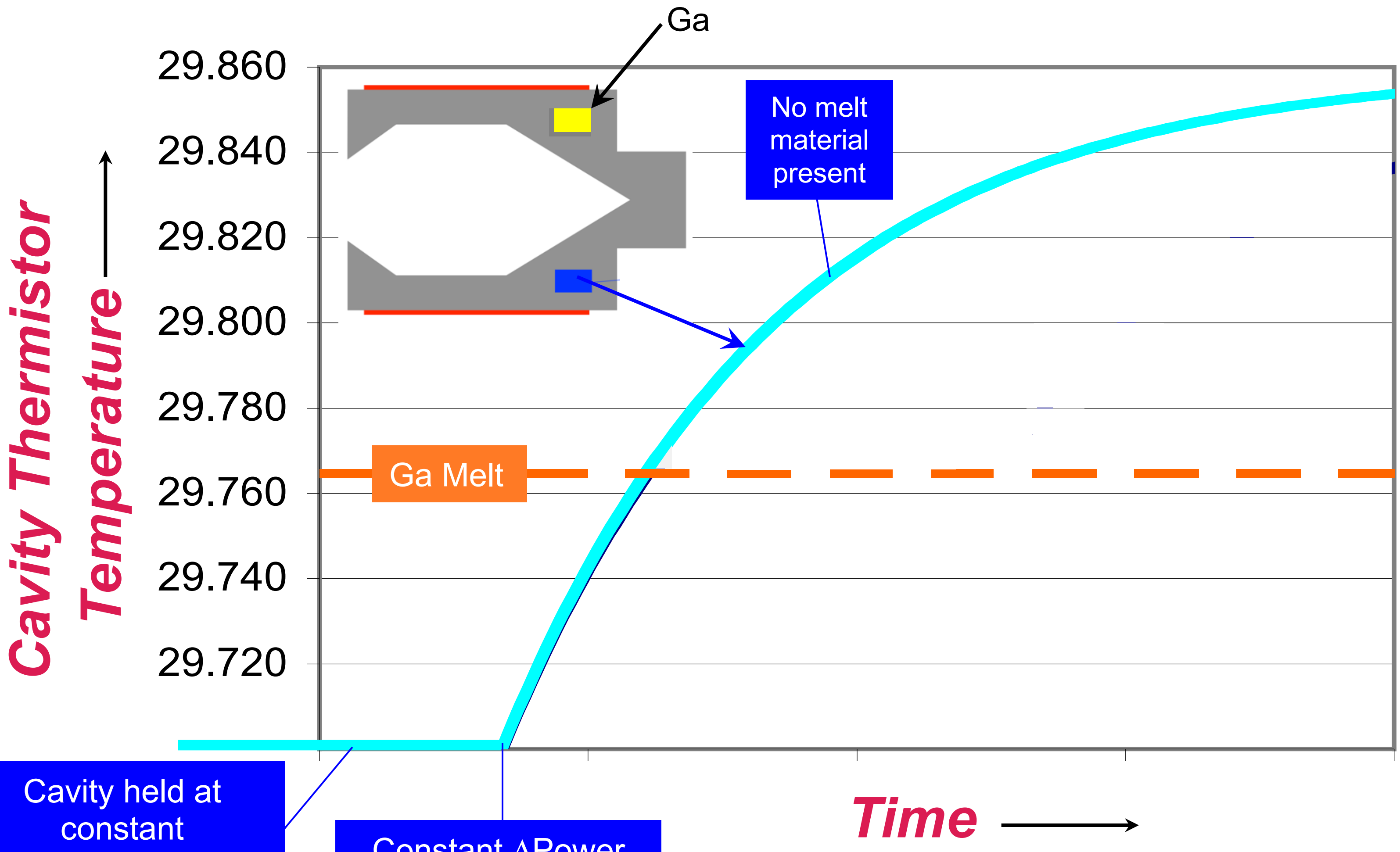
Typical Melt Signature



Cavity held at constant temperature

Constant ΔPower Applied

Typical Melt Signature

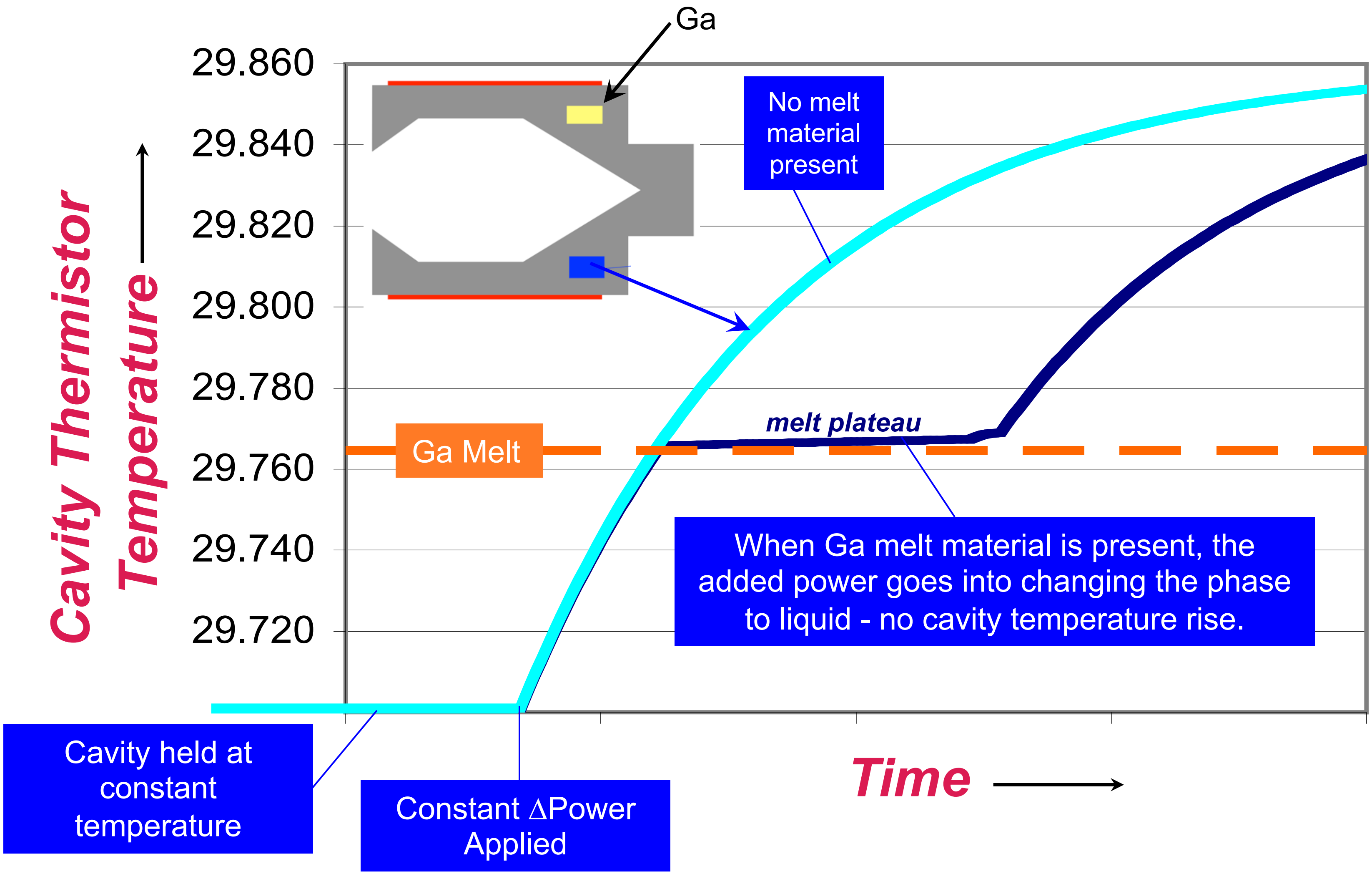


No melt material present

Cavity held at constant temperature

Constant ΔPower Applied

Typical Melt Signature

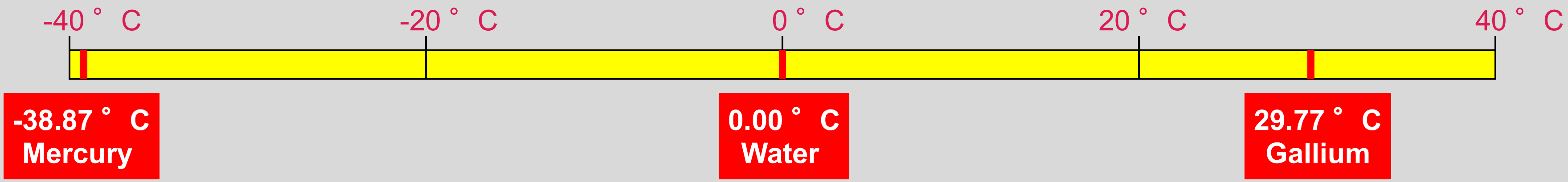


When Ga melt material is present, the added power goes into changing the phase to liquid - no cavity temperature rise.

Cavity held at constant temperature

Constant ΔPower Applied

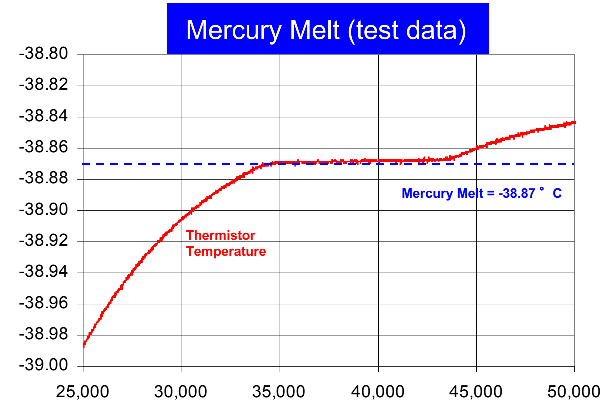
3 Melt Signatures Provide Temperature Scale

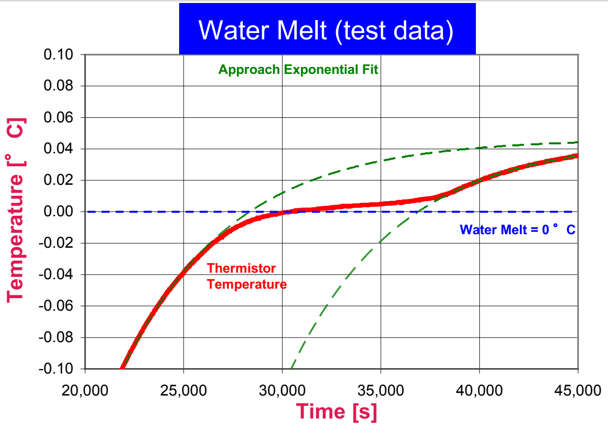


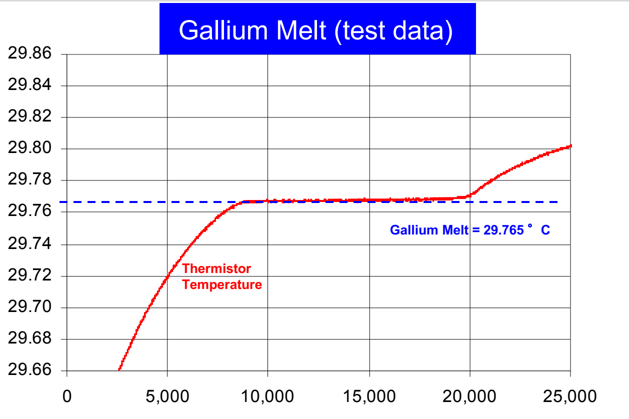
-38.87 ° C Mercury

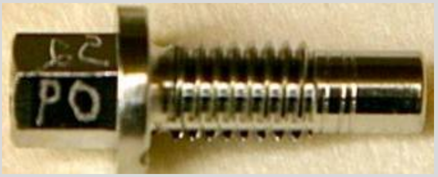
0.00 ° C Water

29.77 ° C Gallium

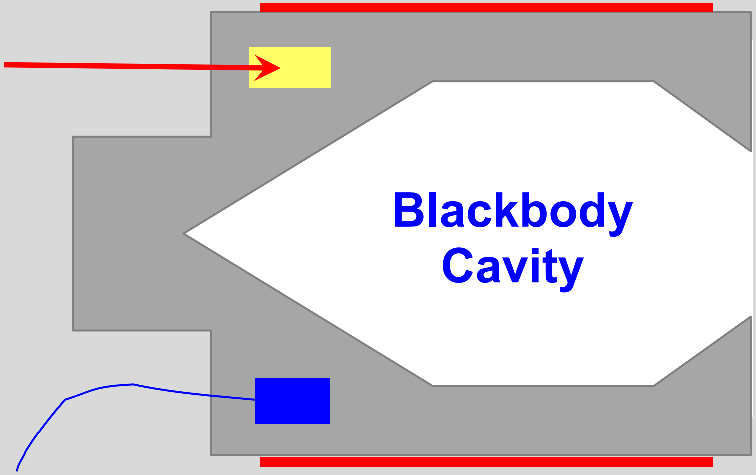

Mercury Melt (test data)


Water Melt (test data)


Gallium Melt (test data)



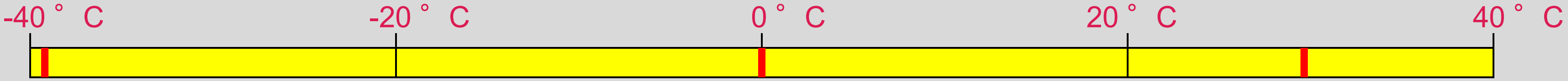
Phase Change Cell (3)
(Ga, H_2O, or Hg)



Blackbody Cavity

Thermistor
(plotted above)

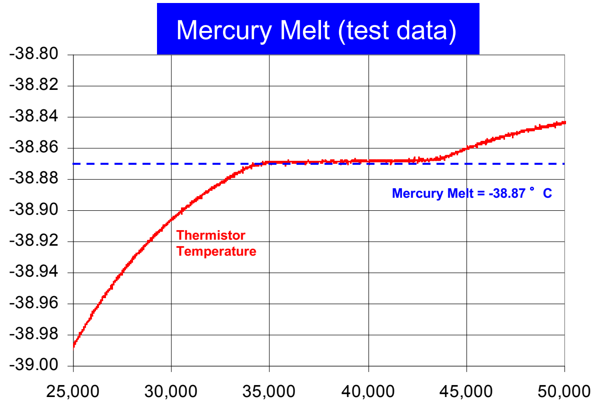
3 Melt Signatures Provide Temperature Scale

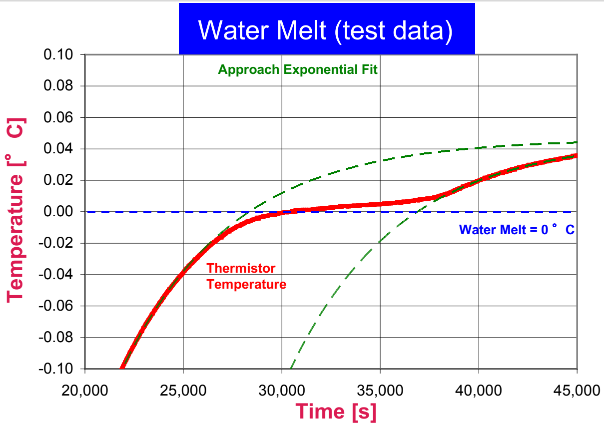


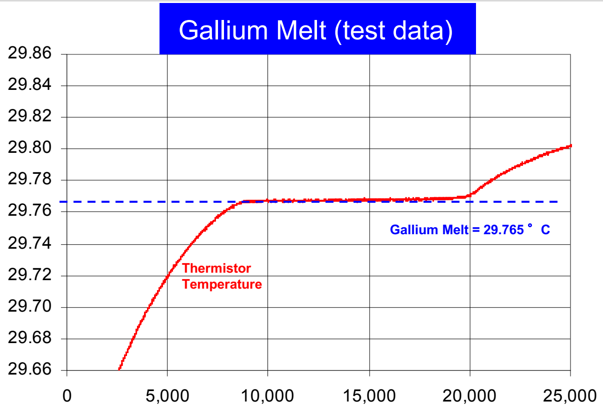
-38.87 ° C
Mercury

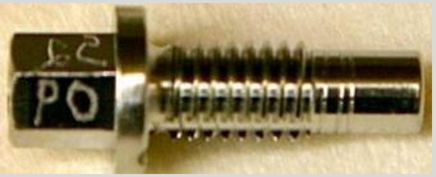
0.00 ° C
Water

29.77 ° C
Gallium

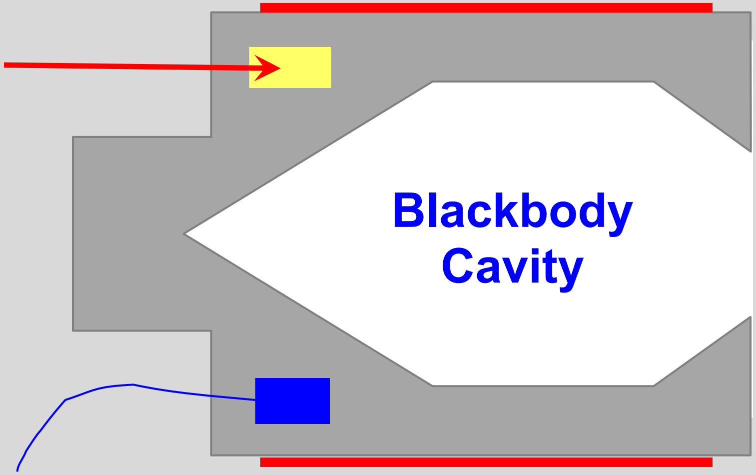

Mercury Melt (test data)


