Progress on a CLARREO IR Instrument Prototype:

Flight Prototype Absolute Radiance Interferometer (ARI) with On-orbit Verification and Test System (OVTS) demonstrates 0.1 K capability in Vacuum

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Space Science and Engineering Center

CLARREO Science Definition Team
Hampton Virginia, 16-18 April 2013

Topics: IR Measurement Science

- Summary of Previous UW/Harvard NASA Instrument Incubator Program (IIP) ARI Results

- New Vacuum Testing of CLARREO Flight Prototype demonstrates 0.1 K 3-sigma performance of Calibrated FTS (CFTS) and On-orbit Verification and Test System (OVTS)

Absolute Radiance Interferometer (ARI):
Definitions of key components

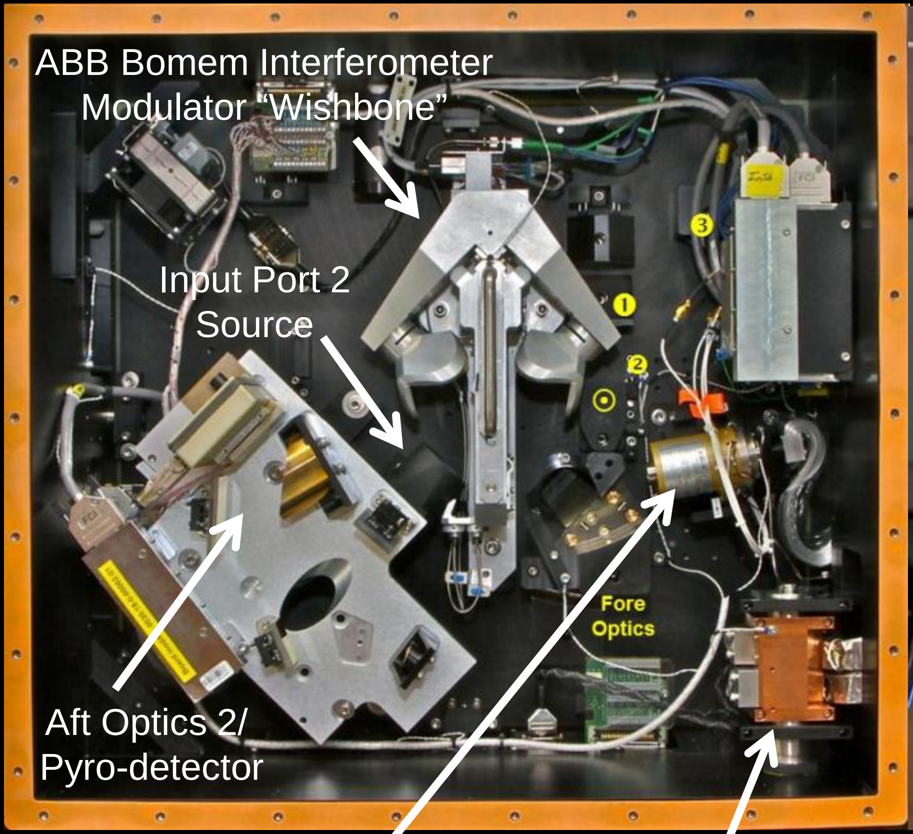
- **Calibrated Fourier Transform Spectrometer (CFTS):**
  - FTS with strong flight heritage
  - 3 Spectral bands covering 3-50 µm
  - 2 Cavity Blackbody References for Calibration
- **On-orbit Verification and Test System (OVTS):**
  - ❶ On-orbit Absolute Radiance Standard (OARS) cavity blackbody using three miniature phase change cells to establish an accurate temperature scale from -40, to +30 C
  - ❷ On-orbit Cavity Emissivity Module (OCEM) using a Heated Halo source that allows the FTS to measure the broadband spectral emissivity of the OARS to better than 0.001
  - ❸ OCEM-QCL* using a quantum cascade laser source to monitor changes in the mono-chromatic cavity emissivity of the OARS
  - ❹ On-orbit Spectral Response Module* (OSRM) using the same QCL to measure the FTS instrument line shape

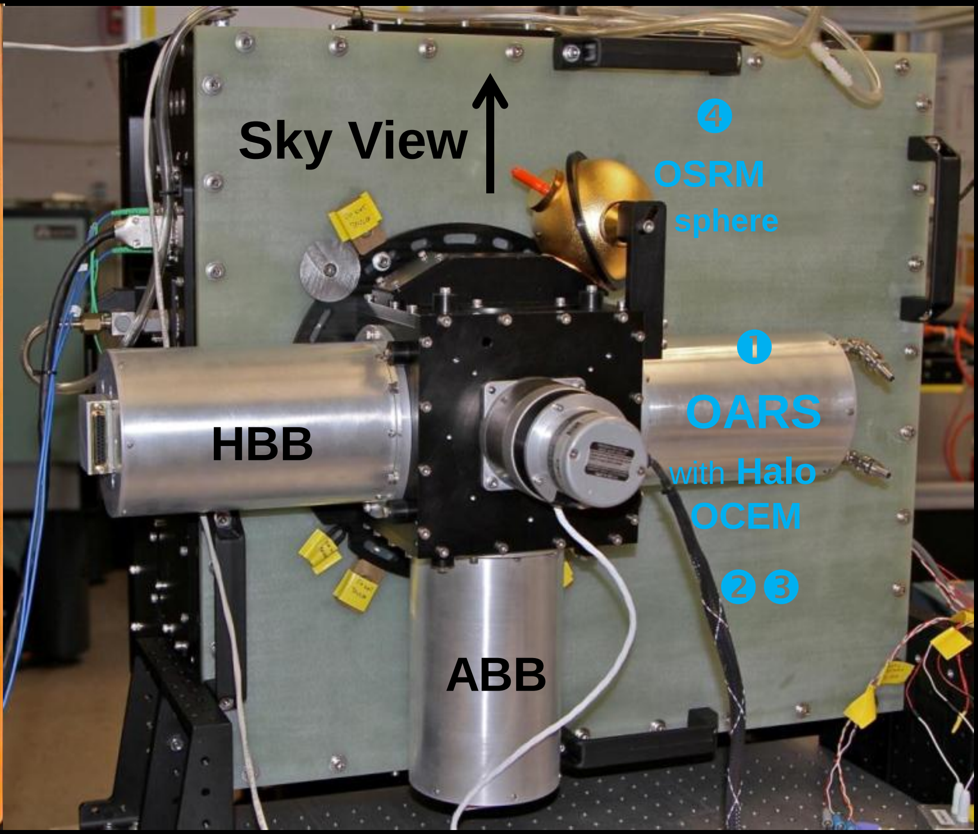
*Not fully implemented in prototype—demonstrated separately

UW Absolute Radiance Interferometer (ARI) Prototype

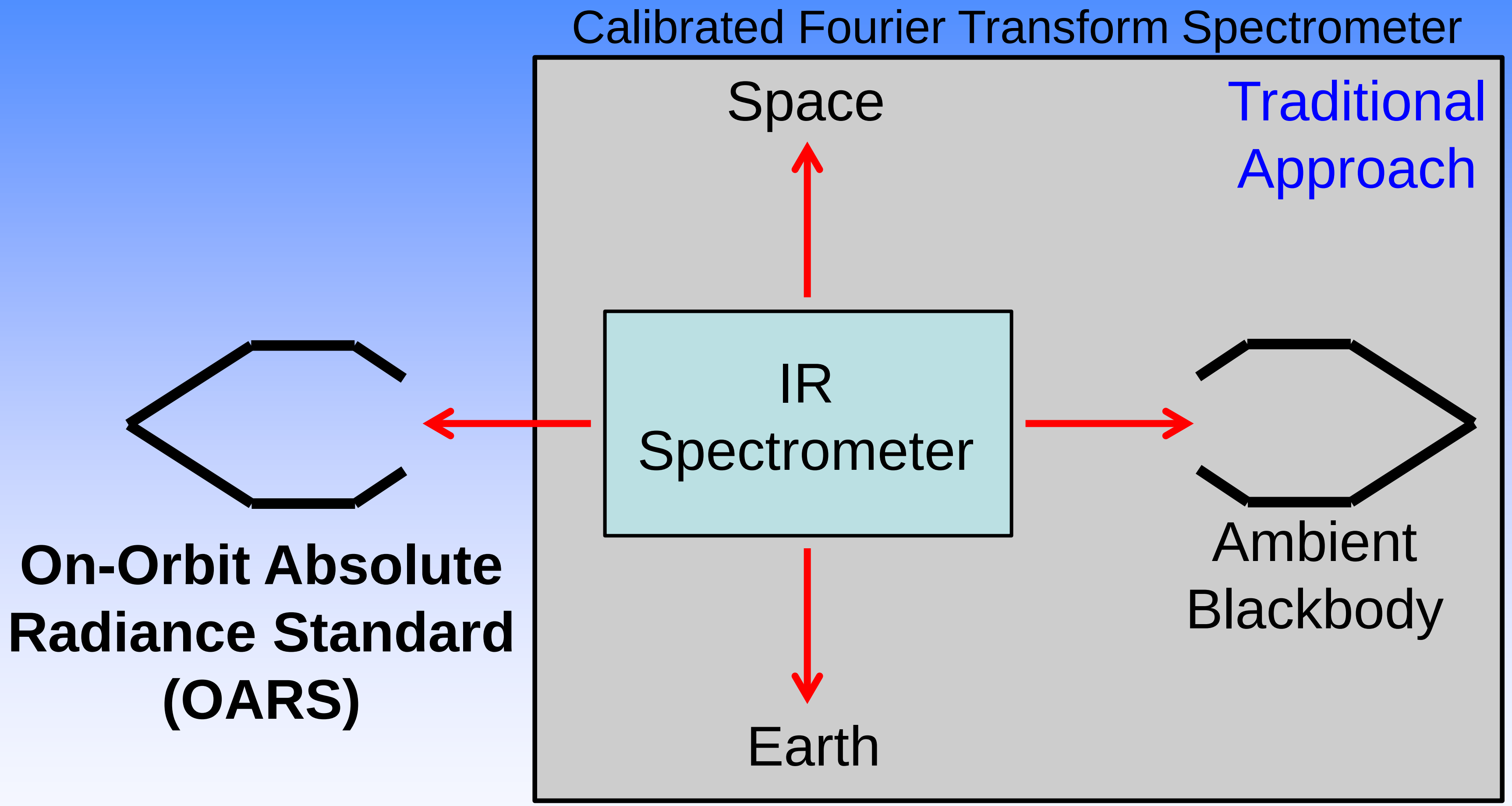
components of Calibrated FTS

On-orbit Verification & Test Sources &
Calibrated FTS Blackbodies (HBB & ABB)





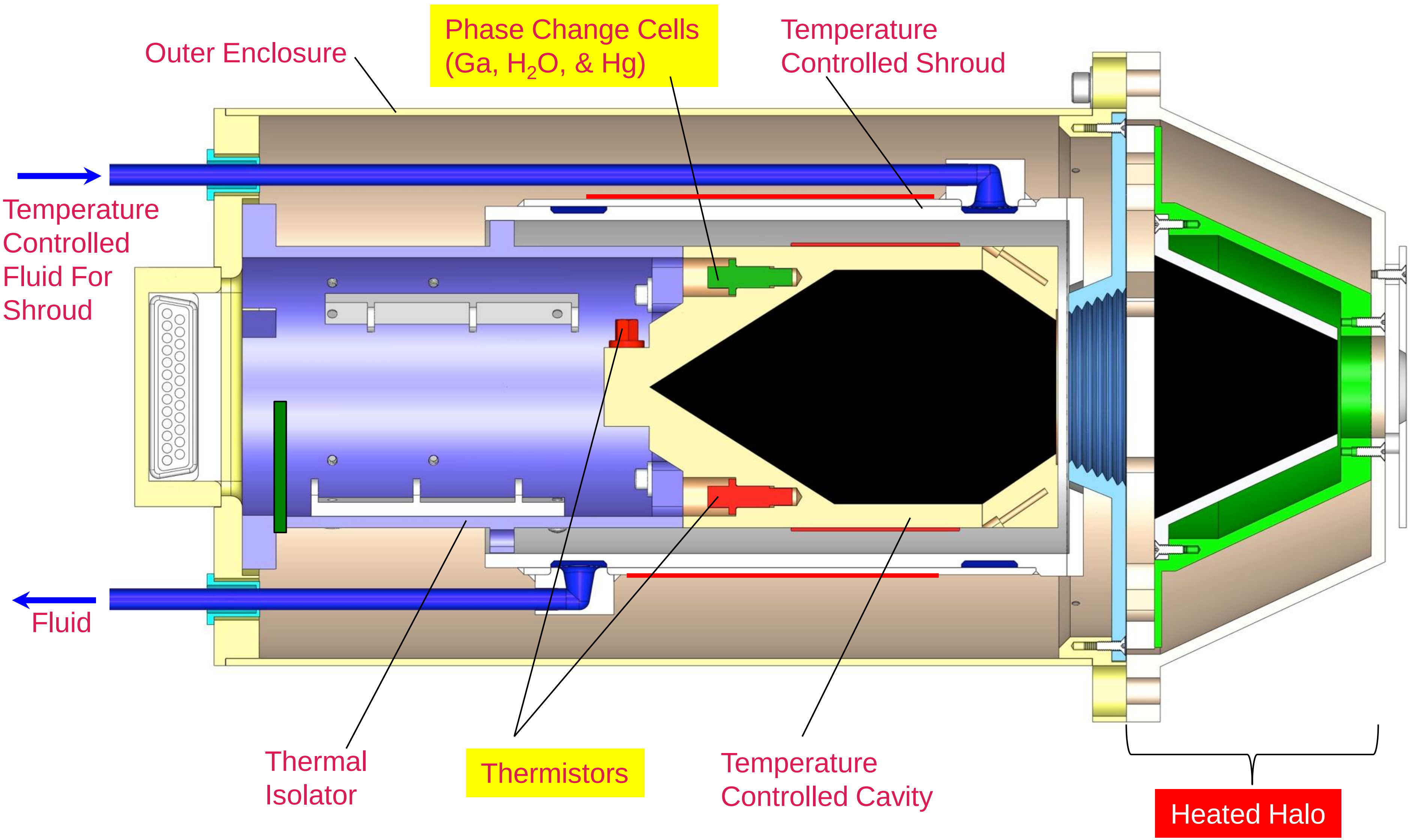
On-Orbit Calibration Verification



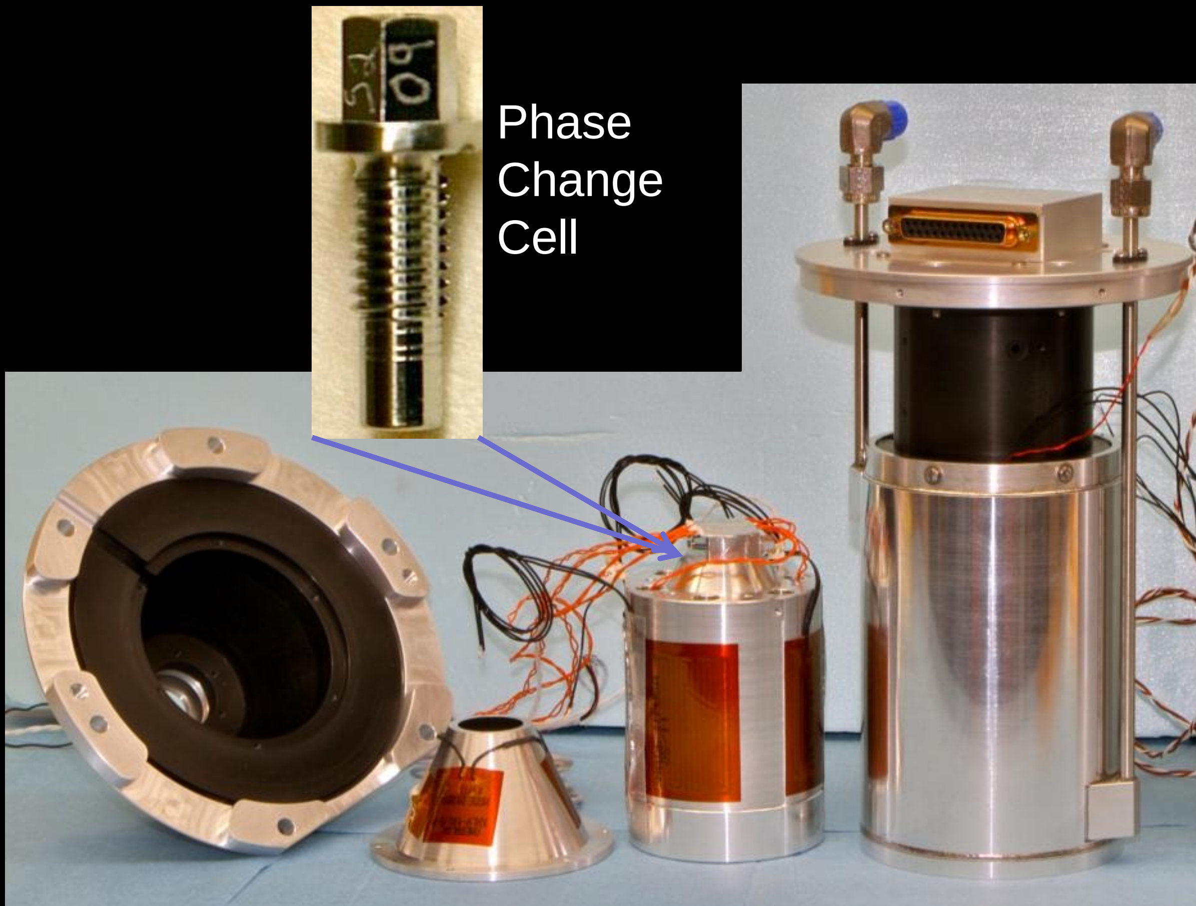
OARS Provides End-to-End Calibration Verification On-Orbit Traceable to Recognized SI Standards

