The Absolute Radiance Interferometer (ARI) for the CLARREO Pathfinder: Instrument Status and Demonstrated Performance

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[c] *Harvard University*

GSICS 2017

- Introduction
- The UW-SSEC Absolute Radiance Interferometer
- Instrument Status and Demonstrated Performance
- Conclusion

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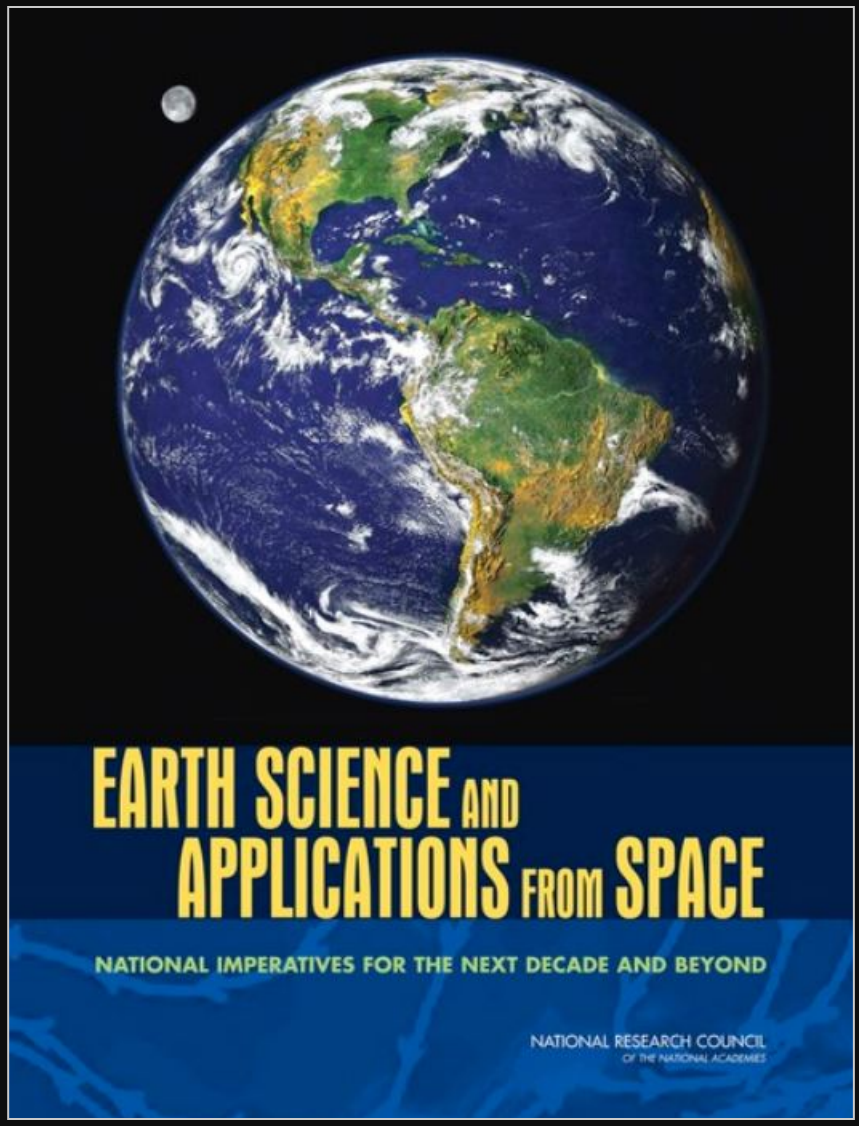
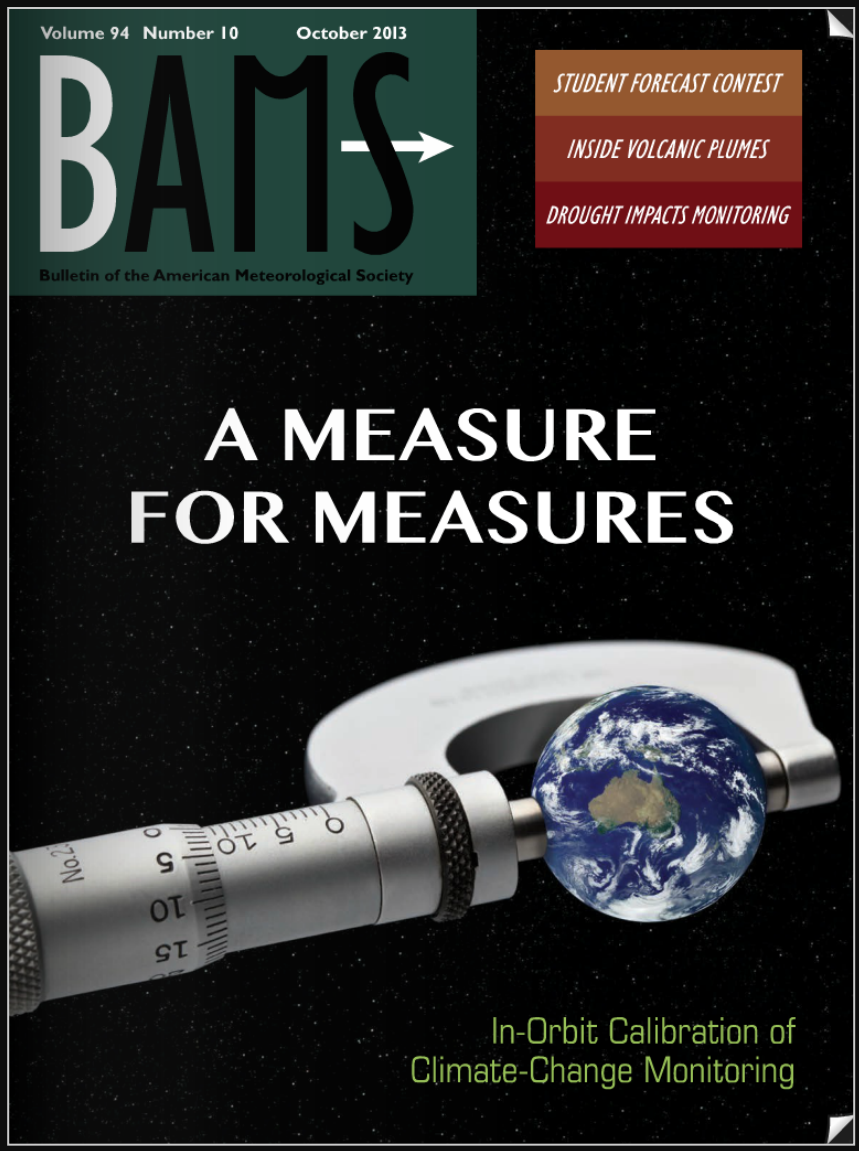
CLARREO (2007 Decadal Survey Tier 1 Mission)

- CLARREO (Climate Absolute Radiance & Refractivity Observatory)
  a 2007 Decadal Survey Tier 1 mission
  - IR & Reflected Solar spectra coupled with GPS RO offer
    1. unprecedented measurement accuracy,
       0.1 K IR Brightness Temp, 0.4 % RS radiance, and
       0.1 % GPS RO refractivity 5-20 km
       (all k = 3, proven on orbit with SI standards)
    2. unbiased spatial and temporal sampling
    3. much higher climate change sensitivity
       than existing CERES-type climate records
  - Metrology lab on-orbit serves as "NIST in orbit"
- CLARREO to Benchmark Earth's climate
  - Analogous to marking a glacier's current extent
  - > 5 year missions repeated every 10-15 years
- CLARREO as an Inter-calibration Standard
  - GSICS (Global Space-based Inter-Cal System)
  - e.g. Greatly enhancing the value of the climate record from high spectral resolution IR sounders starting in 2002 (AIRS, IASI, CrIS…) and RS sensors



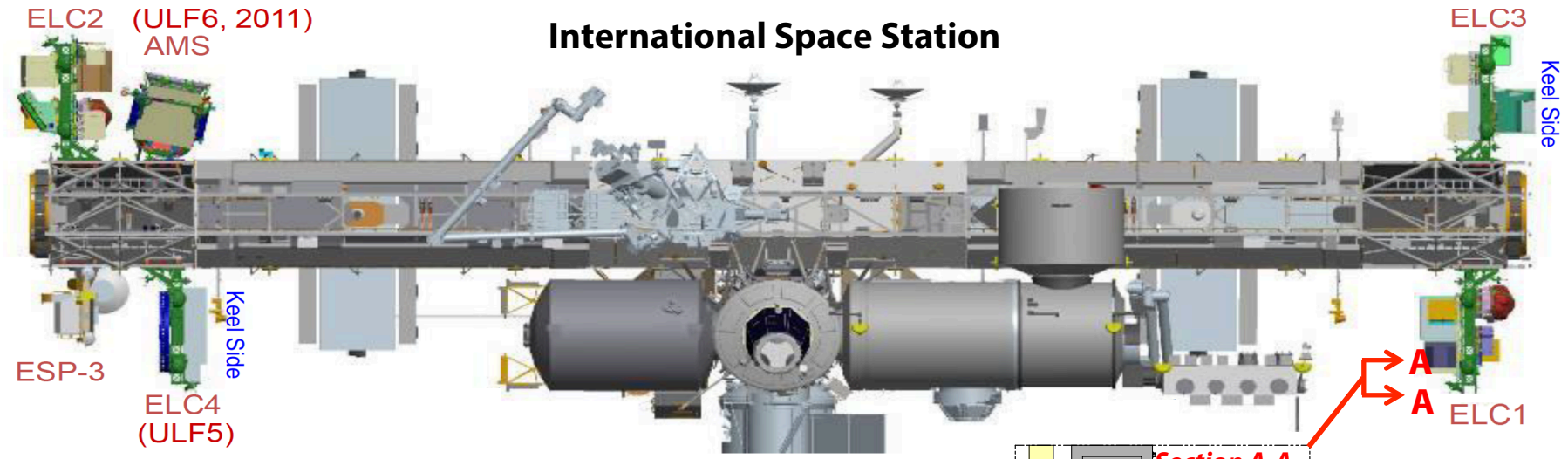
NASA CLARREO Timeline and Status

- 2008-2010 CLARREO – following the DS, NASA assigned mission responsibility to Langley Research Center (LaRC)
  - A Science Team formed and Mission Concept Review passed in November 2010
  - IR and Reflected Solar instrument development conducted under NASA Instrument Incubator Program (IIP) and calibration system studies
- 2011 CLARREO: funding profile removed from the president's budget on 14 February
- 2011 – present: CLARREO – Science Team studies continue. Wielicki et al., BAMS cover in 2013
- 2012-2014 New Instrument Technologies -Achieved TRL 6 under NASA Instrument Incubator Program (IIP) / ESTO support of LASP for RS and UW-SSEC & Harvard for the IR
- 2013-2016 Pathfinder Concept – for flight on International Space Station (ISS) developed

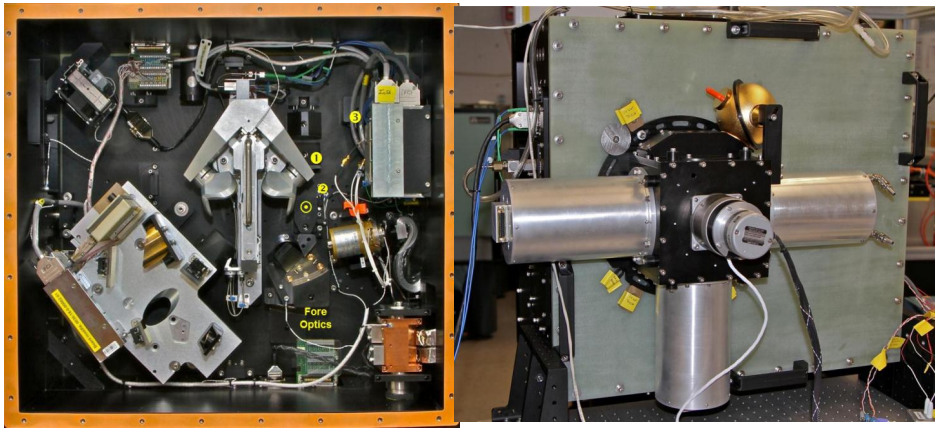


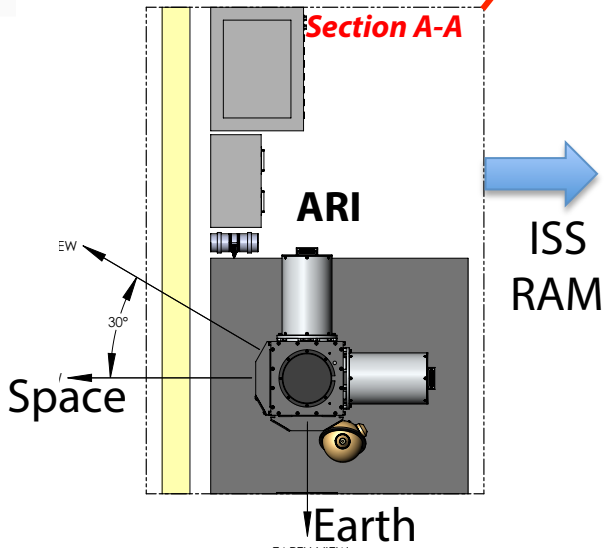
Wielicki et al.