Water Melt (test data)


Gallium Melt (test data)



Phase Change Cell (3)
(Ga, H_2O, or Hg)

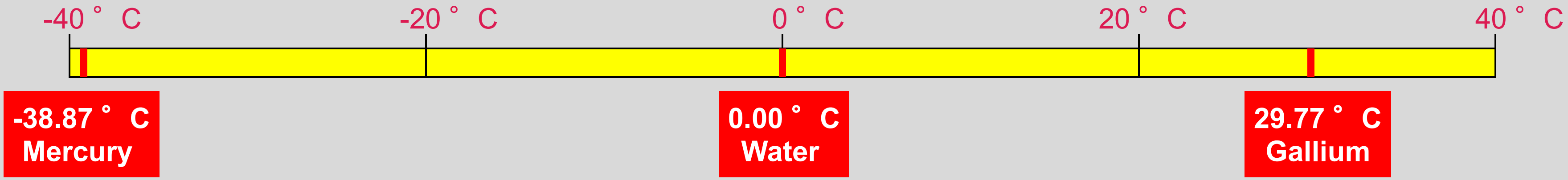


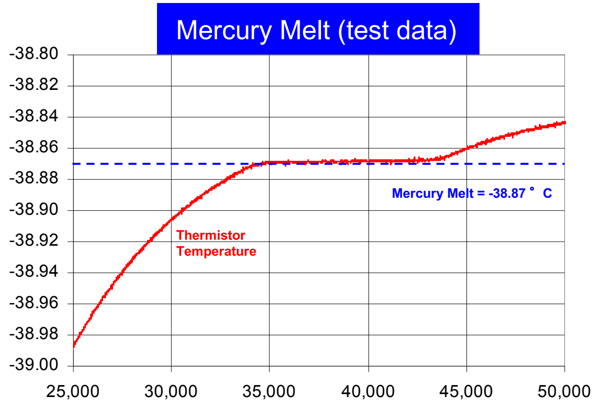
Blackbody Cavity

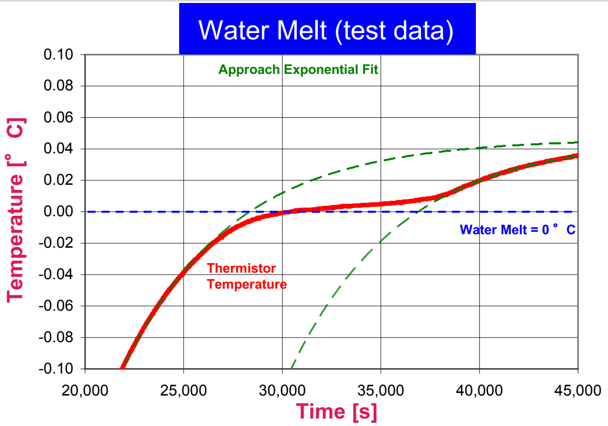
Thermistor
(plotted above)

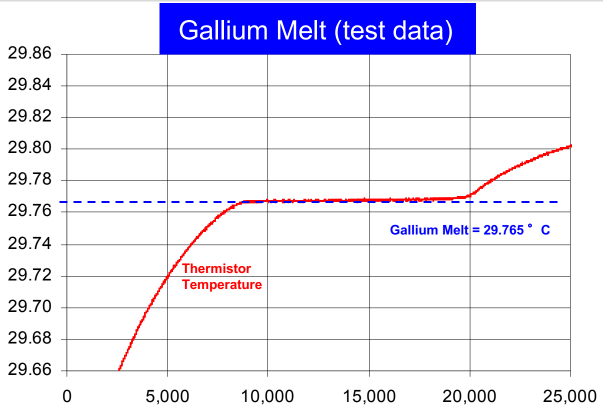
- **Melt Plateaus shown in plots provide known temperatures to better than 10 mK**

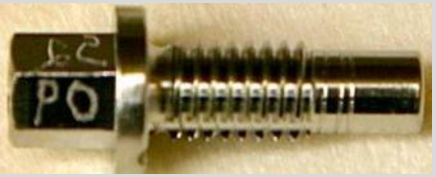
3 Melt Signatures Provide Temperature Scale



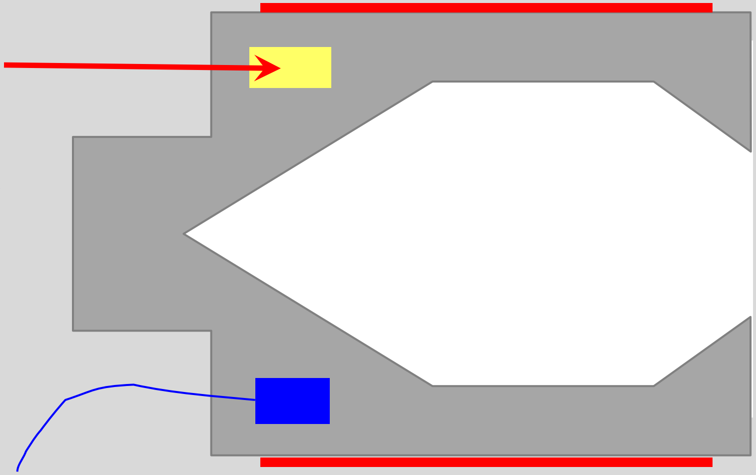








Phase Change Cell (3)
(Ga, H_2O, or Hg)



Thermistor
(plotted above)

- **Melt Plateaus shown in plots provide known temperatures to better than 10 mK**
- **Cavity gradients are less than 2 mK throughout melt**

3 Melt Materials Establish Steinhart-Hart Thermistor Calibration Coefficients

- While at each of the 3 known melt temperatures, each thermistor resistance is measured

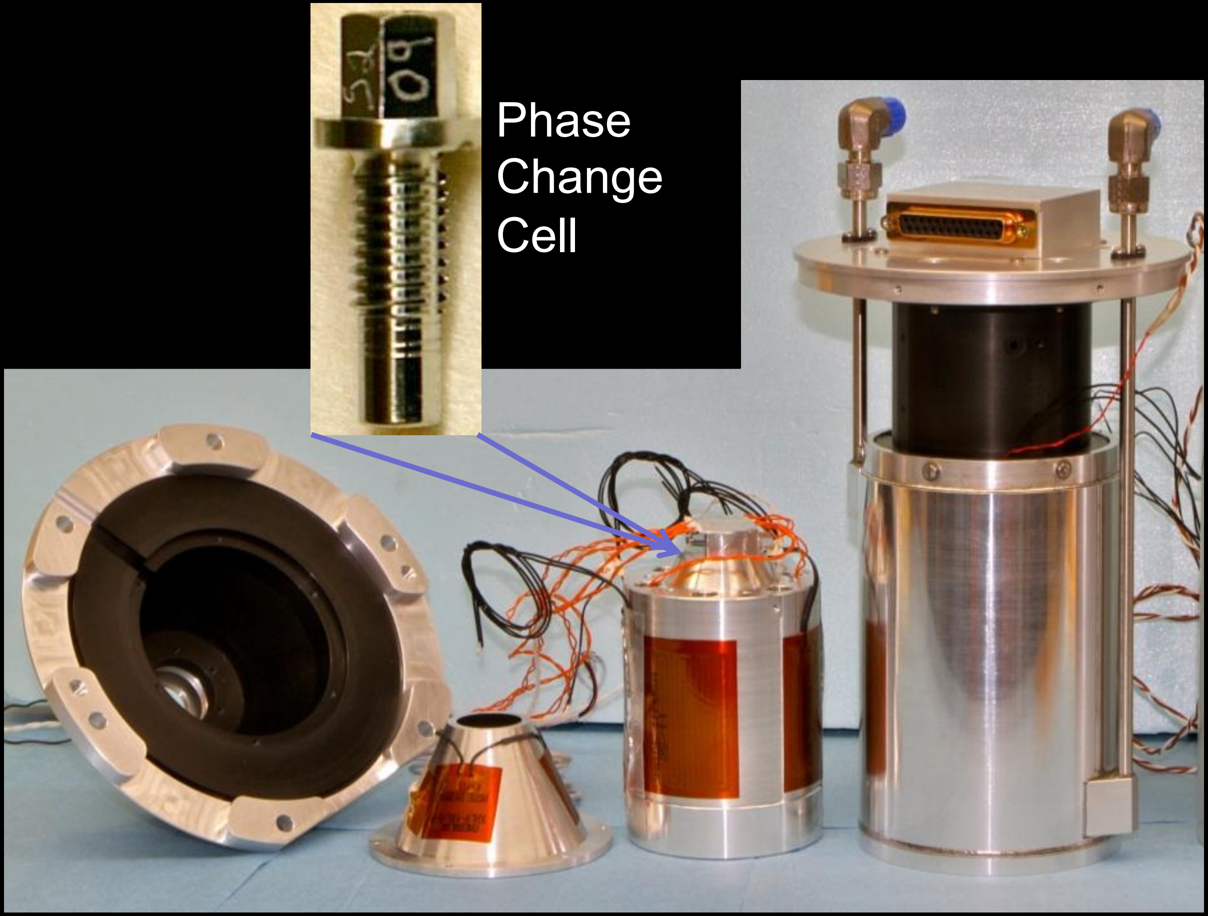
- The traditional Steinhart-Hart Relationship is used

$$T = \frac{1}{A + B \bullet \ln(R) + C \bullet (\ln(R))^3}$$

- For each thermistor, unique coefficients A, B, & C are determined from the three (T,R) points:

$$\begin{vmatrix} A \\ B \\ C \end{vmatrix} = \begin{vmatrix} 1 & \ln R_{Ga} & (\ln R_{Ga})^3 \\ 1 & \ln R_{H_2O} & (\ln R_{H_2O})^3 \\ 1 & \ln R_{Hg} & (\ln R_{Hg})^3 \end{vmatrix}^{-1} \bullet \begin{vmatrix} T_{Ga}^{-1} \\ T_{H_2O}^{-1} \\ T_{Hg}^{-1} \end{vmatrix}$$

OARS For ARI Prototype Vacuum Test Configuration



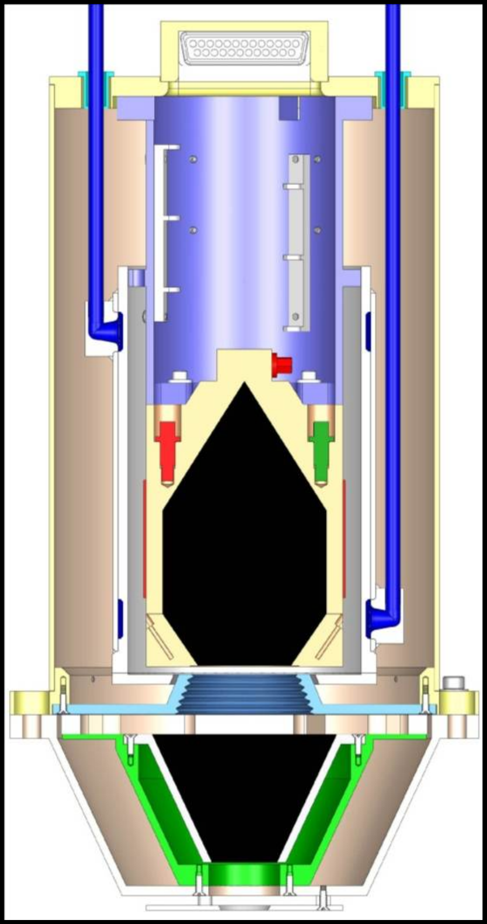
Phase Change Cell

Heated Halo
& Halo Insulator

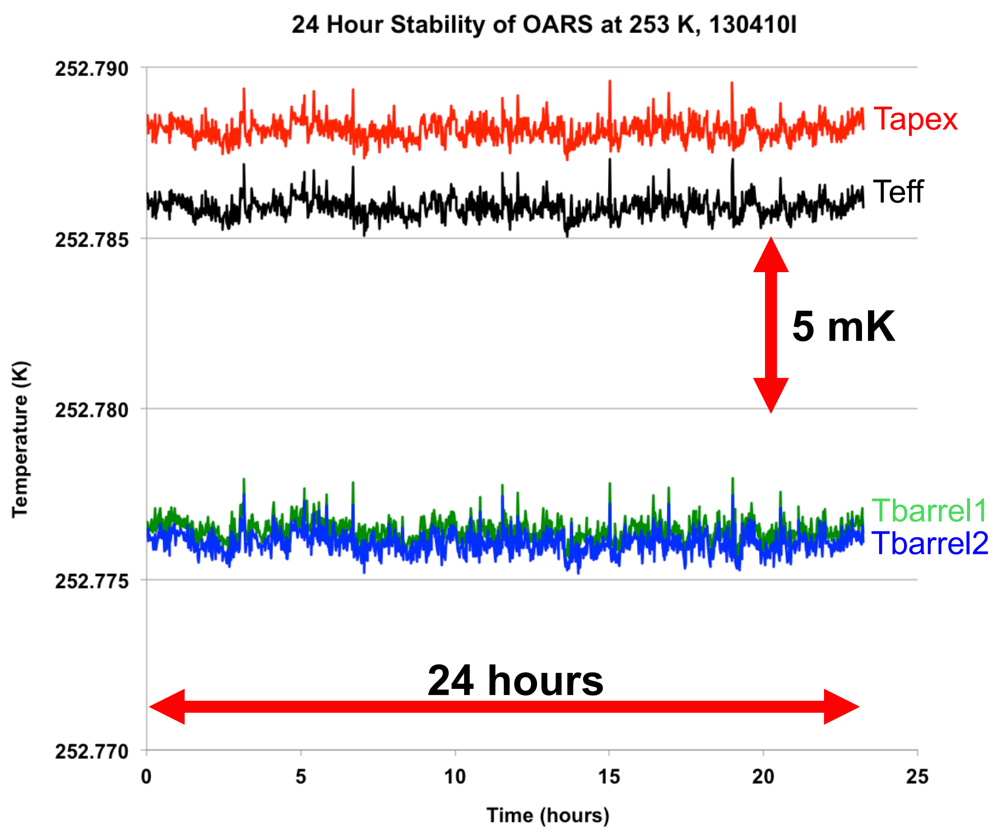
Cavity

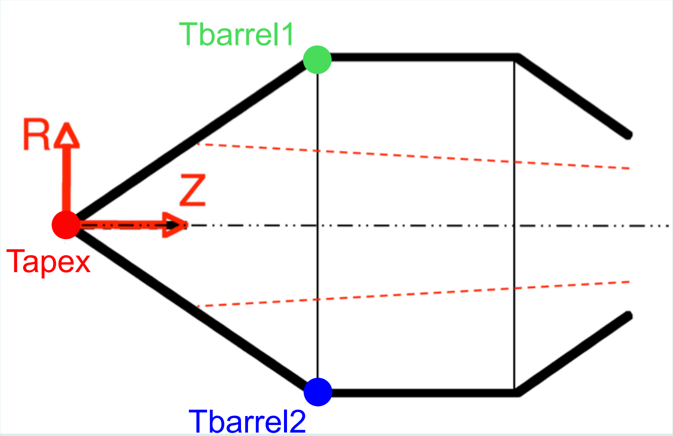
Inner Shield
& Isolator

Assembly Diagram



OARS 24 Hour Stability at -20 C under Vacuum





The maximum gradient of 15 mK shown here at -20 C, would be expected to double to 30 mK at an OARS temperature of -60 C.

