The University of Wisconsin Space Science and Engineering Center Absolute Radiance Interferometer (ARI): Instrument Overview and Radiometric Performance

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CALCON 2012
Logan, UT, USA

Summary

- The University of Wisconsin-Madison Space Science and Engineering Center (UW-SSEC) and Harvard University (HU) submitted a successful joint proposal entitled "A New Class of Advanced Accuracy Satellite Instrumentation (AASI) for the CLARREO Mission" to the NASA Instrument Incubator Program (IIP). The UW-SSEC / HU team has a long history with the scientific and measurement concepts that have formed the foundation for climate benchmark measurements from space

- The objective of this effort is to advance the technological development of advanced accuracy instrumentation for the measurement of absolute spectrally resolved infrared radiances (5 – 50 μm) with high accuracy (< 0.1 K, k = 3, brightness temperature at scene temperature) for climate benchmark measurements from space

- The UW-SSEC, developed a demonstration test bed which includes an FTS instrument and calibration and validation system to demonstrate the feasibility of the far and mid infrared instrumentation for a Climate Benchmark Mission.

Topics

1. Introduction
2. The UW-SSEC Absolute Radiance Interferometer (ARI)
3. Radiometric Performance
4. Conclusion

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Climate Benchmark Measurements

- Satellite Instrument Calibration for Measuring Global Climate Change (NIST Publication NISTIR 7047, 2003)
- ASIC^3 Report: Achieving Satellite Instrument Calibration for Climate Change (2007)
- US NRC Decadal Survey (NRCDS, 2007): *Earth science and applications from space: national imperatives for the next decade and beyond*
  - Climate Absolute Radiance and Refractivity Observatory (CLARREO): Tier 1 (highest priority) mission
- NASA Implementation of CLARREO
  - Selected for development/implementation by NASA (lead: NASA LaRC)
  - Successful MCR (November 2010)
  - Guidance received in the President's FY 2012 budget removed $1.24B from the $2.08B FY'11 proposed Climate Initiative … directed cuts include CLARREO
- ***Zeus***

Capability of Current Systems

- Current generation of high resolution IR sounders: AIRS, IASI, CrIS…
    - Tremendous advance in information content & accuracy
    - Huge advance for climate process studies
- Provide a solid foundation for IR Climate Benchmark Measurement feasibility
- But, not optimized for unequivocal decadal trending of climate change, and for the most part, are not designed to provide:
    - The *radiometric accuracy and sampling* required to detect the small trends associated with global climate change
    - On-orbit calibration traceability to absolute standards
    - Far infrared (FIR) coverage beyond the normal IR sounding region (typically some part or all of the 3-15 μm region)

Requirements for IR Climate Benchmark Measurements

- Absolute Accuracy: < 0.1 K, k = 2, brightness temperature *for combined measurement and sampling uncertainty* for annual averages of 15° zones to approach goal of resolving a climate change signal in the decadal time frame
    - Measurement uncertainty: < 0.1 K, k = 3
    - Sampling uncertainty: < 0.1 K, k = 3
- On-orbit Verification and Test: Provide an On-orbit Absolute Radiance/Brightness Temperature Standard with an accuracy of < 0.1 K, k = 3, to provide SI traceability of on-orbit measurements
- Spectral Coverage and Resolution: 200 – 2000 (goal: 3000) cm^{-1}; ~0.5 cm^{-1} (±1 cm MOPD)
- Spatial Footprint & Angular Sampling: Order 100 km ***or less***, nadir only
- Coverage: Contiguous coverage ***not*** required

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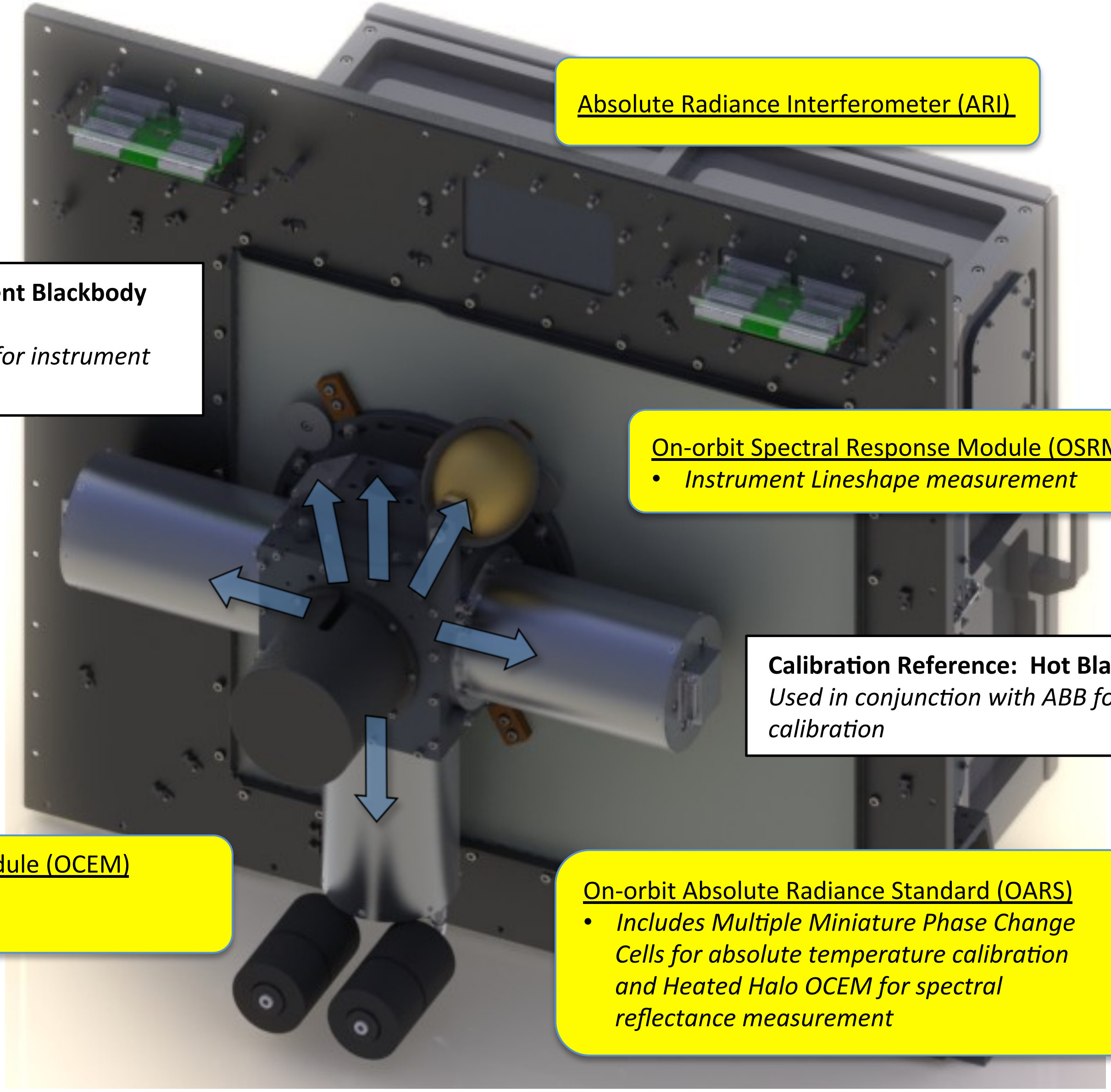
Technology Developments Under NASA IIP



Absolute Radiance Interferometer (ARI)

Calibration Reference: Ambient Blackbody (ABB)
Used in conjunction with HBB for instrument calibration