ISS Pathfinder for CLARREO



ARI Lab Prototype

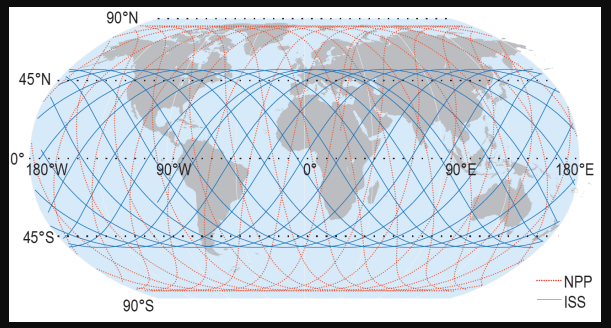




Value of an Infrared ISS Pathfinder for CLARREO

An IR Prototype on ISS will provide, not only a tech demo for CLARREO cost and technical risk reduction, but also the start of an accurate climate benchmark, identified as critically important in the 2007 Decadal Survey.

- Measurement Accuracy: ARI has demonstrated the ability to fully meet the CLARREO 0.1 K 3-sigma requirement over the required spectral range, including the Far IR out to 50 microns.
- Sampling Requirements: Needs for an initial benchmark (unbiased temporal and spatial sampling) are met by ISS below 52 degrees latitude.



- Intercalibration: Use of the AIRS (on EOS Aqua) and CrIS (on Suomi NPP) at 0130/1330 local times, IASI (on EUMETSAT MetOp A and B) at 0930/2130 local times, and likely the Chinese sounder on (FY3E) at 0530/1730, provide good sampling to extend the benchmark to high latitudes for all but the Far IR portion of the spectrum.
- Lifetime: No fundamental life limiting components are required for the sensor, and with ISS life extended until 2024 there is a good chance of creating the 5 year record needed for a credible benchmark.

ISS Pathfinder for CLARREO

US President's FY2016 Budget

- Included a Pathfinder mission to kickoff CLARREO!
- "The CLARREO Pathfinder mission will demonstrate essential measurement technologies; validate the high accuracy radiometry required for long-term climate studies in support of other Decadal Survey and land imaging missions; and initiate measurements that will benchmark the shortwave reflectance and infrared climate record."
- "NASA plans to host the two CLARREO Pathfinder instruments, Reflected Solar (RS) and Infrared (IR) spectrometers, on the International Space Station in FY 2019." (budget $77 M)

ISS Pathfinder for CLARREO

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- "NASA pla… …s, Refle… Inter… …M)

Unfortunately, NASA has now decided that both instruments are not affordable at this level of funding and plans to start with the Reflected Solar. Ways to also conduct an Infrared Pathfinder are being sought.

ISS Pathfinder for CLARREO

US President's FY2016 Budget

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- "NASA r… Refle… Inter…

America First, A Budget Blueprint to Make America Great Again (2017): "The Budget terminates four Earth science missions (PACE, OCO-3, DSCOVR Earth-viewing instruments, and CLARREO Pathfinder) and reduces funding for Earth science research grants."

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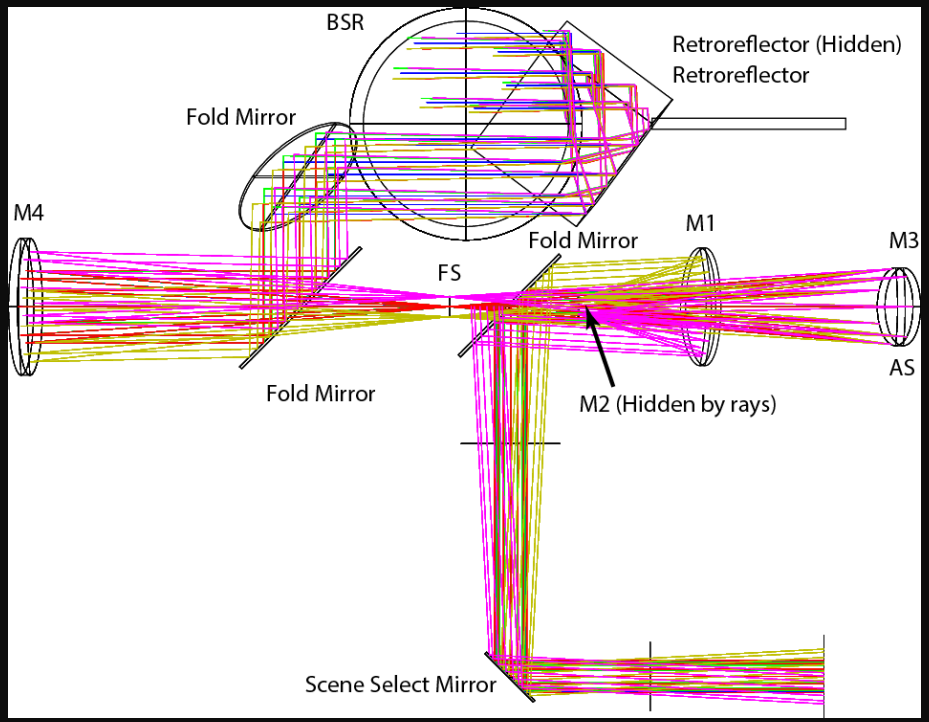
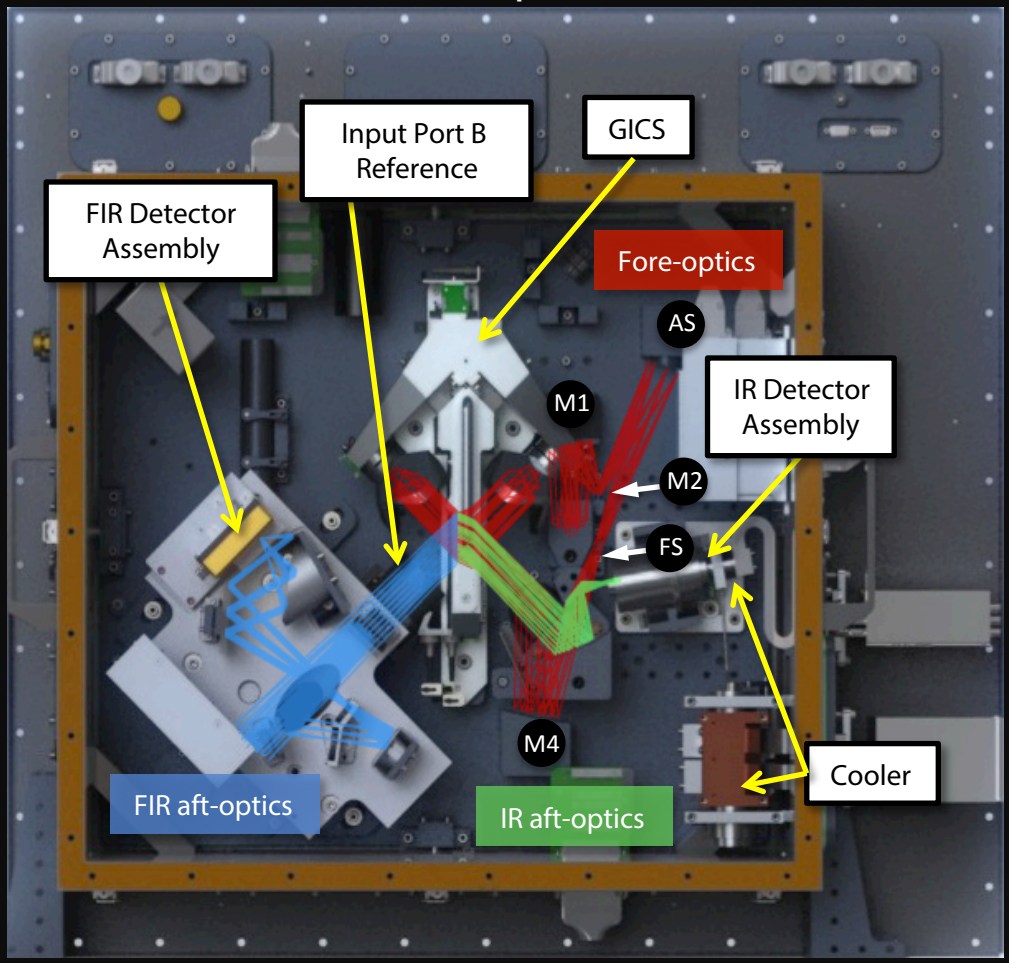
UW-SSEC Absolute Radiance Interferometer (ARI)

Fore-optics ("Side View")

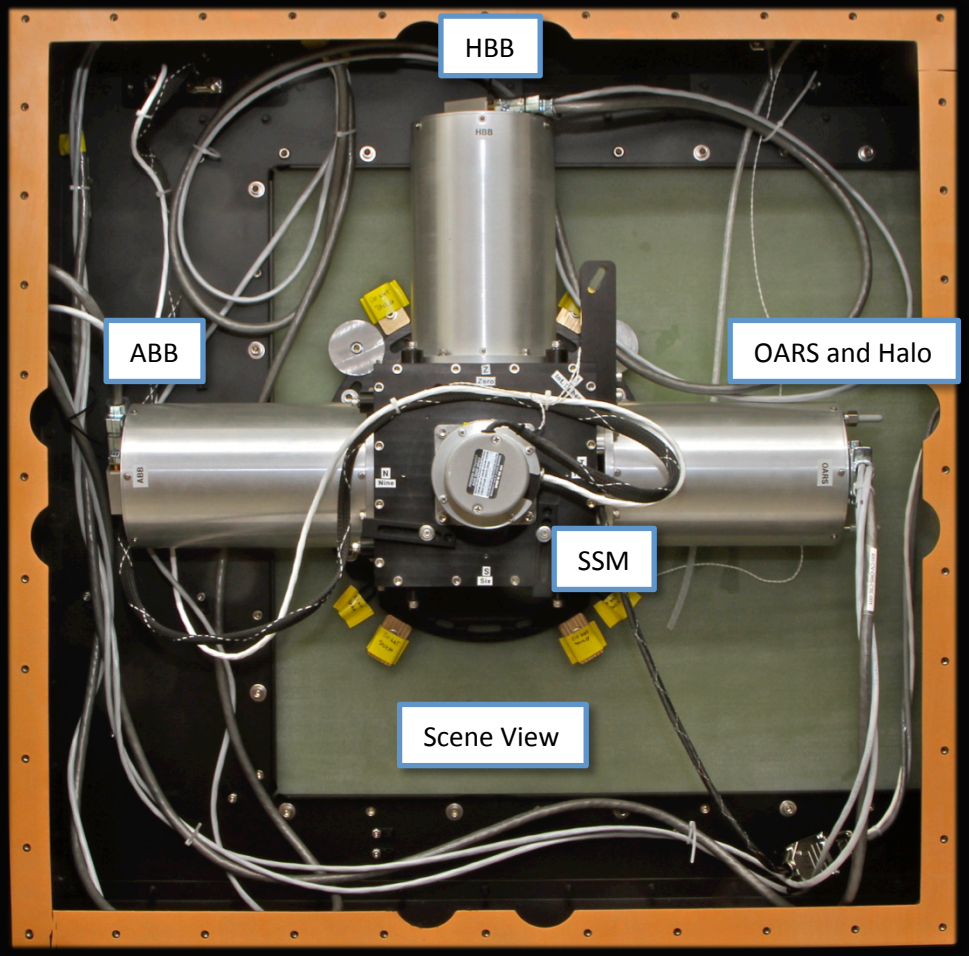


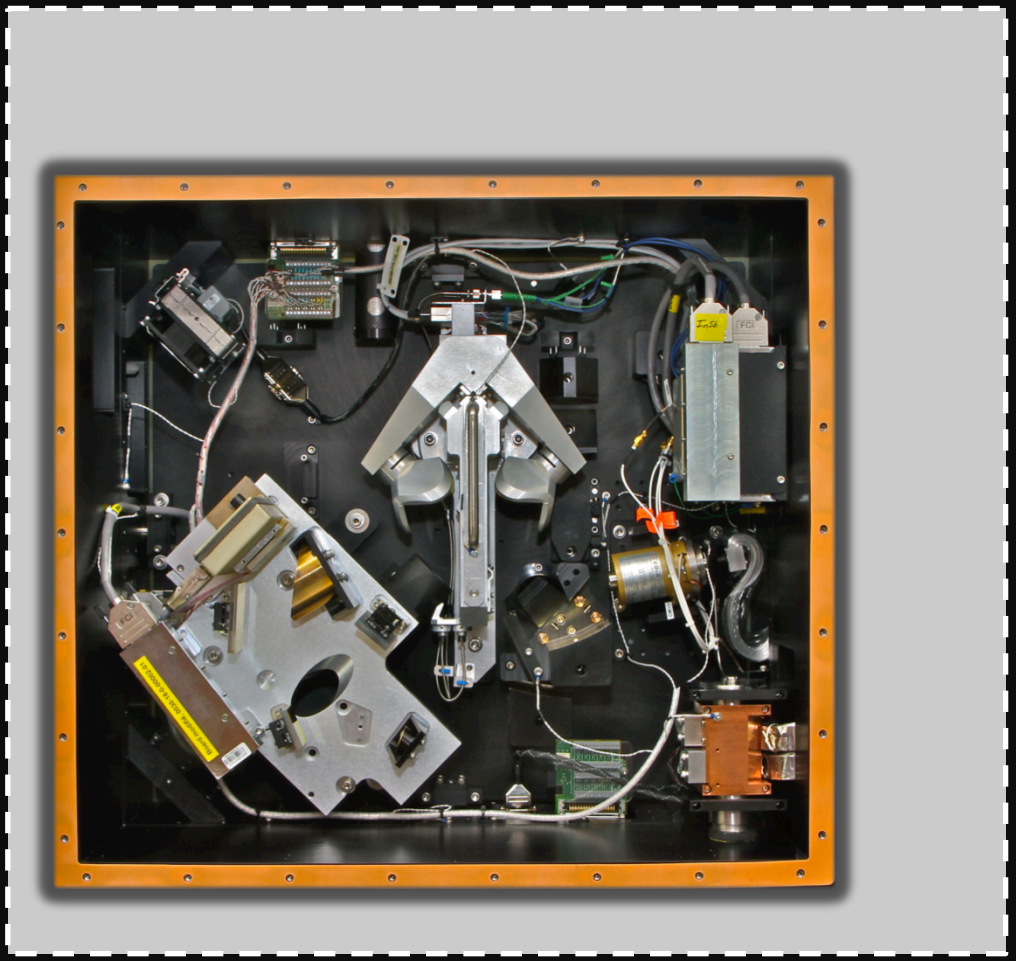
Fore-optics and aft-optics overlaid on solid model ("Top View")