OARS Design Based on GIFTS Blackbody

(designed for operation in lab environment)



On-orbit Absolute Radiance Standard OARS



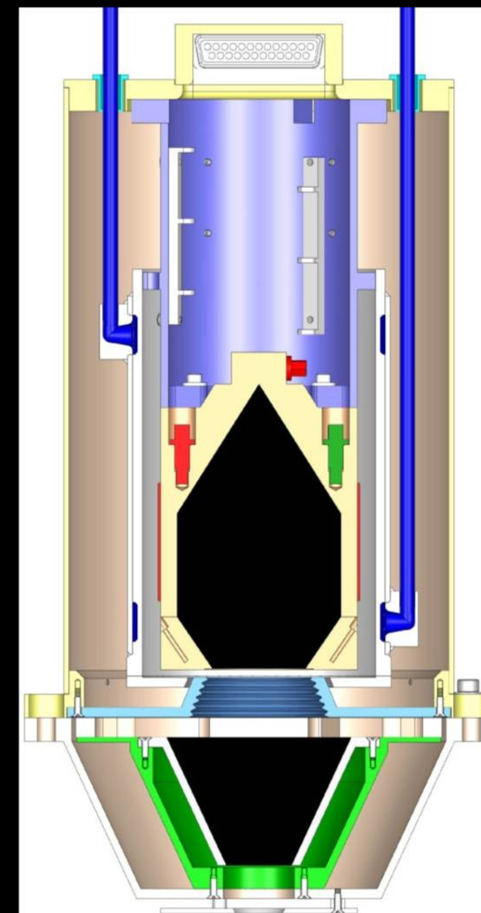
Phase Change Cell

Heated Halo
& Halo Insulator

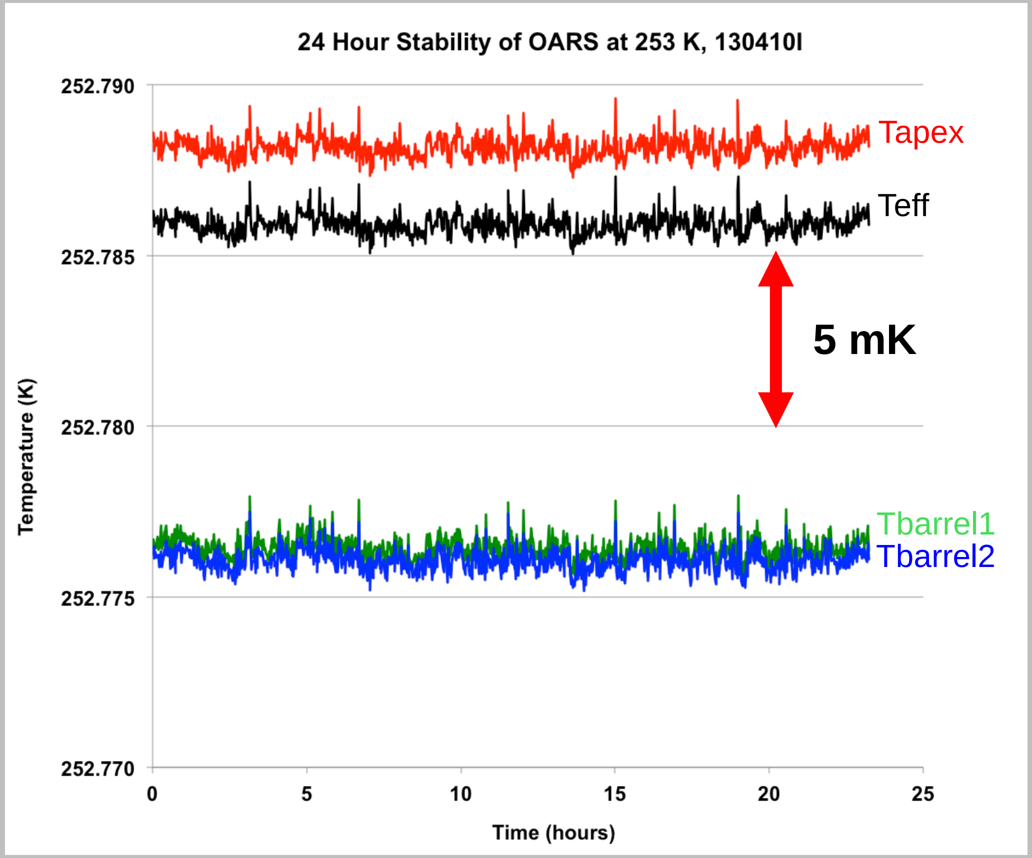
Cavity

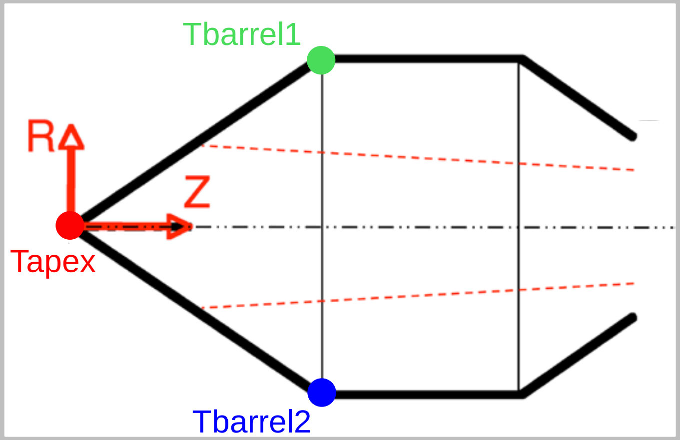
Inner Shield
& Isolator

Assembly Diagram



OARS 24 Hour Stability at -20 C under Vacuum

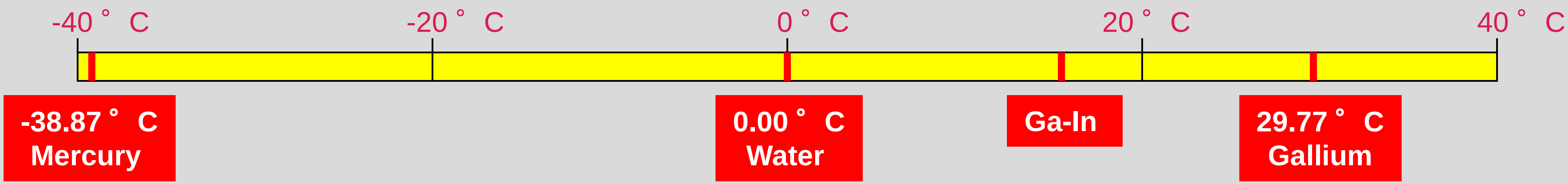


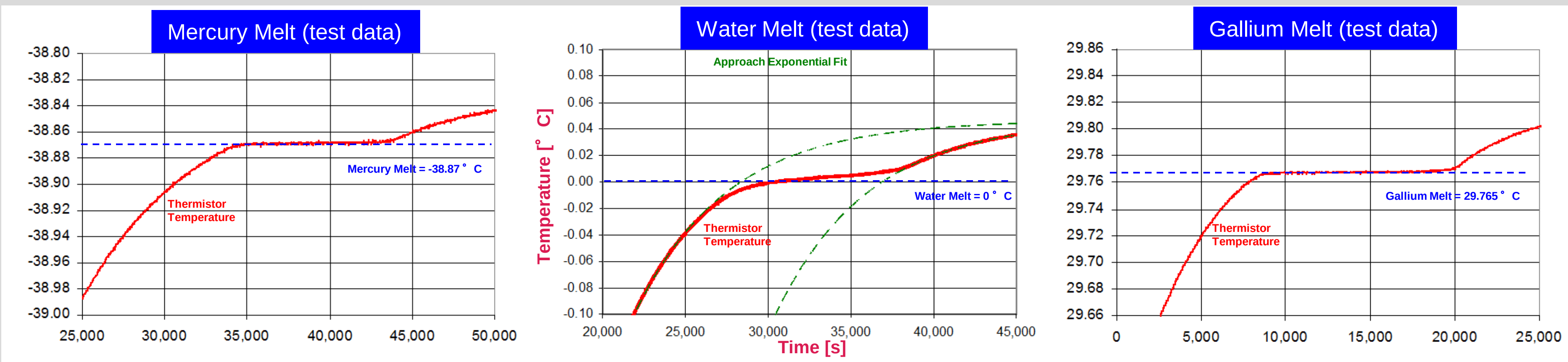


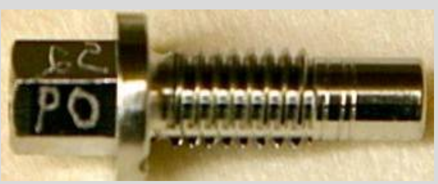
Teff=0.811*Tapex+0.095*Tbarrel1+0.095*Tbarrel2

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.

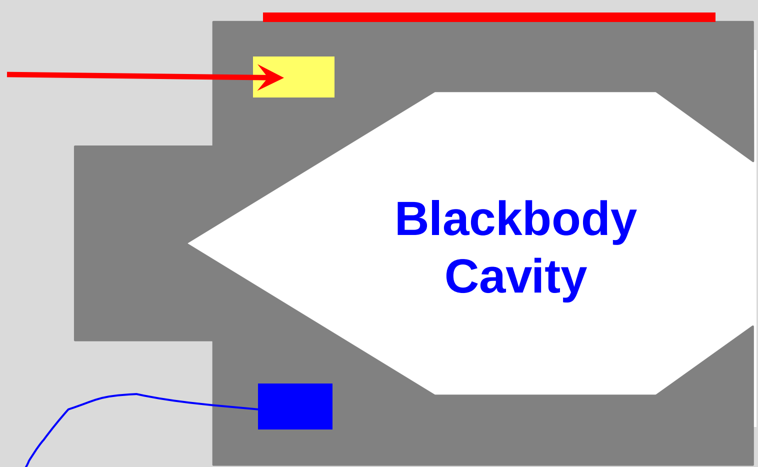
Melt Signatures Provide Temperature Calibration







Phase Change Cell (Ga, H_2O, or Hg)

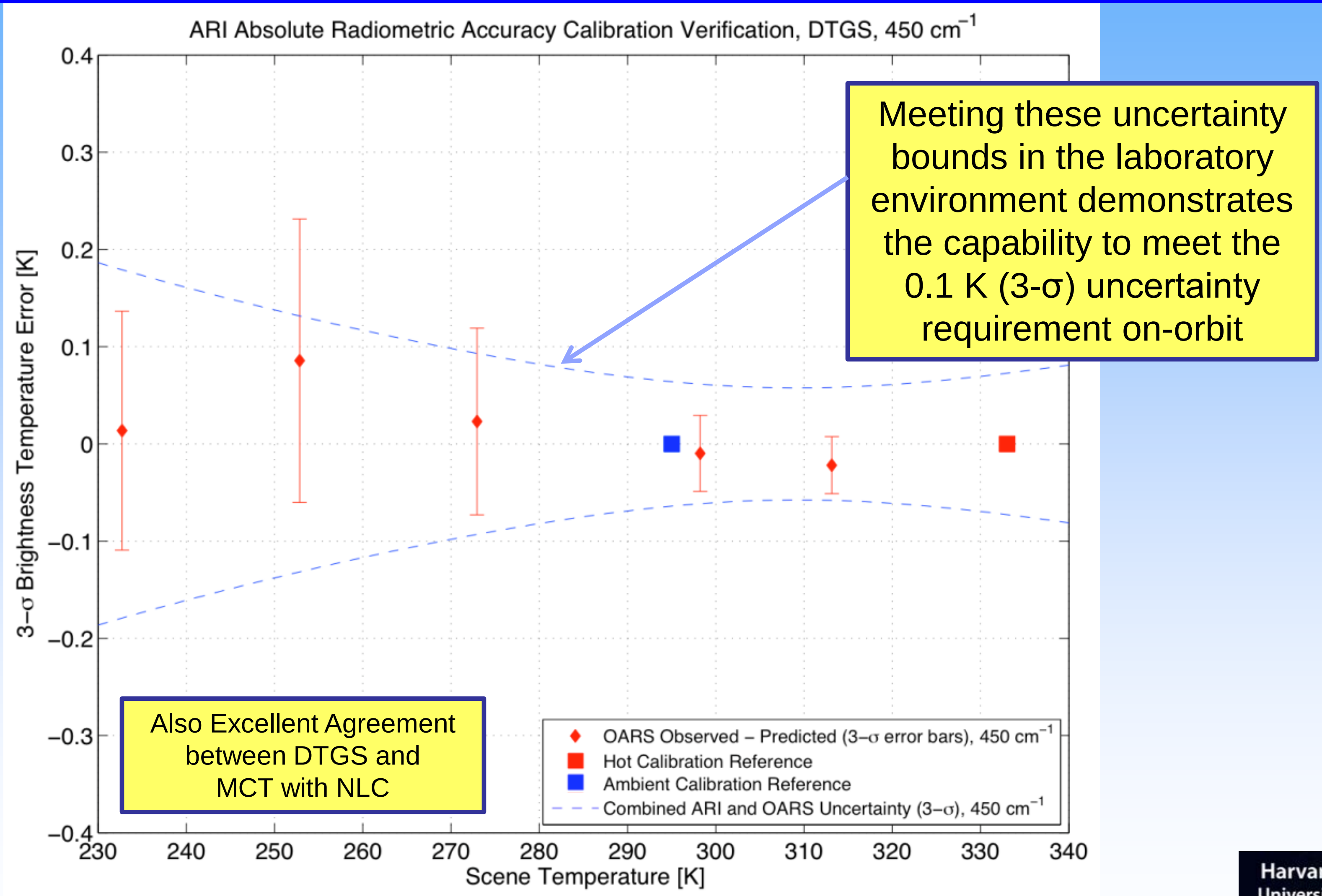


Plateaus (shown in plots) provide known temperatures to better than 10 mK

Thermistor (plotted above)

Sample Radiometric Calibration Verification

DTGS (450 cm^{-1})



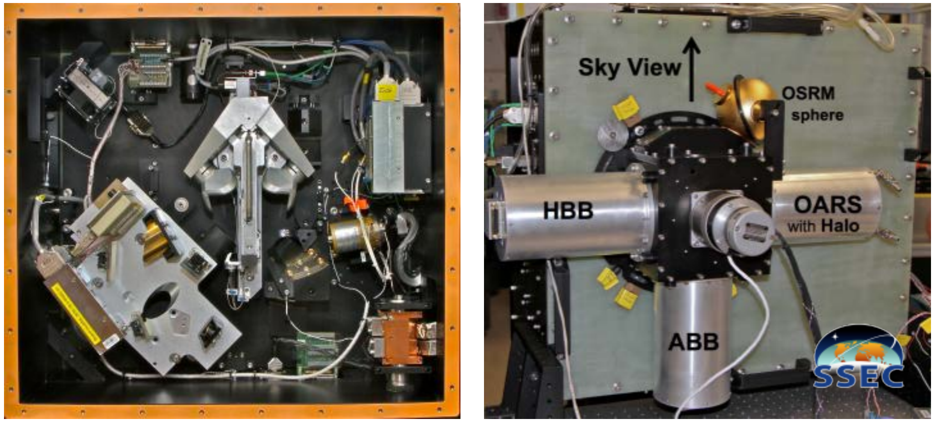
A New Class of Advanced Accuracy Satellite Instrumentation (AASI) for the CLARREO Mission

PI: Hank Revercomb / University of Wisconsin, SSEC

Objective

Develop and demonstrate key technologies necessary to measure IR spectrally resolved radiances with ultra-high accuracy brightness temperature (<0.1 K, 3 sigma at scene temperature) for crucial climate benchmark missions. Technologies include:

- On-orbit Absolute Radiance Standard (OARS) including Miniature Phase Change Cells (MPCC)
- On-orbit Cavity Emissivity Module (OCEM) using quantum cascade laser (QCL) and heated halo (HH) reflection
- On-orbit Spectral Resp. Module (OSRM) using QCL
- Absolute Radiance Interferometer (ARI), giving spectral coverage from 200-2600 cm-1 (3.9-50μm) using 2 output ports



Absolute Radiance Interferometer (ARI) and On-Orbit Verification and Test System (OVTS) Prototype

Accomplishments

- Developed Miniature Phase Change Cells (MPCC) and demonstrated:
    - full simulated on-orbit lifecycle performance after exposure to deep temperature cycling, elevated temperature soaks, and vibration
    - 5 mK absolute calibration performance using melts of Ga, H2O, Hg, and Ga-Sn, to provide temperature calibration from -40 to +40° C
    - 5 mK absolute calibration performance after integration into a blackbody cavity with multiple thermistor sensors
    - Developed the broadband On-Orbit Emissivity Monitor Heated Halo (OCEM-HH) with <0.0006 measurement uncertainty) (TRL_{out} 6)
    - Developed the On-Orbit Absolute Radiance Standard (OARS) with integrated MPCC and OCEM-HH technologies and demonstrated brightness temperature uncertainty of <45 mK for both laboratory and on-orbit applications (TRLout 6)
- Developed packaging for and characterized performance of a Quantum Cascade Laser (QCL) in vacuum for use in measuring blackbody emissivity (OCEM-QCL), and for measuring instrument spectral response on-orbit (OSRM)
    - Demonstrated monochromatic emissivity measurement uncertainty of <0.0002 with the (OCEM-QCL) (TRLout 6)
    - Demonstrated instrument line-shape measurement capability of the (OSRM) by comparison with CO2 laser results (TRLout 6)
- Developed the prototype Absolute Radiance Interferometer laboratory instrument integrated with the OARS, and demonstrated critical radiometric performance in the laboratory with scene temperatures from -40 to +40 ° C consistent with better than 0.1 K measurement accuracy on-orbit. Tests were conducted using expected instrument orbital temperature variations. (TRL_{out} 5)

Co-Is/Partners: Fred Best, John Perepezko, Univ. of Wisconsin;
John Dykema, Harvard Univ.