On-orbit Spectral Response Module (OSRM)
- *Instrument Lineshape measurement*

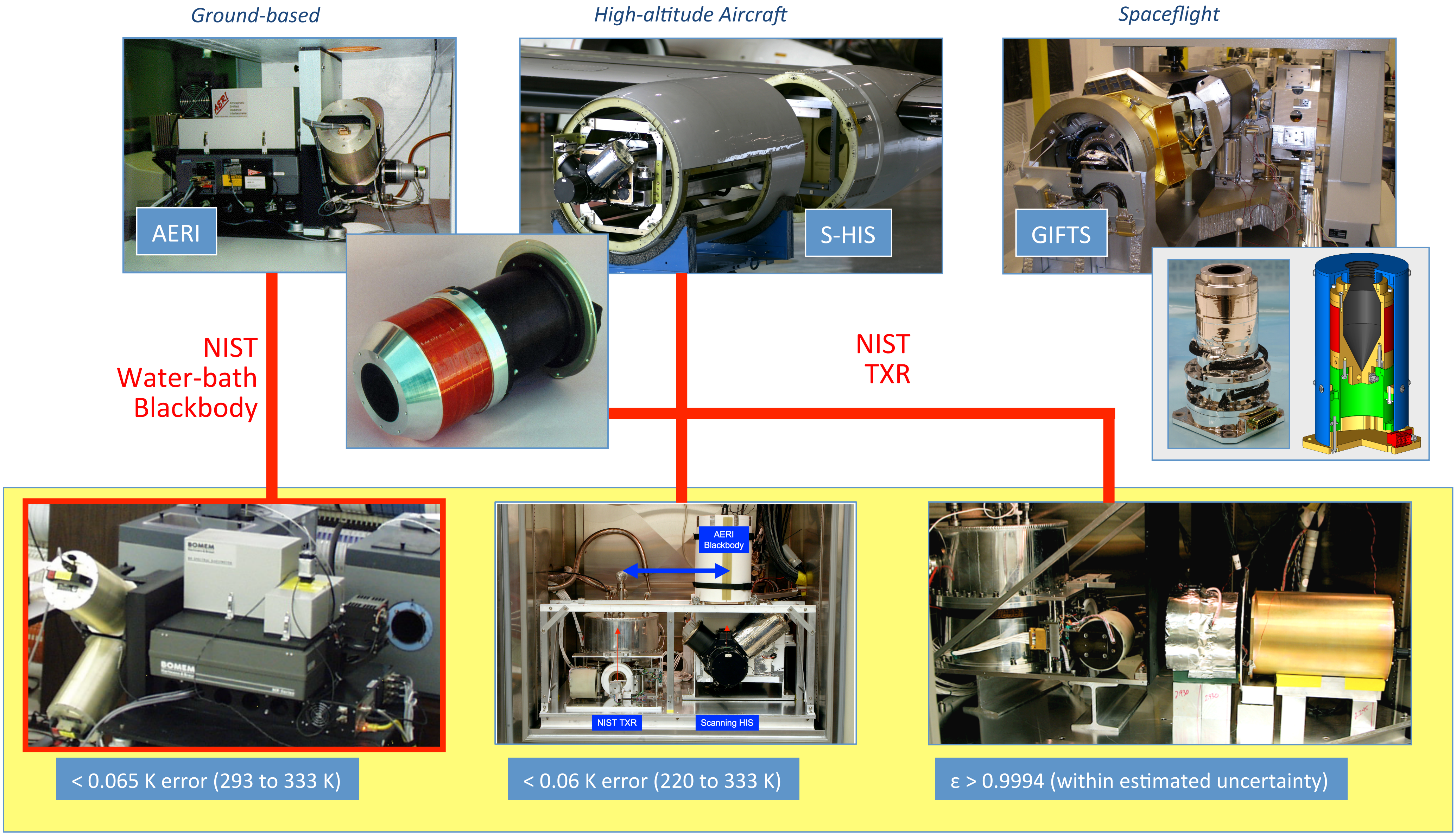
Calibration Reference: Hot Blackbody (HBB)
Used in conjunction with ABB for instrument calibration

On-orbit Cavity Emissivity Module (OCEM)
- *Heated Halo*
- *QCL*

On-orbit Absolute Radiance Standard (OARS)
- *Includes Multiple Miniature Phase Change Cells for absolute temperature calibration and Heated Halo OCEM for spectral reflectance measurement*

Fred Best: *"On-Orbit Absolute Radiance Standard for the Next Generation of IR Remote Sensing Instruments (Monday, 13:35 – 13:55)*
Jon Gero: *"The Heated Halo for Space-Based Blackbody Emissivity Measurement" (Tuesday, 16:30 – 16:50)*

UW-SSEC Spectrometer, Blackbody Heritage & Ties to NIST



Ground-based

High-altitude Aircraft

Spaceflight

NIST
Water-bath
Blackbody

NIST
TXR

< 0.065 K error (293 to 333 K)

< 0.06 K error (220 to 333 K)

ε > 0.9994 (within estimated uncertainty)

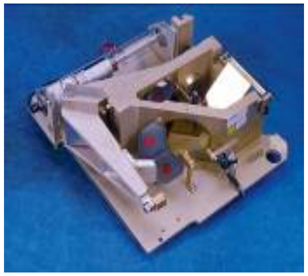
UW-SSEC Absolute Radiance Interferometer

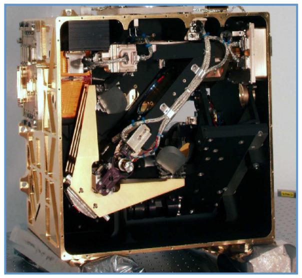
- The UW-SSEC Absolute Radiance Interferometer includes:
  - A scene selection mirror assembly;
  - Fore optics designed specifically for high radiometric accuracy;
  - A 4-port cube corner, rocking arm interferometer with a diode laser based metrology system;
  - Two aft optics assemblies, 1 at each output port of the interferometer;
  - A 77 K multiple semi-conductor detector (400 – 3000 cm^{-1}) and dewar assembly, and associated mechanical cooler;
  - A DTGS pyroelectric detector (200 – 1800 cm^{-1}) assembly.

Each chosen for their strong spaceflight heritage such that detailed performance testing can be conducted on a system with a clear path to space. *For compatibility with an IIP budgets, the electronics are not flight designs*

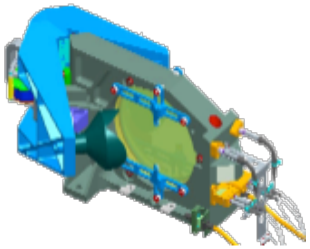
The Generic Flight Interferometer (GFI)

- The UW ARI is based on ABB’s Generic Flight Interferometer (GFI) architecture: a flex blade-based frictionless double pendulum scanning mechanism with 25 years of heritage and a direct evolution of 2 successful spaceborne interferometers:
  - **SCISAT / ACE-FTS (2003):** Initial design life of 2 years and still operating in compliance with performance requirements after 9 years
  - **GOSAT / TANSO-FTS (2009)**: Currently meets all performance requirements in flight
- Additionally, the GFI baseline includes:
  - Fiber-linked metrology for reduced heat load on interferometer and simplified alignment / redundancy management
  - Monolithic cube corner mirror for increased robustness to launch vibration


MB series (1985)


SCISAT (2003)

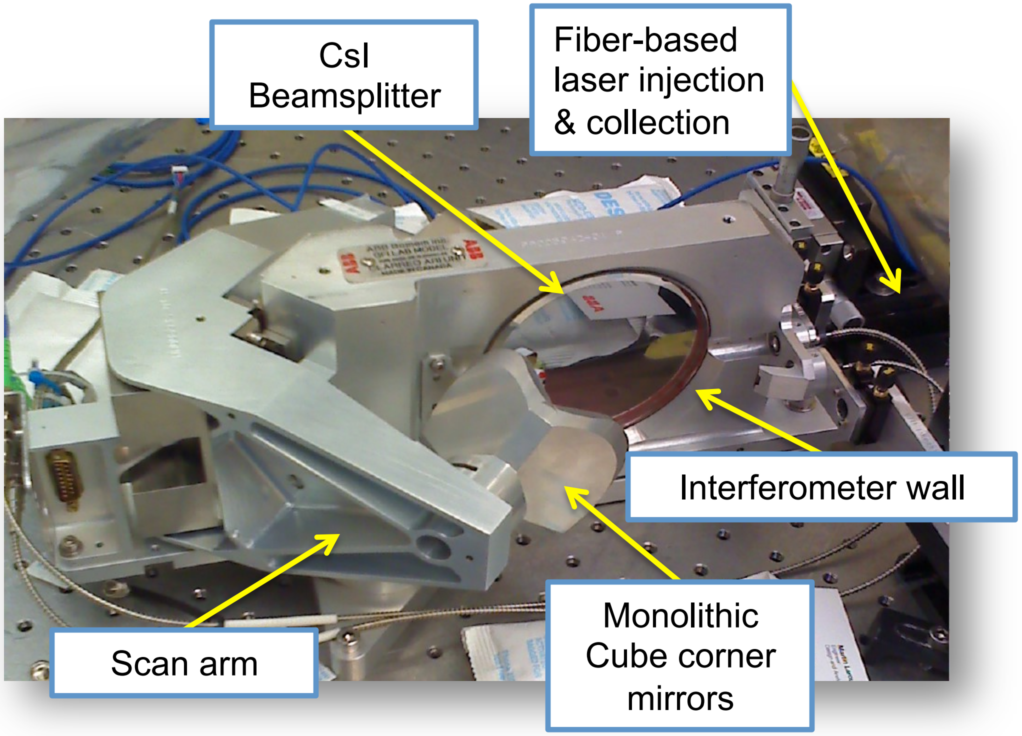

GOSAT (2009)