$$T_{eff} = 0.811 * T_{apex} + 0.095 * T_{barrel1} + 0.095 * T_{barrel2}$$

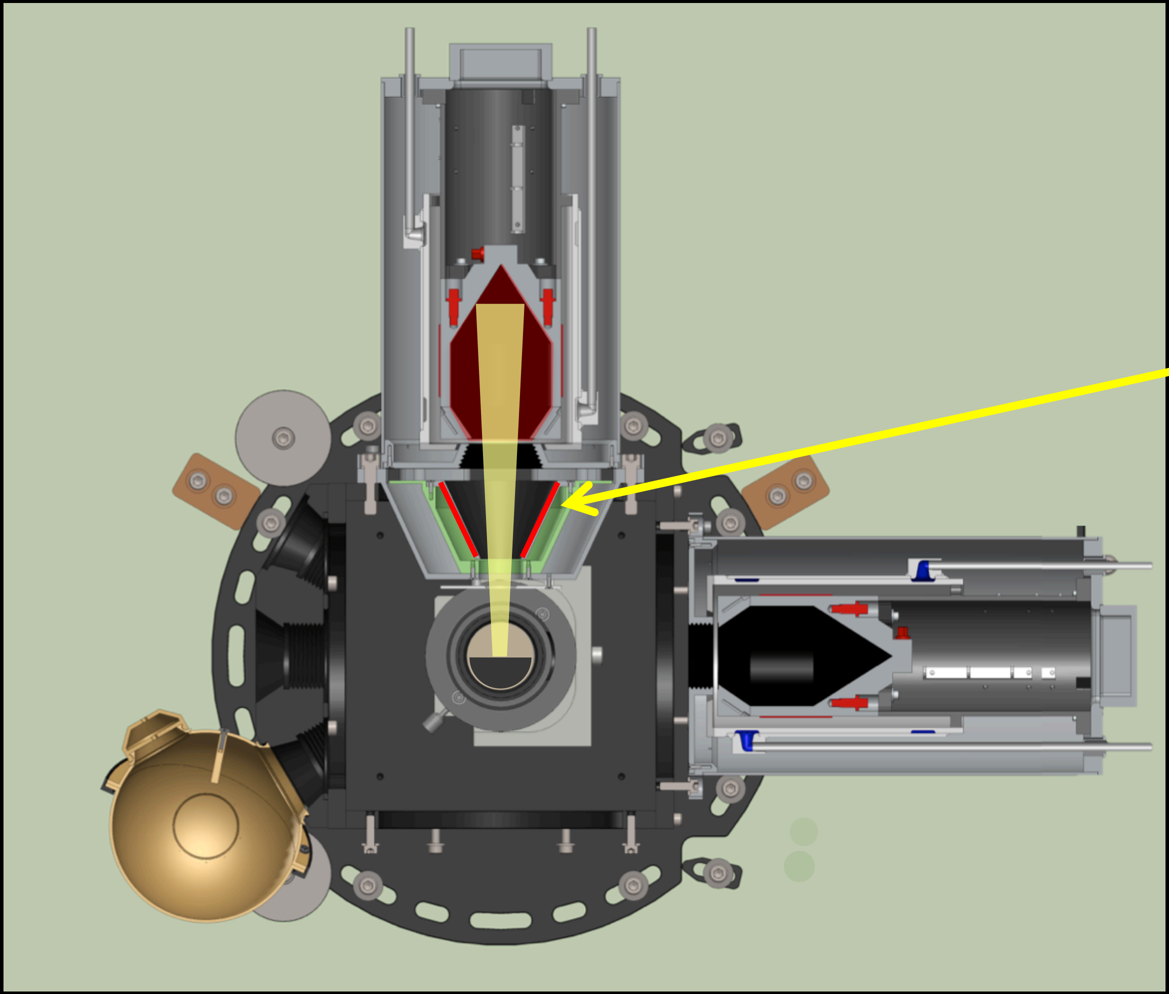
The thermistor weighting takes into account the linear temperature gradient from the cavity barrel to the apex, and the geometry of the field of view. The temperature at the cavity aperture is 0.1K lower than Teff.

OARS Effective Radiometric Temperature Uncertainty Budget (3 sigma)

Error Source	Temperature Error [K]
Thermistor Temperature Calibration Uncertainty	
Melt Plateau Determination	0.010
Thermistor Calibration Equation Interpolation Error	0.015
Transfer of Melt Cell to Thermistor Uncertainty *(due to gradients during calibration)*	0.008
Cavity Temperature Uniformity Uncertainty	
Cavity to Thermistor Gradient Uncertainty *(1/2 of max expected gradient)*	0.015
Thermistor Wire Heat Leak Temperature Bias Uncertainty*	0.020
Paint Gradient *(due to radiative coupling to surrounding temperatures)*	0.018
**(due to conductive coupling of leads to a temperature different that the cavity)*	
Stability Between Calibrations	
Blackbody Thermistor *(conservative value: for 8 years of drift assuming 100 °C)*	0.005
Blackbody Thermistor Readout Electronics	0.005
Effictive Radiometric Temperature Weighting Factor Uncertainty	
Monte Carlo Ray Trace Model Uncertainty in Determining Teff	0.025
(radiometric error that accounts fodr non-isothermal cavty temperature)	
RSS Combination	**0.045**

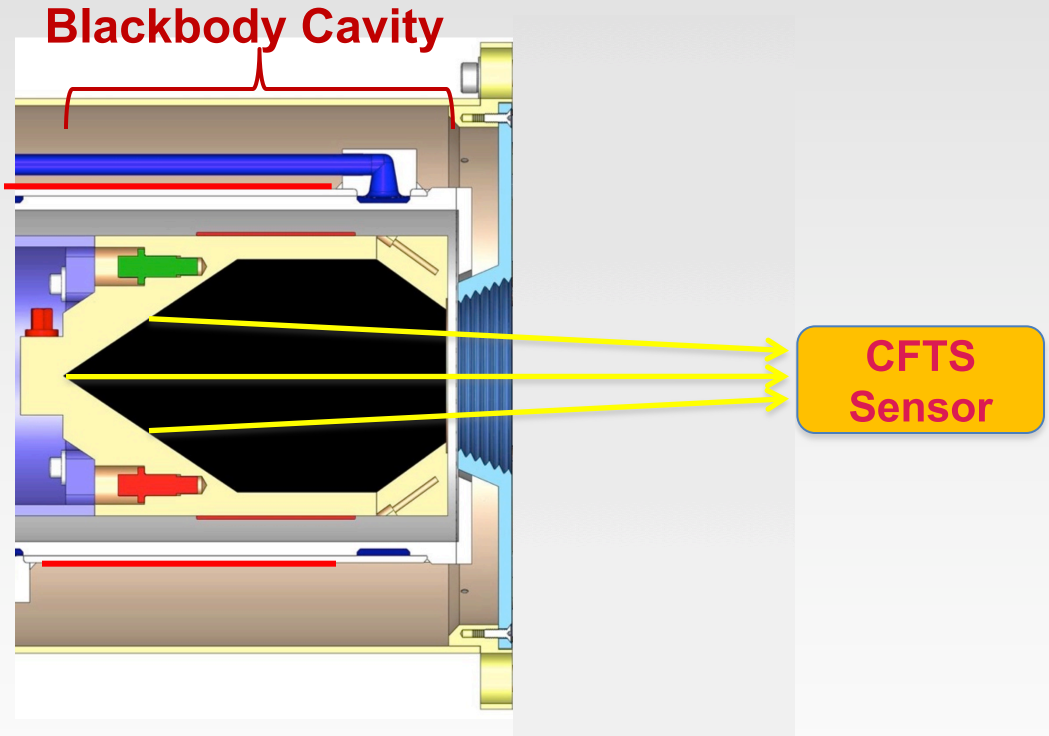
Emissivity Measurement Using the Heated Halo Method

OVTS: OARS Spectral Emissivity – Heated Halo

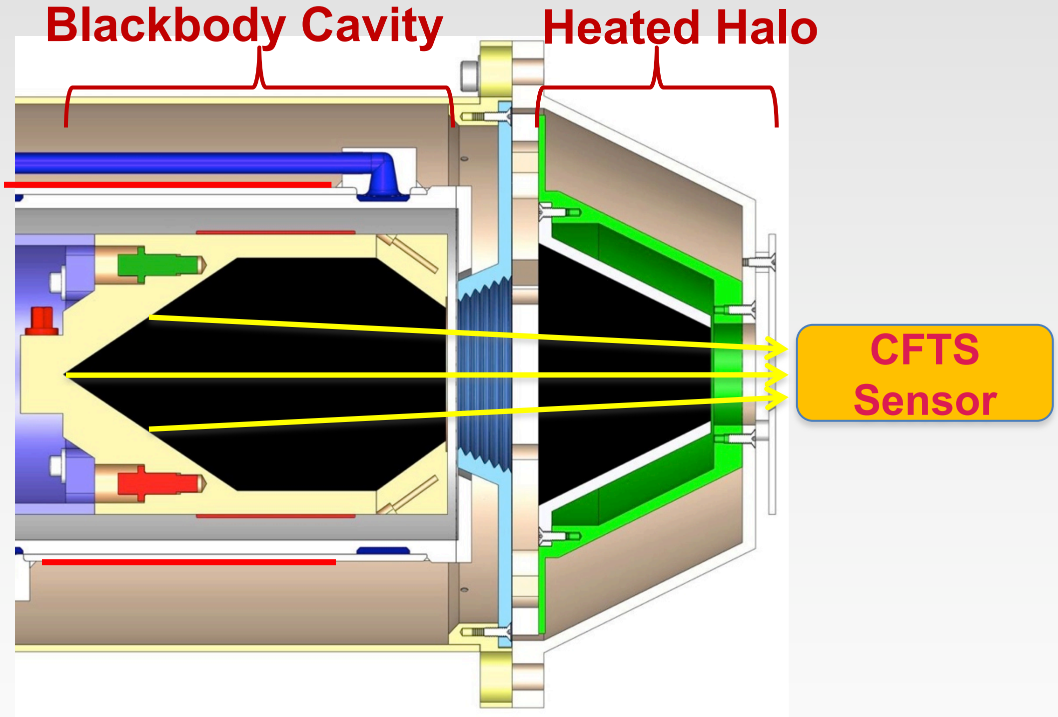


The Heated Halo is used periodically for measuring the blackbody cavity spectral emissivity.

OARS Blackbody Cavity Radiance Standard

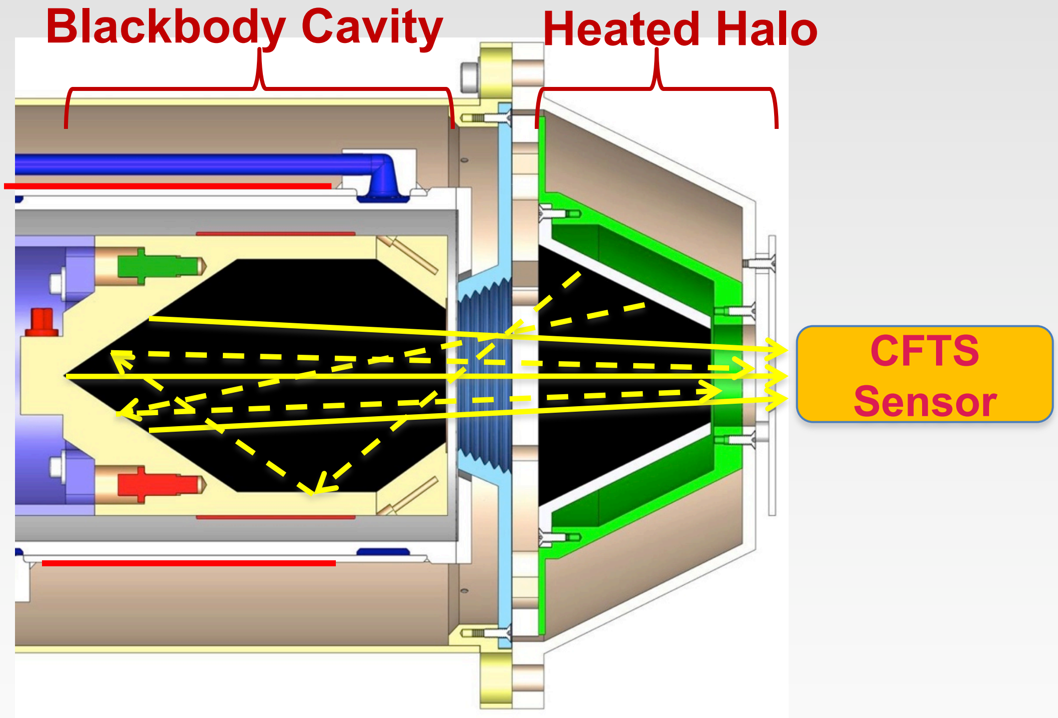


Heated Halo Used for Measuring Cavity ε



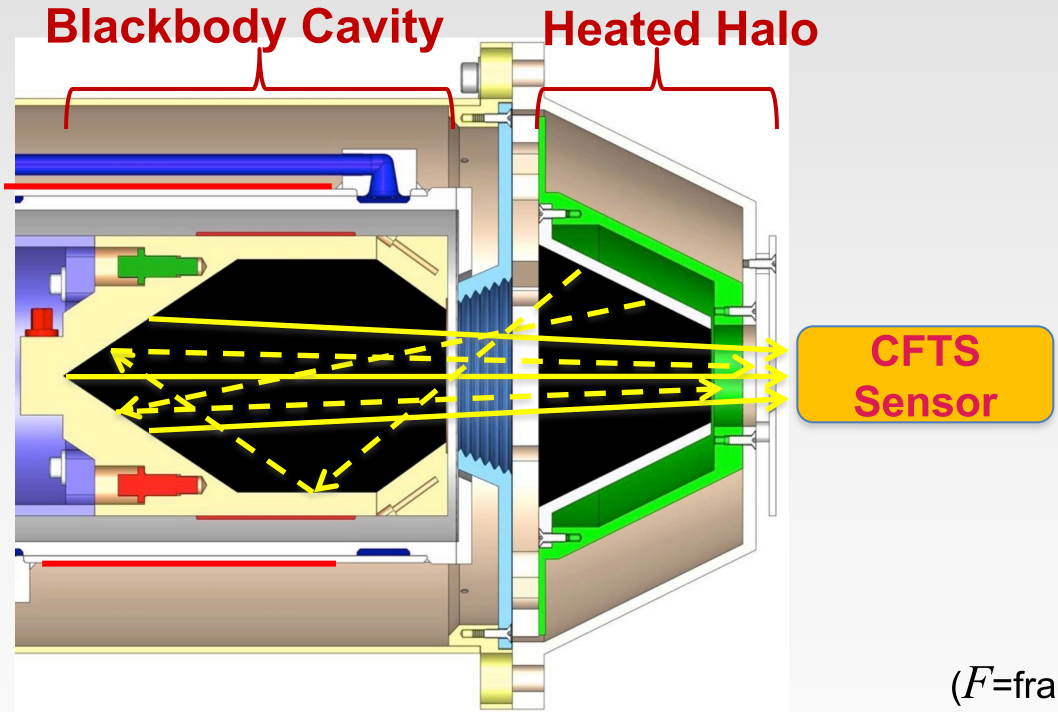
Under normal operation the Heated Halo is in place, but run at ambient temperature

Heated Halo Concept



During the Heated Halo Cavity Emissivity Measurement the Halo is elevated to 90 ° C, and the Blackbody is held at ambient temperature

Heated Halo Concept



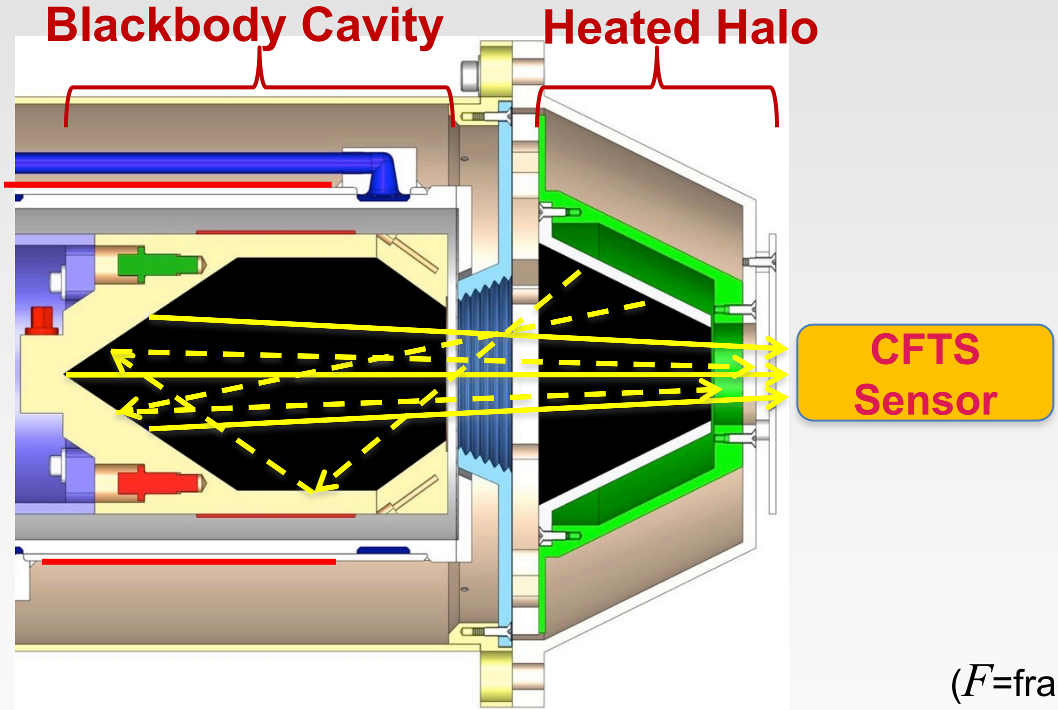
$$R_{BB} = \varepsilon \bullet B(T_{\mathrm{BB}}) + \underbrace{(1-\varepsilon) \bullet \overbrace{[F \bullet B(T_{\mathrm{Halo}}) + (1-F) \bullet B(T_{\mathrm{room}})]}^{(F\text{=fractional view to Halo})}}_{\text{Radiance Reflected from BB}}$$