- Pupil at cube-corner apex (and near halo)
- FS image at M2

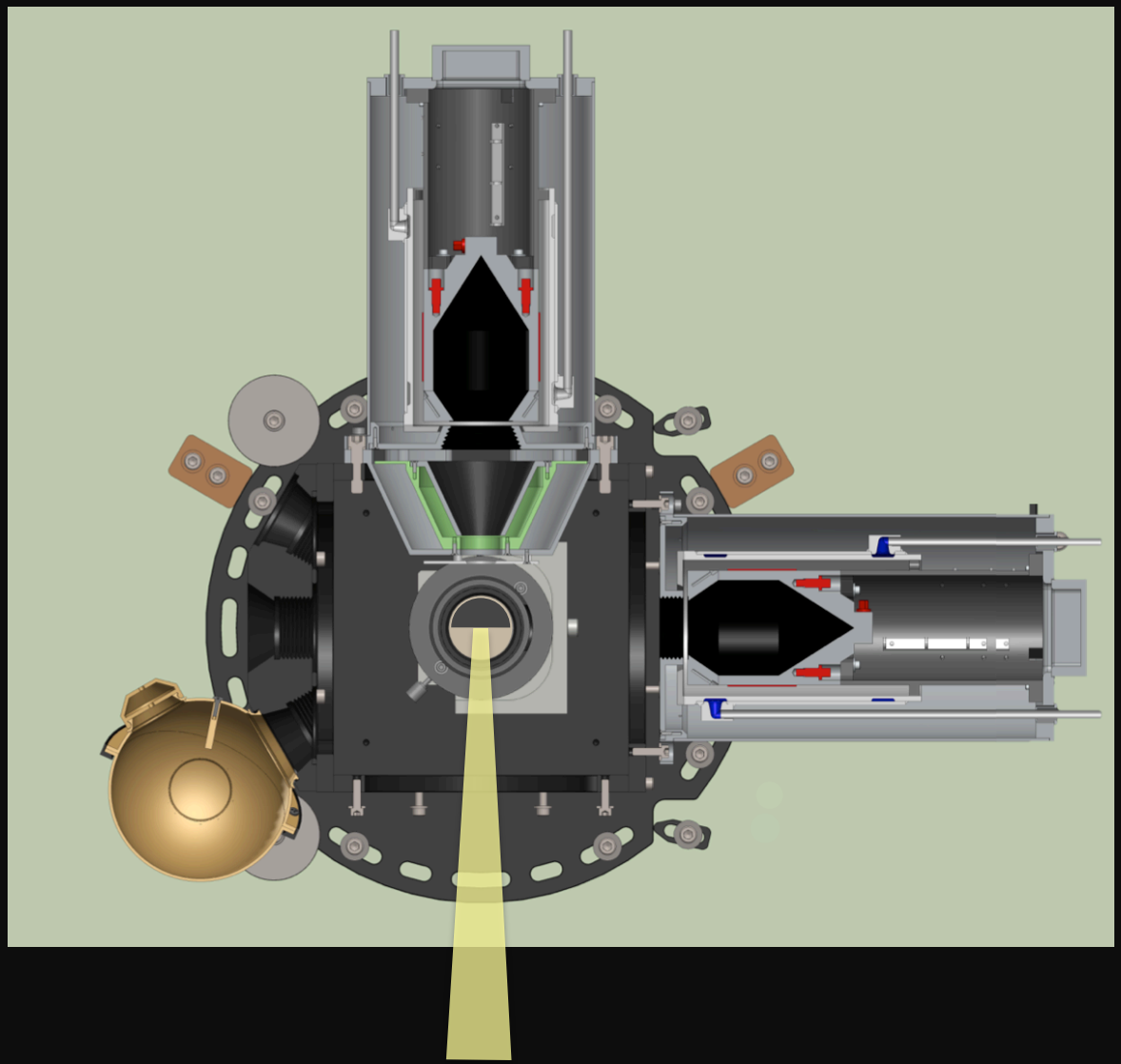
UW-SSEC Absolute Radiance Interferometer (ARI)

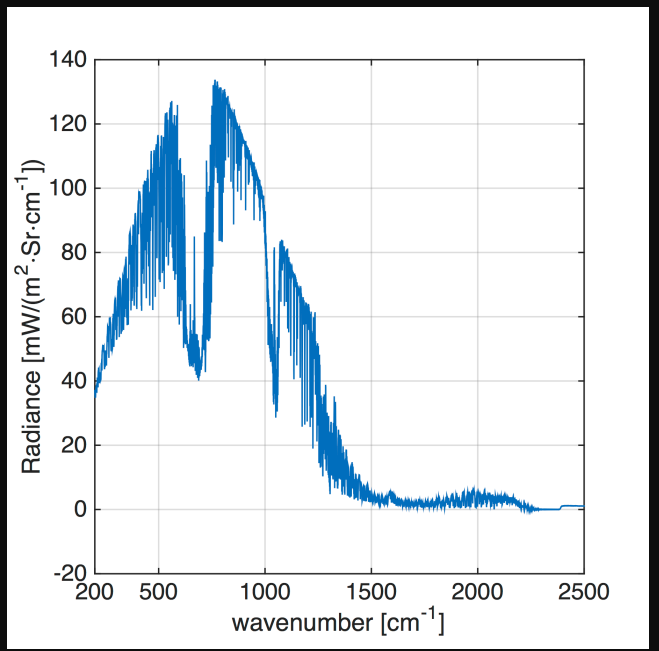




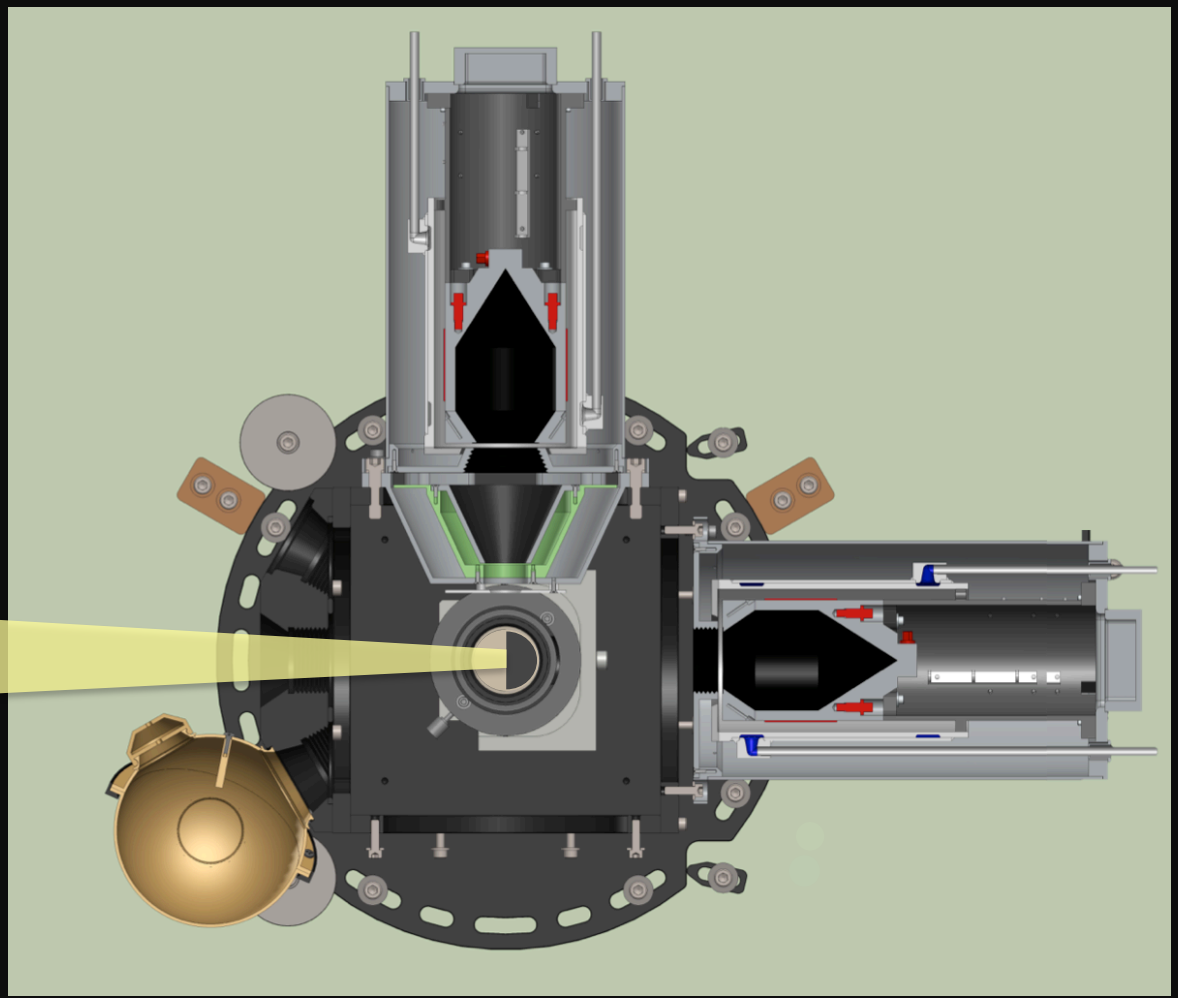
Dashed line indicates OTV enclosure envelope.