GFI

The Generic Interferometer for Climate Studies (GICS)

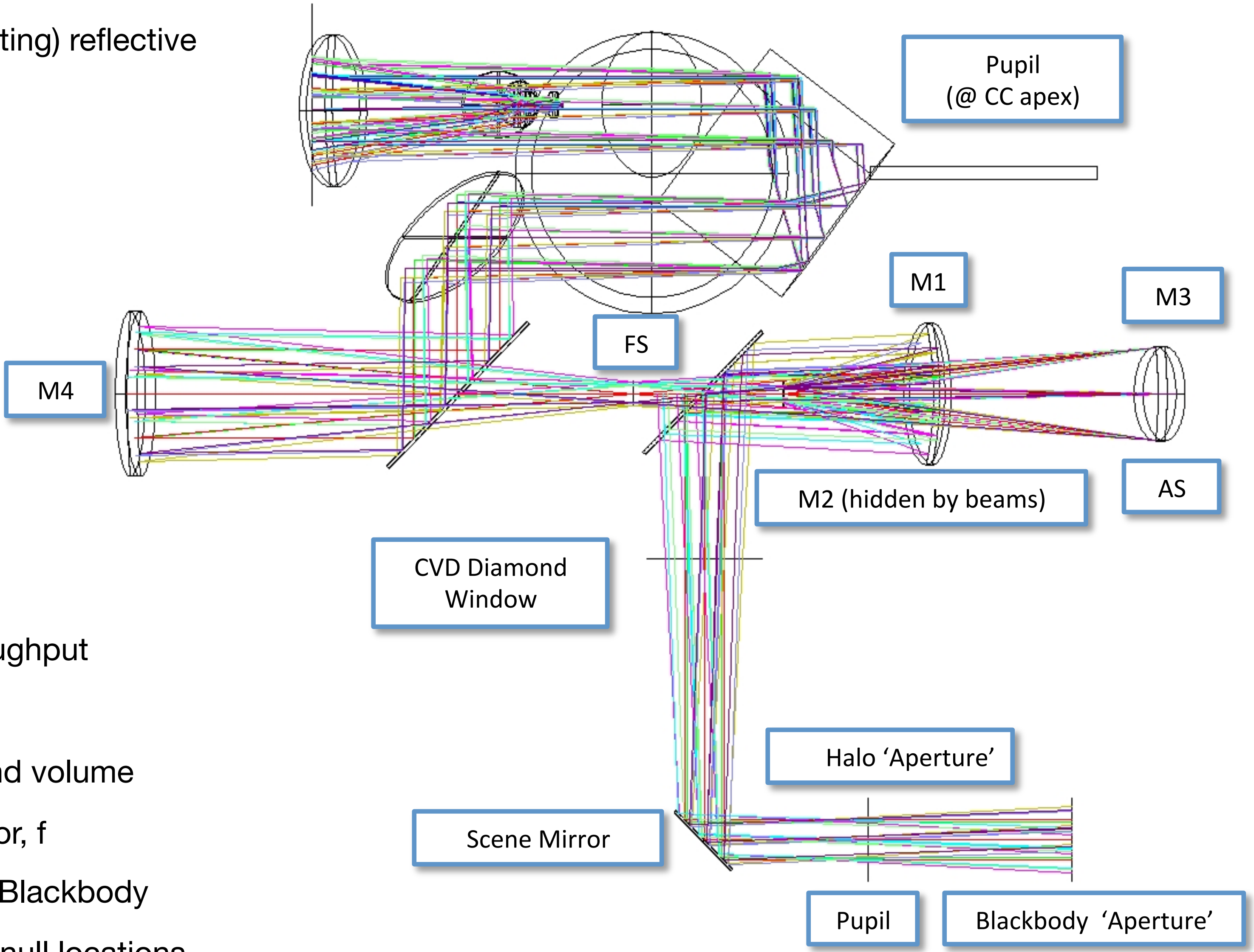
- 4 port
- Different met laser path
- CsI beamsplitter to cover spectral range
- Mounting adapted for CsI
- Self compensated beamsplitter instead of substrate and compensator
- Replicated monolithic cube corner

- Vacuum compatible Interferometer
- Modified COTS electronics and software used for IIP
- Mass: < 7 kg (GICS, Aluminum)
- Power: Avg 18 W / Pk 23 W (flight design)



Optical Design

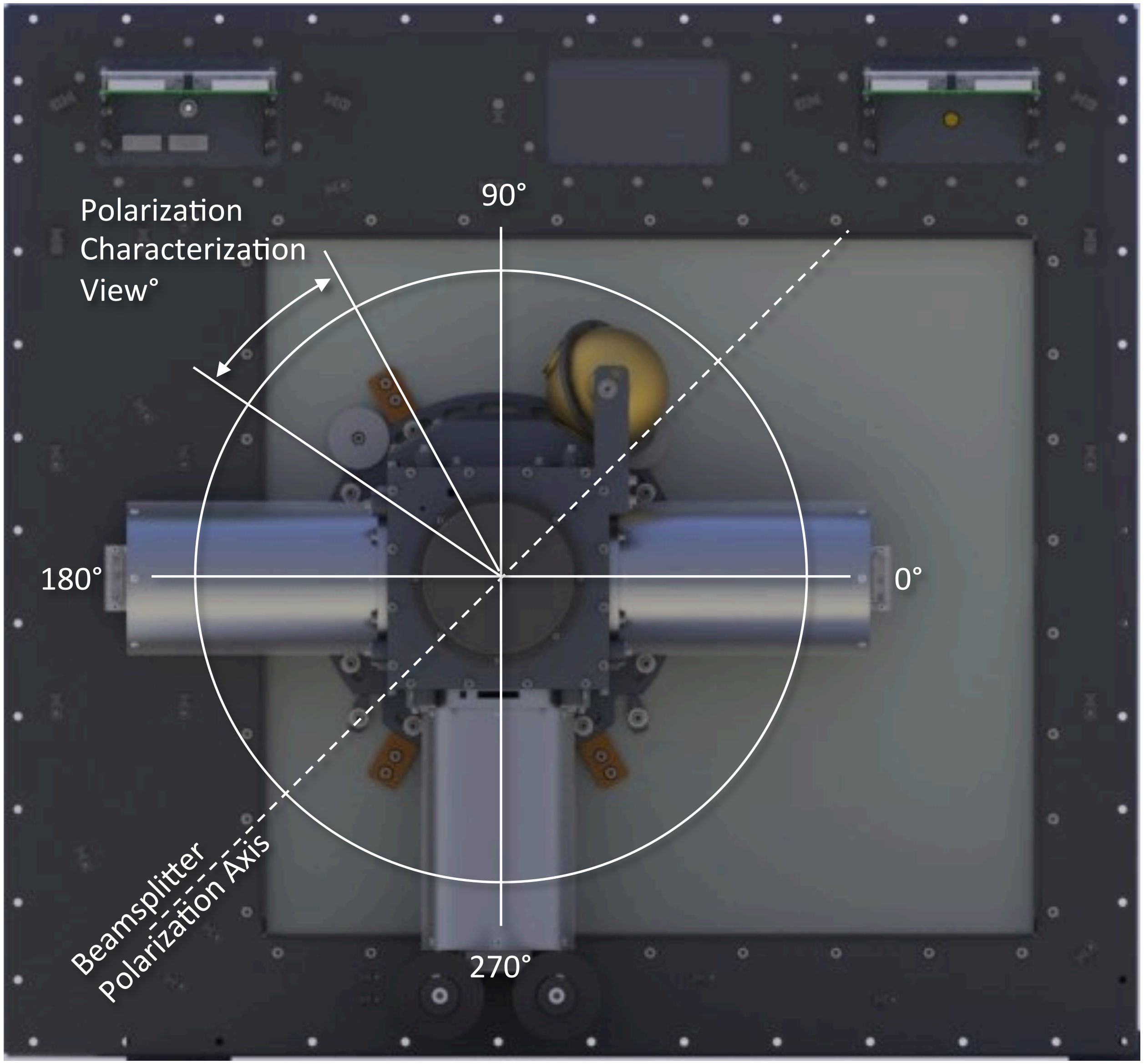
Gold coated Aluminum (no AR coating) reflective components