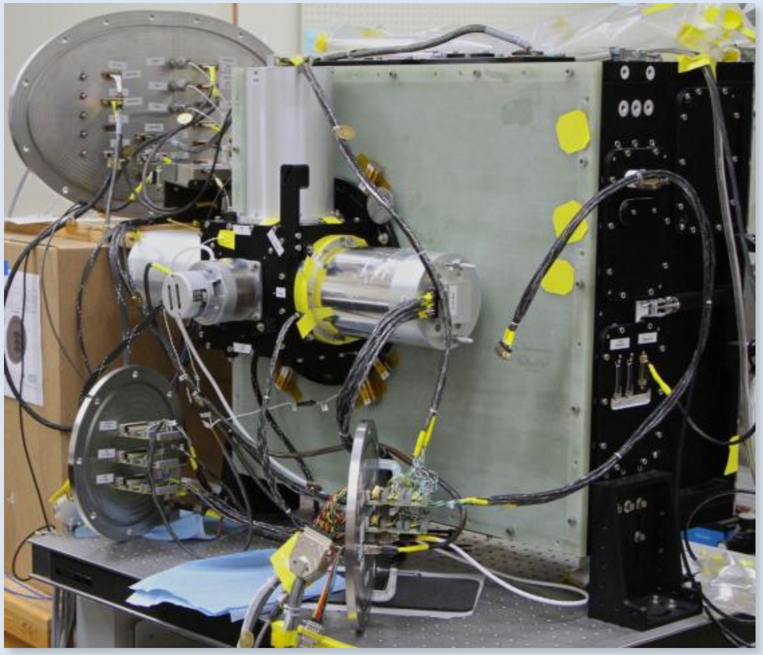
TRL_{in} = 3; TRL_{out} = 5

Topics: IR Measurement Science

- **Summary of Previous UW/Harvard NASA Instrument Incubator Program (IIP) ARI Results**

- **New Vacuum Testing of CLARREO Flight Prototype demonstrates 0.1 K 3-sigma performance of Calibrated FTS (CFTS) and On-orbit Verification and Test System (OVTS)**

NASA ESTO currently supporting additional ARI testing in vacuum

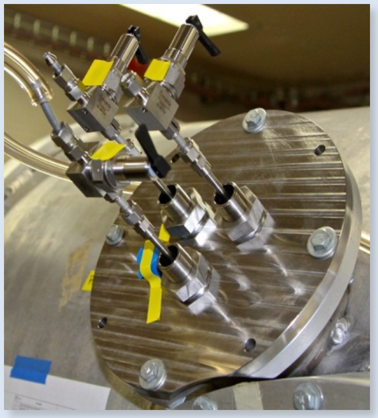


- While **all new technology components achieved TRL 6**, NASA ESTO considered the rolled up ARI to be just under 6
- Therefore, **NASA ESTO made funding available to bring the ARI to TRL 6**, by verifying operation and performance in a vacuum environment

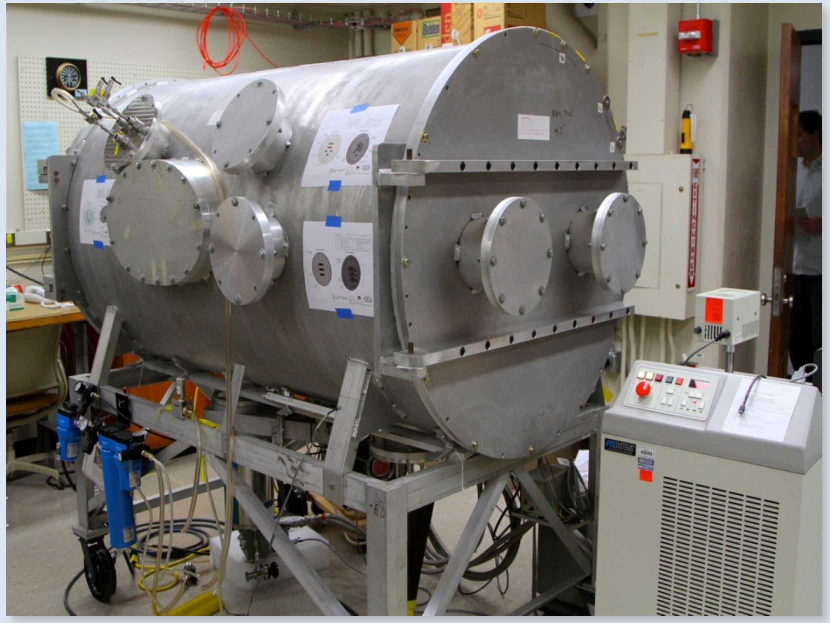
- Bringing the ARI to TRL 6 is a huge step because it provides the US with a **flight-like IR prototype instrument ready to support CLARREO or other Climate Benchmark Missions**, a high priority of the NRC

(final testing to be performed in April/May)

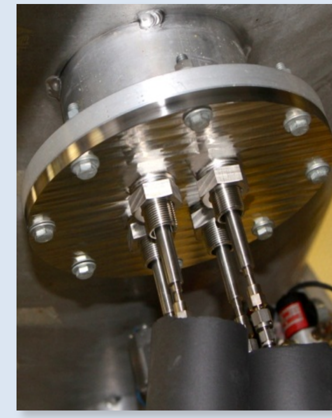
Chamber With Feed-thrus



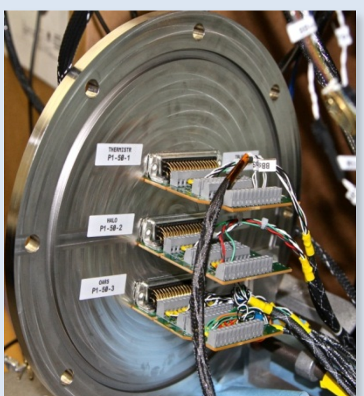
Gas Purge Feed-Thru



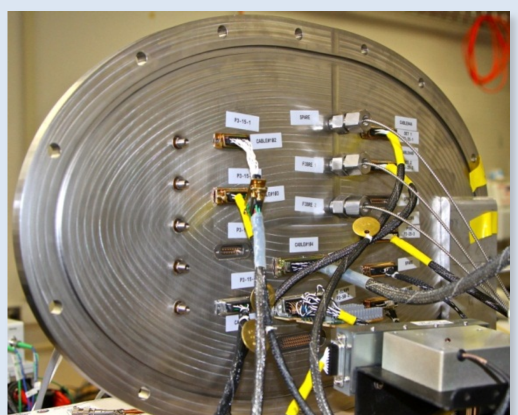
Blanked-Off Chamber gets down to 1.2 x 10-6 Torr using Cryo-Pump



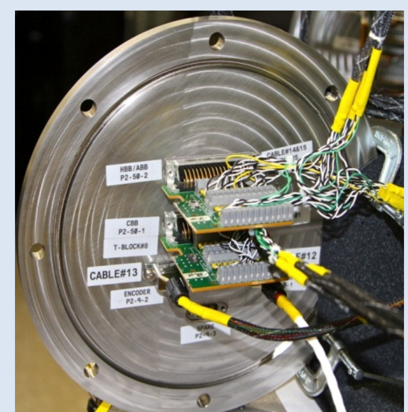
Cooling Lines for OARS & new CBB



Electronics Feed-Thru-1

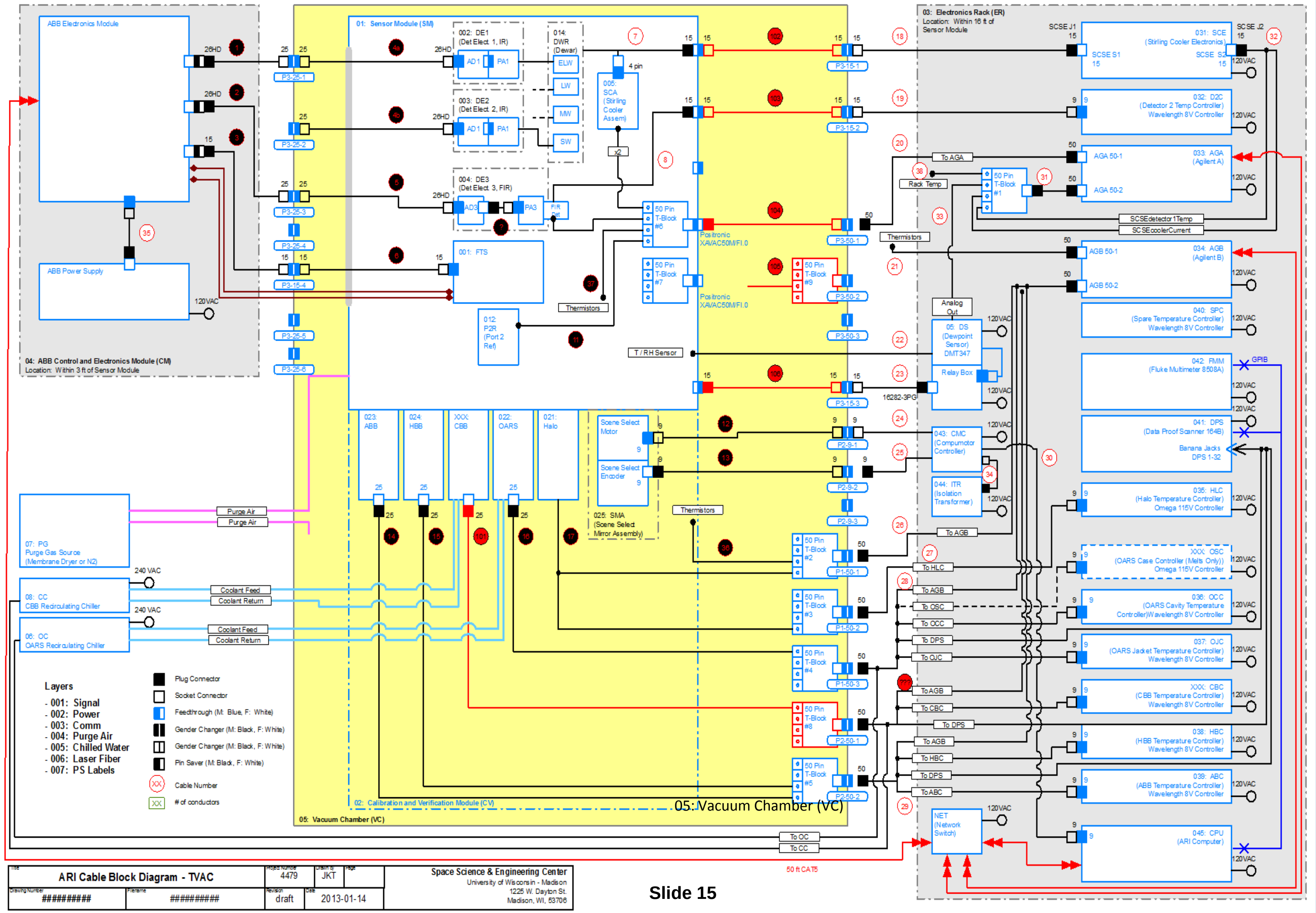


Electronics Feed-Thru-Elliptical

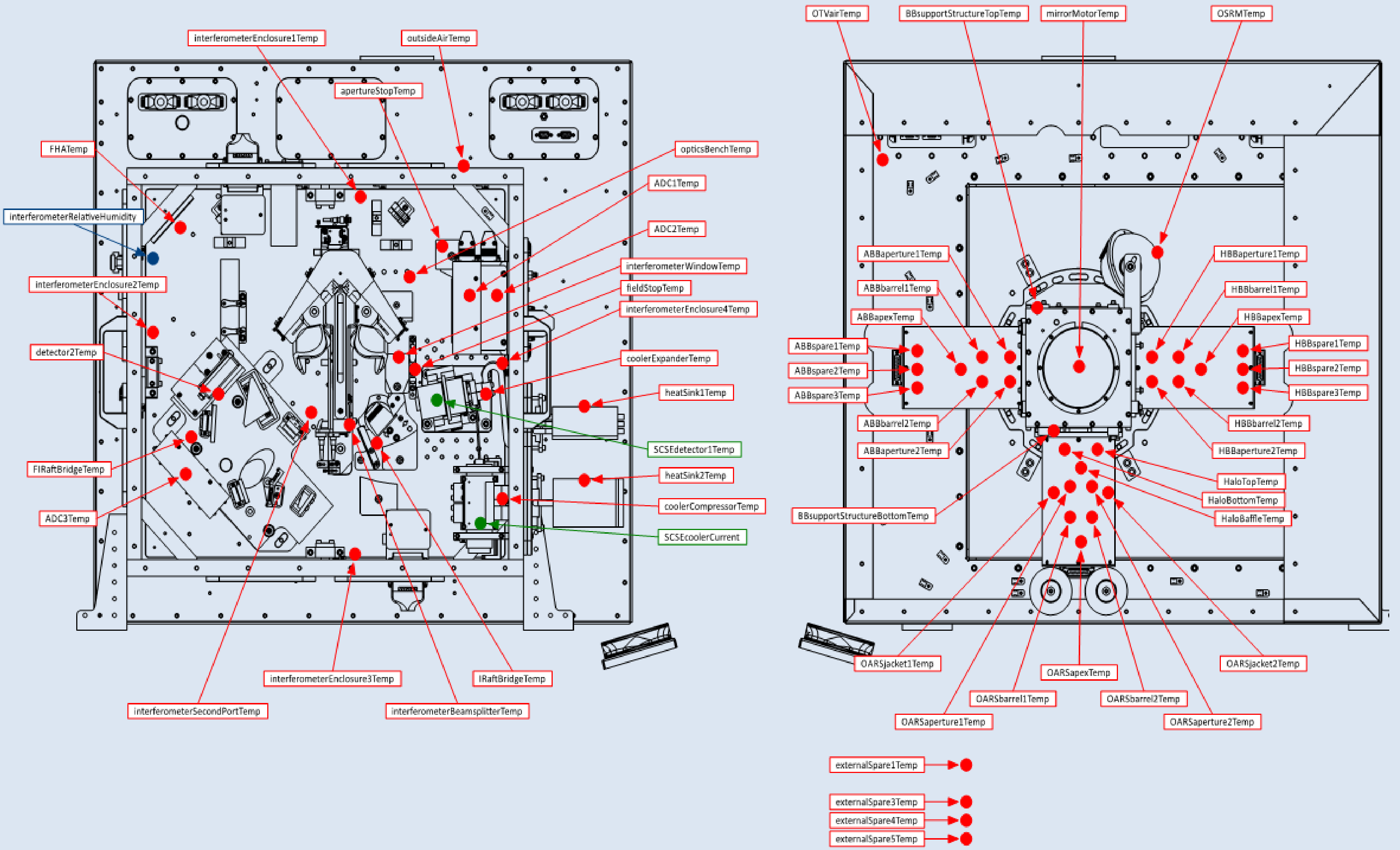


Electronics Feed-2

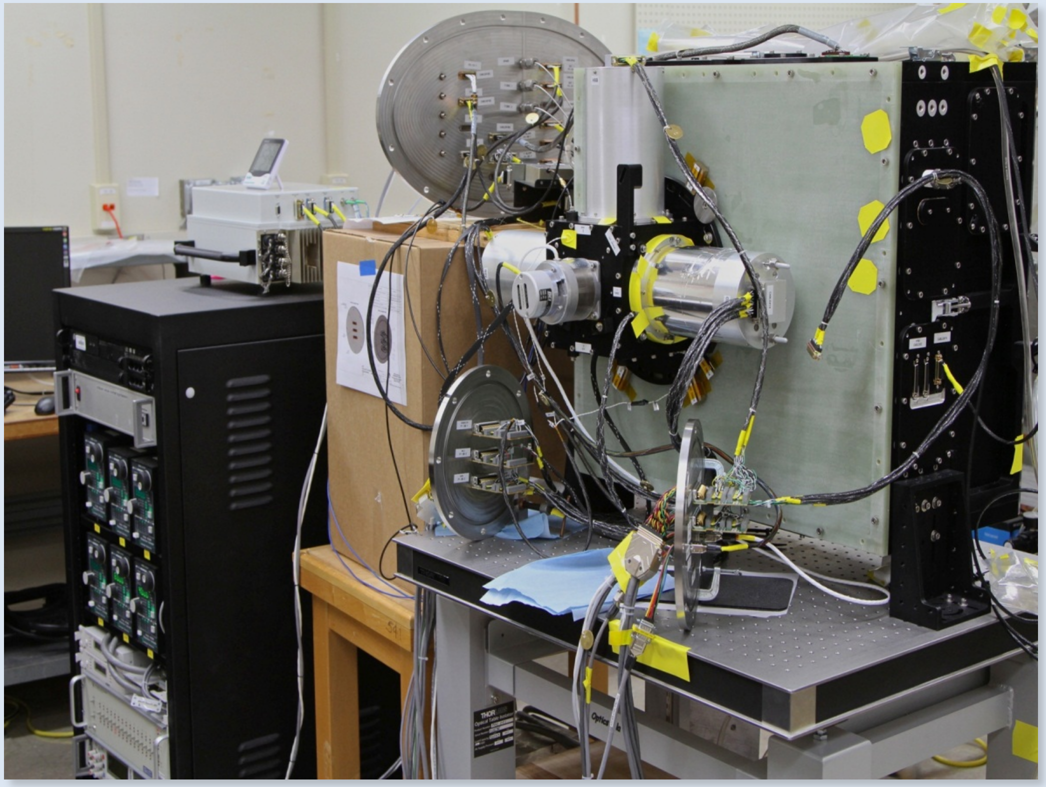
ARI Wiring Diagram for Vacuum Configuration