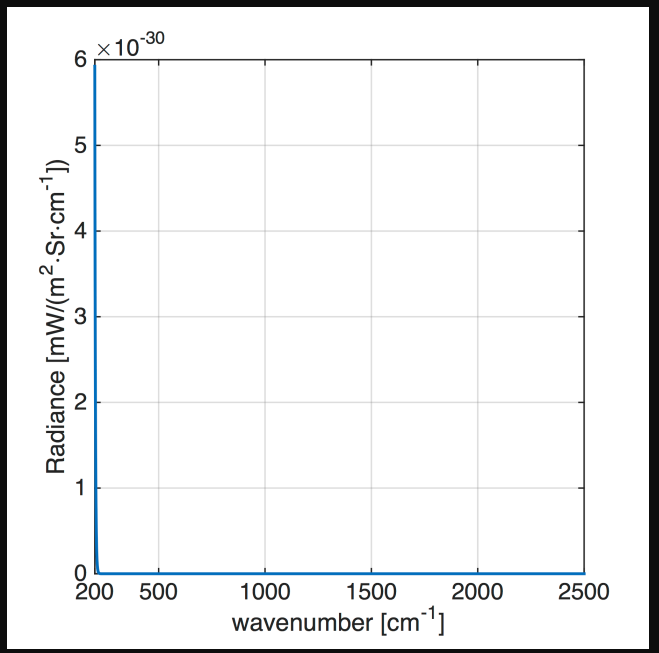
Calibrated FTS: Earth View



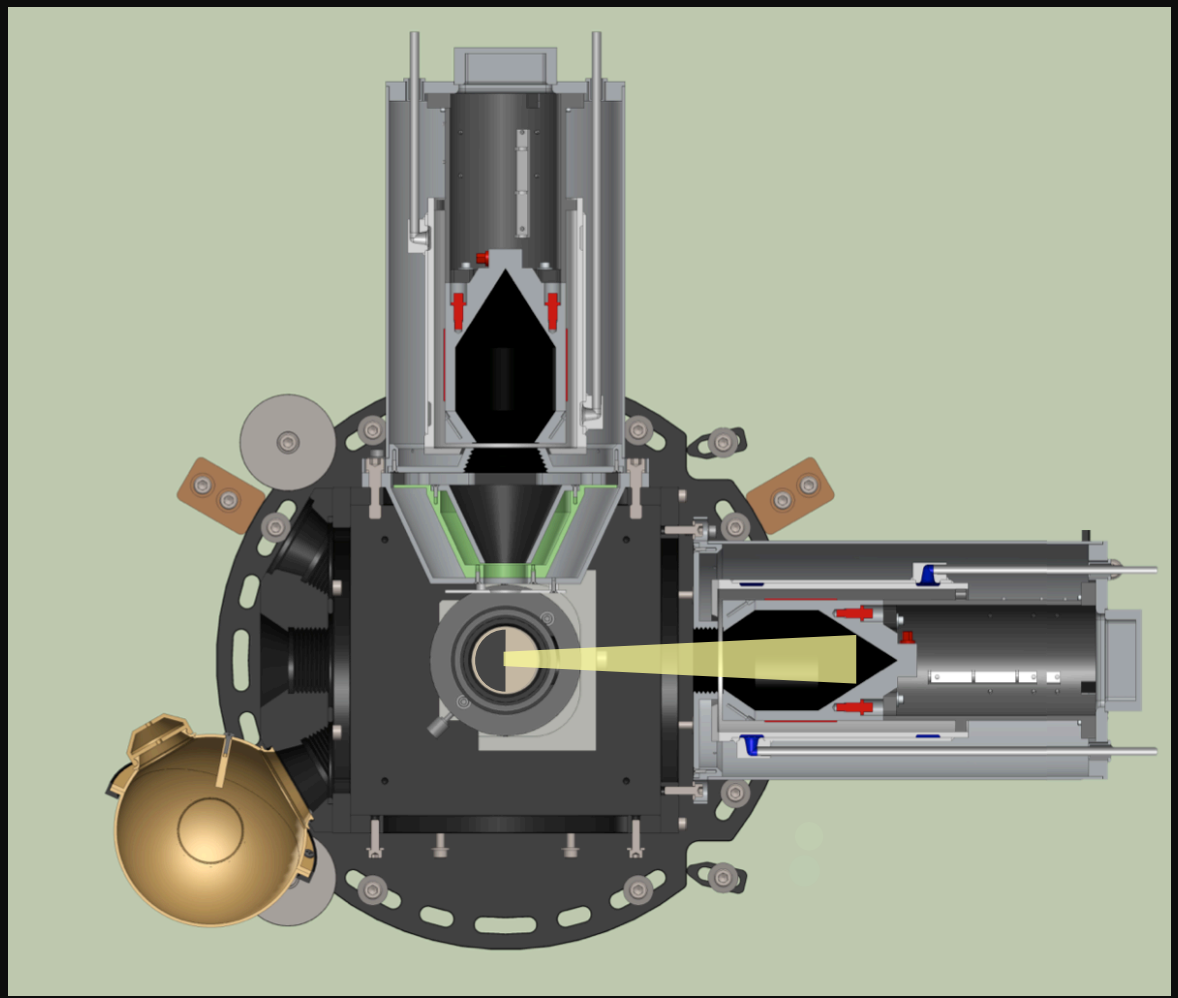


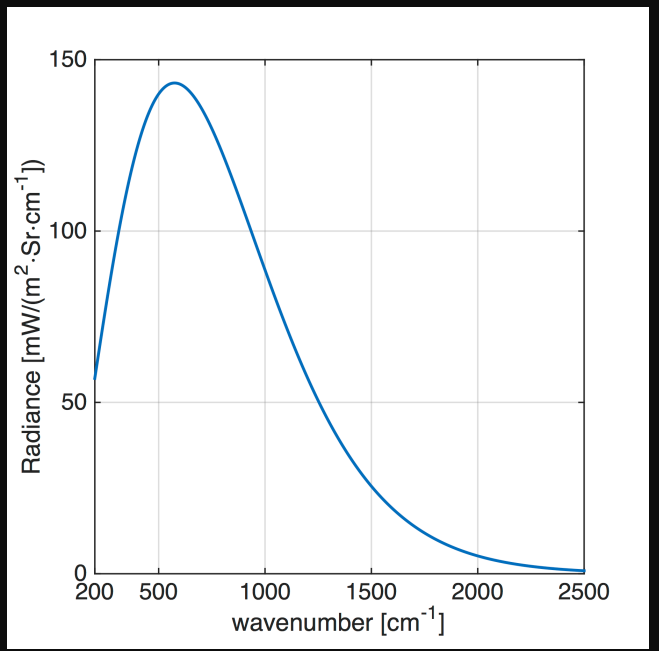
Calibrated FTS: Space Calibration View





Calibrated FTS: Ambient Blackbody (ABB)





On-orbit Verification and Test System (OVTS) Technologies

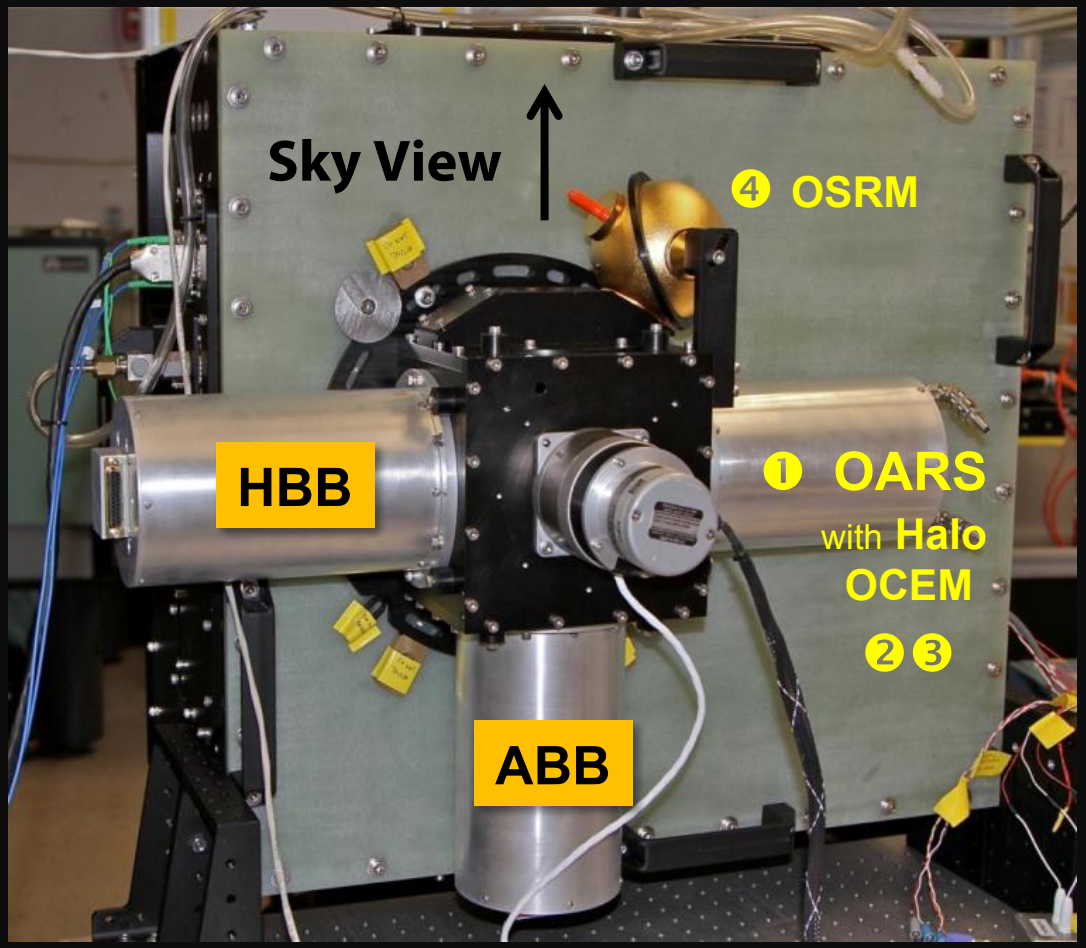
❶ On-orbit Absolute Radiance Standard (OARS) cavity blackbody using three miniature phase change cells to establish the temperature scale from -40, to +30 C to better than 10 mK

❷ On-orbit Cavity Emissivity Module (OCEM) using Heated Halo source allowing 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 & Cal BB to better than 0.001

❹ On-orbit Spectral Response Module* (OSRM) QCL used to measure the ILS

OVTS Sources

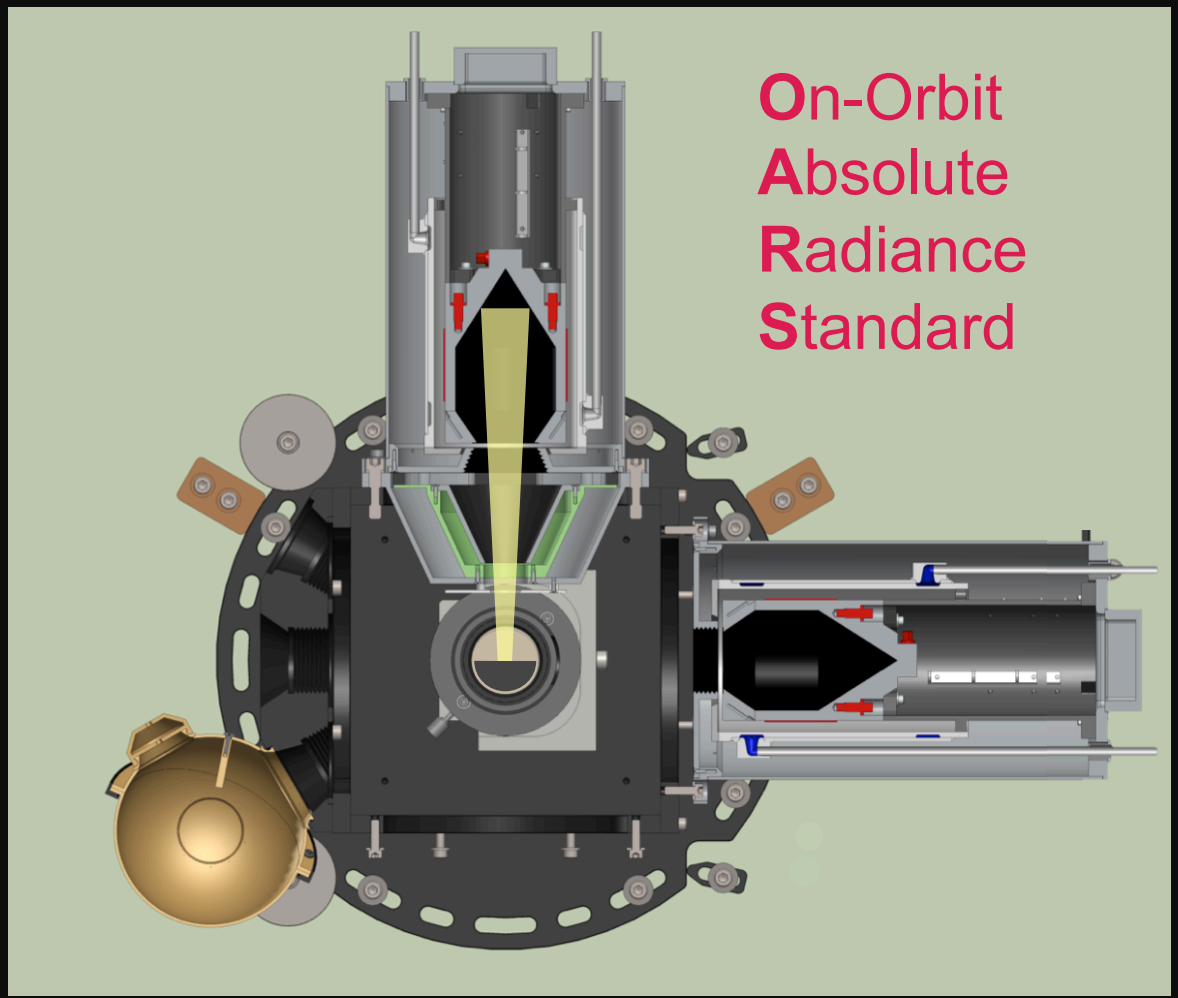


Calibrated FTS Blackbodies (HBB & ABB)