Design goals included:

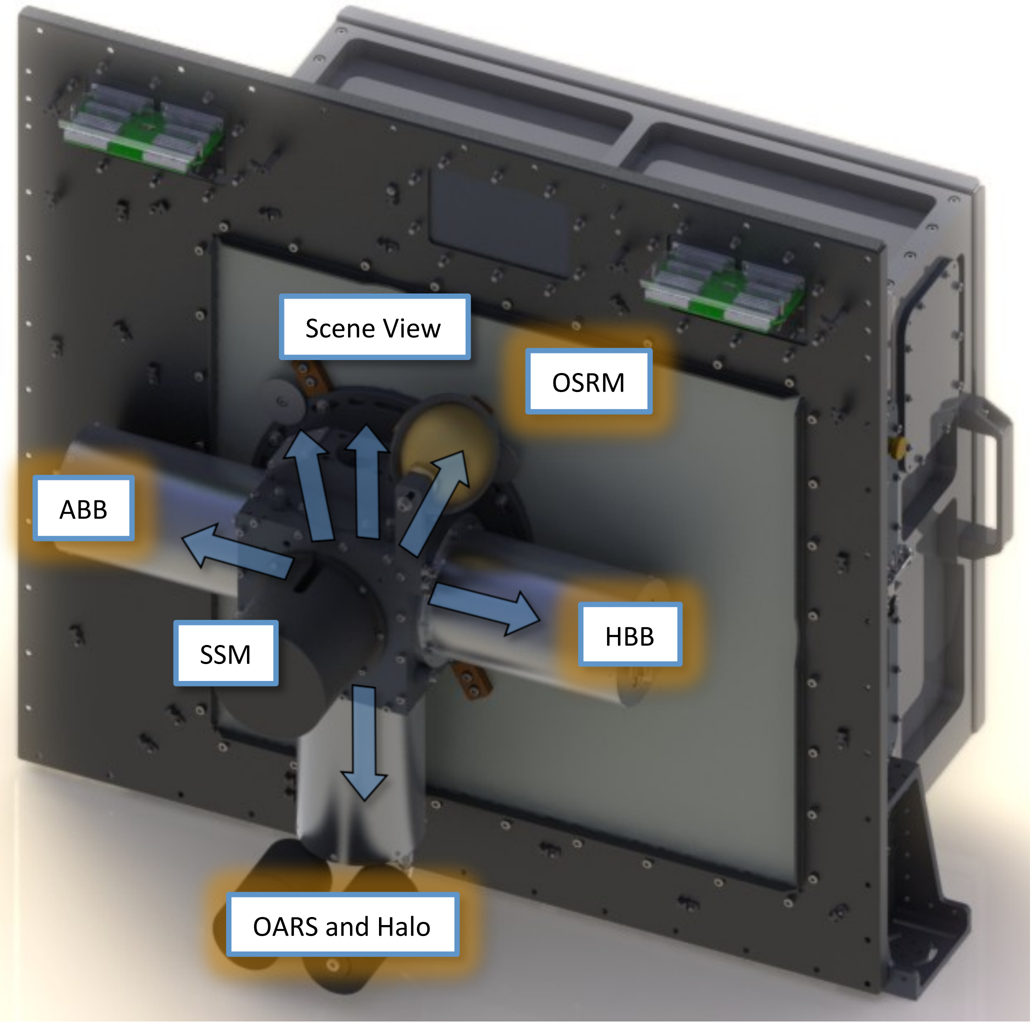
- Optimize interferometer throughput
- Maximize Stray light control
- Minimize instrument mass and volume
- Optimize heated halo fill factor, f
- Compatible with 1" aperture Blackbody
- Allow 'tuning' of polarization null locations

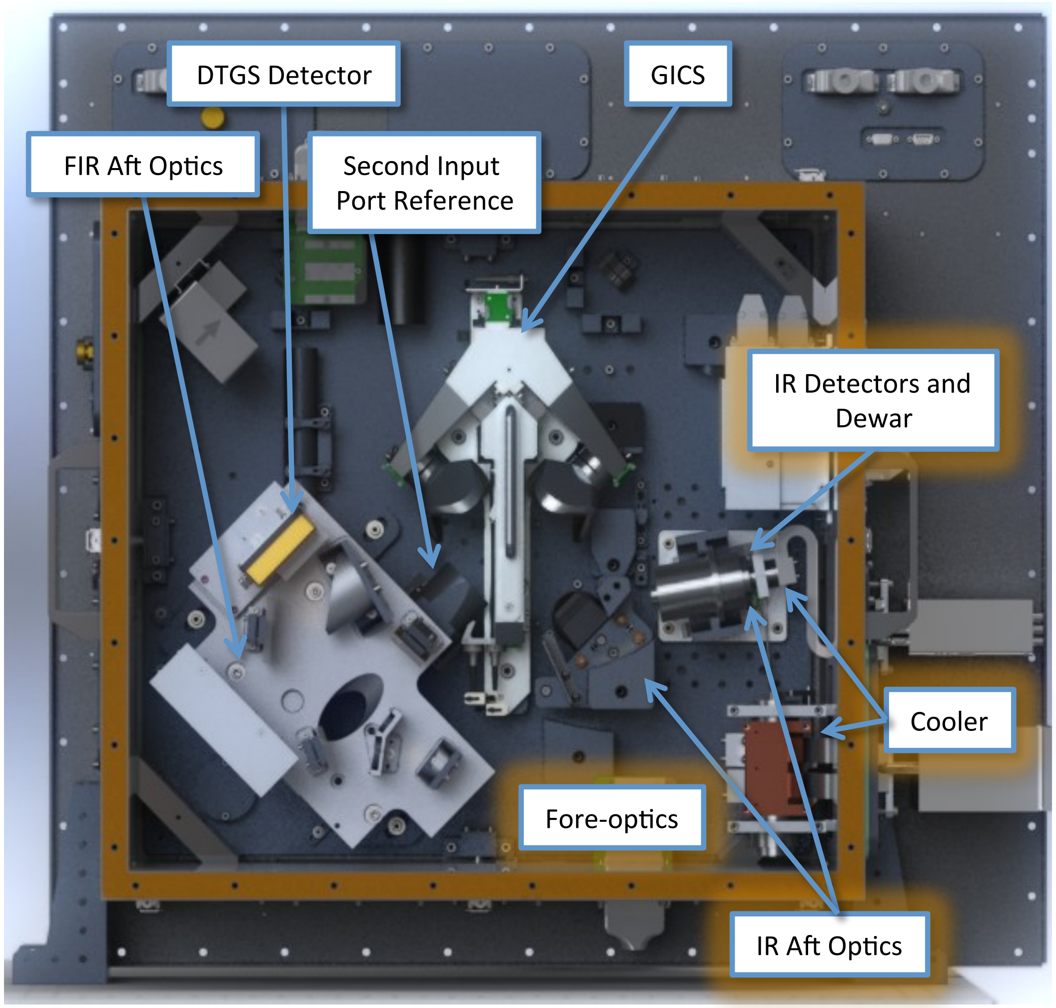
Absolute Radiance Interferometer



Viewing configuration providing immunity to polarization effects.