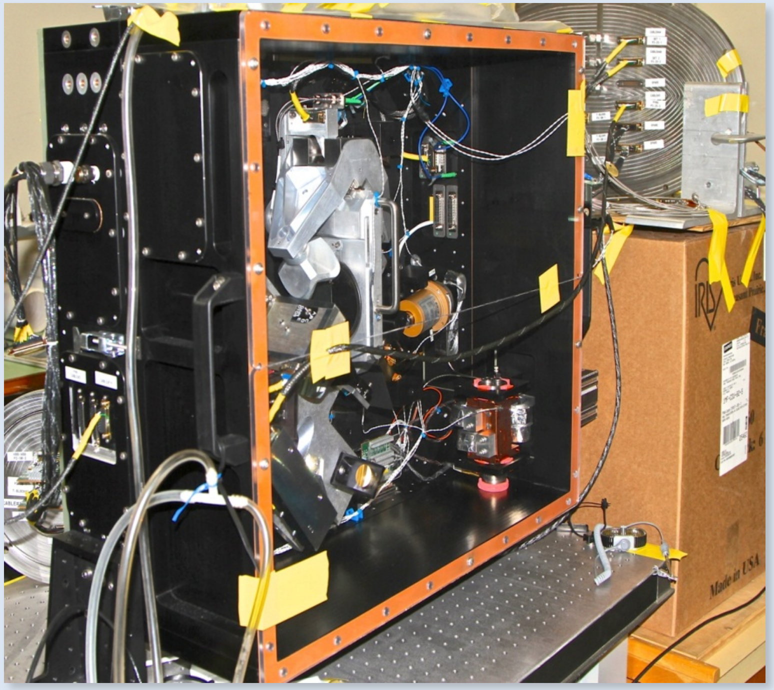


ARI Housekeeping Sensors for Vacuum Configuration



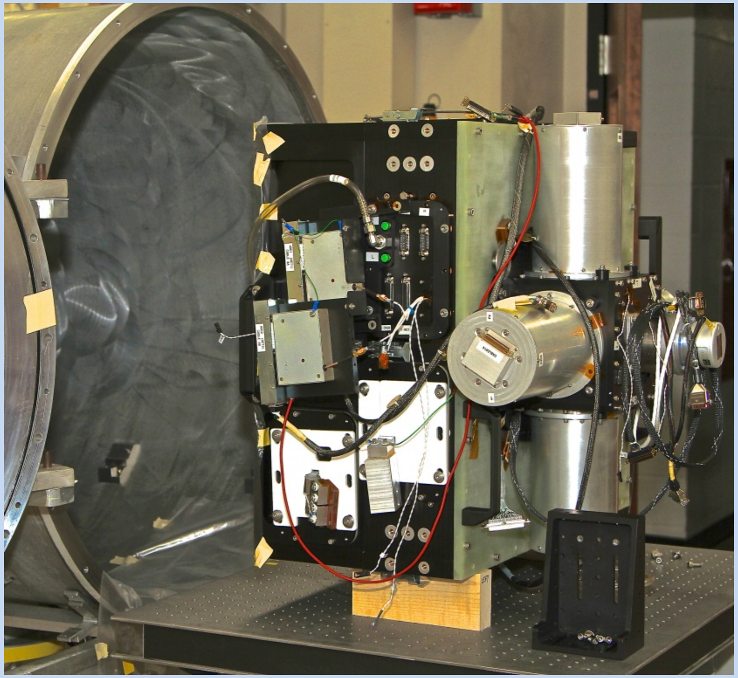
ARI Checkout Before Chamber Integration

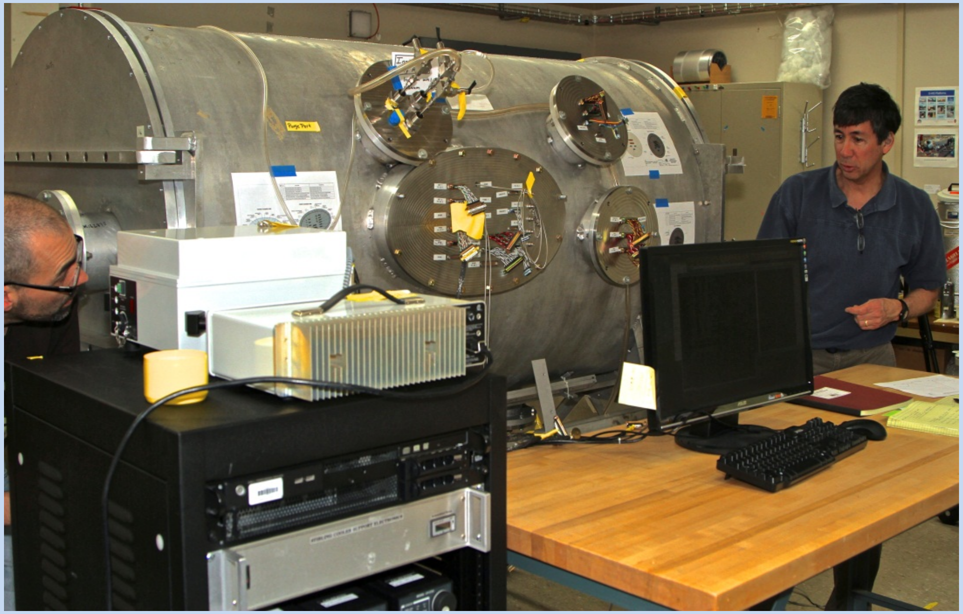


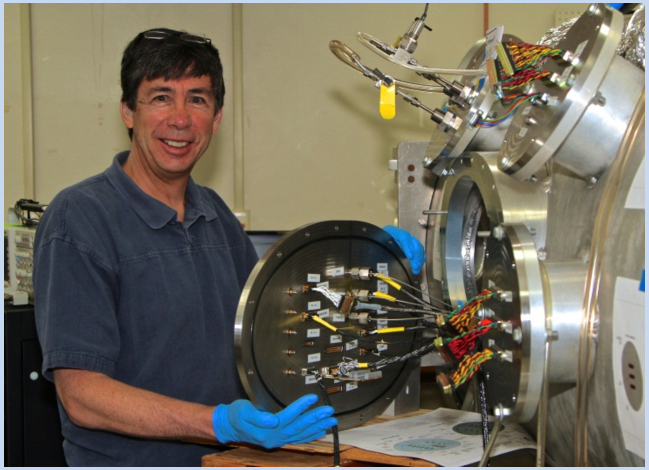


- Electrical Topology and Connectivity (including grounding) was the same as with the ARI located inside the chamber.
- Full functionality was verified before installation into the chamber.

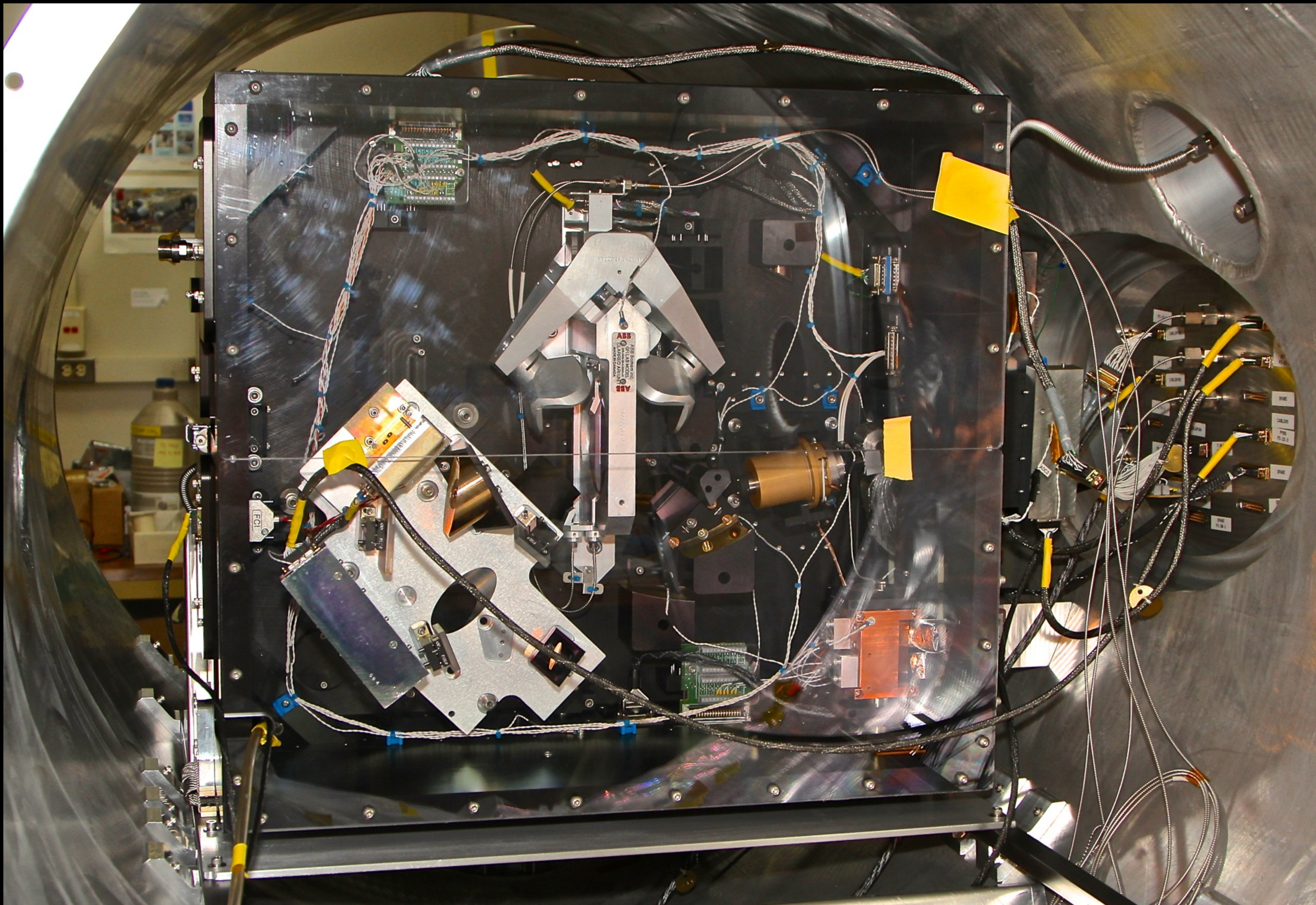
Getting into the Vacuum Chamber



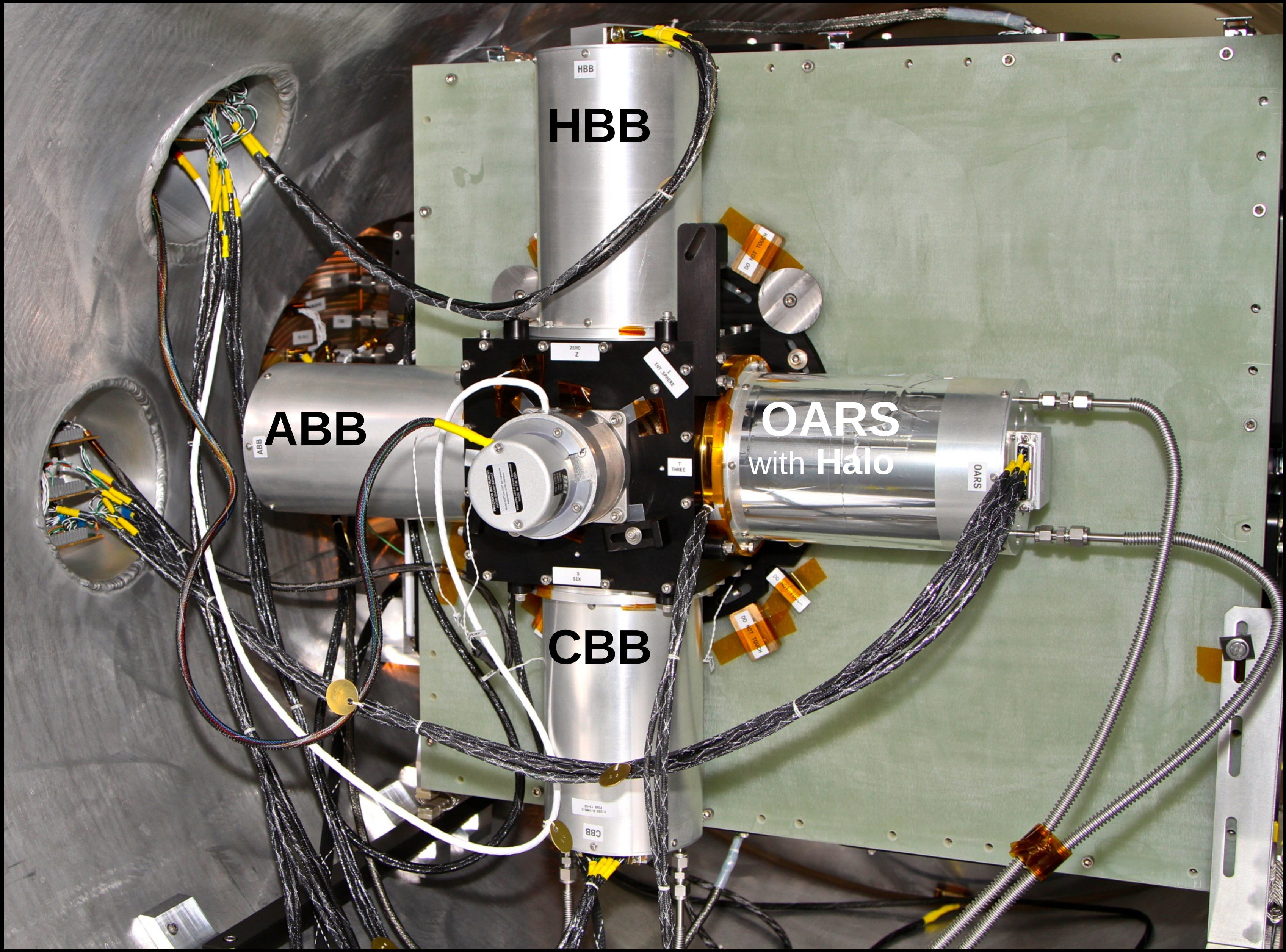




UW ARI Prototype in Vacuum Chamber



ARI Calibration Blackbodies & OVTS in Chamber



Further Characterization Preparing for Vacuum Testing

- EMI optimization
- Spectral Testing and Tuning
  - Instrument Line Shape measurement
  - IR sampling delay tuning (relative to laser trigger) to minimize sample-position-error spectral ghosts

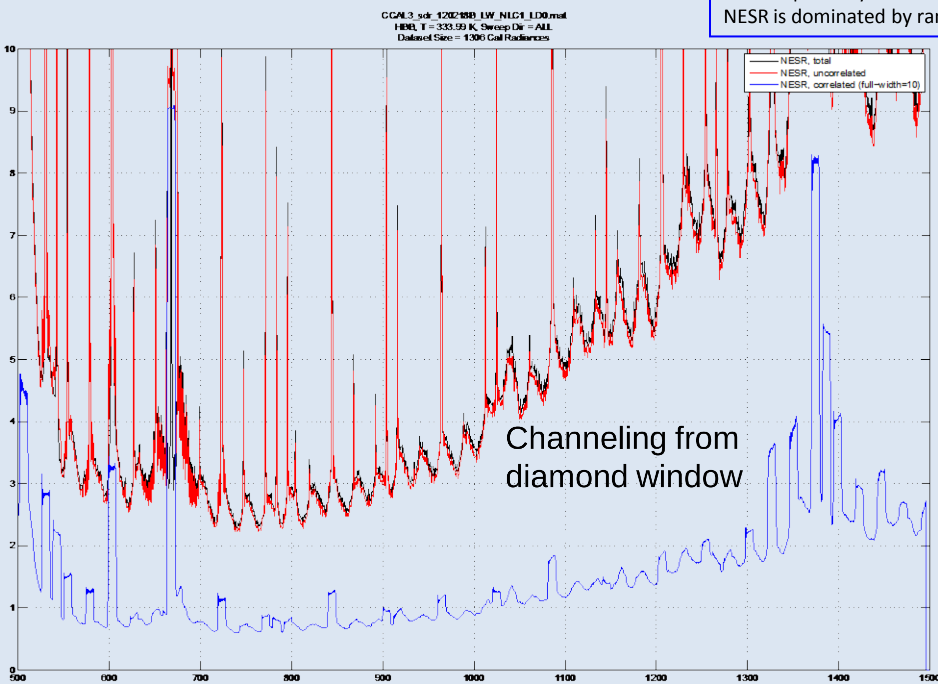
Longwave Noise Comparison

Noise performance was greatly improved due to new grounding and shielding scheme

2 cm/s scan rate, no co-adding

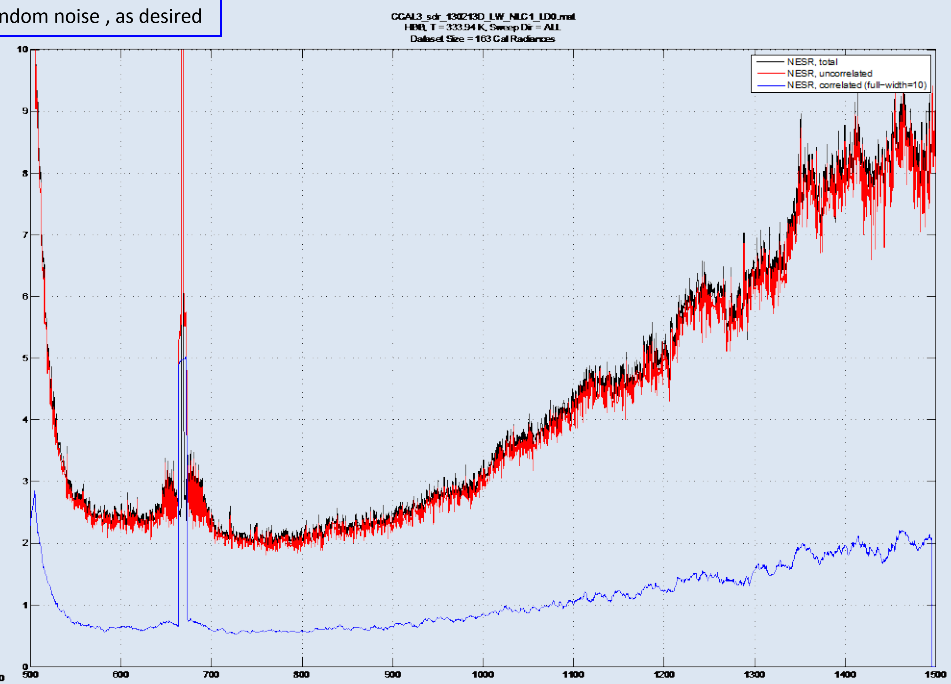
Black is total noise
Red is random noise
Blue is spectrally correlated noise
NESR is dominated by random noise , as desired

Post IIP



LW NESR, HBB @ 334K, Sweep Dir All
AE120218B – IIP Dataset

Pre Vacuum



LW NESR, HBB @ 334K, Sweep Dir All
AE130213D *– NO Filter at Dewar, ARI Front Window Removed*
3-body test, cryo-pump on, chiller on

These noise levels are within expected performance, and consistent with other instruments for which we have experience.