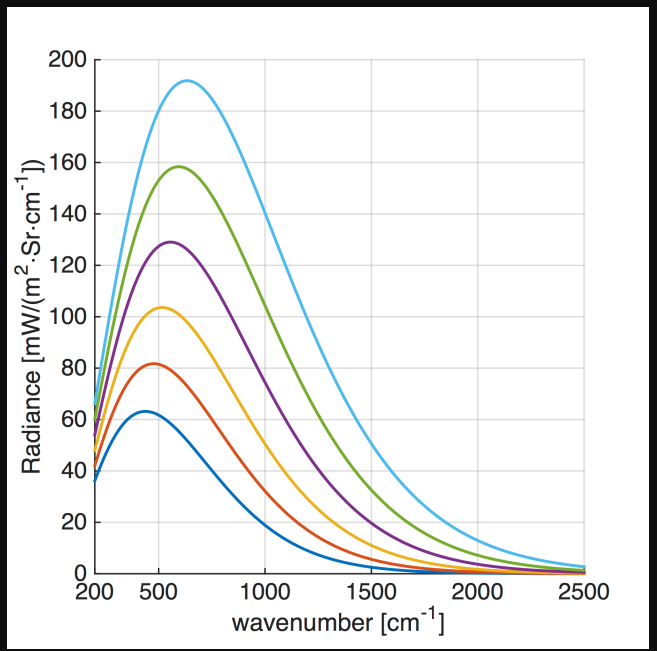
All components at flight scale

** QCL functions demonstrated by Harvard separately*

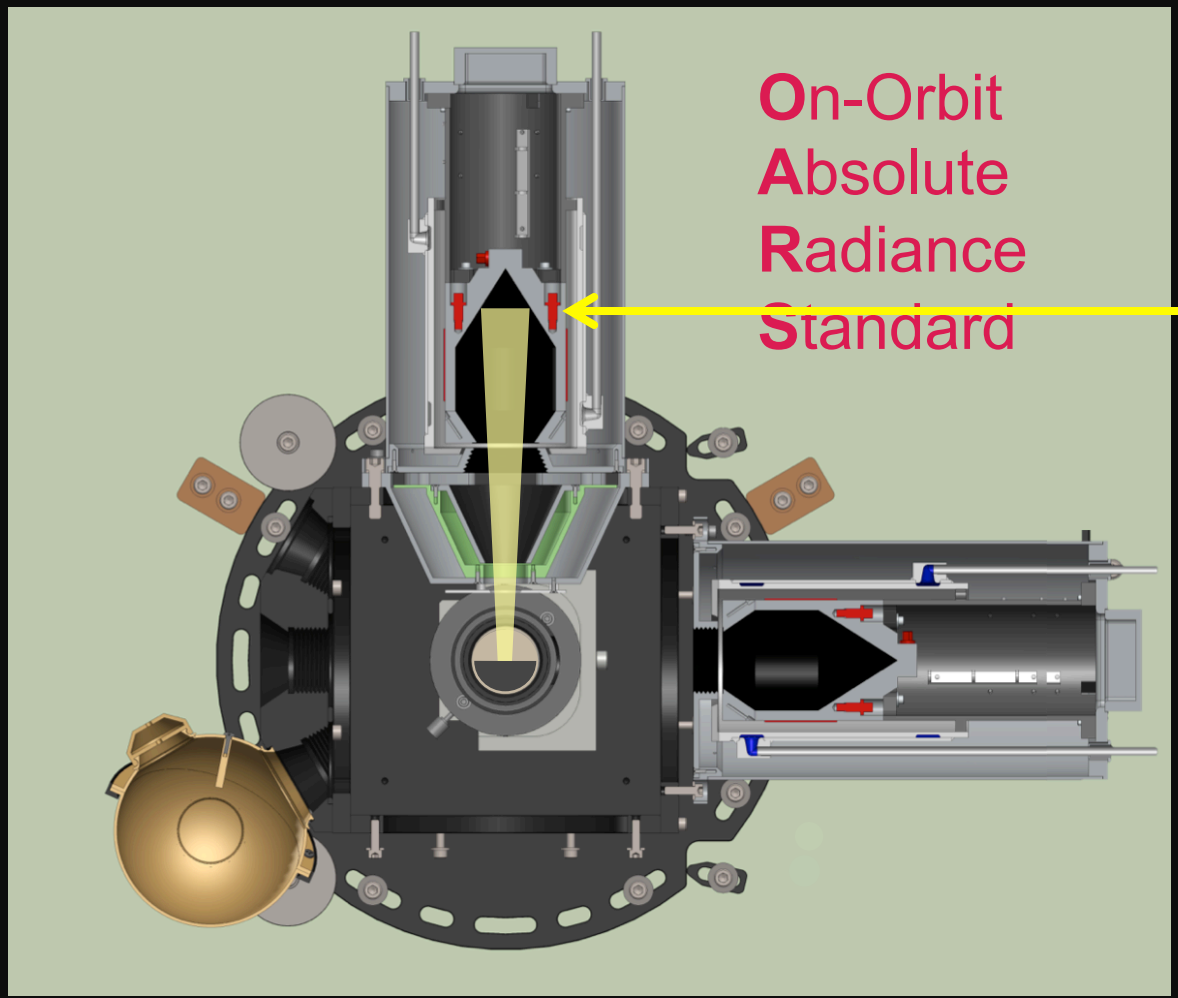
OVTS: View of the Variable Temperature OARS



The OARS is controllable to a wide range of temperatures to provide an “absolute radiance” and assess instrument linearity

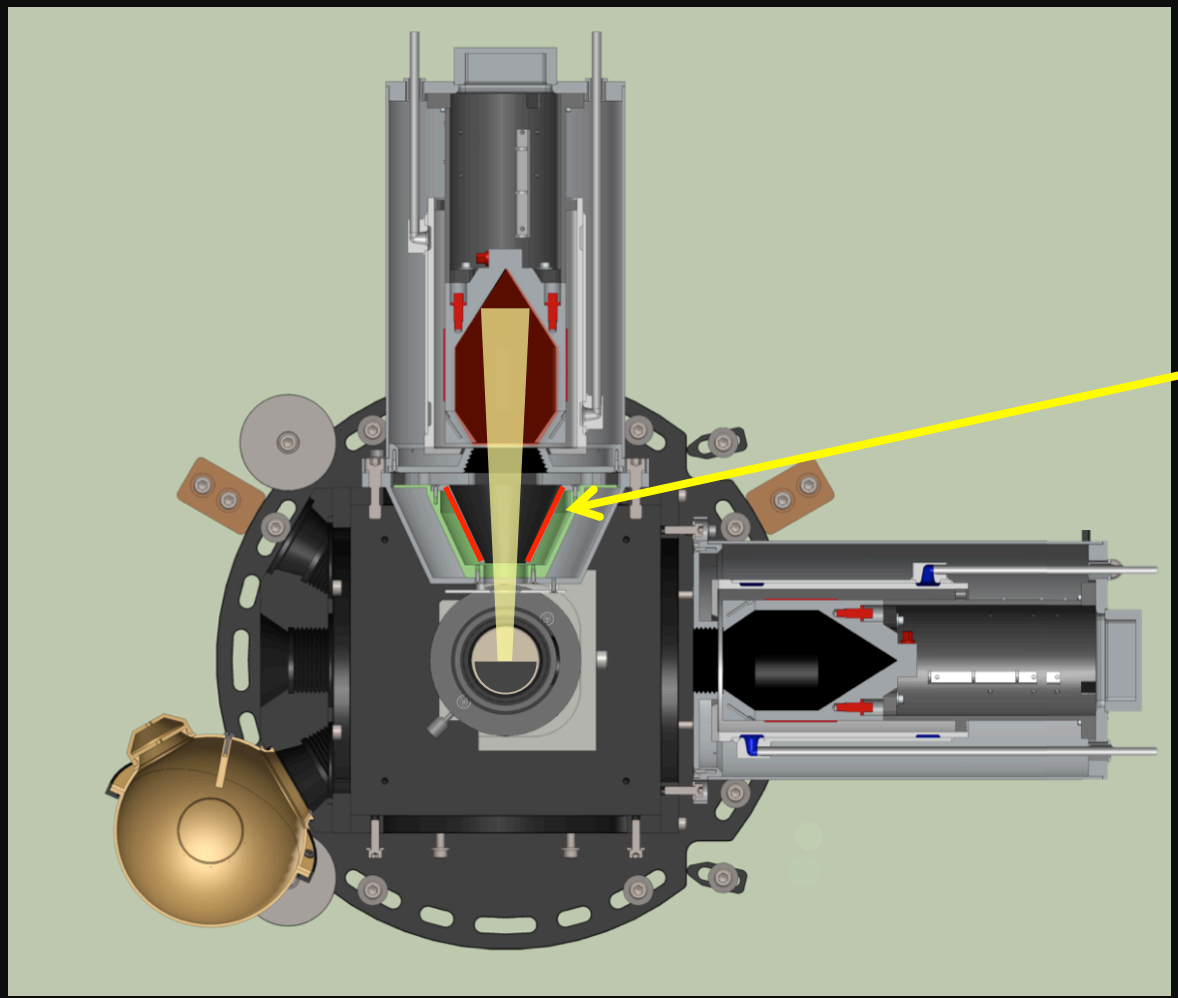


OVTS: View of the Variable Temperature OARS



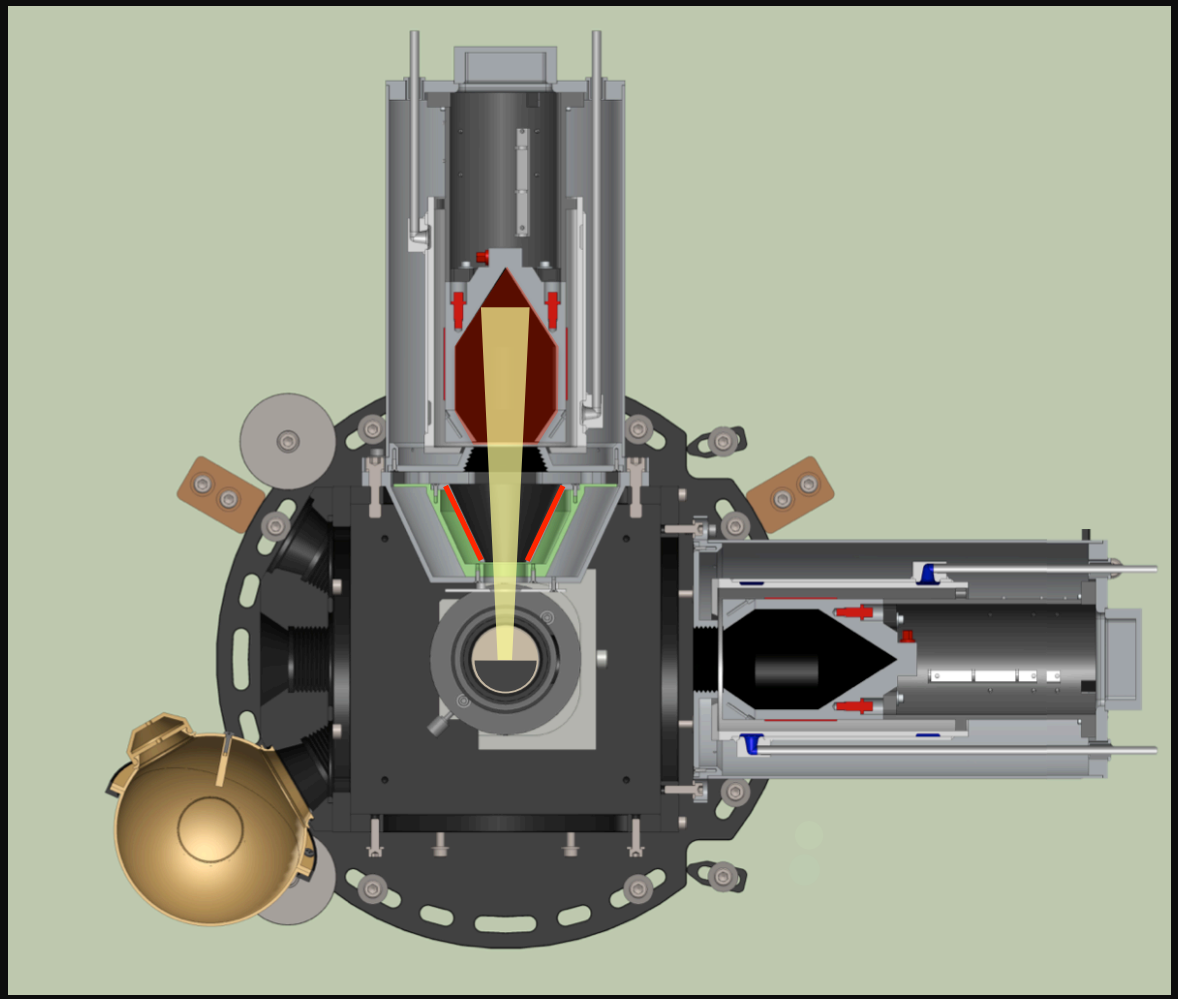
The OARS has 3 different miniature phase change cells containing Ga, H_2O, and Hg, used for periodic temperature calibration at 303.15, 273.15, and 235.15K

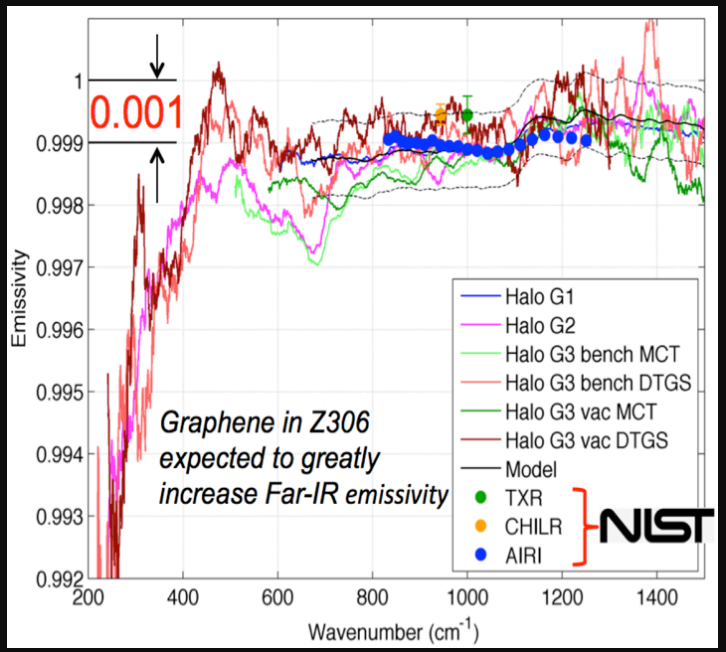
OVTS: OARS Spectral Emissivity – Heated Halo



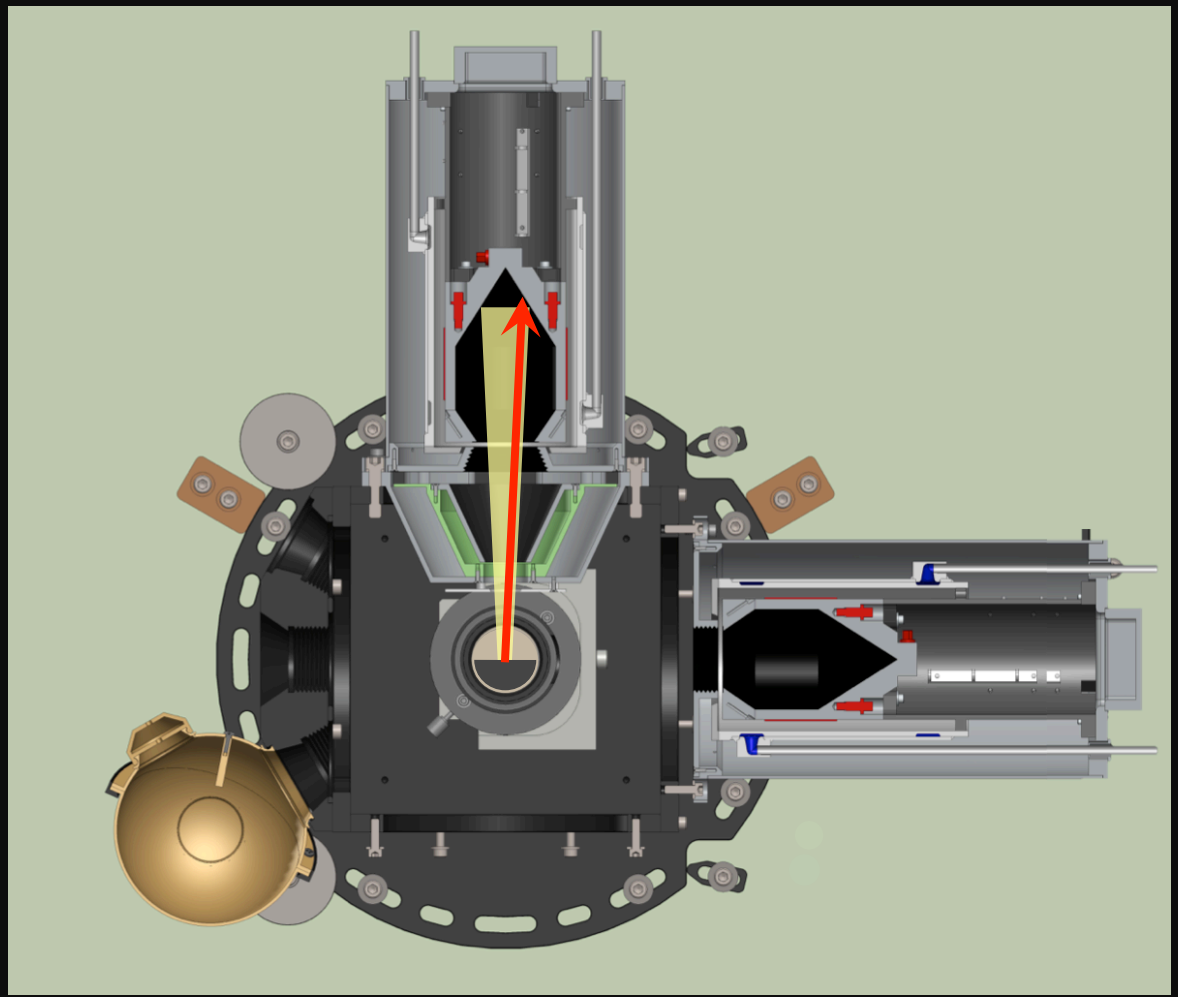
The Heated Halo is used periodically for measuring the blackbody cavity spectral emissivity.