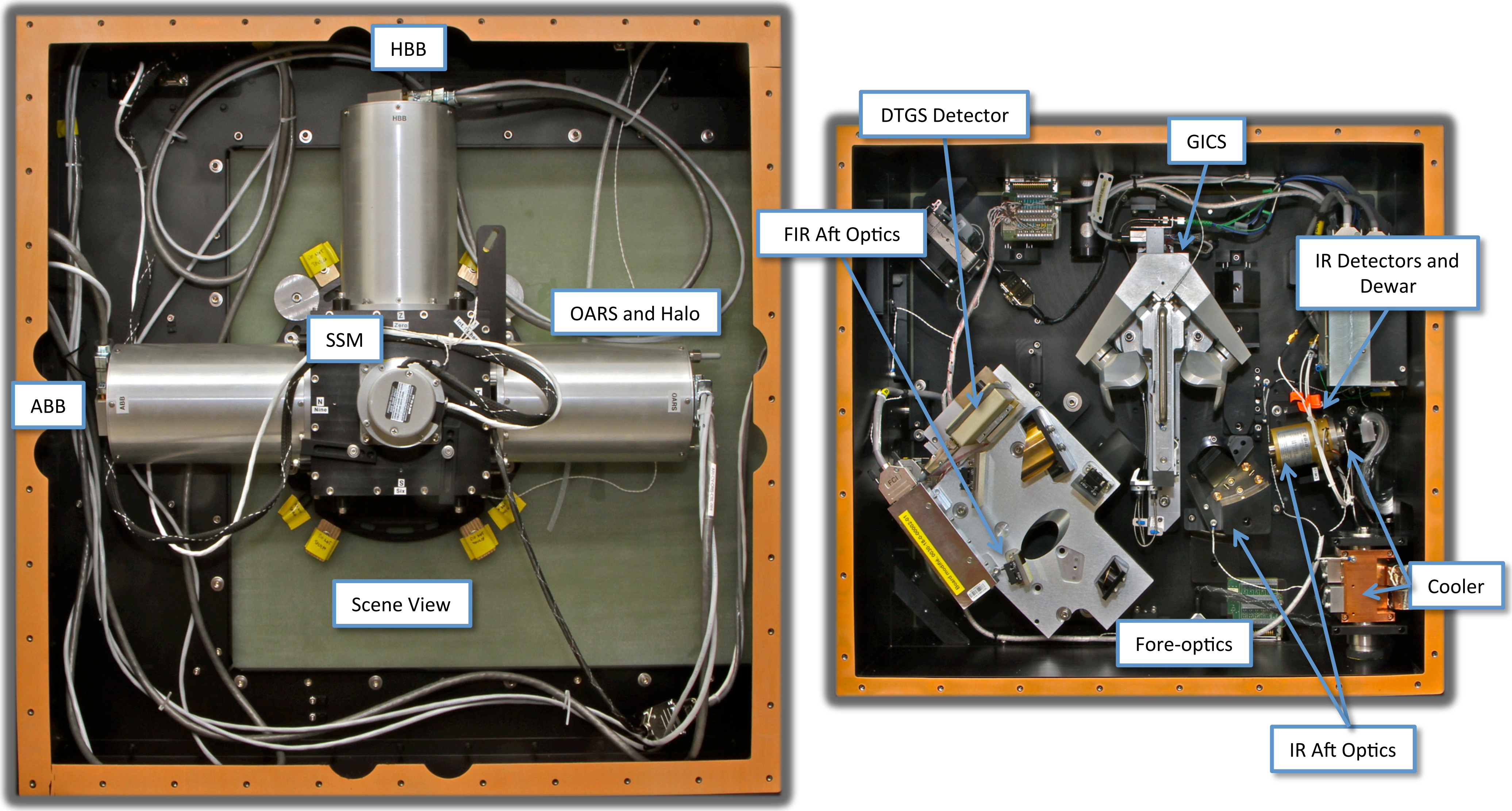
Absolute Radiance Interferometer





Solid Model (Solidworks)

Absolute Radiance Interferometer



Completed Prototype

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Instrument Testing

- Near Field Response Mapping
- Detector Performance Testing and Demonstrations
- Interferometric Noise Testing and Analysis
- Spectral Calibration Verification
- Nonlinearity Characterization and Analysis
- Radiometric Calibration Verification: OARS
- Radiometric Calibration Verification: Ice Bath Blackbody
- OCEM Heated Halo

Radiometric Uncertainty

- Recall the basic calibration expression for the complex calibration method:

$$N = \left(L_H - L_C\right) \mathrm{Re}\left\{ \frac{C_S - C_C}{C_H - C_C} \right\} + L_C\,,$$

$$L = eB(T) + \left(1 - e\right) B(T_R)$$

- Radiometric uncertainty estimate: Differential error analysis (and/or perturbation analysis) of the calibration equation
- The uncertainty in the *verification* of the calibrated radiance includes a contribution from the uncertainty in the determination of the predicted radiance in addition to the uncertainty in the measured radiance

Radiometric Uncertainty (Predicted On-orbit)

- On-orbit:
  - Space view for cold calibration reference
  - Onboard ambient calibration blackbody for “hot” calibration reference
  - These values satisfy the Zeus/CLARREO accuracy requirements

Temperatures			**Associated Uncertainty (3-σ)**	
Cold Cal Ref (Space Target)	T_C	4 K	$u(T_C)$	0 K
Hot Cal Ref (Internal Cal Target)	T_H	295 K	$u(T_H)$	0.045 K
Verification Target (OARS)	T_{OARS}	220 – 320 K	$u(T_{OARS})$	0.045 K
Reflected Radiance, Cold Cal Ref	$T_{R,C}$	290 K	$u(T_{R,C})$	0 K
Reflected Radiance, Hot Cal Ref	$T_{R,H}$	290 K	$u(T_{R,H})$	4 K
Reflected Radiance, Verification Target	$T_{R,OARS}$	290 K	$u(T_{R,OARS})$	4 K
Emissivities				
Cold Cal Ref (Space Target)	e_C	1	$u(e_C)$	0.0006
Hot Cal Ref (Internal Cal Target)	e_H	0.999	$u(e_H)$	0.0006
Verification Target (OARS)	e_{OARS}	0.999	$u(e_{OARS})$	0.0006*