Far IR Noise Comparison

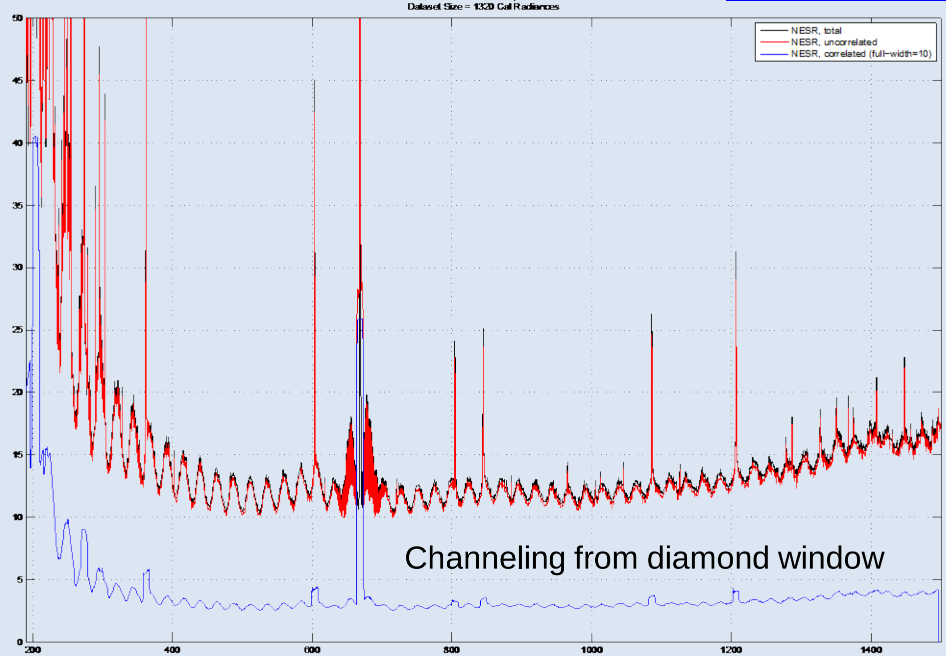
Noise performance was greatly improved due to new grounding and shielding scheme

0.5 cm/s scan rate, no co-adding

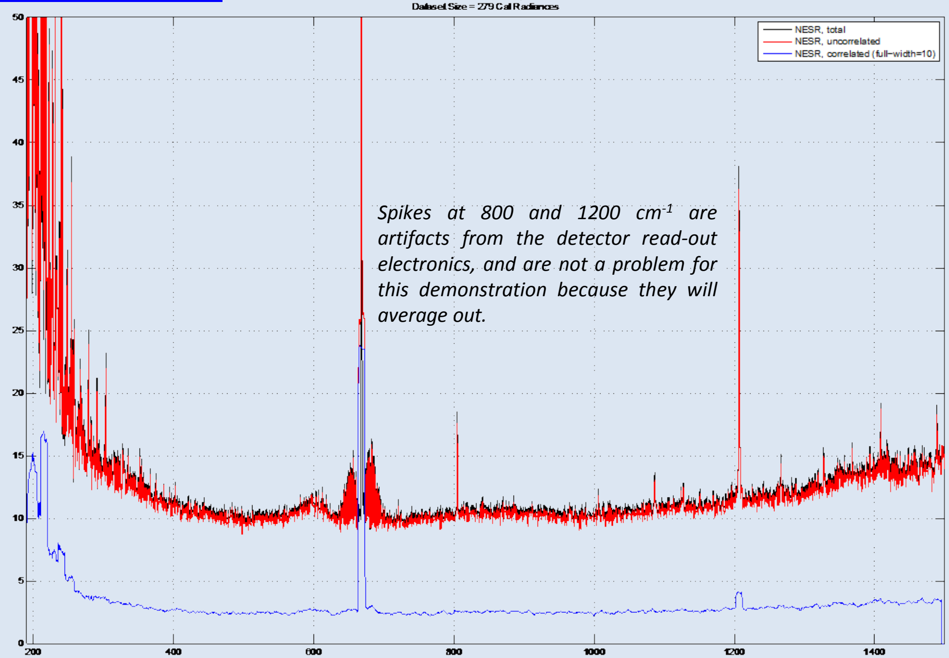
Post IIP

Black is total noise
Red is random noise
Blue is spectrally correlated noise
NESR is dominated by random noise , as desired

Pre Vacuum



FIR NESR, HBB @ 333.94K, Sweep Dir All
AE120218B – IIP Dataset
0.5 cm/s Scan Speed

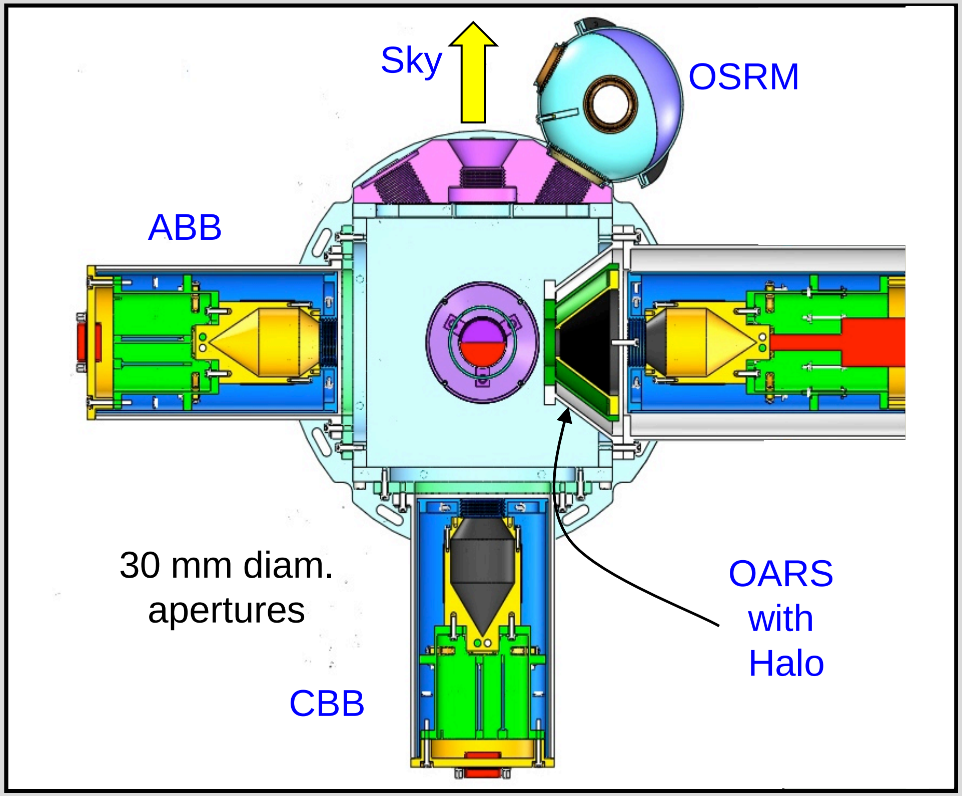


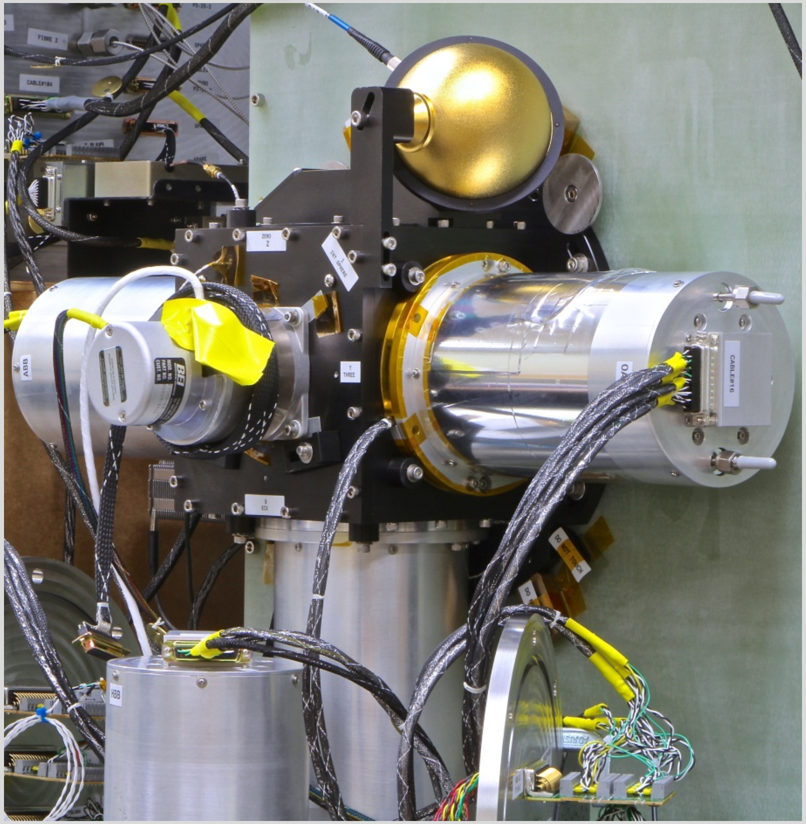
FIR NESR, HBB @ 333.94K, Sweep Dir All
AE130213C – NO Filter at Dewar, ARI Front Window Removed
3-body test, cryo-pump on

These noise levels are within expected performance, and consistent with other instruments for which we have experience.

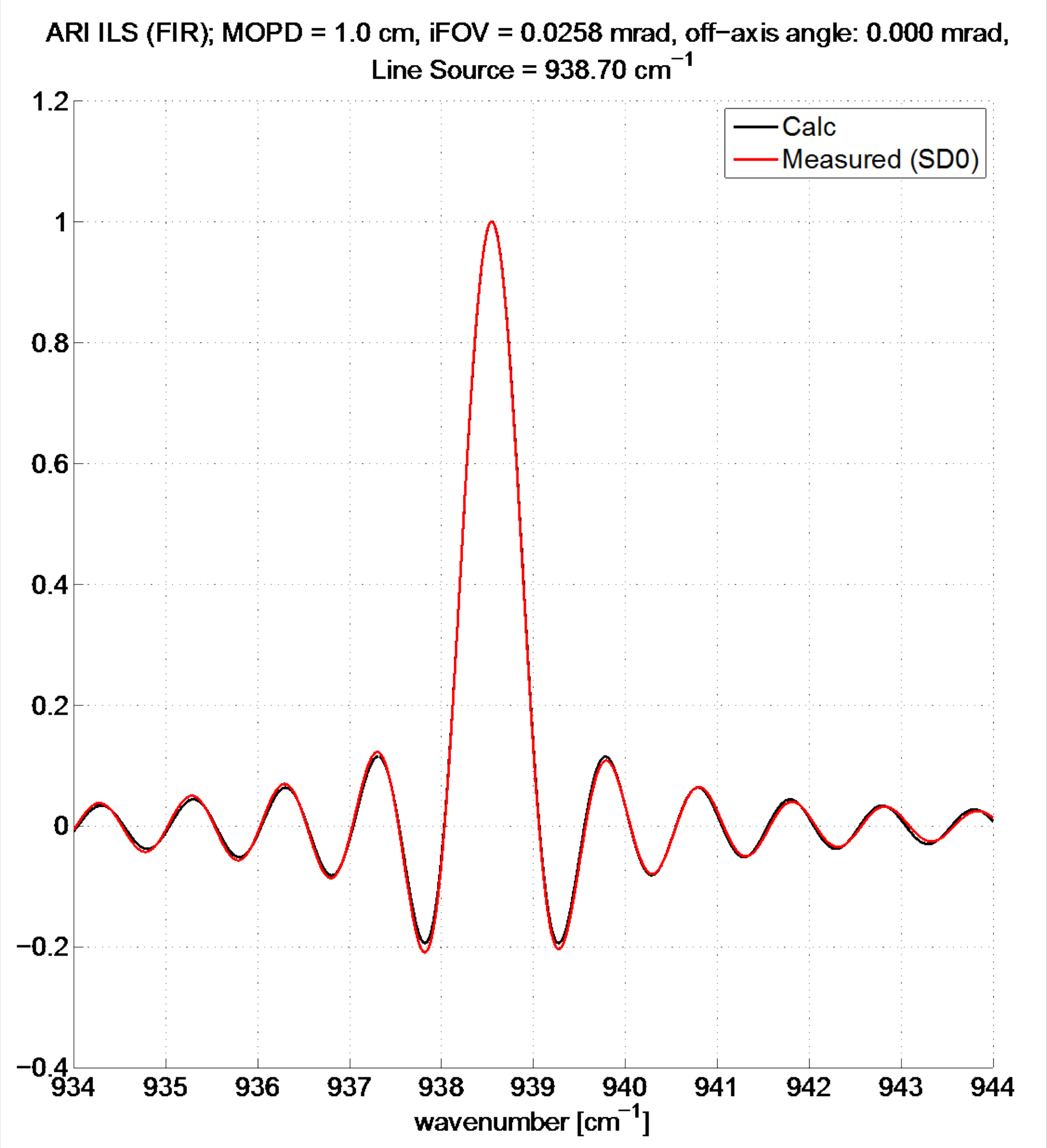
Configuration for Instrument Line Shape (ILS) Test

CO_2 laser injected into gold integrating sphere





Measured ILS (red) Compared to Calculation



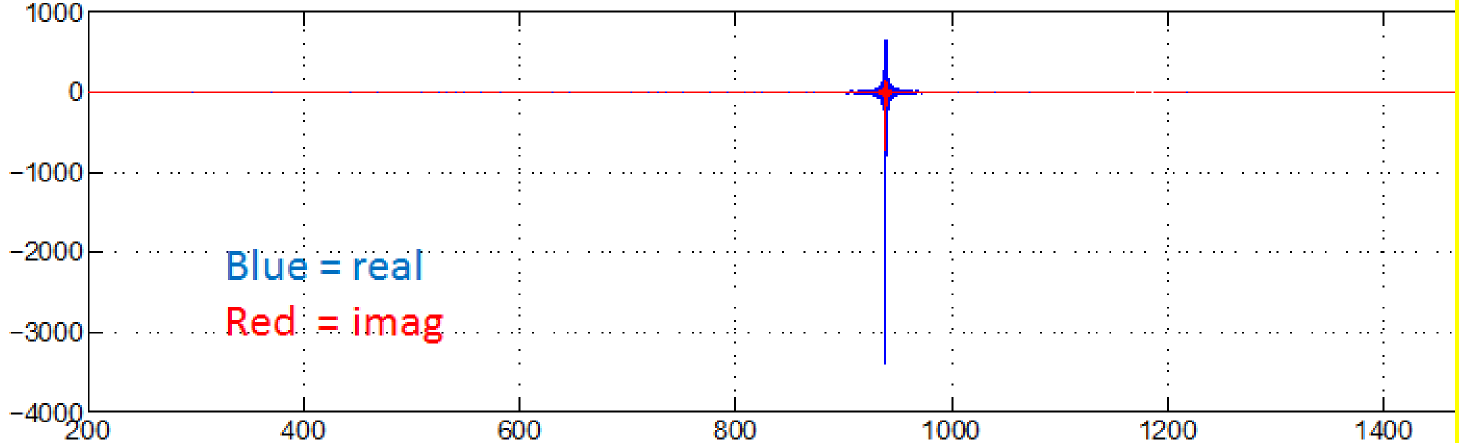
Measured Instrument Line Shape (ILS) is well understood

Calculation assumes:

- -Expected angular field-of-view in interferometer
- -Perfect alignment
- -Perfect laser beam filling