$\underbrace{\varepsilon \bullet B(T_{\mathrm{BB}})}_{\text{Radiance emitted from BB}}$

Radiance emitted from BB

Radiance Reflected from BB

Heated Halo Concept



(*F*=fractional view to Halo)

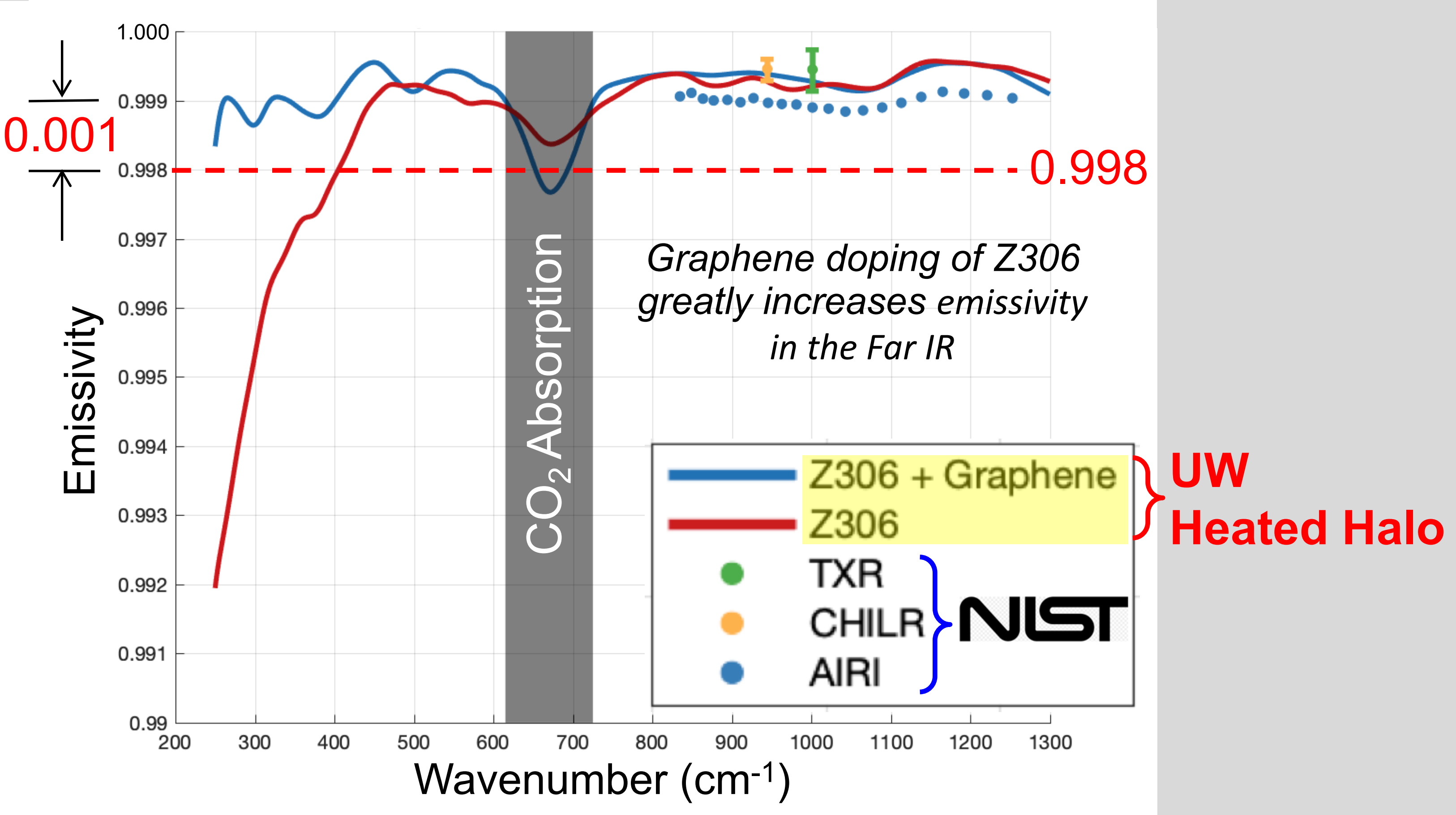
$$R_{\text{scene}} = \underbrace{\varepsilon \bullet B(T_{\text{BB}})}_{\text{Radiance emitted from BB}} + \underbrace{(1-\varepsilon)\bullet \overbrace{[F \bullet B(T_{\text{Halo}}) + (1-F)\bullet B(T_{\text{room}})]}^{}}_{\text{Radiance Reflected from BB}}$$

Radiance emitted from BB

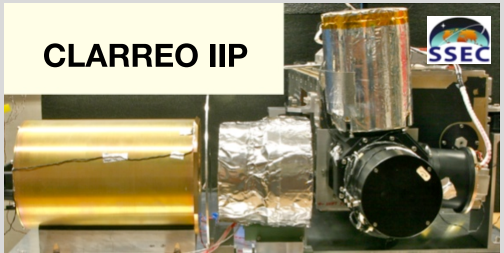
Radiance Reflected from BB

$$\left\langle 1-\varepsilon_{\tilde{v}}(t)\right\rangle_t = \left\langle \frac{R_{\text{scene}}(t) - B[T_{\text{BB}}(t)]}{R_{\text{background}}(t) - B[T_{\text{BB}}(t)]} \right\rangle_t$$

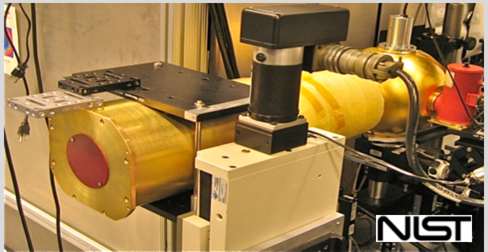
Blackbody Emissivity Measurement Comparisons



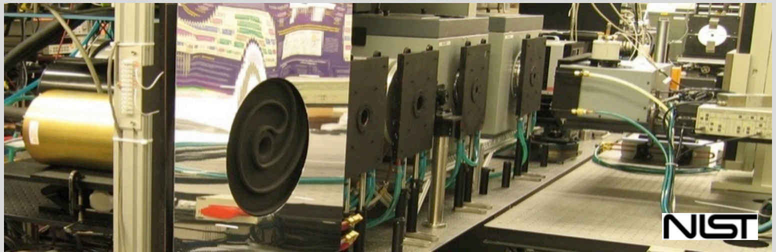
UW Heated Halo



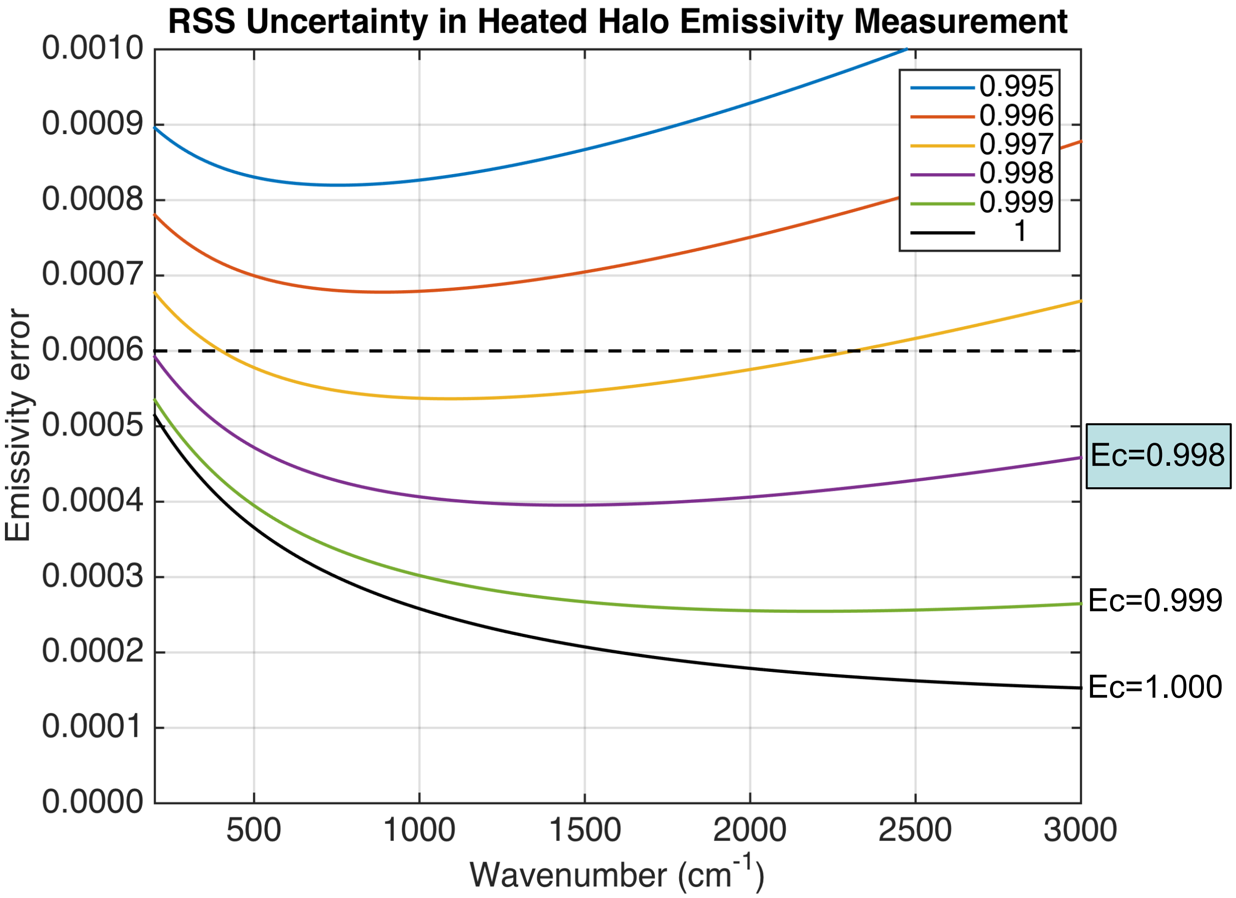
NIST CHILR



NIST AIRI



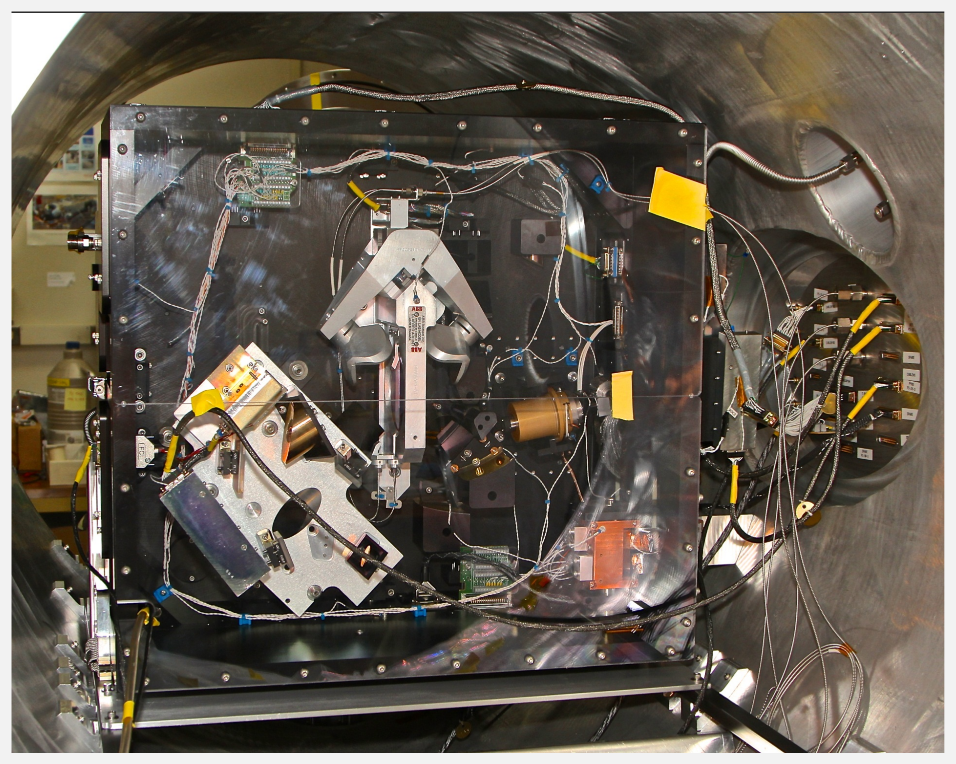
Required Emissivity to Meet Heated Halo Uncertainty Requirement of 0.0006

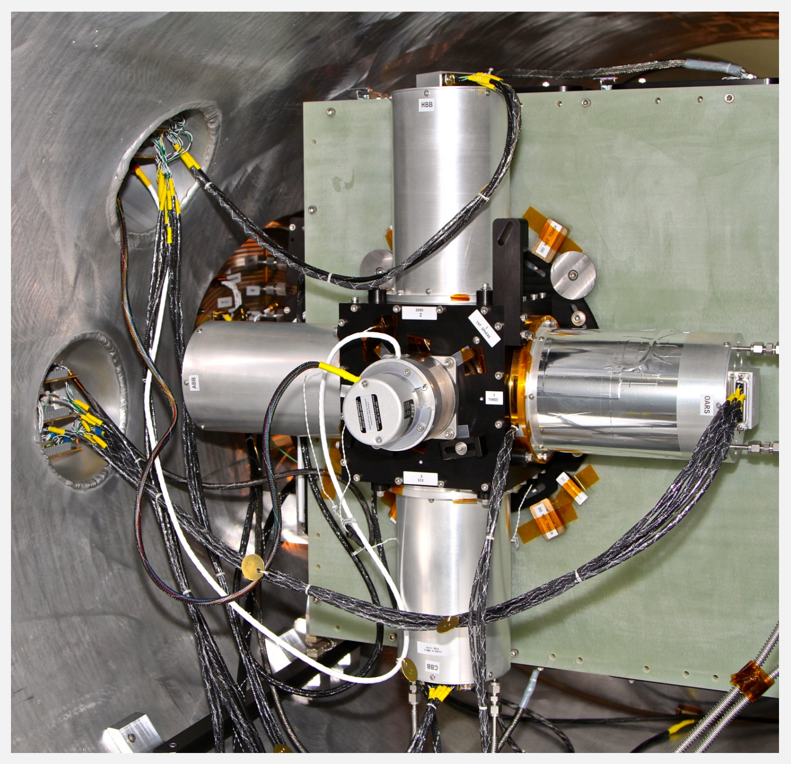


A cavity emissivity (Ec) of 0.998 is required to meet the Heated Halo uncertainty requirement of 0.0006.