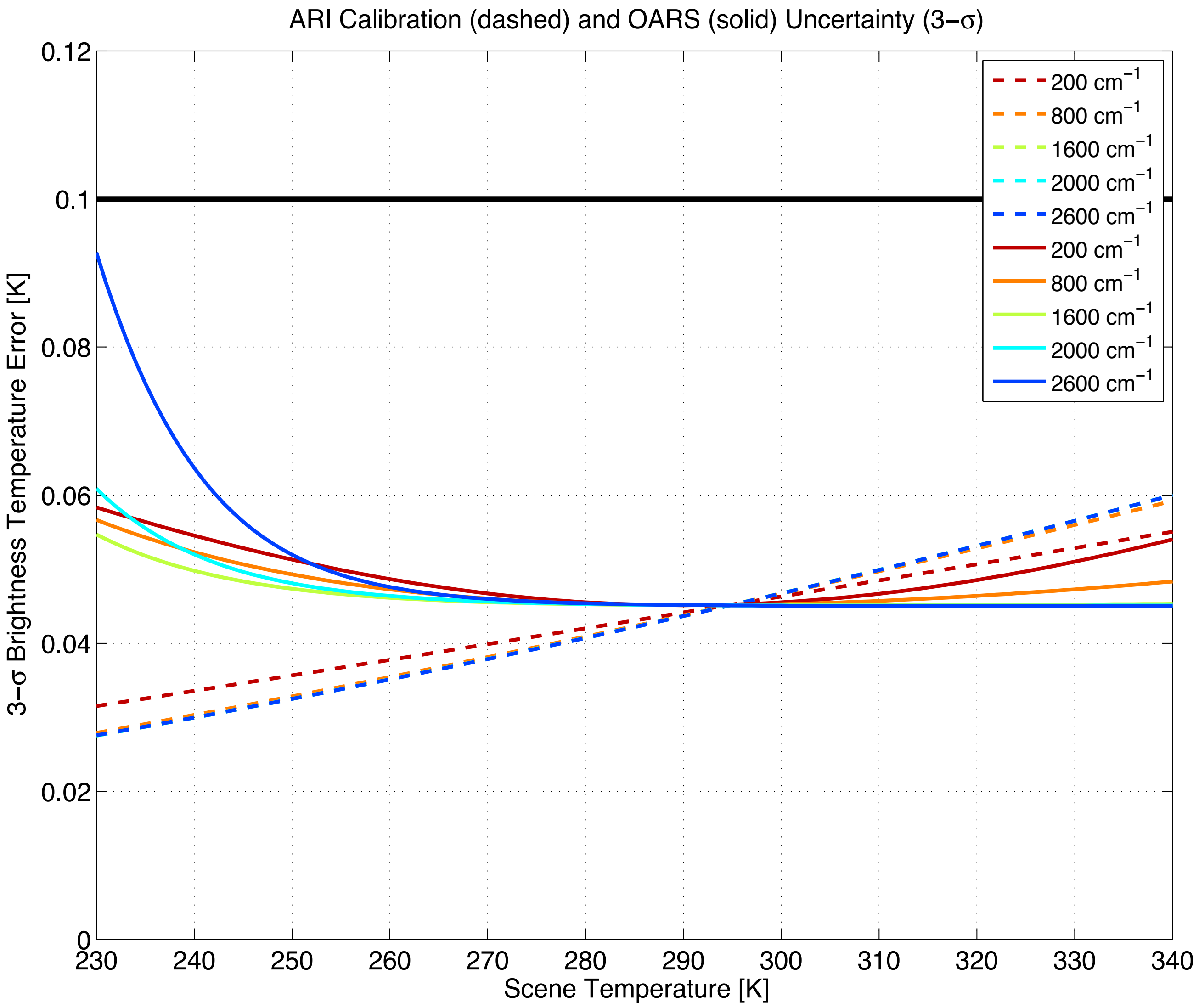
Cal BB / OARS Uncertainty Analysis

Halo Uncertainty Analysis

* ***For the On-orbit uncertainty analysis***, it has been assumed that the OARS emissivity and associated uncertainty is determined from prelaunch TVAC testing with a very high emissivity source

- e_{OARS} = 0.9990 ± 0.0006 (200 cm^{-1})
- e_{OARS} = 0.9990 ± 0.0004 (800 cm^{-1})
- e_{OARS} = 0.9990 ± 0.0002 (1400 cm^{-1})
- e_{OARS} = 0.9990 ± 0.0001 (2000 cm^{-1})
- e_{OARS} = 0.9990 ± 0.00075 (2600 cm^{-1})

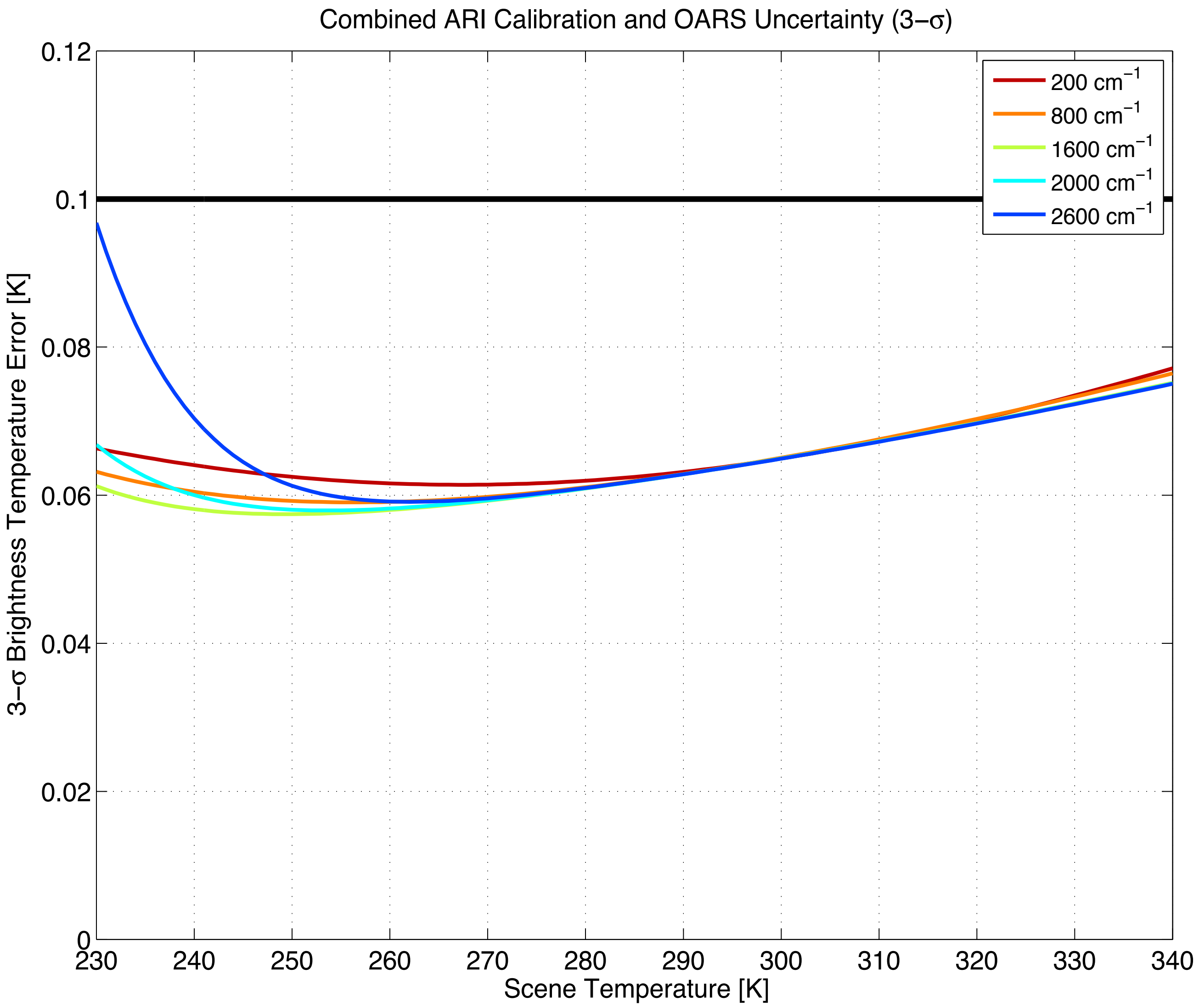
Radiometric Uncertainty (Predicted On-orbit)



* Uncertainty due to residual nonlinearity not shown

Radiometric Uncertainty (Predicted On-orbit)

Combined UW – ARI Calibration and OARS Uncertainty (k = 3)



* Uncertainty due to residual nonlinearity not shown

Radiometric Uncertainty (Laboratory Environment)

- IIP Demonstration (Laboratory Environment):
  - Onboard ambient calibration blackbody for “cold” calibration reference
  - Onboard hot calibration blackbody for “hot” calibration reference