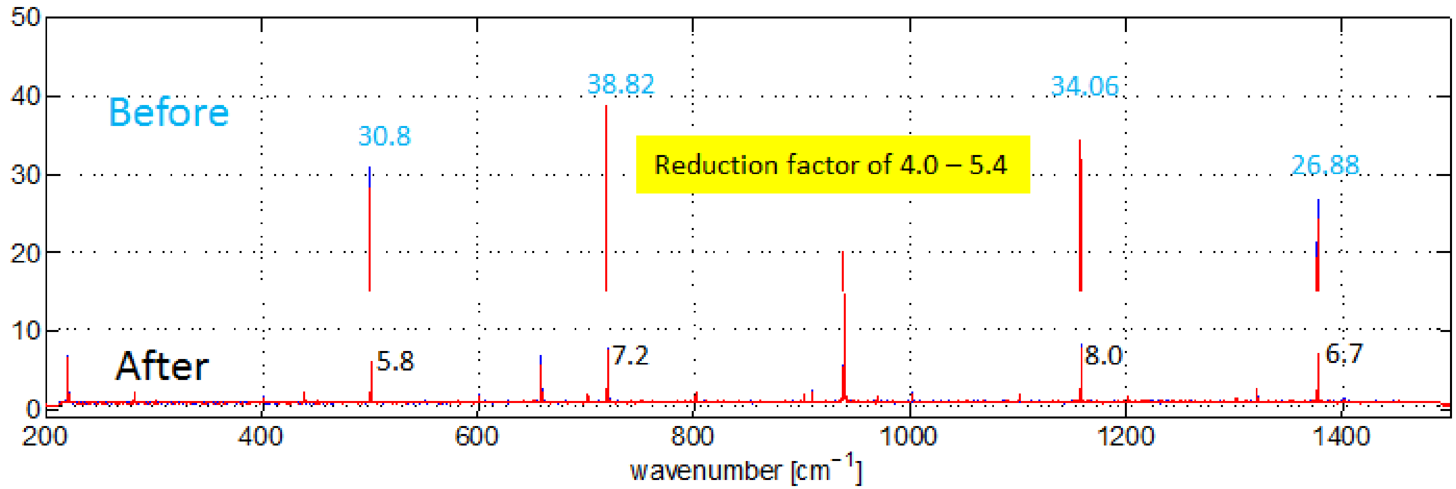
IR Sampling Delay Tuning to minimize spectral ghosts

CO_2 Laser Mean Spectrum from Pyroelectric Detector



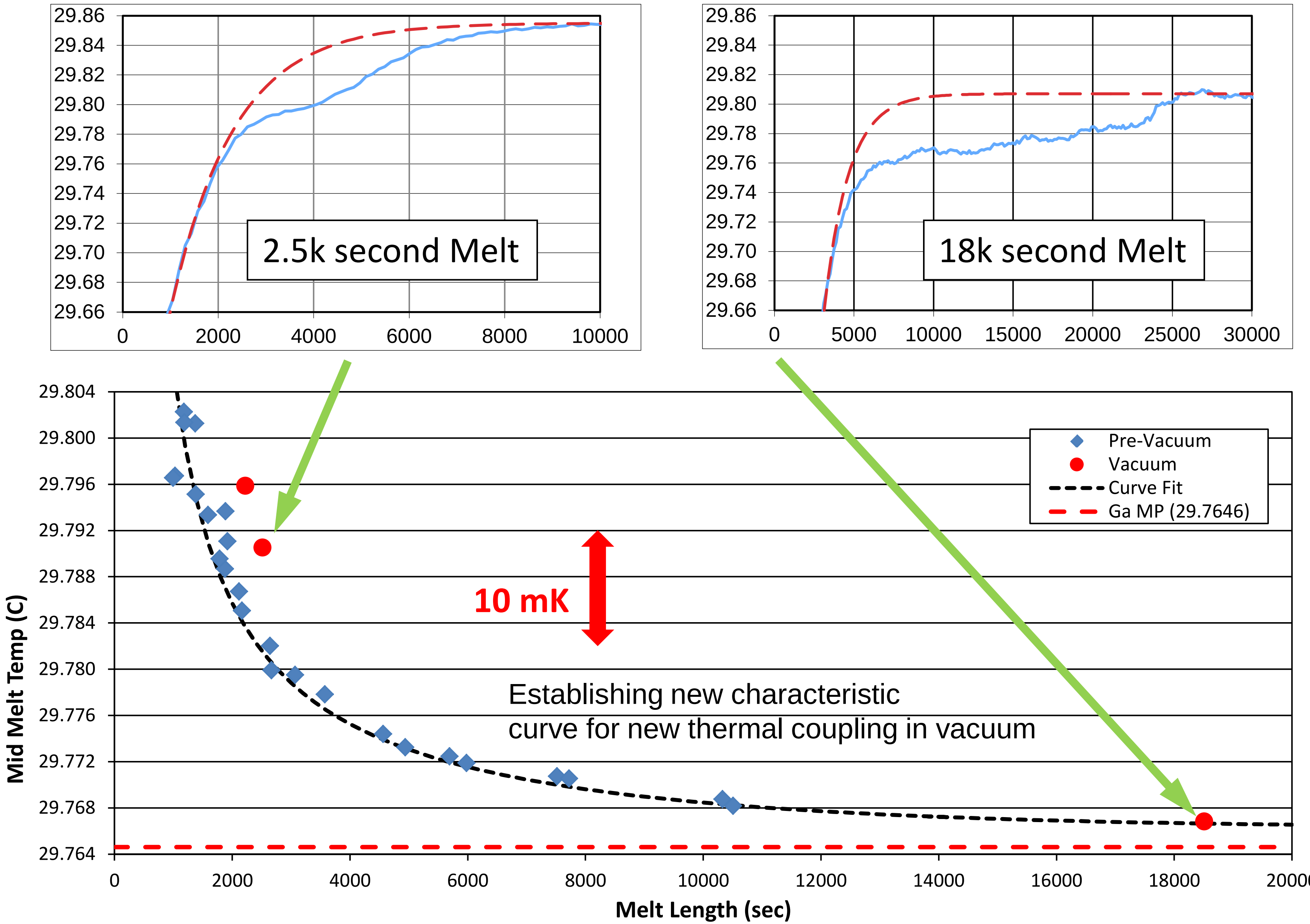
Stirling Cooler Sidelobes are 10^{-4} x less than Laser peak for single spectra after tuning & much smaller for mean spectra

Std Dev Spectrum: Show induced sidelobe reduction After tuning to 160 µs delay



Stinger with 440 Hz fundamental and 2 cm/s OPD scan rate

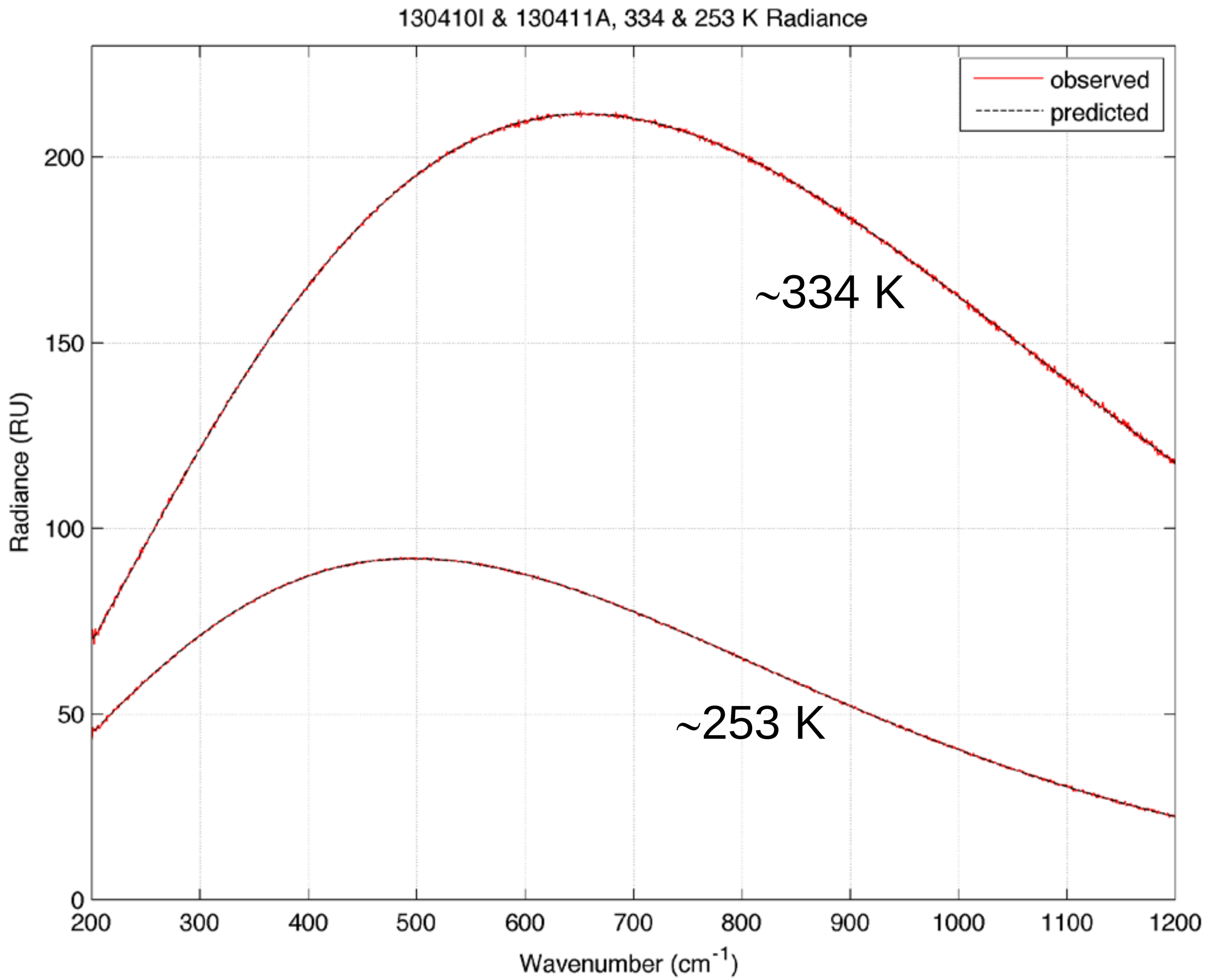
OARS Gallium Melt Signature



Radiometric Calibration Verification

- Pyroelectric Detector Mean OVTS/OARS Spectra
- CFTS Expected Uncertainty
- OVTS Expected Uncertainty
- CFTS and OVTS Radiometric Verification (-58 C and 60 C)
- Verification of -58 C under expected on-orbit thermal transient conditions

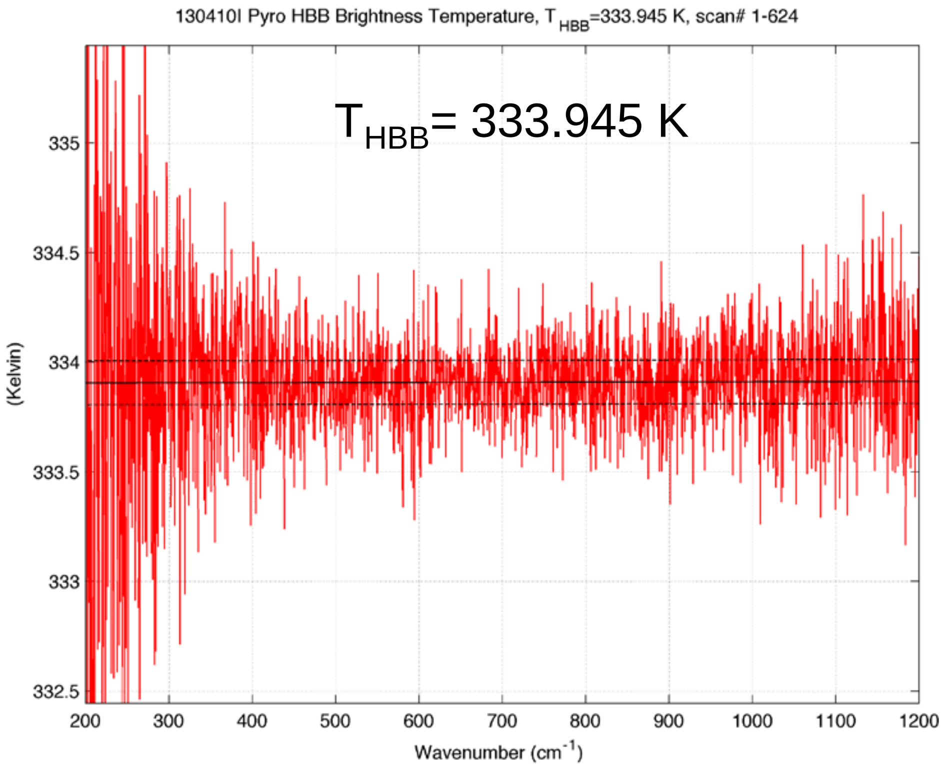
Mean Calibrated Radiance Spectra

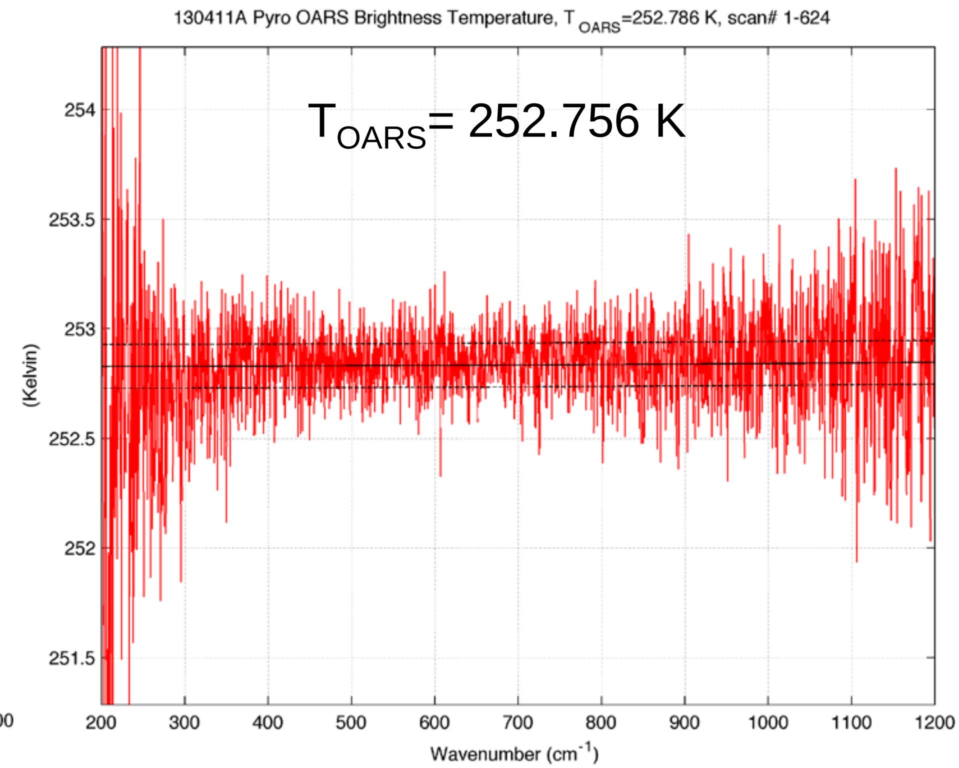


Calibration Blackbodies at ~300 K & ~215 K

Accurate Calibrated Spectra— great agreement with verification spectra

Brightness T Residuals





Difference from expected value is very close to zero + random noise

(noise is ~4 x noise for on-orbit noise spec due to shorter dwell times)

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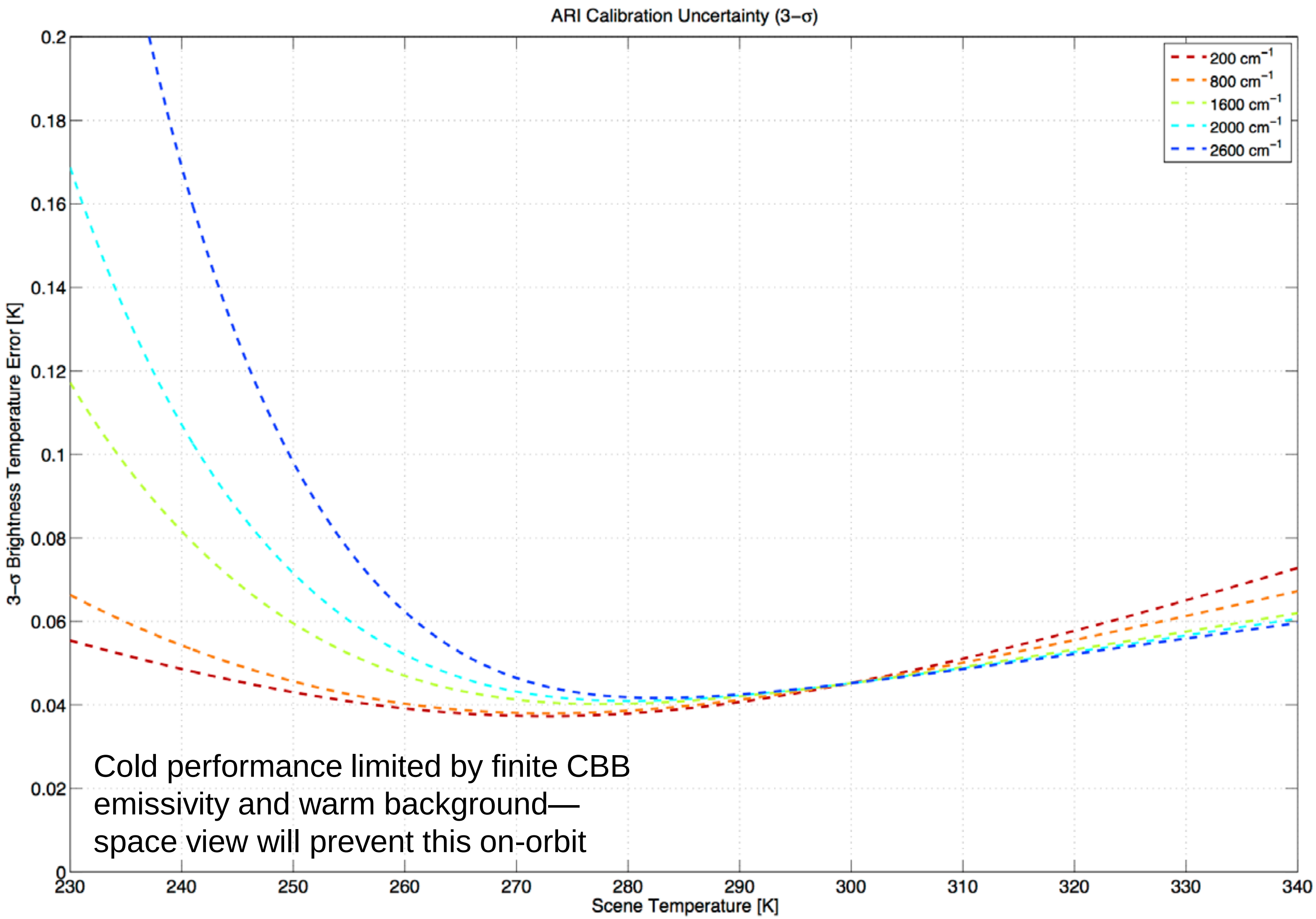
Radiometric Uncertainty, Vacuum Test