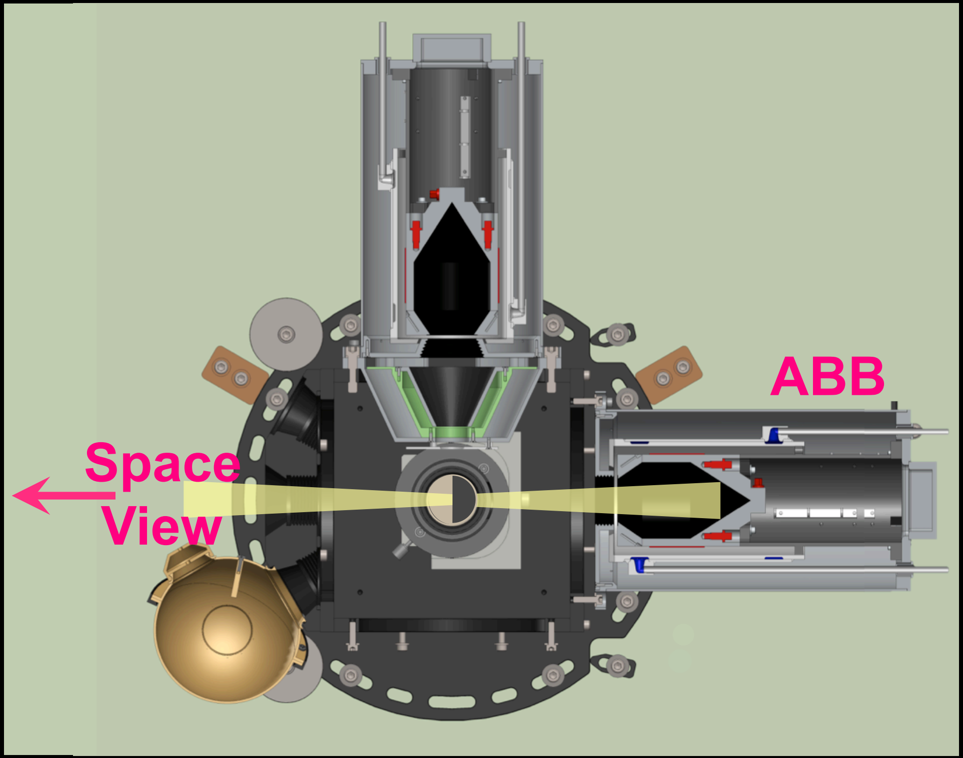
Vacuum Test Results Demonstrating 0.1K (3 sigma) Radiometric Performance

Vacuum Testing: Demonstration of Required Radiometric Accuracy





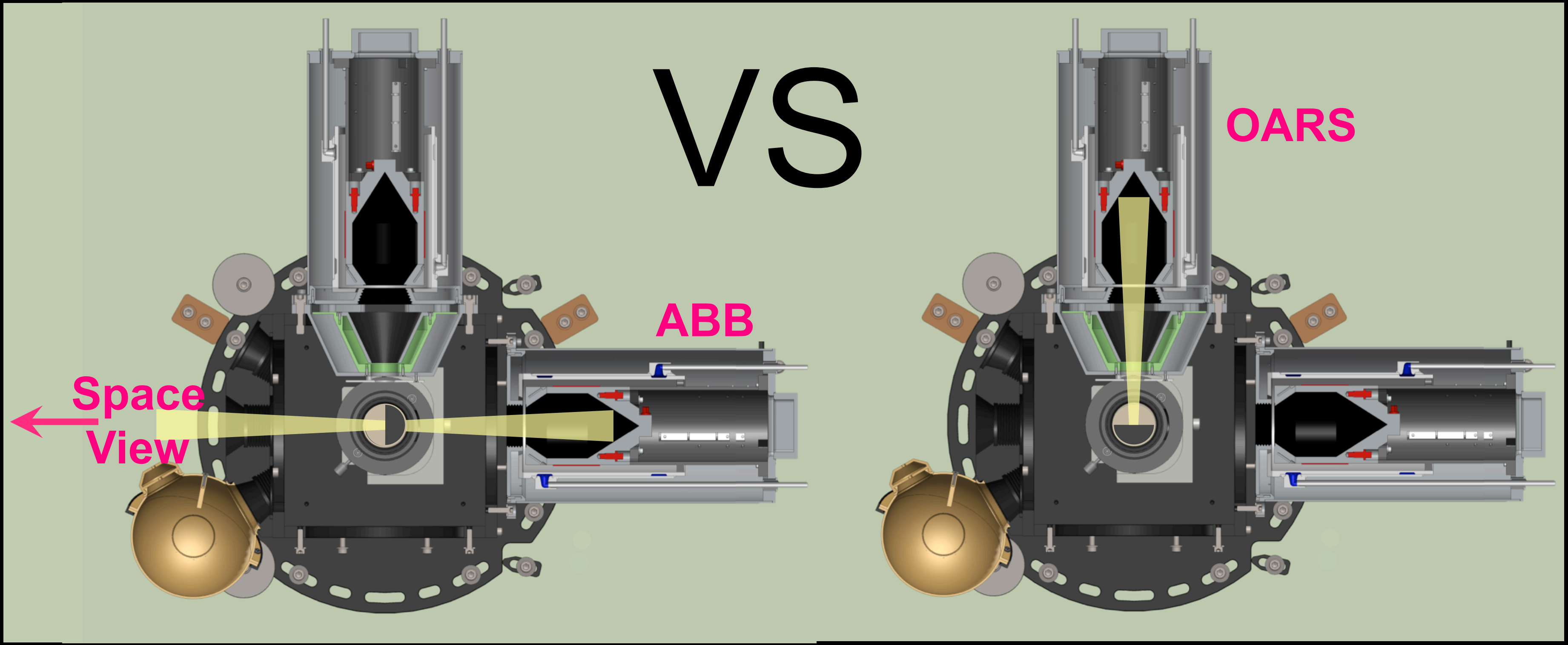
CFTS



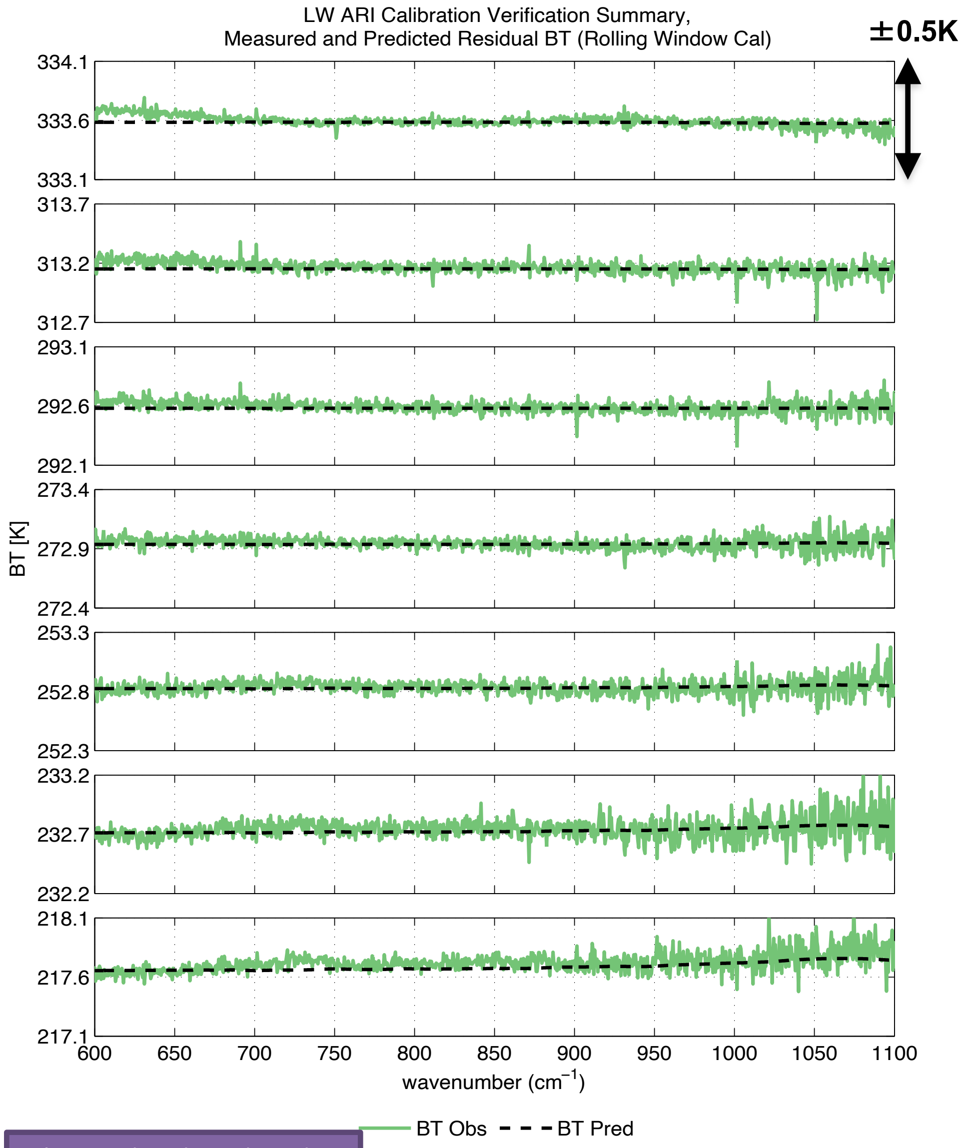
CFTS Calibration

VS

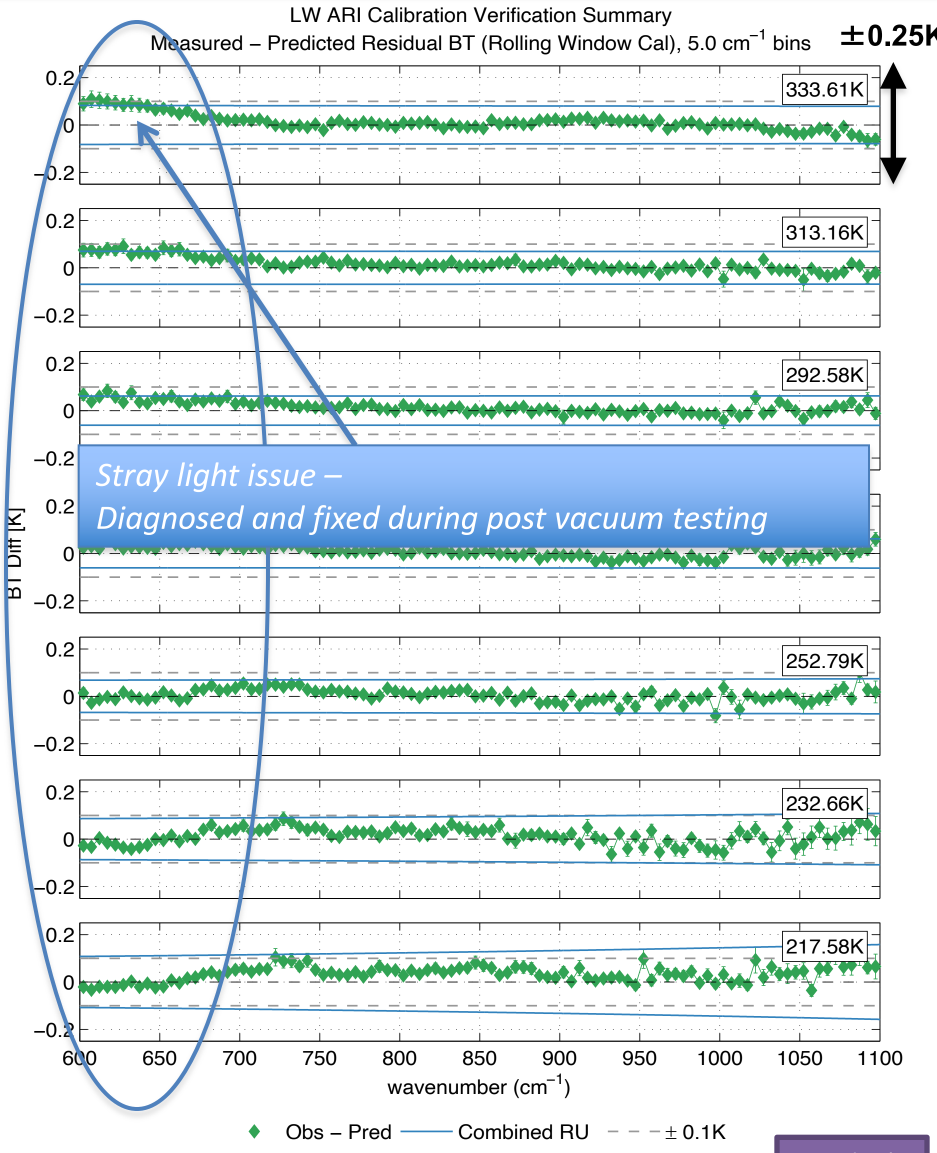
OARS Verification of CFTS



Demonstration of Required Radiometric Accuracy, LW MCT


LW ARI Calibration Verification Summary,
Measured and Predicted Residual BT (Rolling Window Cal)

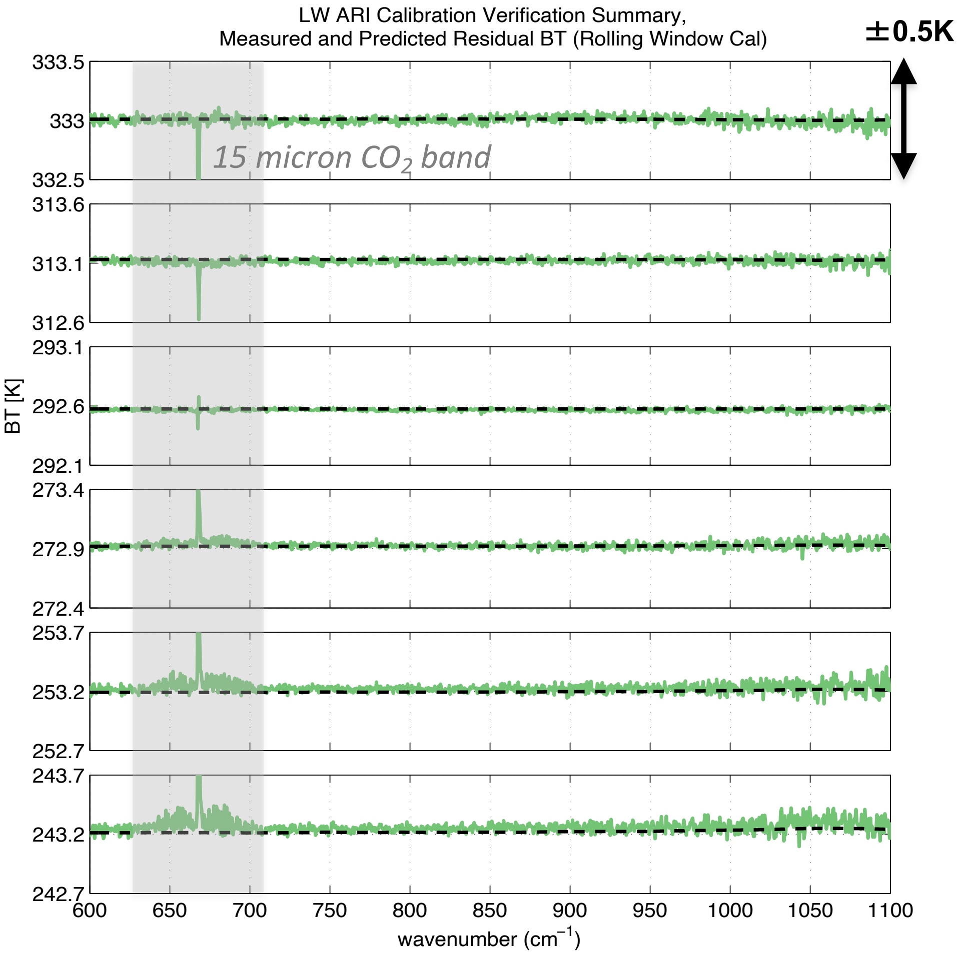
Observed and Predicted

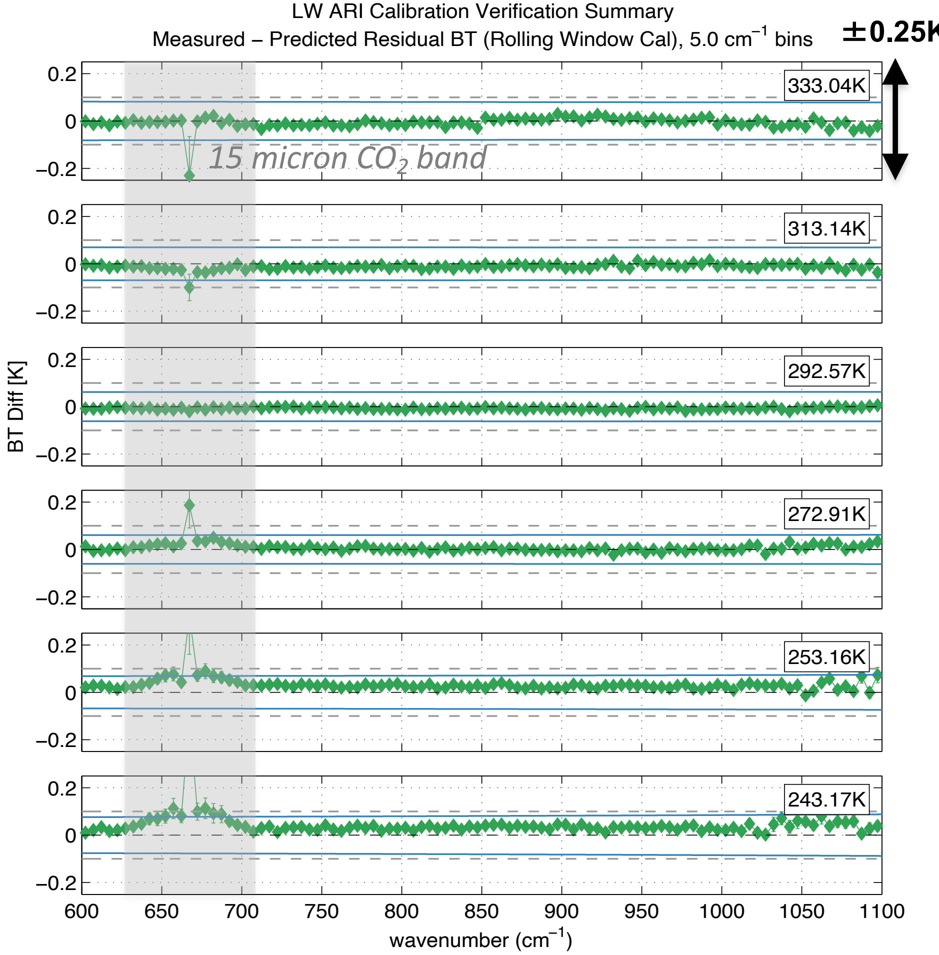

LW ARI Calibration Verification Summary
Measured – Predicted Residual BT (Rolling Window Cal), 5.0 cm^{-1} bins