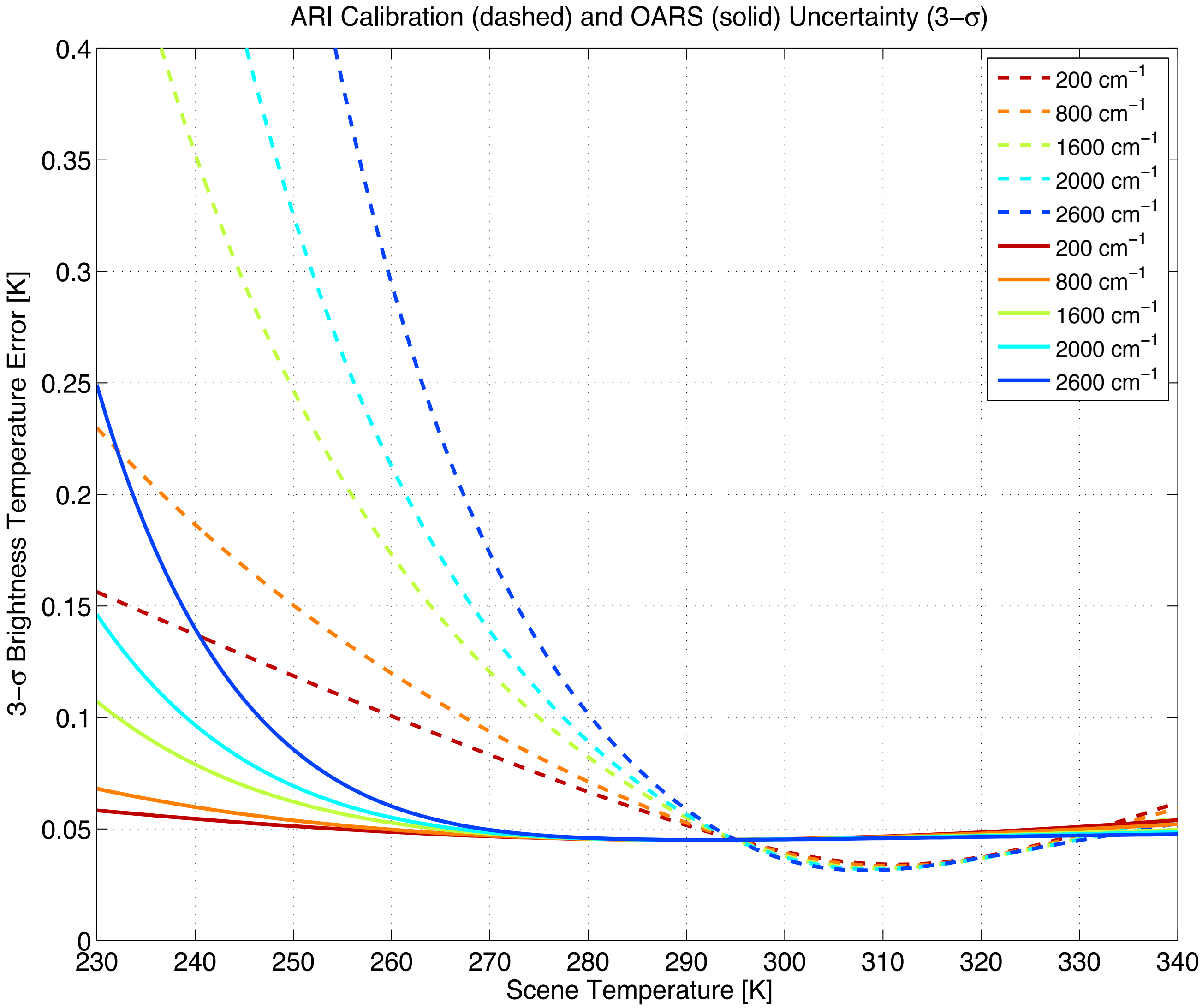
Temperatures			**Associated Uncertainty (3-σ)**	
Cold Cal Ref (Ambient Blackbody)	T_C	293 K	$u(T_C)$	0.045 K
Hot Cal Ref (Hot Blackbody)	T_H	333 K	$u(T_H)$	0.045 K
Verification Target (OARS)	T_{OARS}	213 – 333 K	$u(T_{OARS})$	0.045 K
Reflected Radiance, Cold Cal Ref	$T_{R,C}$	290 K	$u(T_{R,C})$	4 K
Reflected Radiance, Hot Cal Ref	$T_{R,H}$	290 K	$u(T_{R,H})$	4 K
Reflected Radiance, Verification Target	$T_{R,OARS}$	290 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

Cal BB / OARS Uncertainty Analysis

Halo Uncertainty Analysis

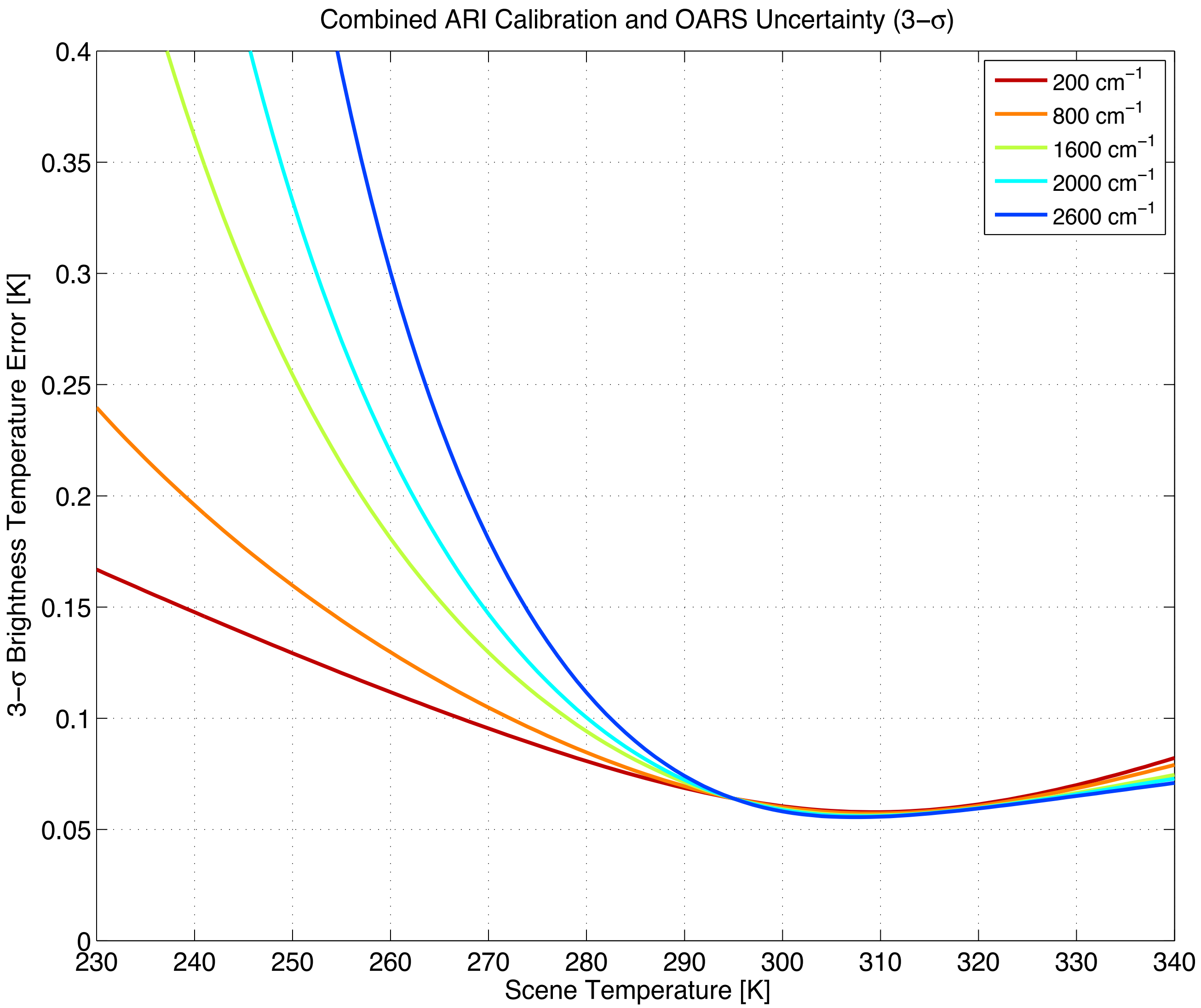
Radiometric Uncertainty (Laboratory Environment)

UW – ARI Calibration and OARS Uncertainty (k = 3)