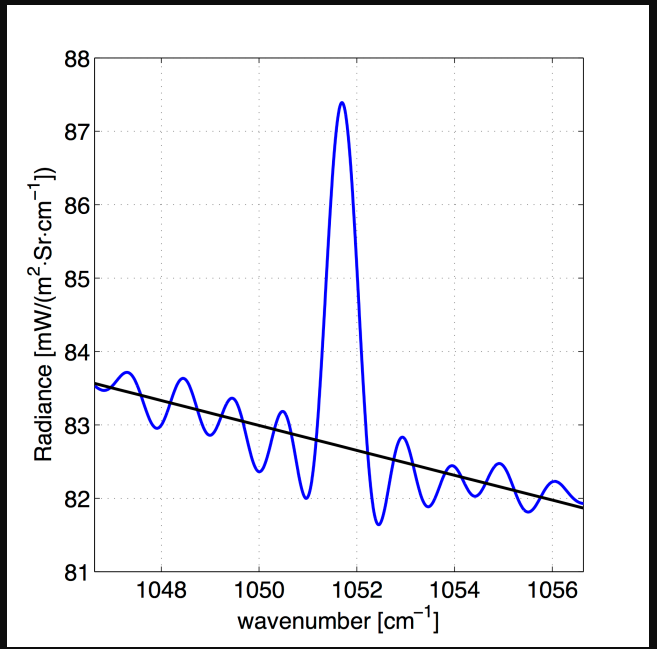
OVTS: OARS Spectral Emissivity – Heated Halo