Stray light issue –
Diagnosed and fixed during post vacuum testing

Residual

Demonstration of Required Radiometric Accuracy, LW MCT 2015 Data Collect – Dry Air Purge





2015 Data Collect – *Confirms small stray light issue diagnosed and fixed during post vacuum test*

BT Obs - - - BT Pred

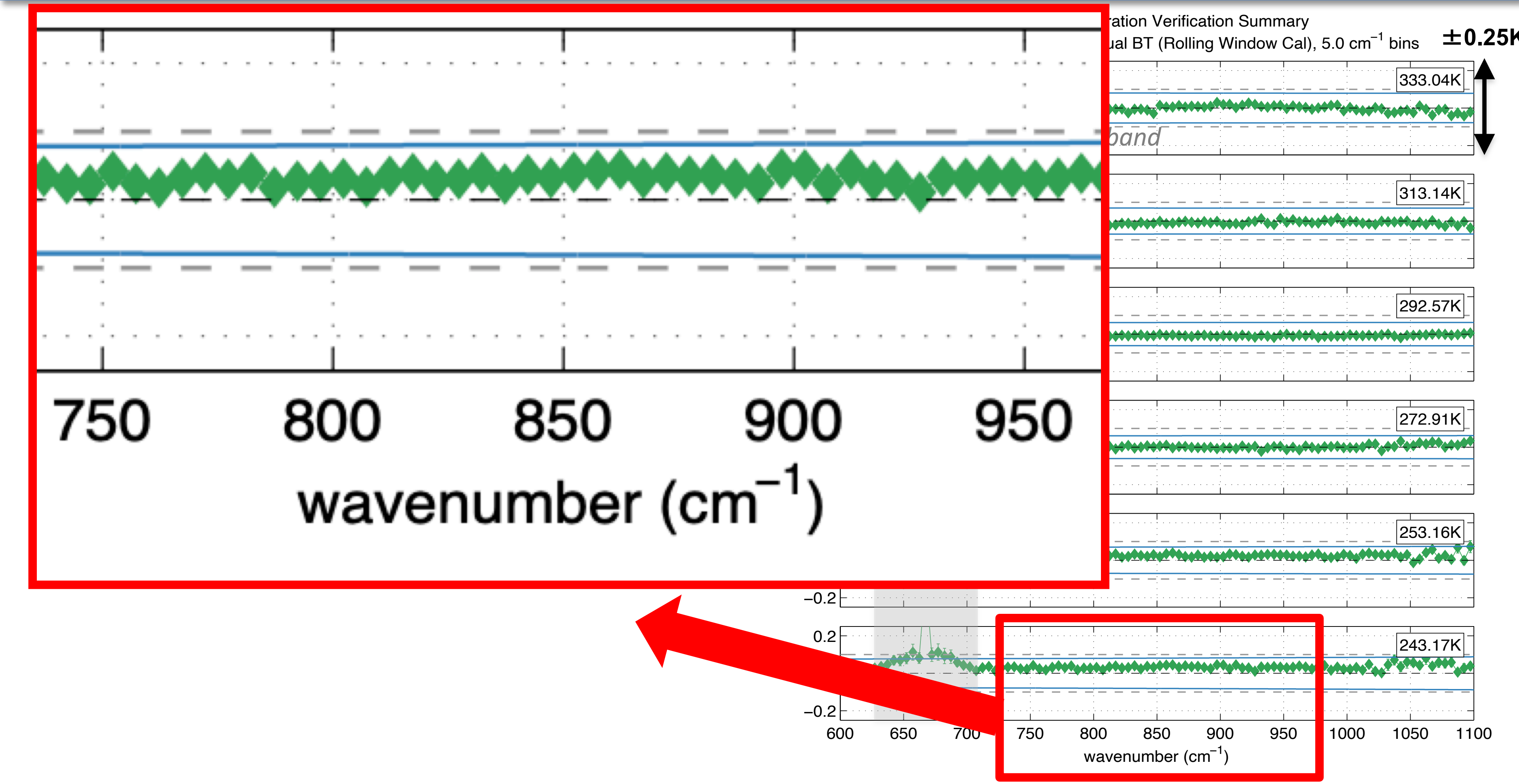
Observed and Predicted

♦ Obs – Pred — Combined RU - - - ± 0.1K

Residual

24-Jul-2018

Demonstration of Required Radiometric Accuracy, LW MCT
2015 Data Collect – Dry Air Purge

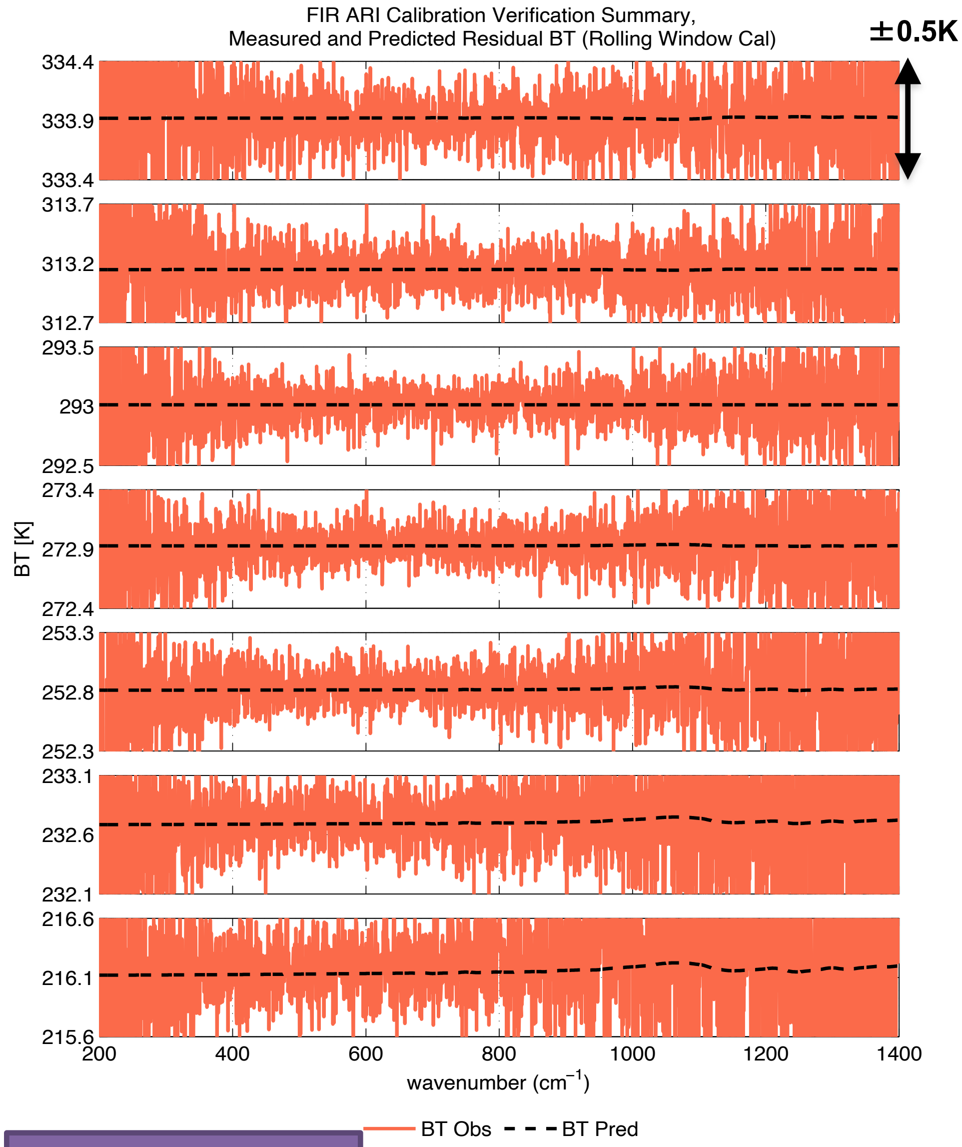


2015 Data Collect – *Confirms small stray light issue diagnosed and fixed during post vacuum test*

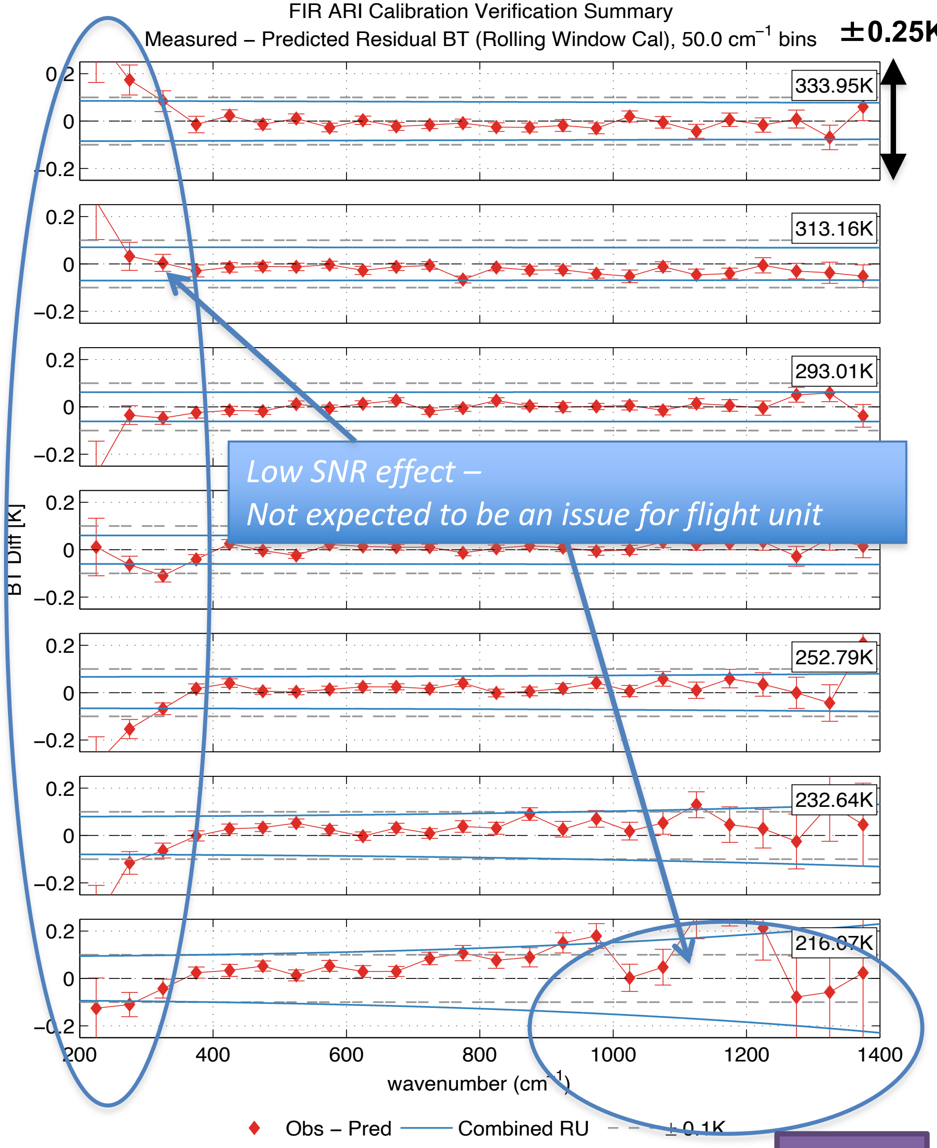
Observed and Predicted

Residual

Demonstration of Required Radiometric Accuracy, DTGS



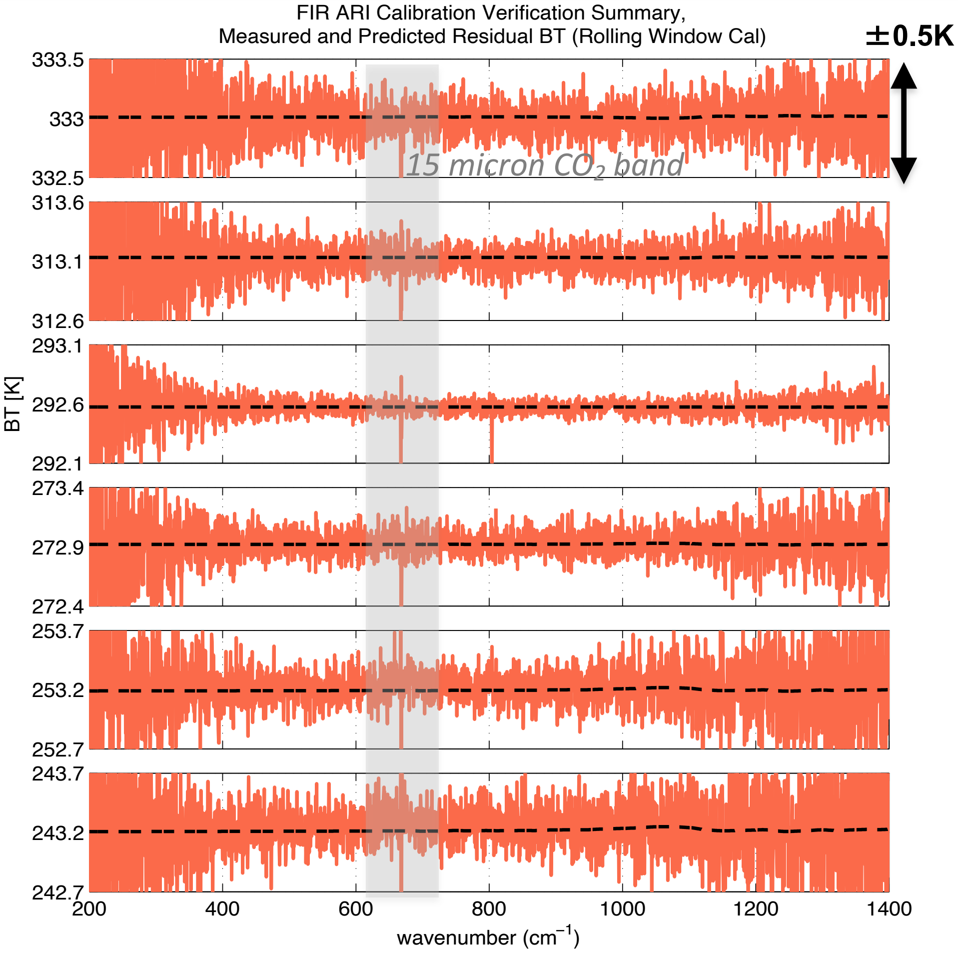
Observed and Predicted

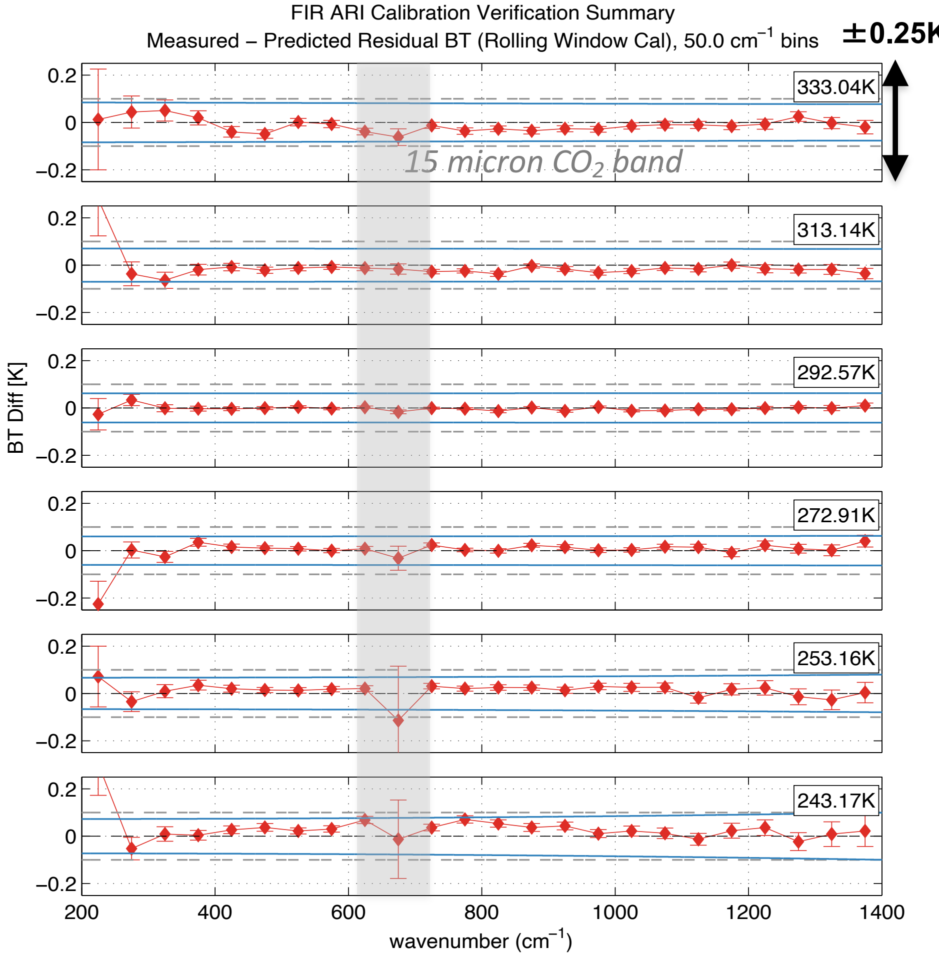


Low SNR effect –
Not expected to be an issue for flight unit

Residual

Demonstration of Required Radiometric Accuracy, DTGS 2015 Data Collect – Dry Air Purge