Parameter values for uncertainty analysis

Temperatures			**Associated Uncertainty (3-σ)**	
Cold Cal Ref (Cold Blackbody)	T_C	215 K	$u(T_C)$	0.045 K
Hot Cal Ref (Ambient Blackbody)	T_H	300 K	$u(T_H)$	0.045 K
Verification Target (OARS)	T_{OARS}	213 – 333 K	$u(T_{OARS})$	0.045 K
Reflected Radiance, Cold Cal Ref	$T_{R,C}$	295 K	$u(T_{R,C})$	4 K
Reflected Radiance, Hot Cal Ref	$T_{R,H}$	295 K	$u(T_{R,H})$	4 K
Reflected Radiance, Verification Target	$T_{R,OARS}$	295 K	$u(T_{R,OARS})$	4 K
Emissivities				
Cold Cal Ref (Ambient Blackbody)	e_C	0.999	$u(e_C)$	0.0006
Hot Cal Ref (Hot Blackbody)	e_H	0.999	$u(e_H)$	0.0006
Verification Target (OARS)	e_{OARS}	0.999	$u(e_{OARS})$	0.0006

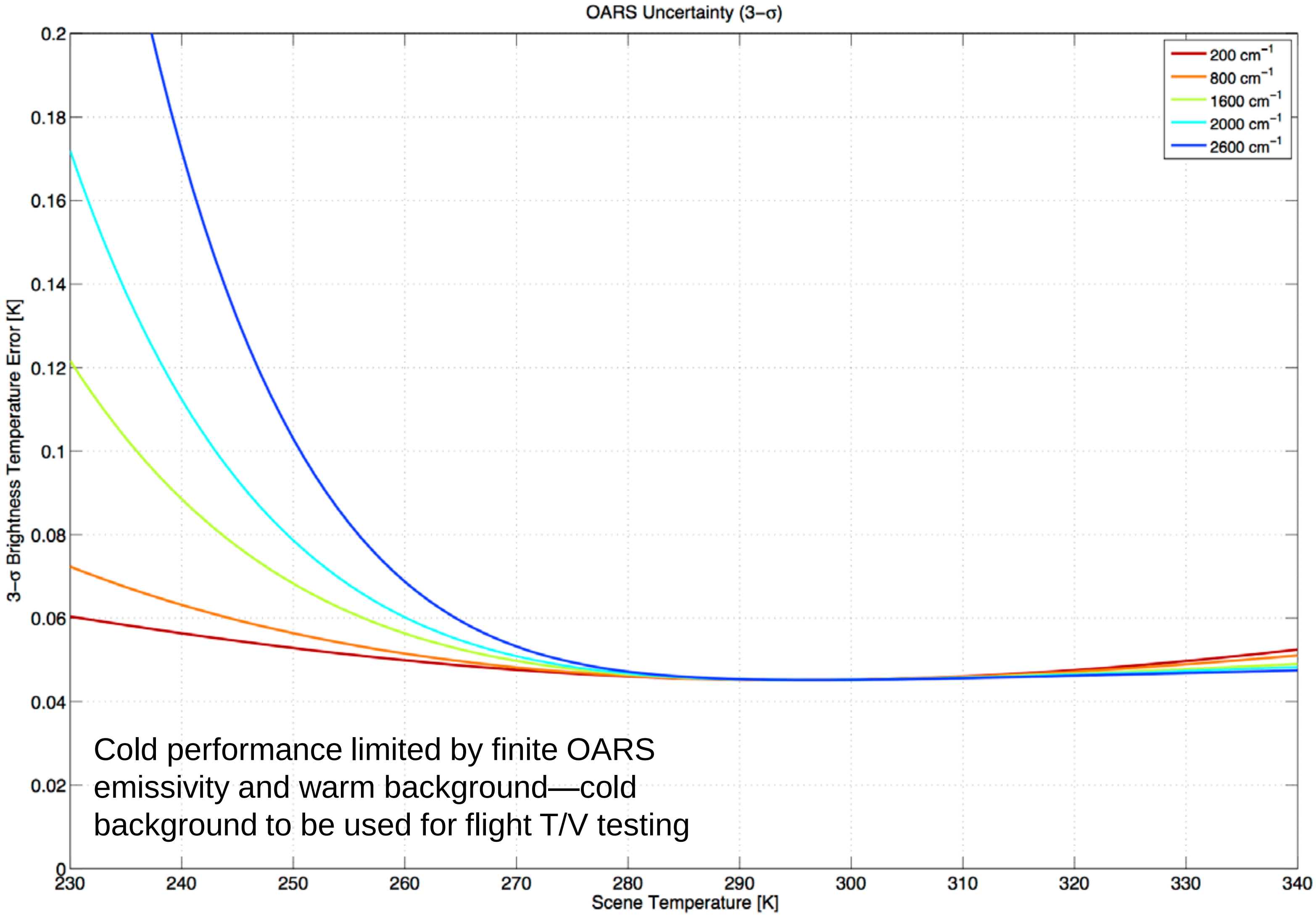
Radiometric Uncertainty, Vacuum Test

CFTS Calibration Uncertainty (3-σ)



Radiometric Uncertainty, Vacuum Test

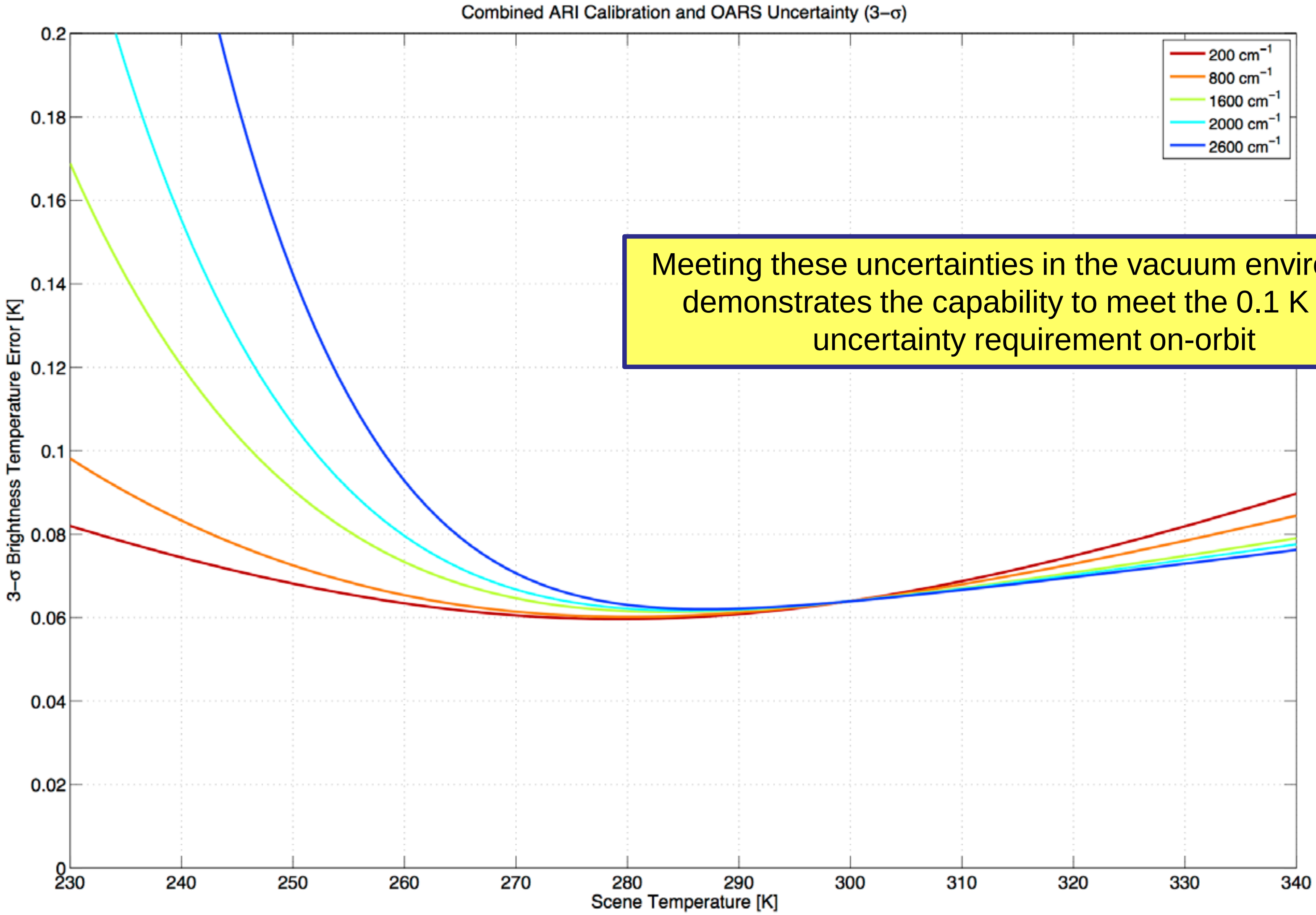
OARS Uncertainty (3-σ)



Cold performance limited by finite OARS emissivity and warm background—cold background to be used for flight T/V testing

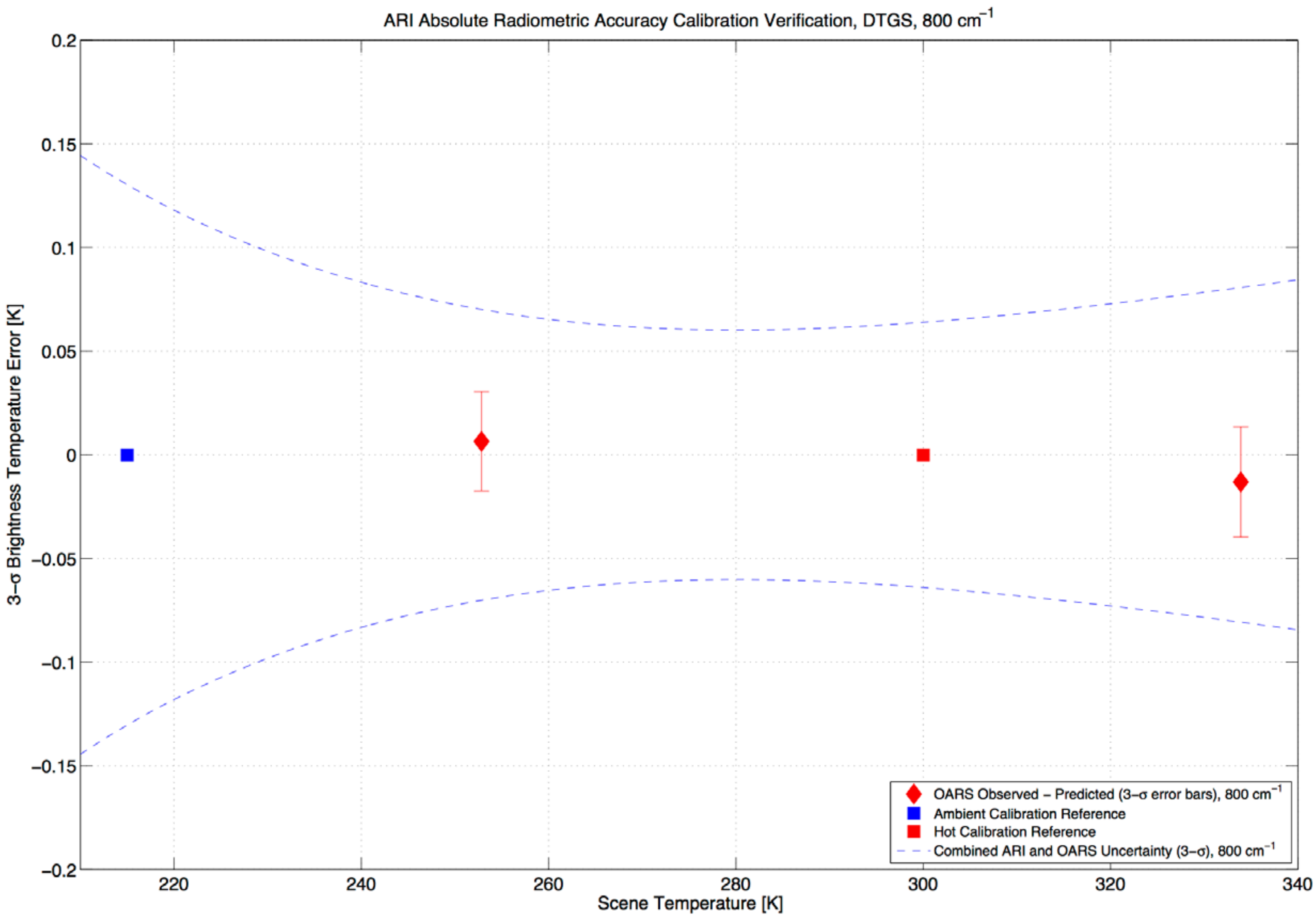
Radiometric Uncertainty, Vacuum Test

RSS of CFTS and OARS Uncertainty (3-σ)

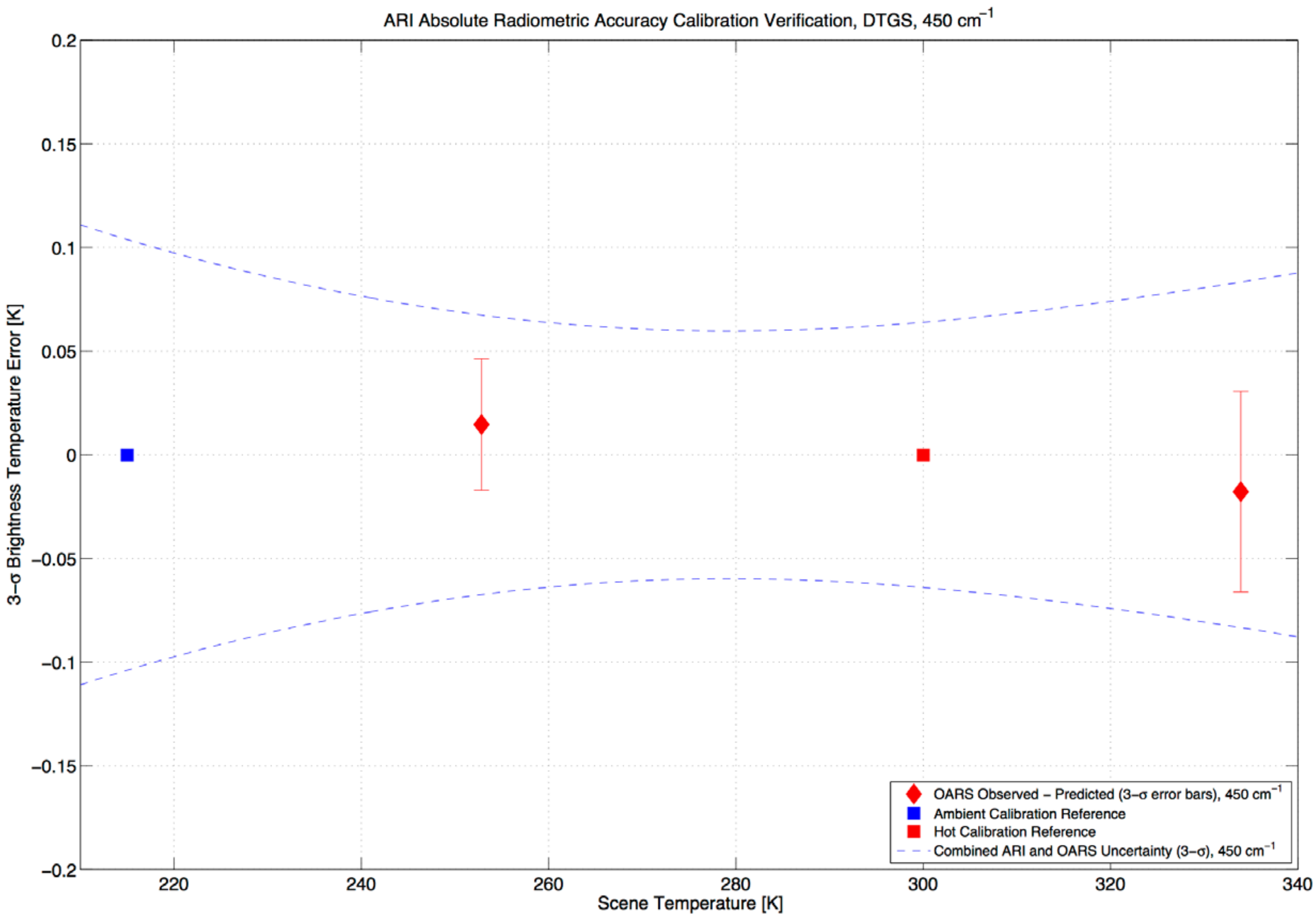


Meeting these uncertainties in the vacuum environment demonstrates the capability to meet the 0.1 K (3-σ) uncertainty requirement on-orbit