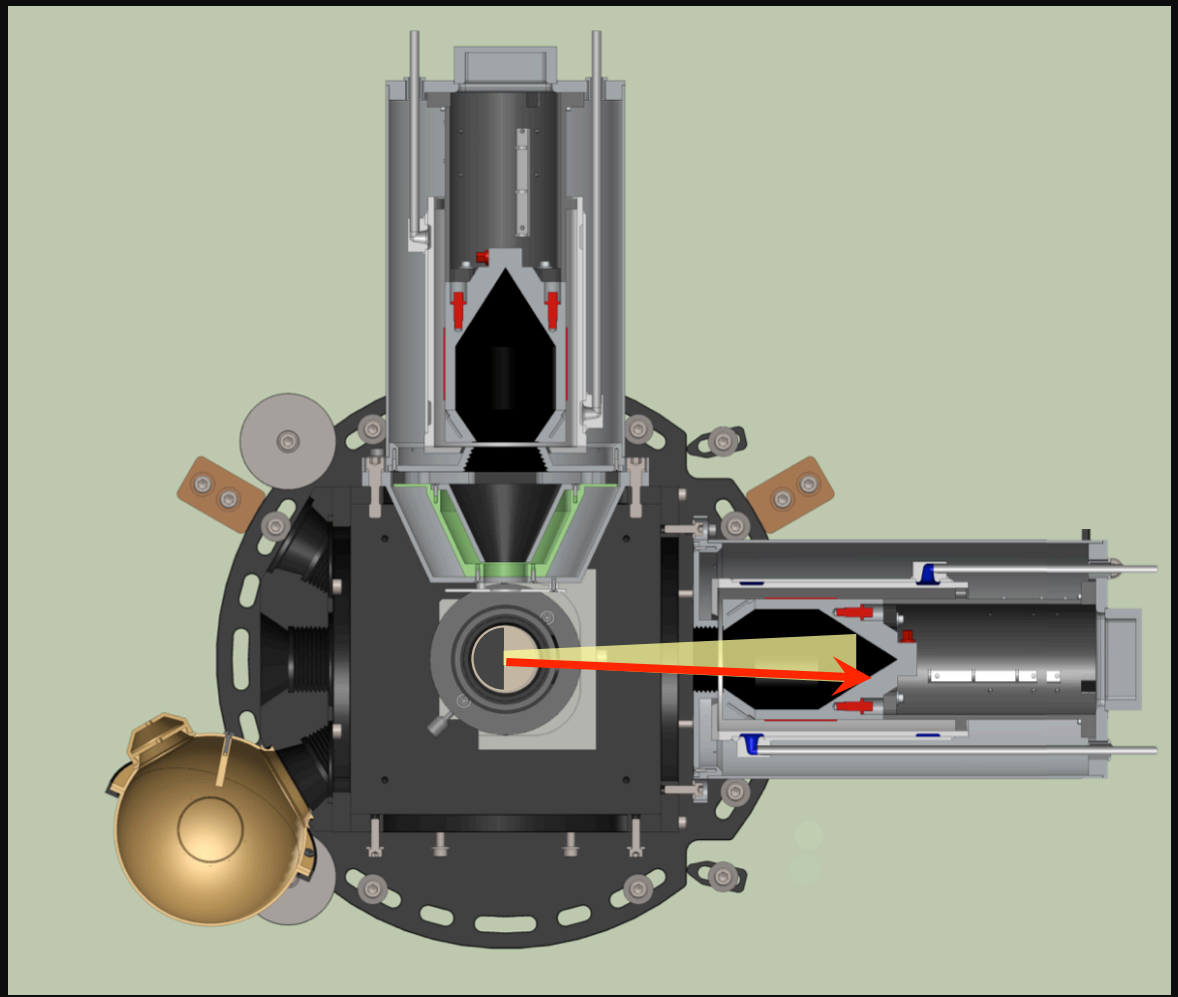


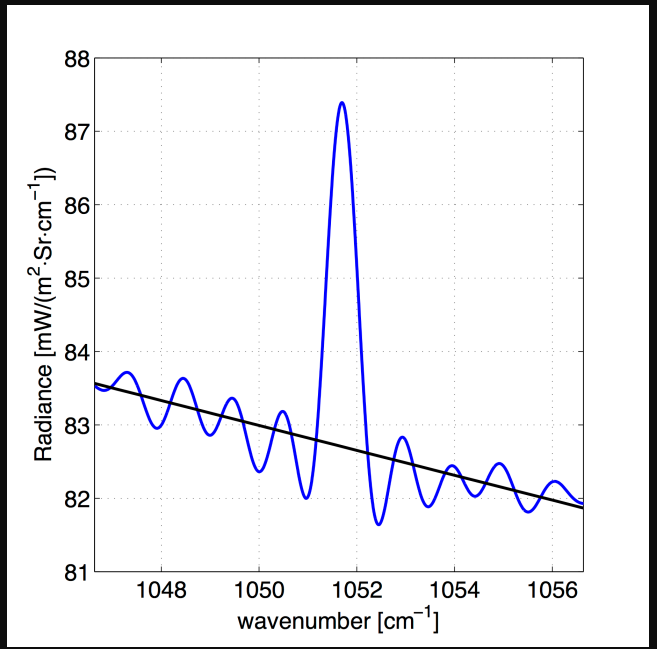
OVTS: OARS Emissivity – QCL



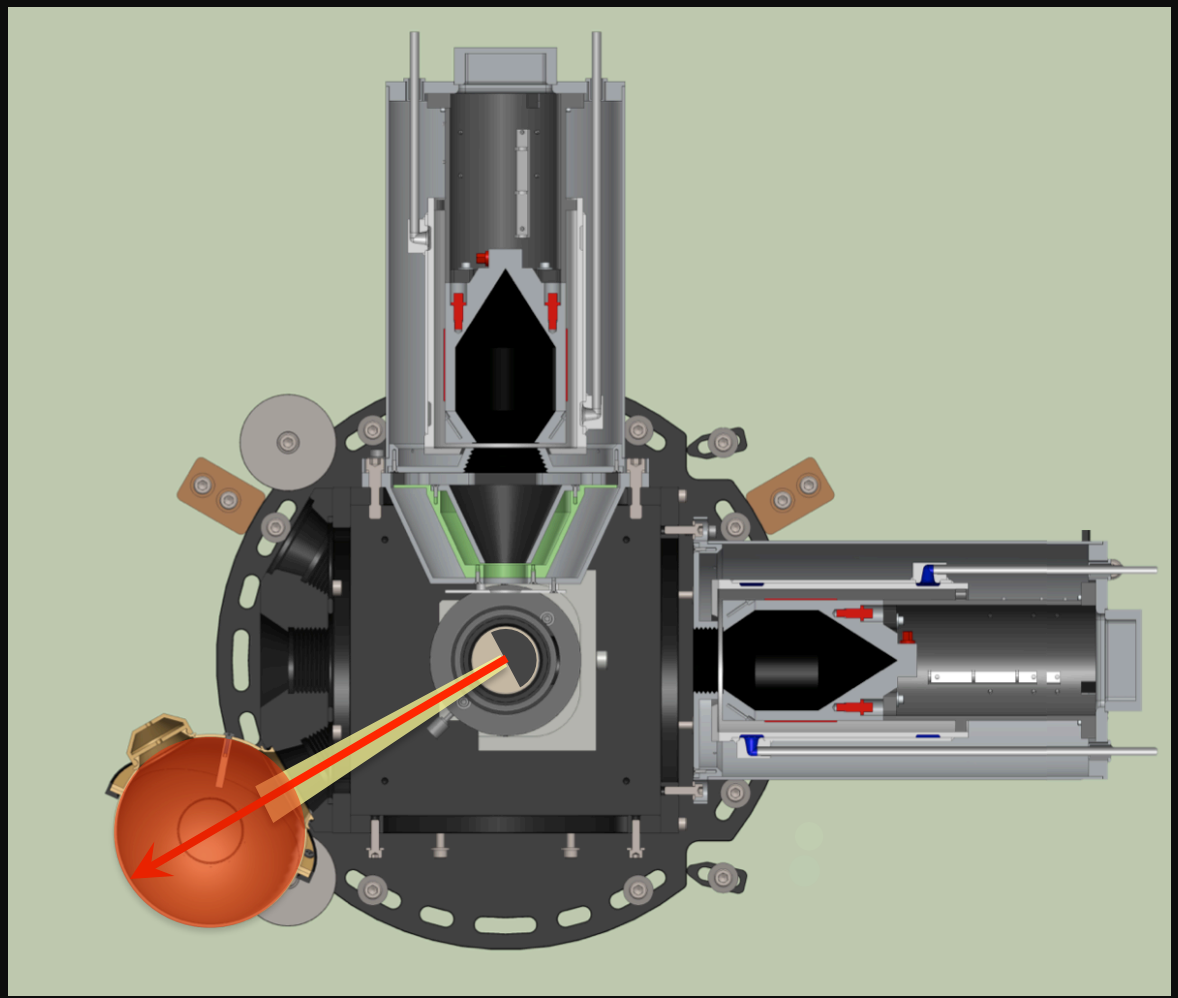


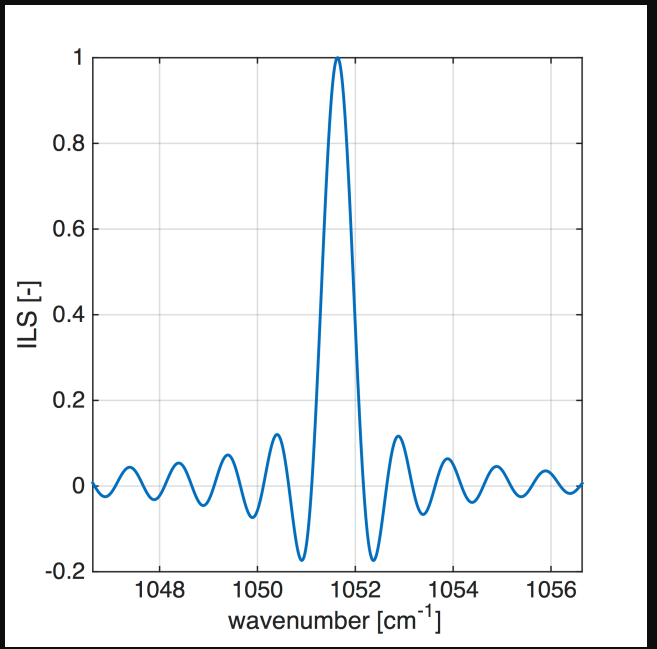
OVTS: ABB Emissivity – QCL



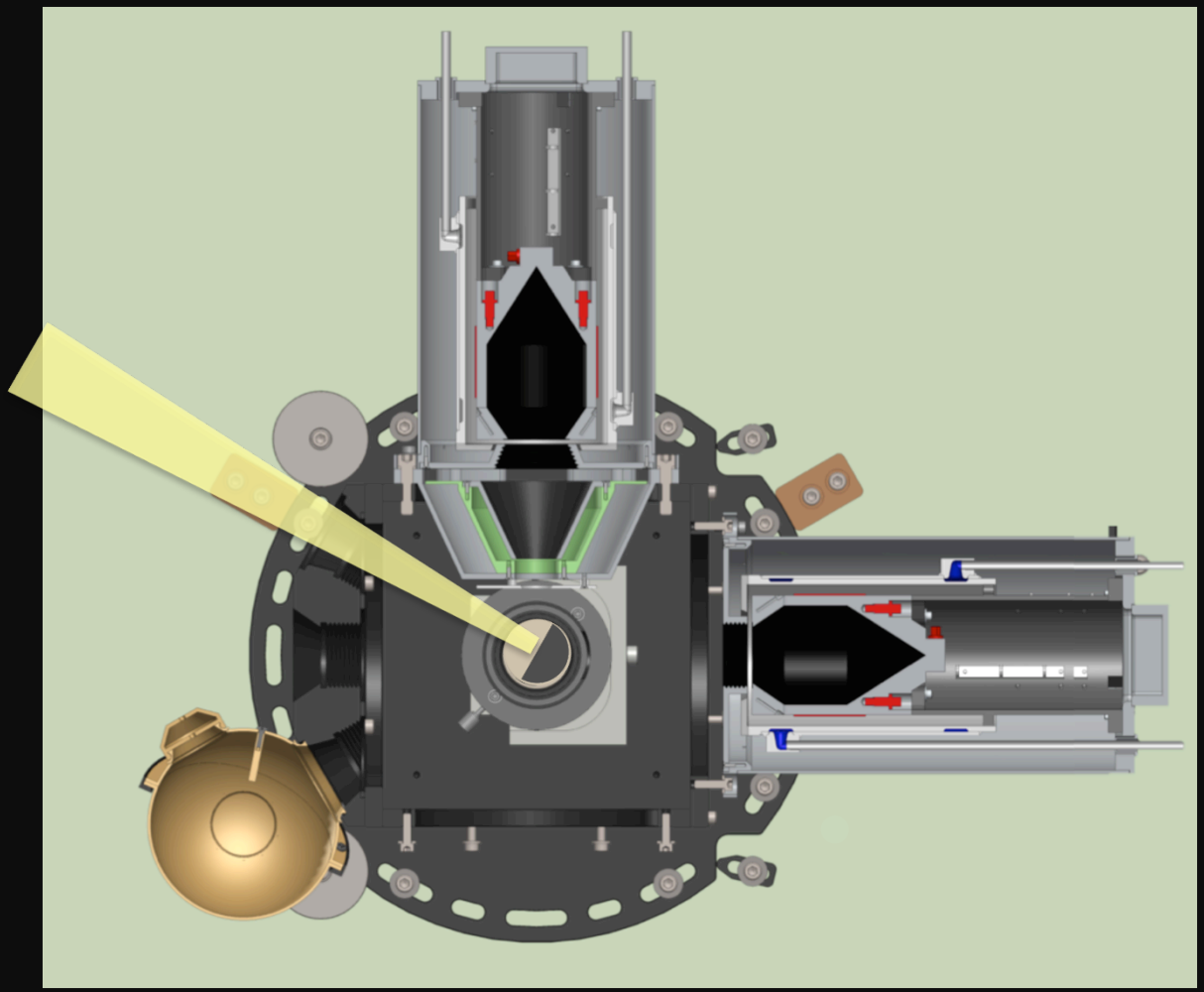


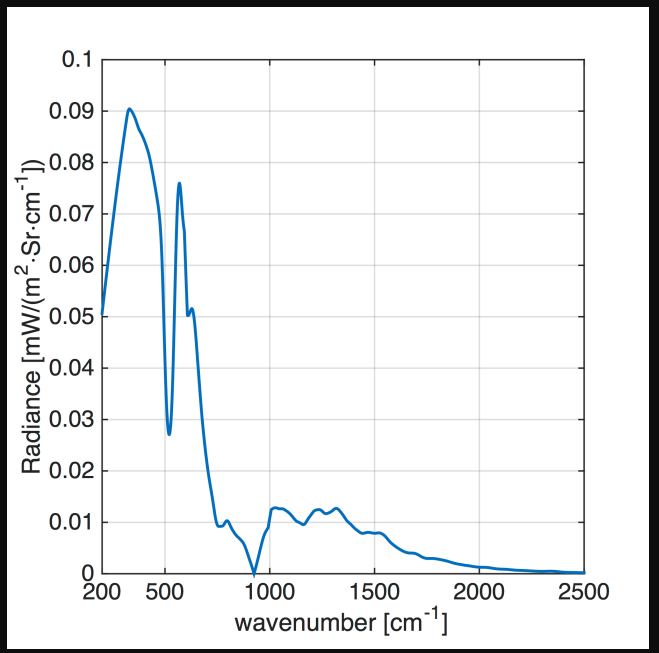
OVTS: Instrument Line Shape - QCL





OVTS: Space-2 View
Used to characterize polarization*





*Instrument optical design provides immunity to polarization for Earth, OARS, Space 1, and ABB Views

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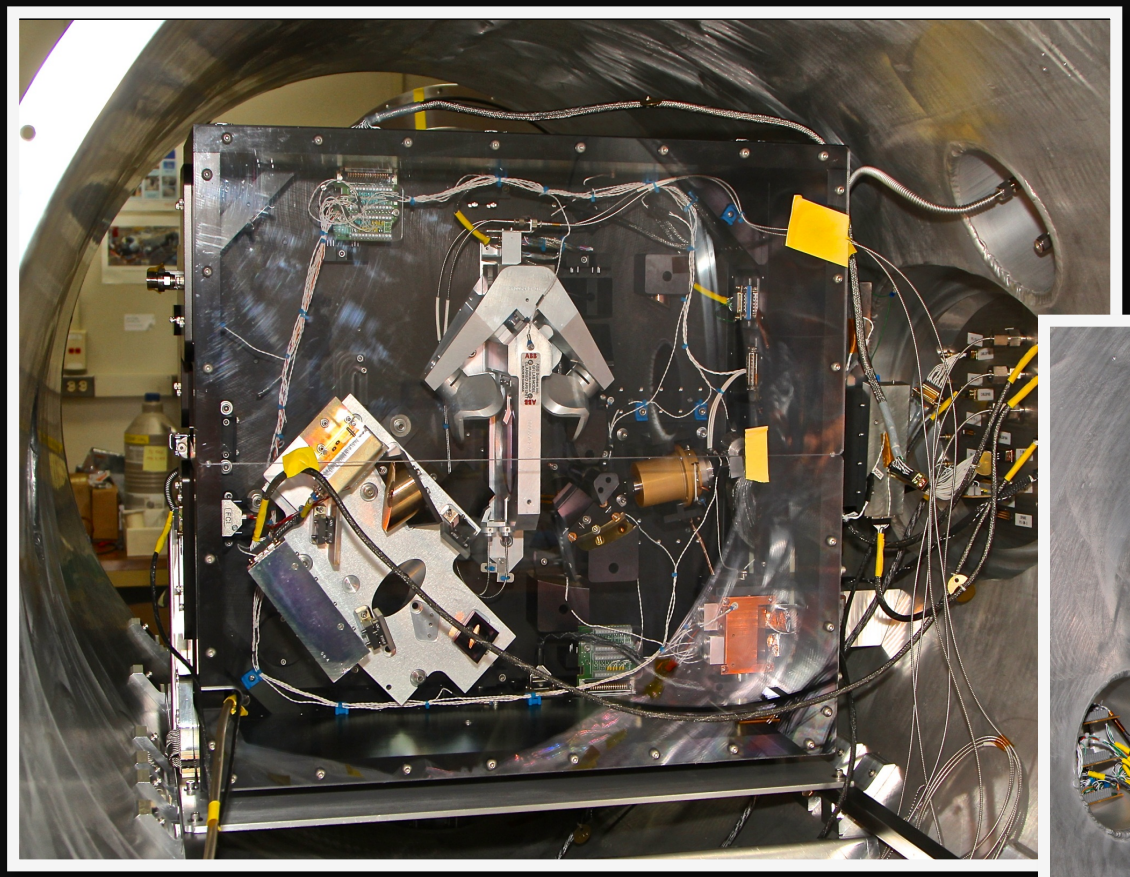
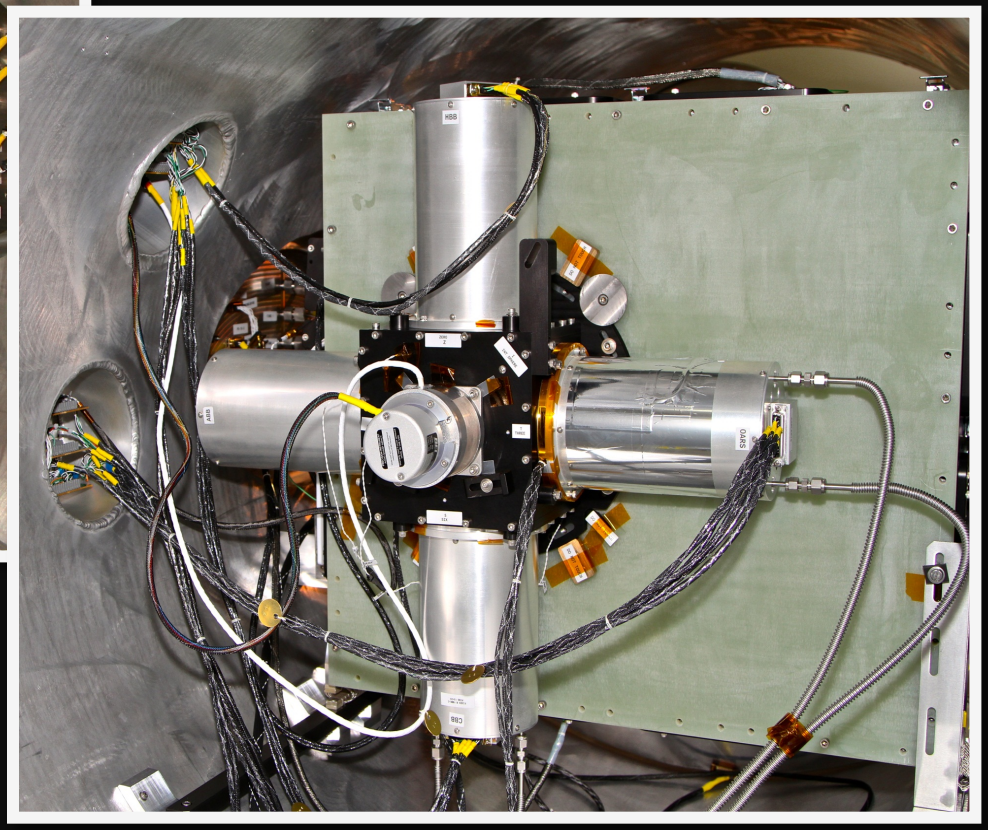
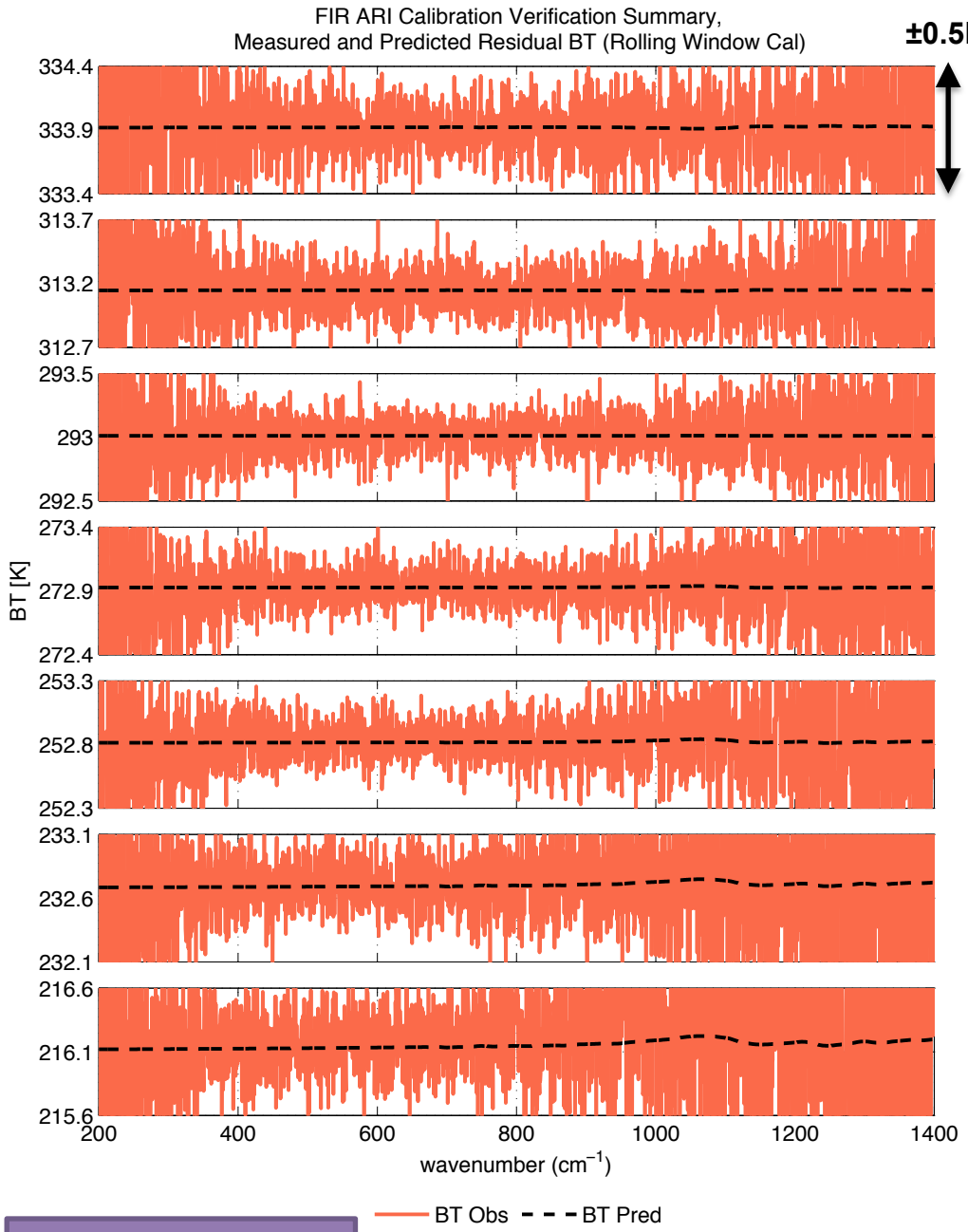
- Standard metrology methods (JCGM 100:2008. GUM) used to assess radiometric uncertainty assessment for instrument calibration and on-orbit calibration validation systems for laboratory, vacuum, and expected on-orbit environments
- The Instrument was tested end-to-end under vacuum and in the presence of the expected on-orbit thermal environment, bringing the TRL to 6.
- The ability to achieve the 0.1 K (99% confidence, k = 3) on-orbit measurement accuracy required for climate benchmark measurements in the infrared and far infrared was *successfully demonstrated*
- Extensive characterization of the instrument performance has been completed (nonlinearity, polarization, low SNR calibration effects, miniature phase change cell performance, …)
- Successful demonstration of the enabling technologies for the CLARREO IR