FIR ARI Calibration Verification Summary,
Measured and Predicted Residual BT (Rolling Window Cal)


FIR ARI Calibration Verification Summary
Measured – Predicted Residual BT (Rolling Window Cal), 50.0 cm^{-1} bins

2015 Data Collect – *Confirms small stray light issue diagnosed and fixed during post vacuum test*

BT Obs - - - BT Pred

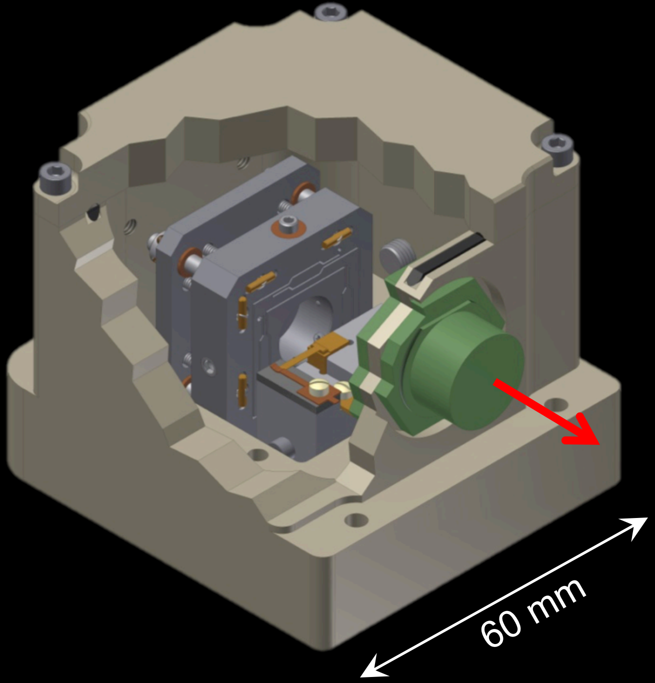
♦ Obs – Pred — Combined RU - - - ± 0.1K

Observed and Predicted

Residual

Emissivity and Instrument Line Shape Measurements Using a Quantum Cascade Laser

OVTS: Quantum Cascade Laser (QCL)



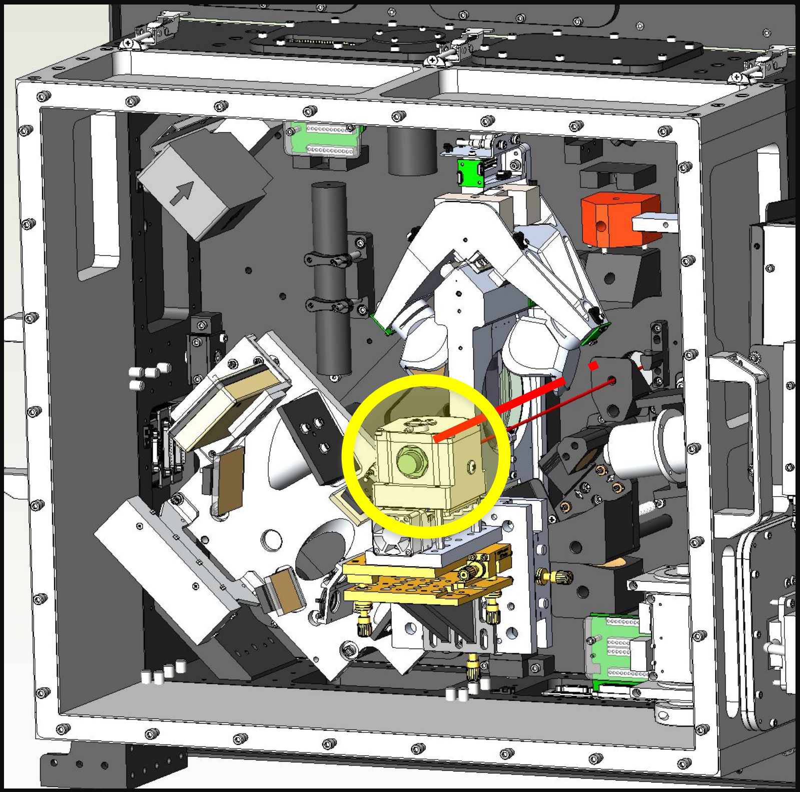
Output:
9.5 μm
80 mW

- QCL developed by Harvard under an IIP and brought to TRL 6 through testing under vacuum
- QCL is injected through the Scene Selection Mirror into the OARS and ABB for emissivity comparison, and an Integrating Sphere for ILS measurement
- Laser output power is determined by interleaving views of the Integrating Sphere

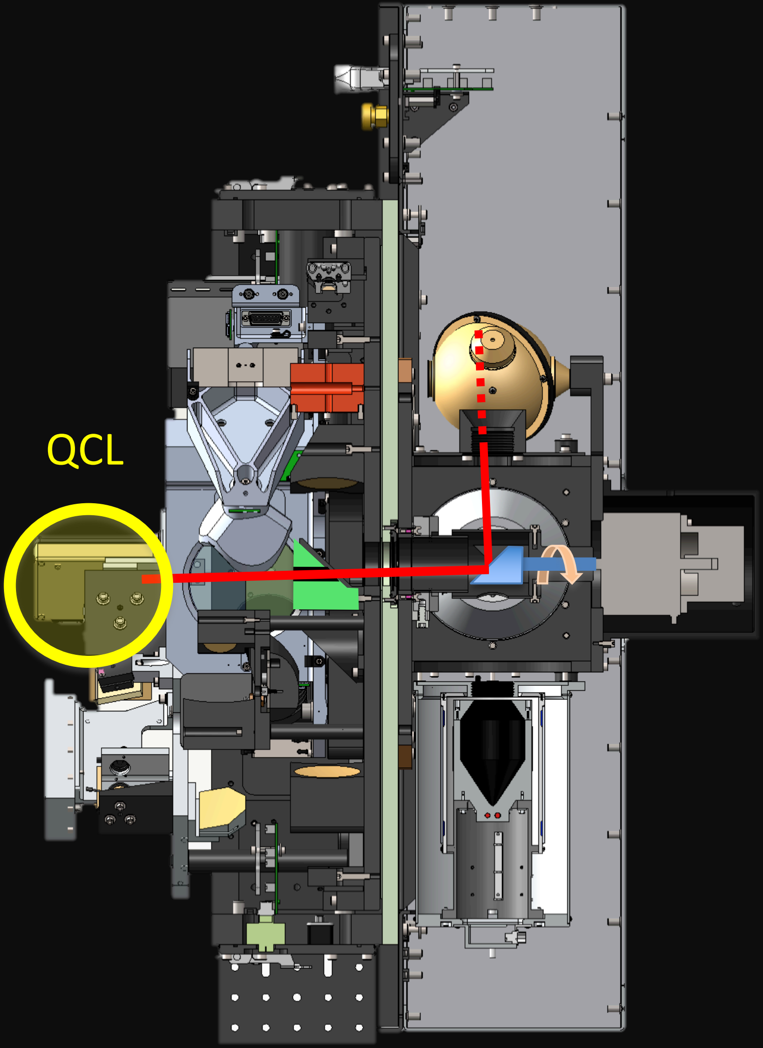
Harvard University

Injection of Quantum Cascade Laser for Emissivity and Instrument Line Shape Measurements

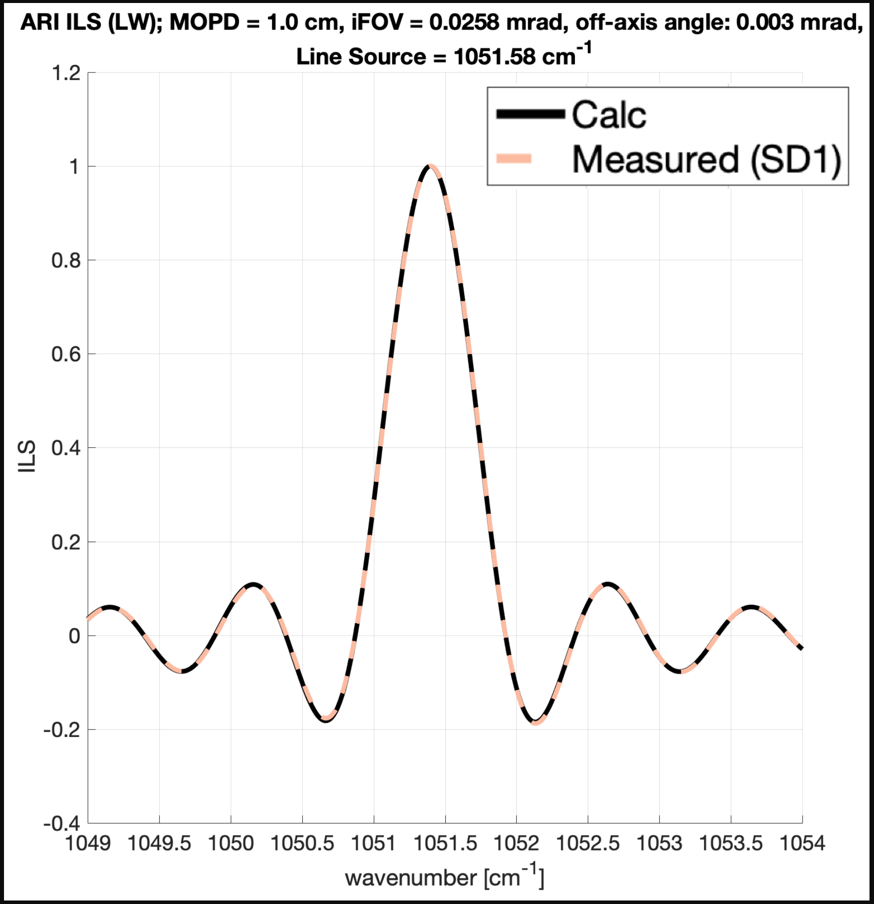
The QCL is injected to the center of the Scene Mirror from the back of the optical system, allowing all targets to be illuminated in identical fashion, while being viewed by the FTS.



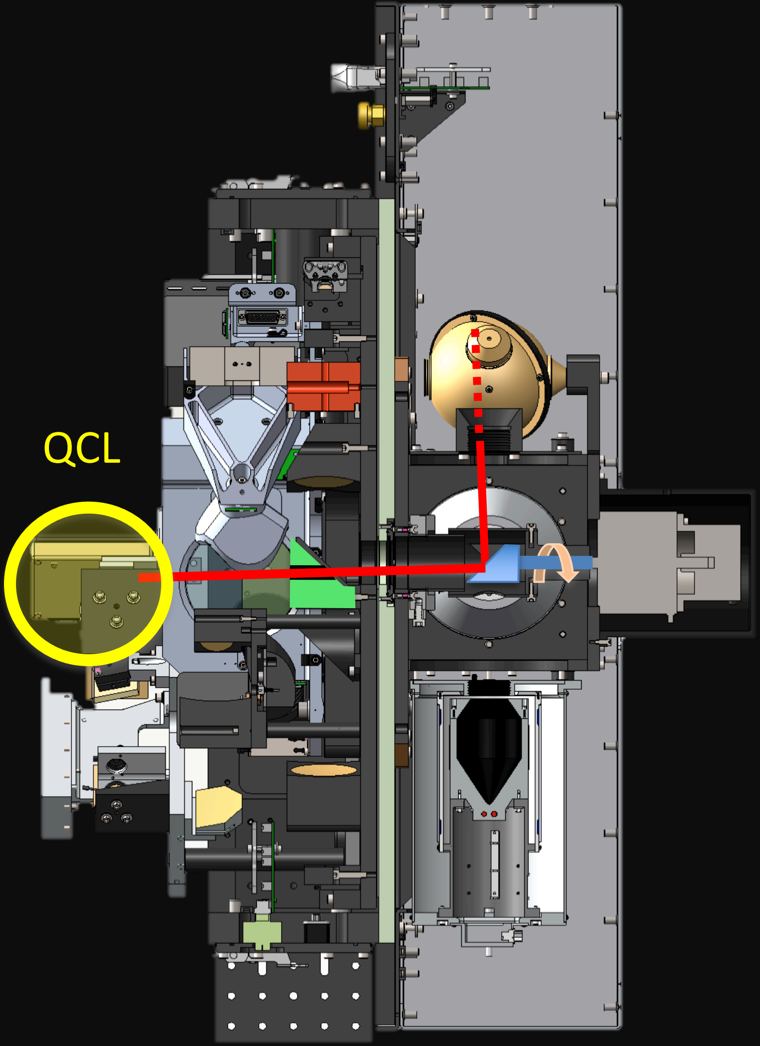
Side View



Instrument Line Shape (ILS) Measurement Using QCL

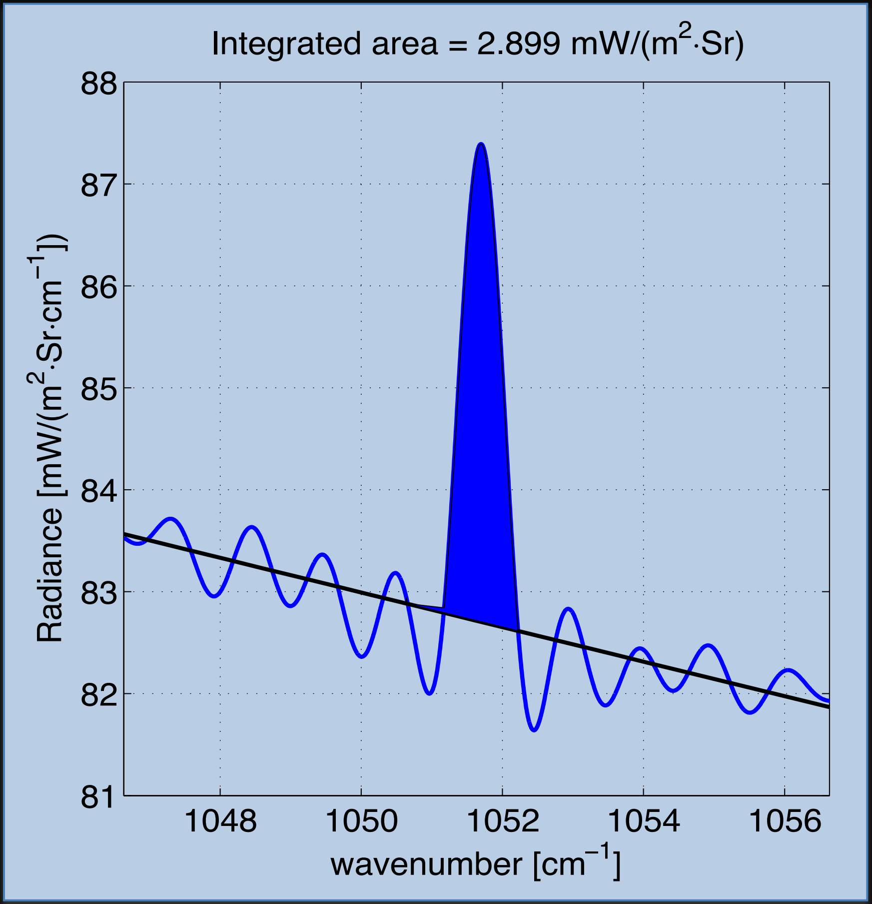


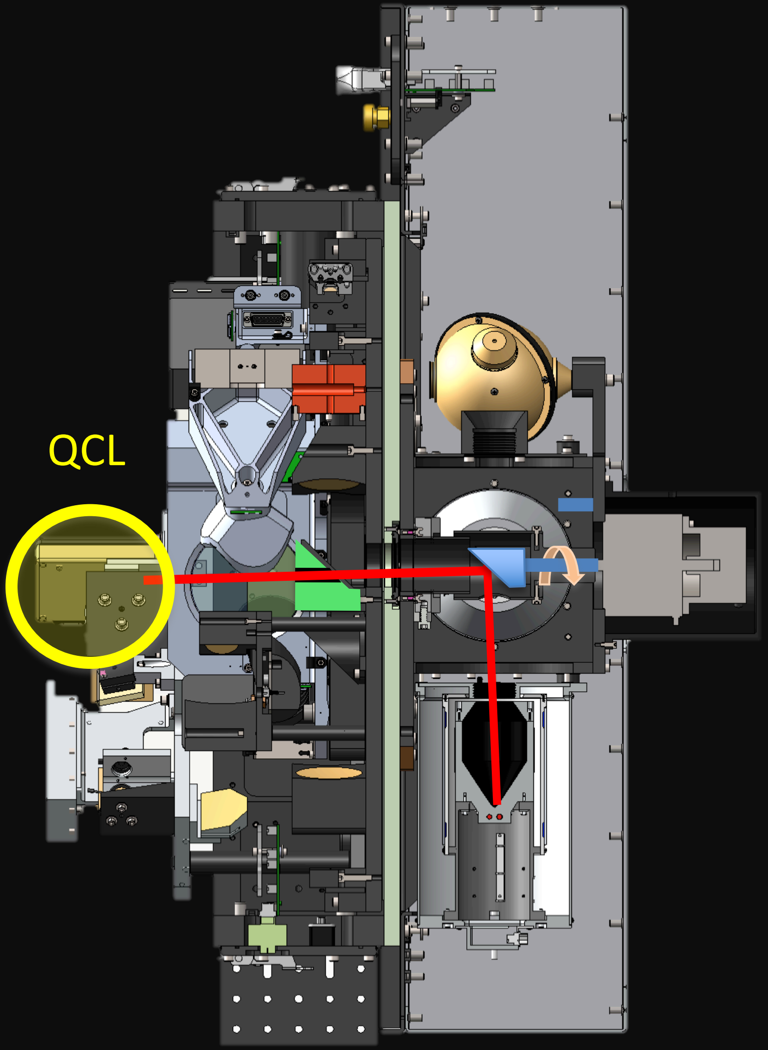
Instrument Line Shape measurement compared to Calculation