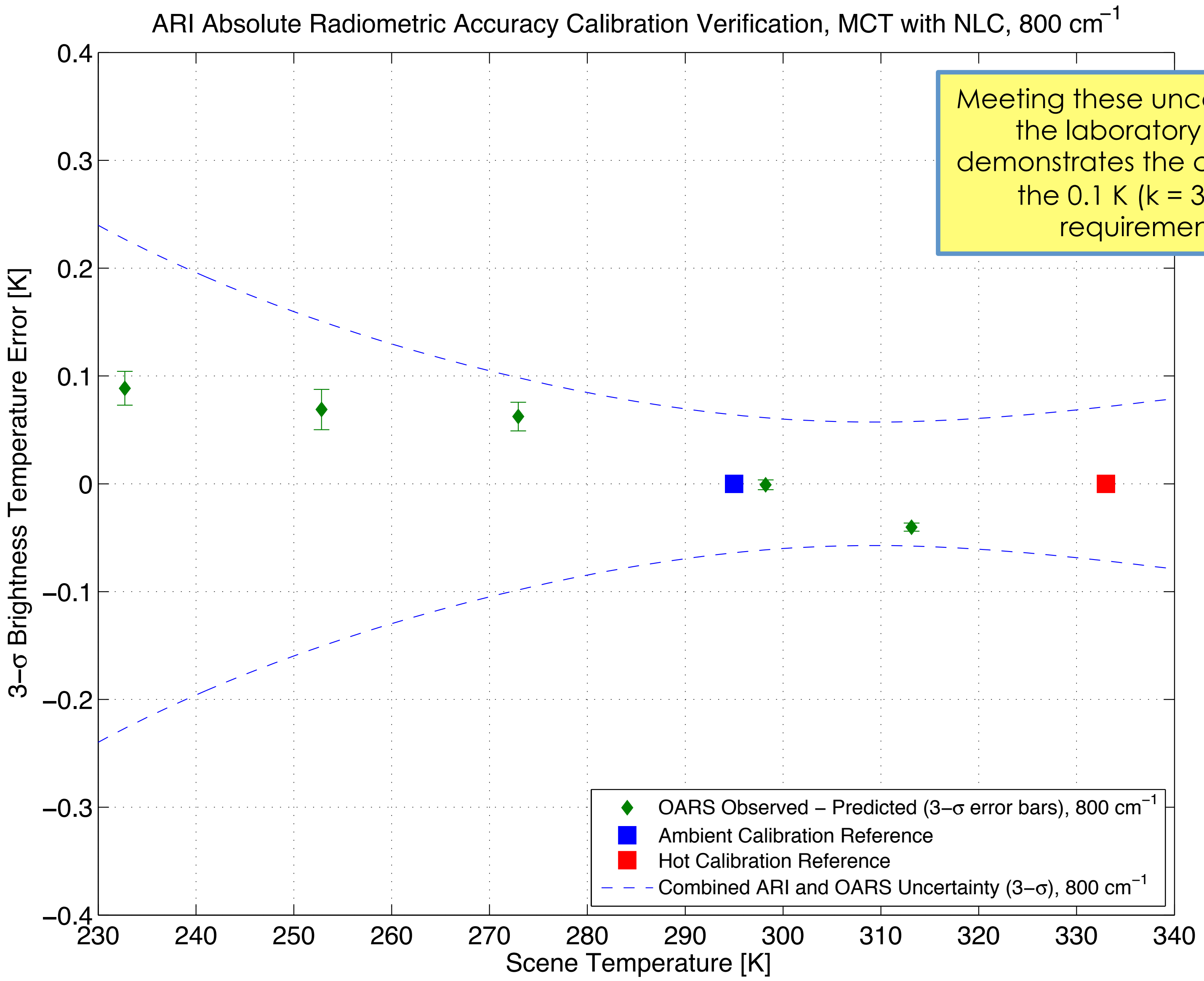
Radiometric Uncertainty (Laboratory Environment)

Combined UW – ARI Calibration and OARS Uncertainty (k = 3)



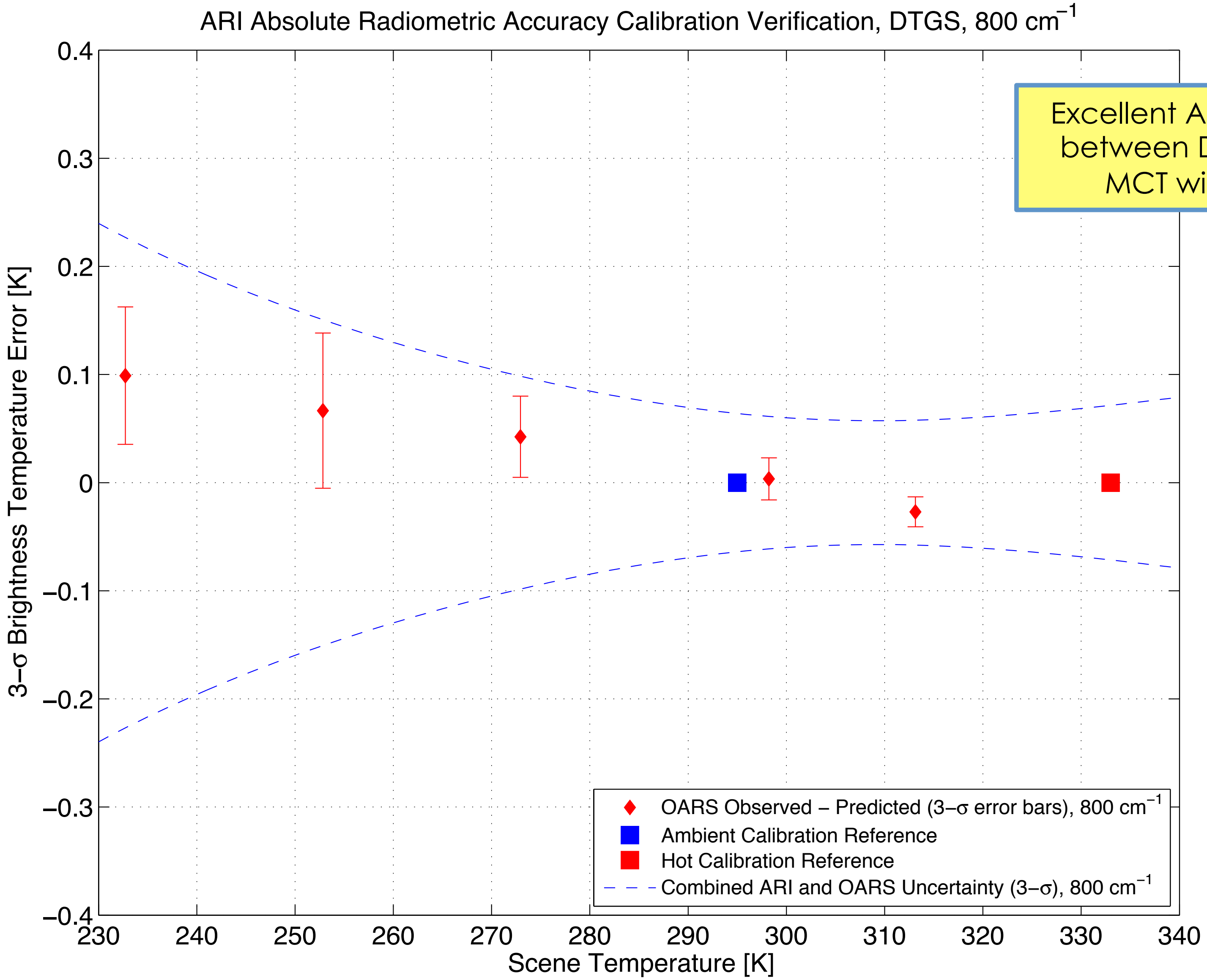
Meeting these uncertainties in the laboratory environment demonstrates the capability to meet the 0.1 K (k = 3) uncertainty requirement on-orbit

Radiometric Calibration Verification – MCT with NLC



Meeting these uncertainty bounds in the laboratory environment demonstrates the capability to meet the 0.1 K (k = 3) uncertainty requirement on-orbit

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



Excellent Agreement between DTGS and MCT with NLC

Conclusion

- An excellent, low cost, climate benchmark mission has been defined
- The proposed IR measurement requirements are supported by good technical readiness
- The UW-SSEC ARI (and OT/V)
    - Facilitates the demonstration of the technology necessary to measure IR spectrally resolved radiances (5 – 50 µm) with ultra high accuracy (< 0.1 K, k = 3, brightness temperature at scene temperature) for a benchmark climate mission.
    - Subsystems have been selected and developed to provide a system with a clear path to space.
    - Initial end to end system tests have been completed – meets radiometric uncertainty goals
    - Vacuum testing preparation underway
- This technology can form the basis of a future climate benchmark mission, such as CLARREO or Zeus.

THANK YOU