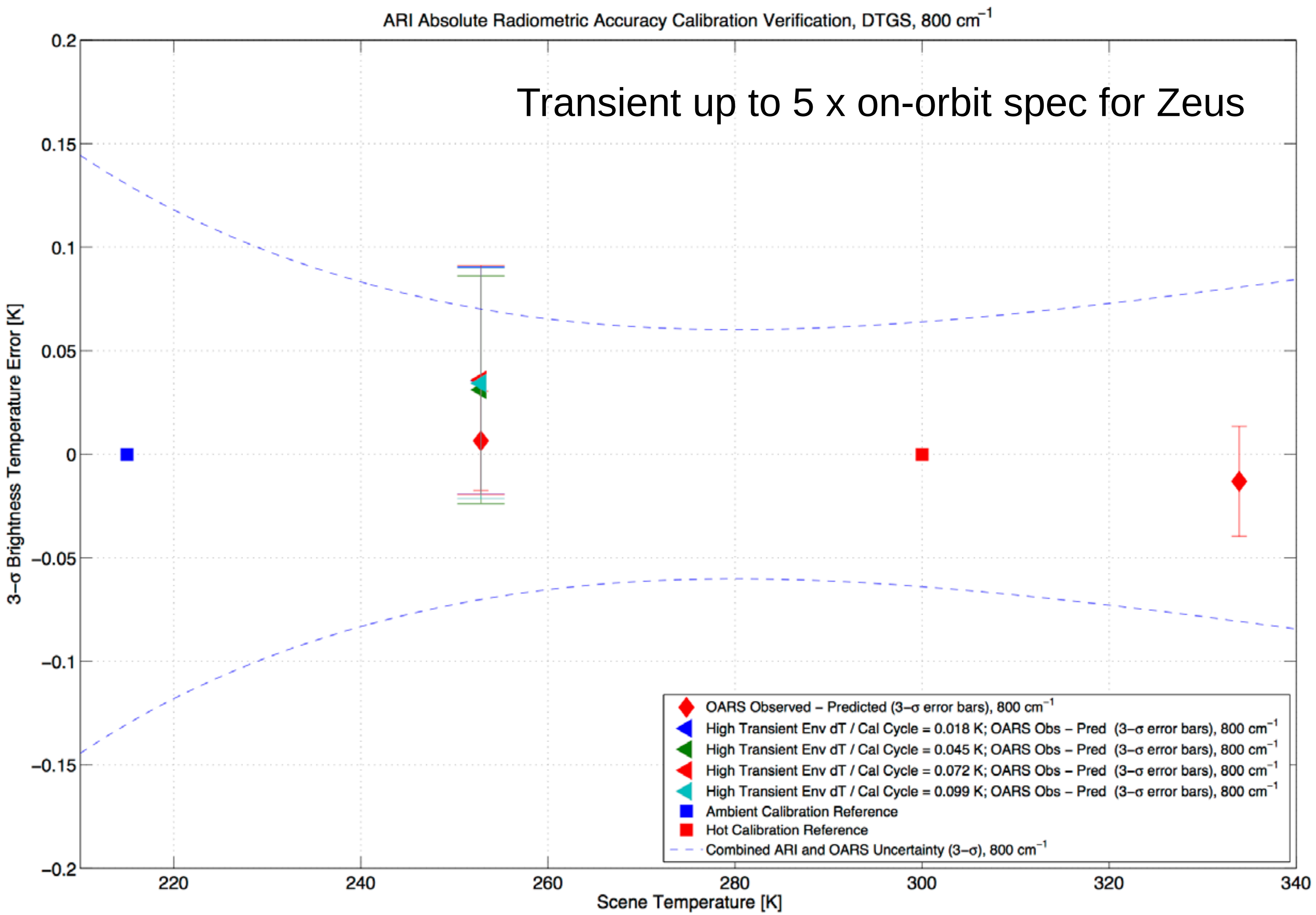
Calibration Verification – DTGS (800 cm^{-1})



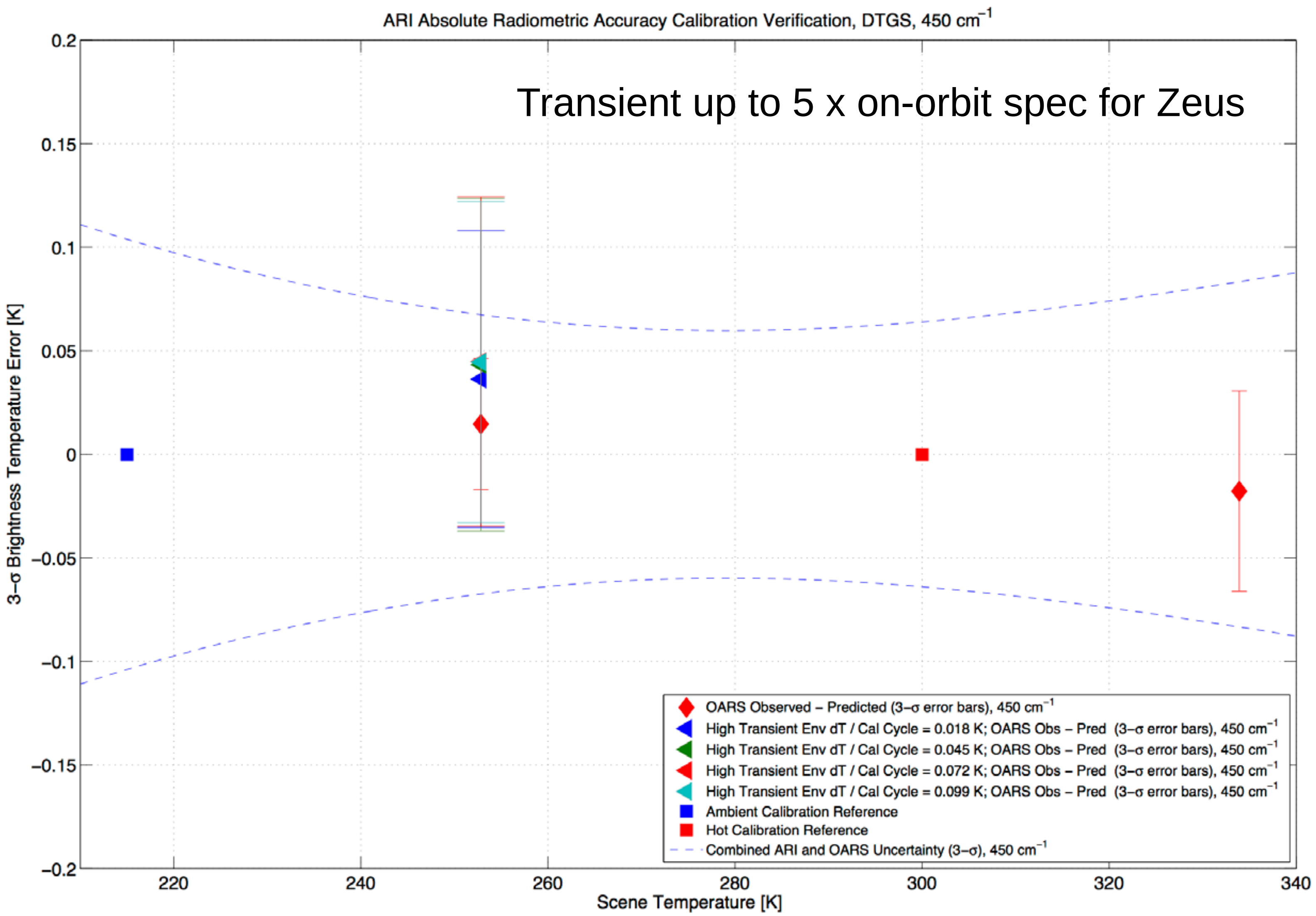
Calibration Verification – DTGS (450 cm^{-1})



Calibration Verification – DTGS (800 cm^{-1})
High Thermal Transient Cases



Calibration Verification – DTGS (450 cm^{-1})
High Thermal Transient Cases



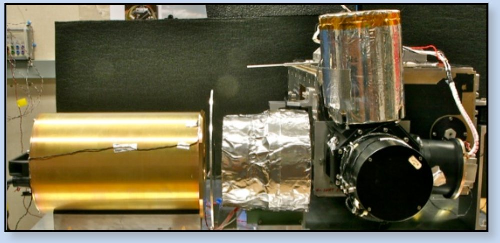
Full ARI Tests Planned Under Vacuum

- ✓ Detector performance testing and characterization
- ✓ Signal chain nonlinearity characterization and analysis
- ✓ Instrument spectral radiometric uncertainty analysis
- ✓ Radiometric verification using OARS (-50 C to +60 C)
- ✓ Instrument spectral radiometric uncertainty demonstration in presence of expected on-orbit thermal perturbations
- ✓ Collect phase change melt signatures in vacuum
- OCEM Heated Halo verification blackbody emissivity measurement demonstration
- OARS thermal gradient and temperature measurement uncertainty analysis

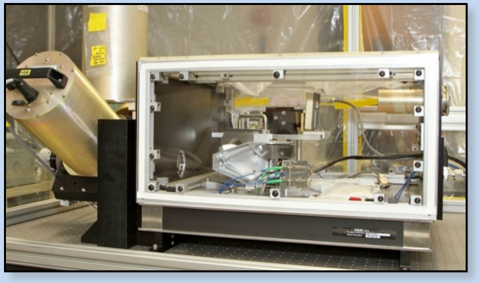
UW IIP Technology Development

Miniature Phase Change Cell (MPCC)

MPCC Component Integration, Characterization and Accelerated Life Testing

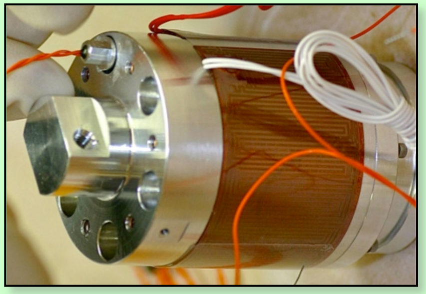


Heated Halo Generation-1 (Breadboard Halo, AERI BB with Scanning HIS Aircraft FTIR)

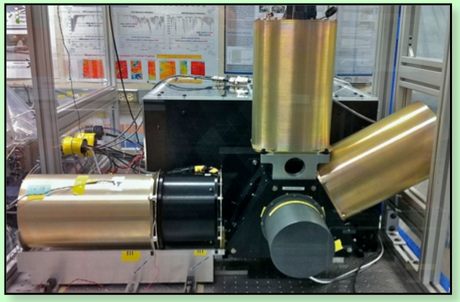


Absolute Radiance Interferometer (ARI) Breadboard

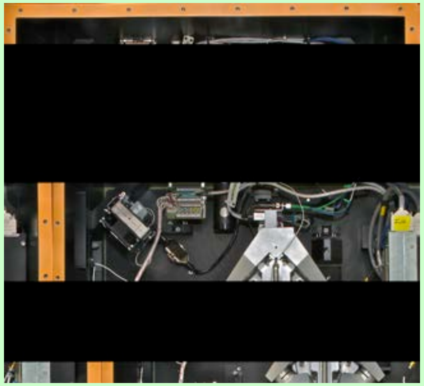
TRL 4



Integration of MPCC into Breadboard Blackbody for Thermal Testing

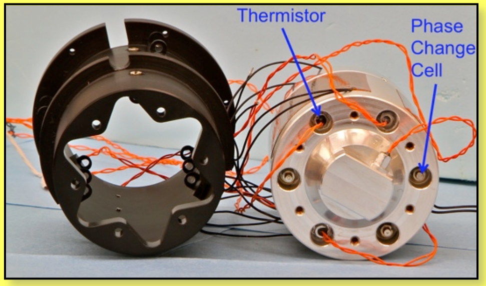


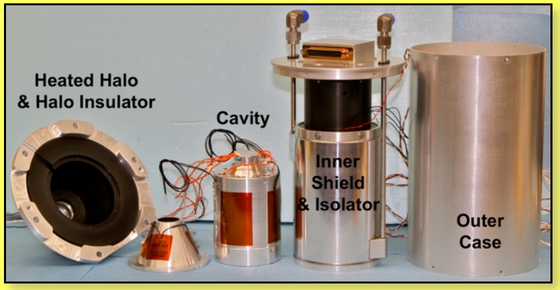
Heated Halo Generation-2 (Large Conical Halo, AERI BB with ARI Breadboard FTIR)



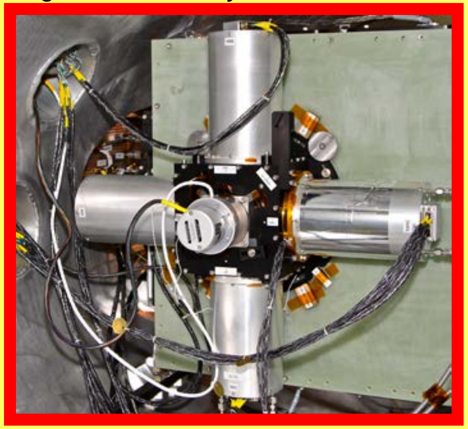
Absolute Radiance Interferometer Prototype

TRL 5





On-Orbit Absolute Radiance Standard: New 30 mm Aperture BB with MPCC integrated into cavity, and Heated Halo



NEAR COMPLETION

ARI Prototype Tested in Vacuum

TRL 6

ARI Technology Advancement to TRL 6

- Under the original IIP Absolute Radiance Interferometer (ARI) was advanced to …“well above TRL 5, but not crossing the threshold of TRL 6.” *
- **We would like to acknowledge Keith Murray and Parminder Ghuman of NASA ESTO for recognizing the importance of conducting the ARI system vacuum test and for advocating for the appropriate funding**
- The vacuum testing will conclude in May, with all technologies at TRL 6

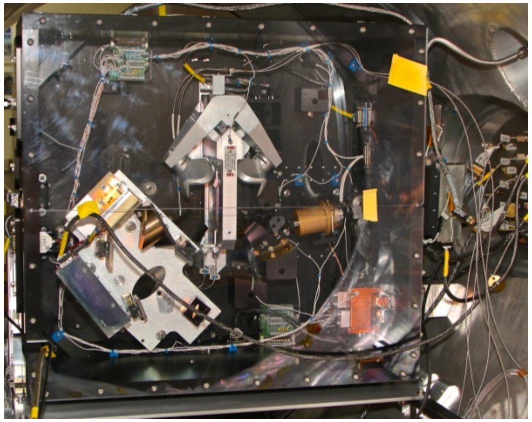
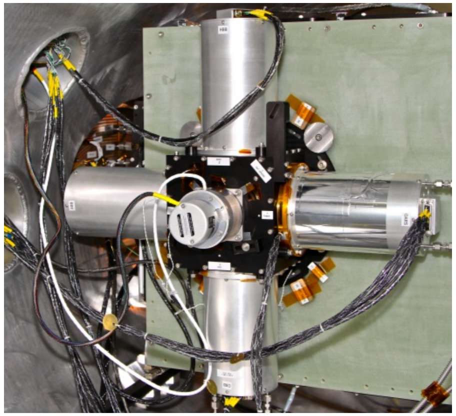
**Reference: Final Aerospace Review of “A New Class of Advanced Satellite Instrumentation for the CLARREO Mission;” George S. Rossano, February 28, 2012.*

End-to-End Verification Tests of the UW Absolute Radiance Interferometer (ARI) in a Vacuum Environment

PI: Hank Revercomb, University of Wisconsin, SSEC

Objective

- Advance key technologies necessary to measure IR spectrally resolved radiances with ultra-high accuracy brightness temperature (<0.1 K, 3 sigma at scene temperature) for crucial climate benchmark missions.
    - Perform vacuum testing of the ARI system, developed under a previous ESTO investment, to advance the TRL from 5 to 6
    - Demonstrate and characterize system performance under simulated space environment vacuum and thermal conditions.
- The ARI provides spectral coverage from 200-2600 cm-1 (3.9-50μm) using 2 output ports.

Absolute Radiance Interferometer (ARI) and On-Orbit Verification and Test System (OVTS) Prototype integrated into Vacuum Chamber

Approach:

- Ruggedize and configure the entire optical and validation system for testing in the thermal/vacuum chamber.
- Conduct end-to-end verification tests with the ARI under a vacuum environment using the integrated On-Orbit Verification and Test System (OVTS).
- Demonstrate operation and characterization of the On-Orbit Absolute Radiance Standard (OARS). The system is comprised of a high emissivity blackbody that includes: 1) multiple miniature phase change cells that provide absolute temperature calibration; and 2) a heated halo for measuring spectral emissivity.
- Analyze and document the performance data and verify adequate system performance for future radiance missions.

Key Milestones

- Complete test preparation — 10/12*
- Conclude integration and checkout — 04/13*
- Complete end-to-end verification — 05/13
- Finalize analysis and document findings — 06/13

**Completed Milestone*

TRL_{in} = 5, expected TRL_{out} = 6
i.e. ready to go!

Conclusions

- Recent UW Vacuum Testing of ***<u>CLARREO flight</u>*** <u>prototype (ARI</u>*)* combined with prior UW/Harvard IIP technology developments and test results provide even stronger support of readiness for an IR Climate Benchmark Mission

- We need to push for something to happen well before 2022