Data shown collected with QCL injected into SSM through front-end port

Cavity Emissivity Measurement Using QCL





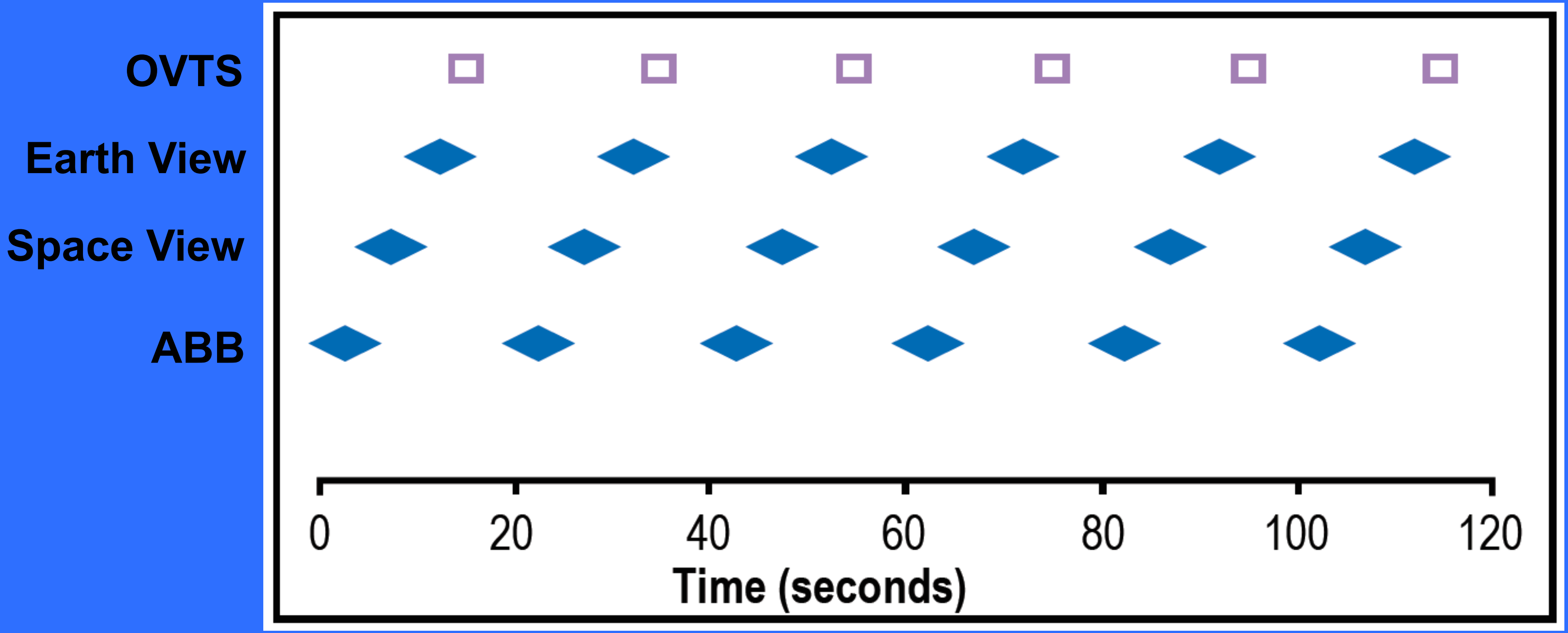
The monochromatic cavity emissivity of the OARS & Cal BB is expected to be measured to better than 0.001

Data shown collected with QCL injected into SSM through front-end port

Concept of Operations
ARI and OVTS

Concept of Operations ARI

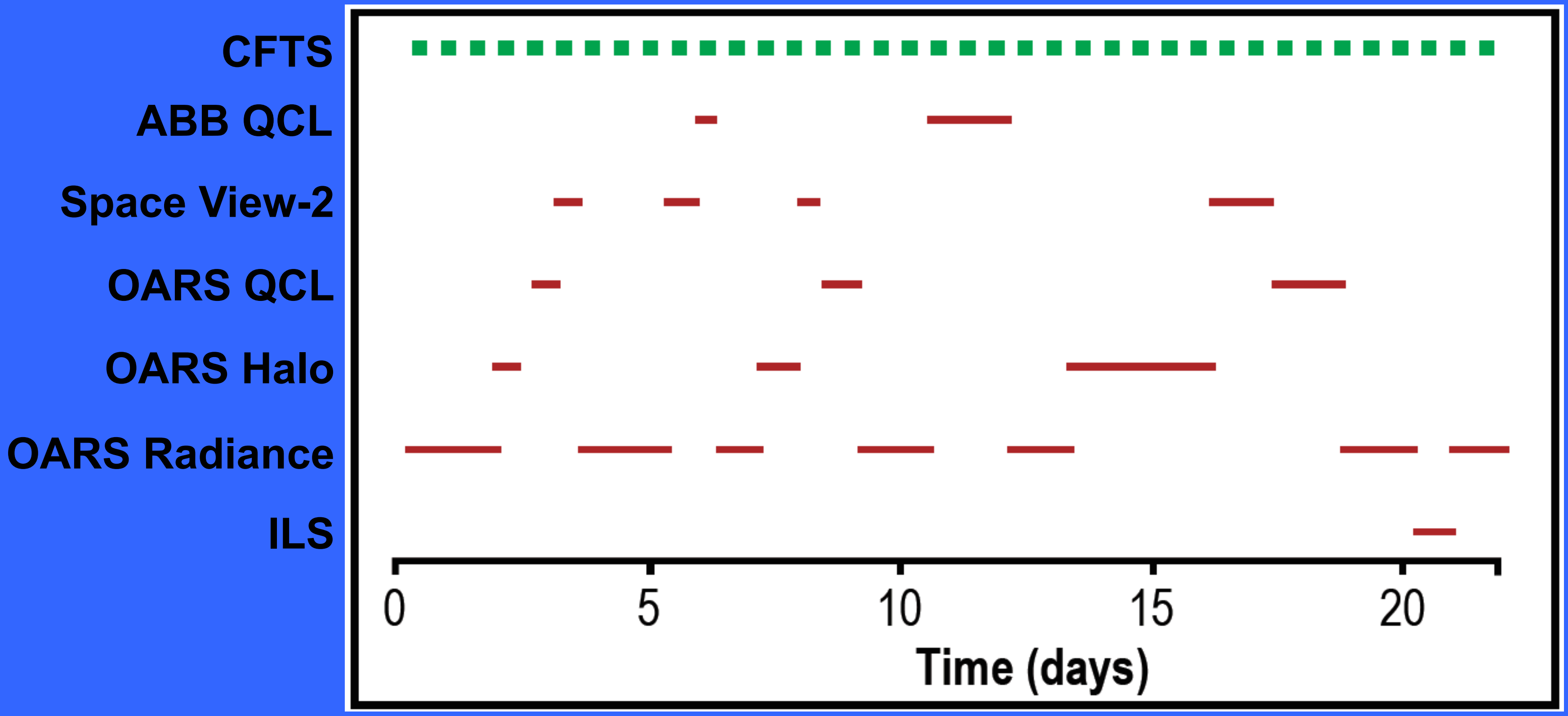
Over Two Minutes



- The Absolute Radiance Interferometer (ARI) continuously collects an interferogram every 5 seconds.
- The scene mirror is used to sequence through a calibration cycle (Earth, Space, and Ambient Blackbody) and a view of the OVTS every 20 seconds.

Concept of Operations ARI

Over 22 Days



- On a longer time scale (22 days), elements of the (OVTS) are viewed in the sequence shown above.

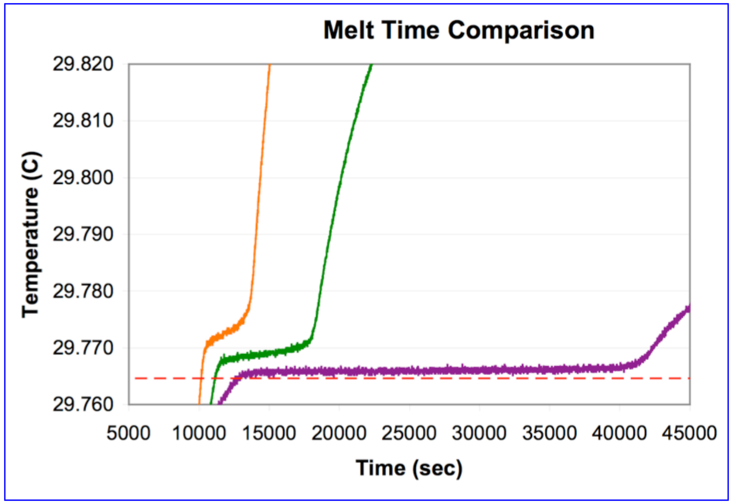
Summary

- The ARI has demonstrated the enabling technologies and the required radiometric performance for a CLARREO-type Climate Benchmark Mission, and now possesses a Technical Readiness Level of 6.
- It is ready for a space flight mission.

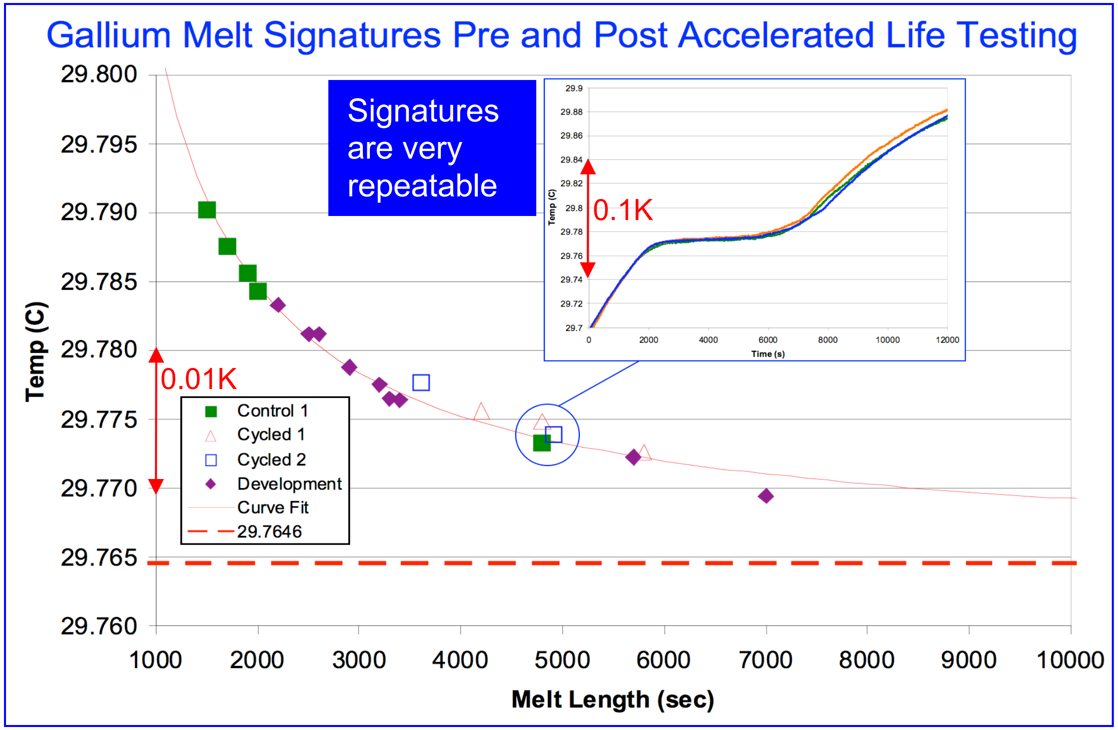
QUESTIONS

Back-up Slides

Signature Dependence on Melt Length



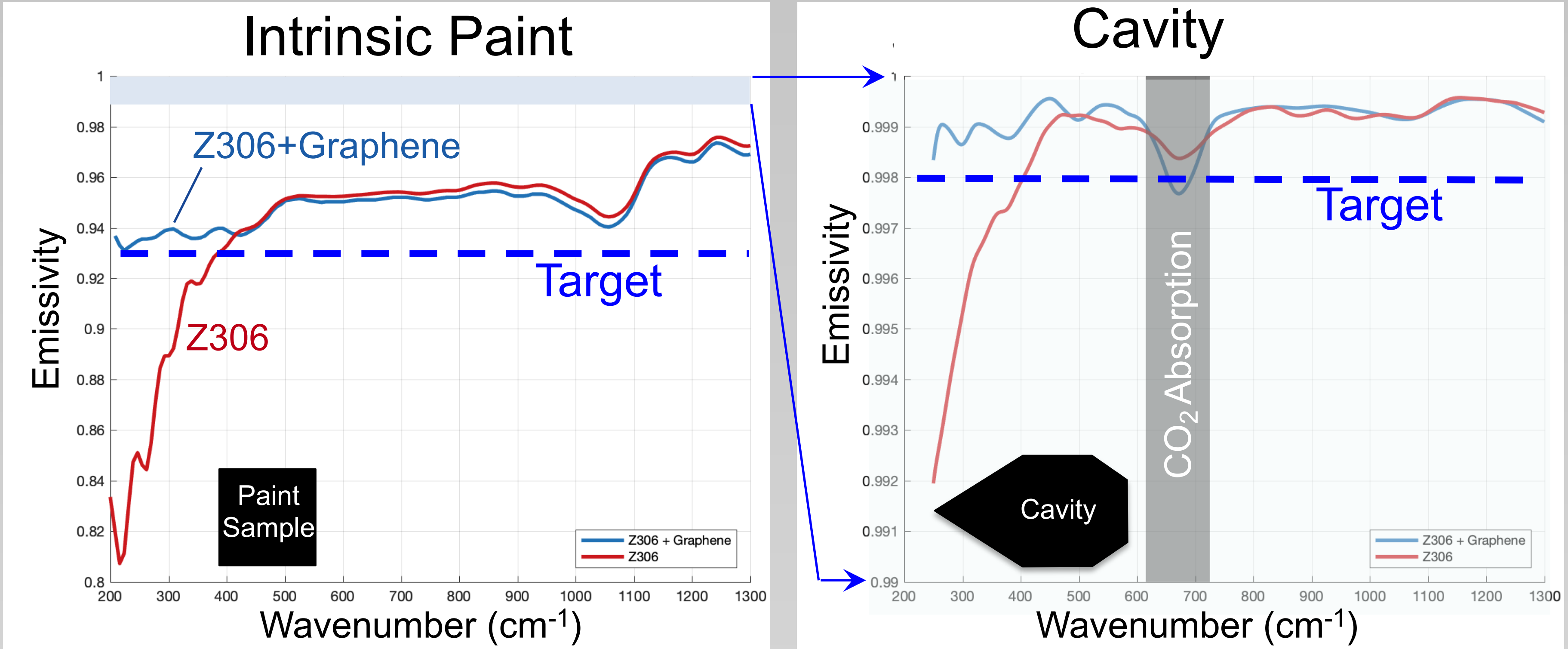
Melt curves that are flatter and approach the theoretical melt temperature are obtained with longer melt times.



Signatures are very repeatable

Mid-melt temperature vs melt length relationship is stable and can be very well characterized.

Emissivity of Intrinsic Paint and Cavity (Aeroglaze Z306, with and without Graphene)



Measured at Surface Optics

Measured at UW
Using Heated Halo Method