Vacuum Testing: Demonstration of Required Radiometric Accuracy

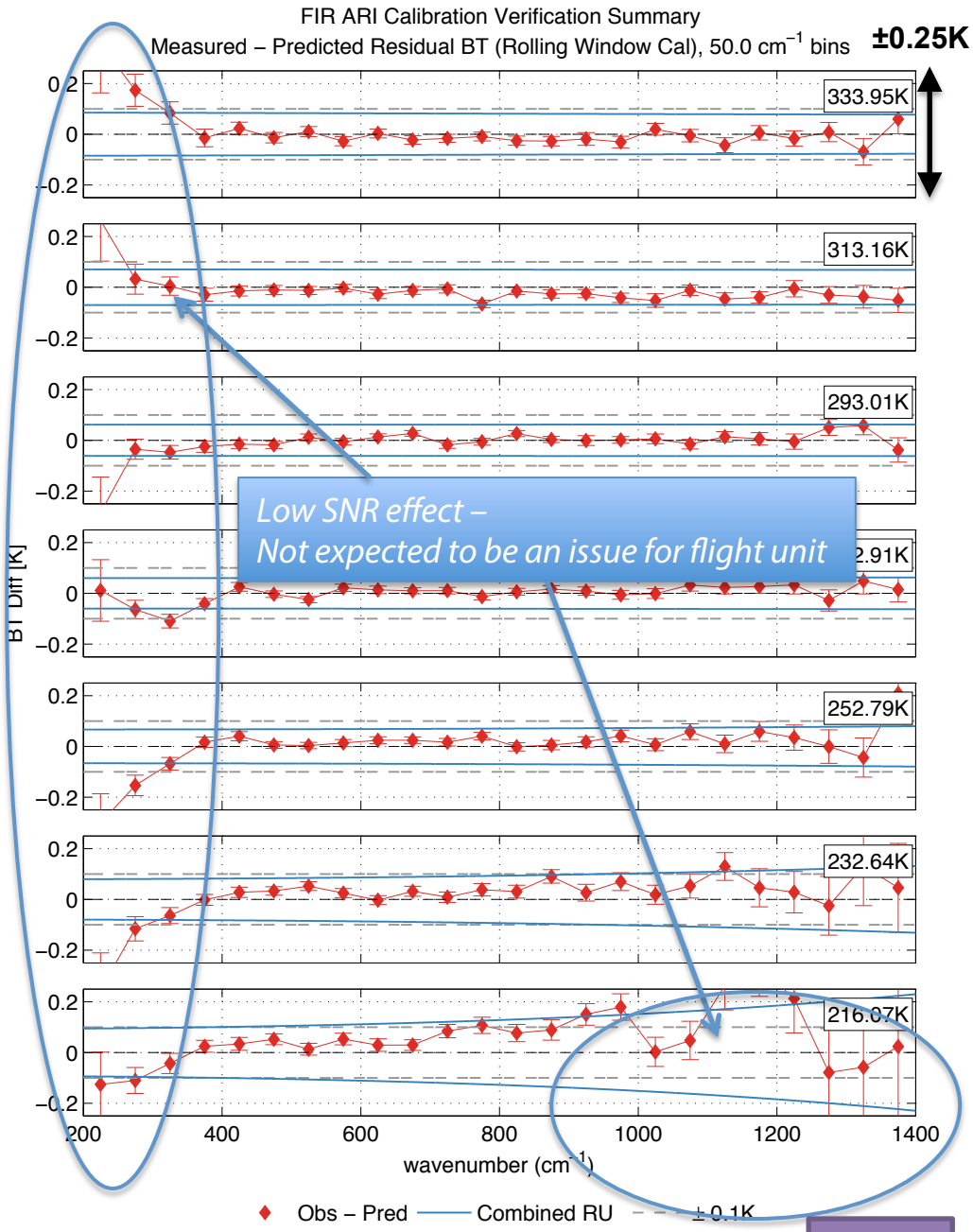




Demonstration of Required Radiometric Accuracy, DTGS

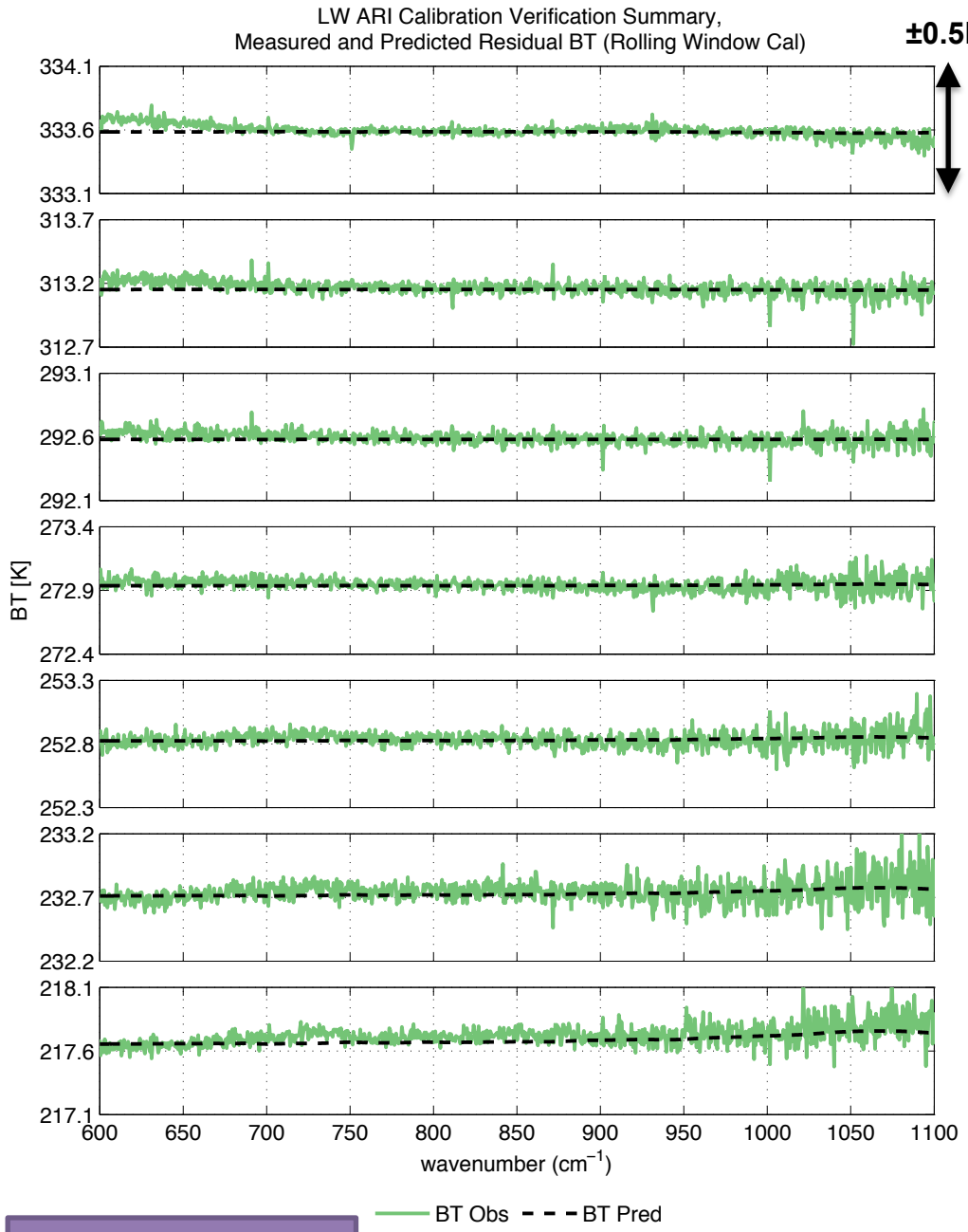


Observed and Predicted

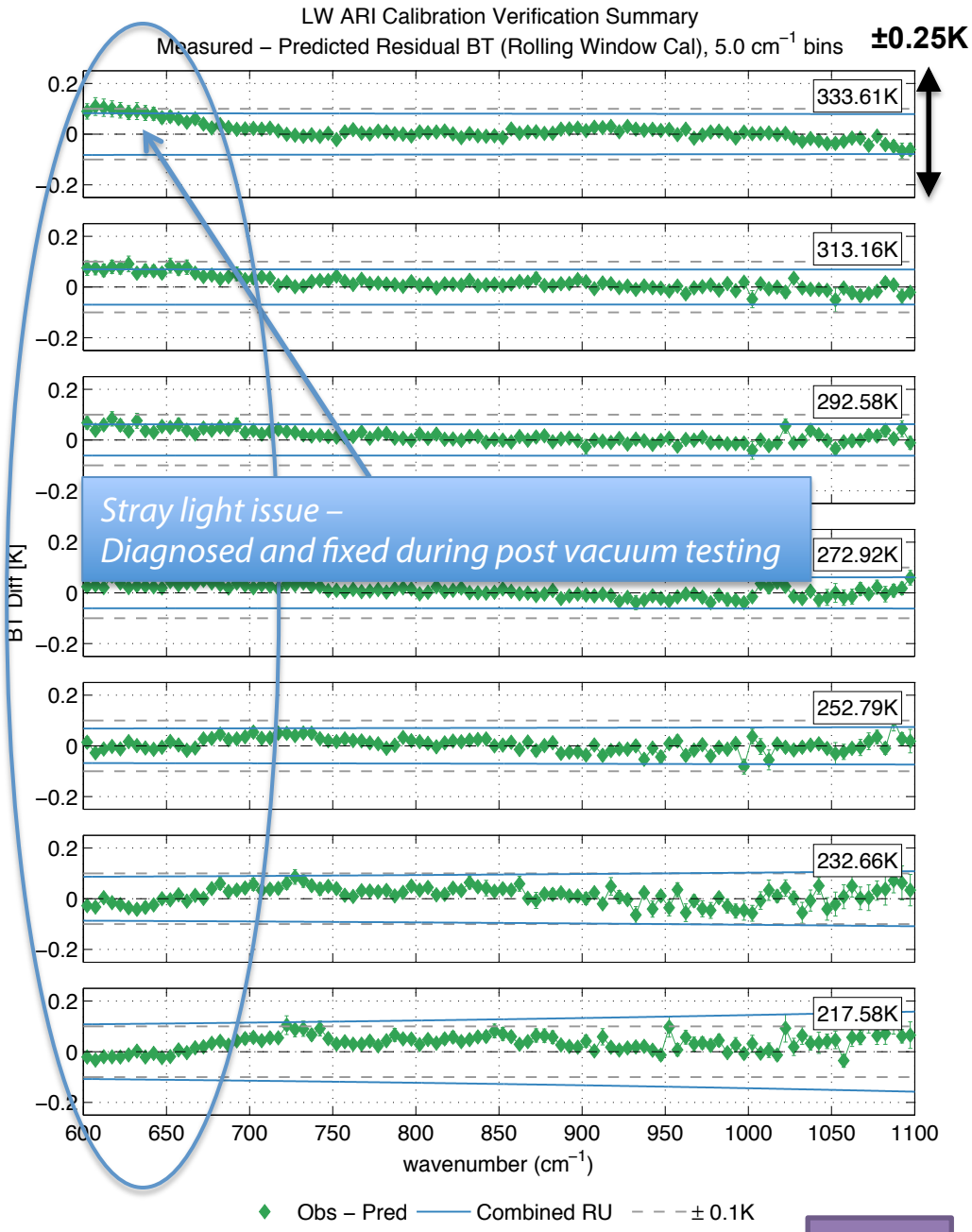


Residual

Demonstration of Required Radiometric Accuracy, LW MCT

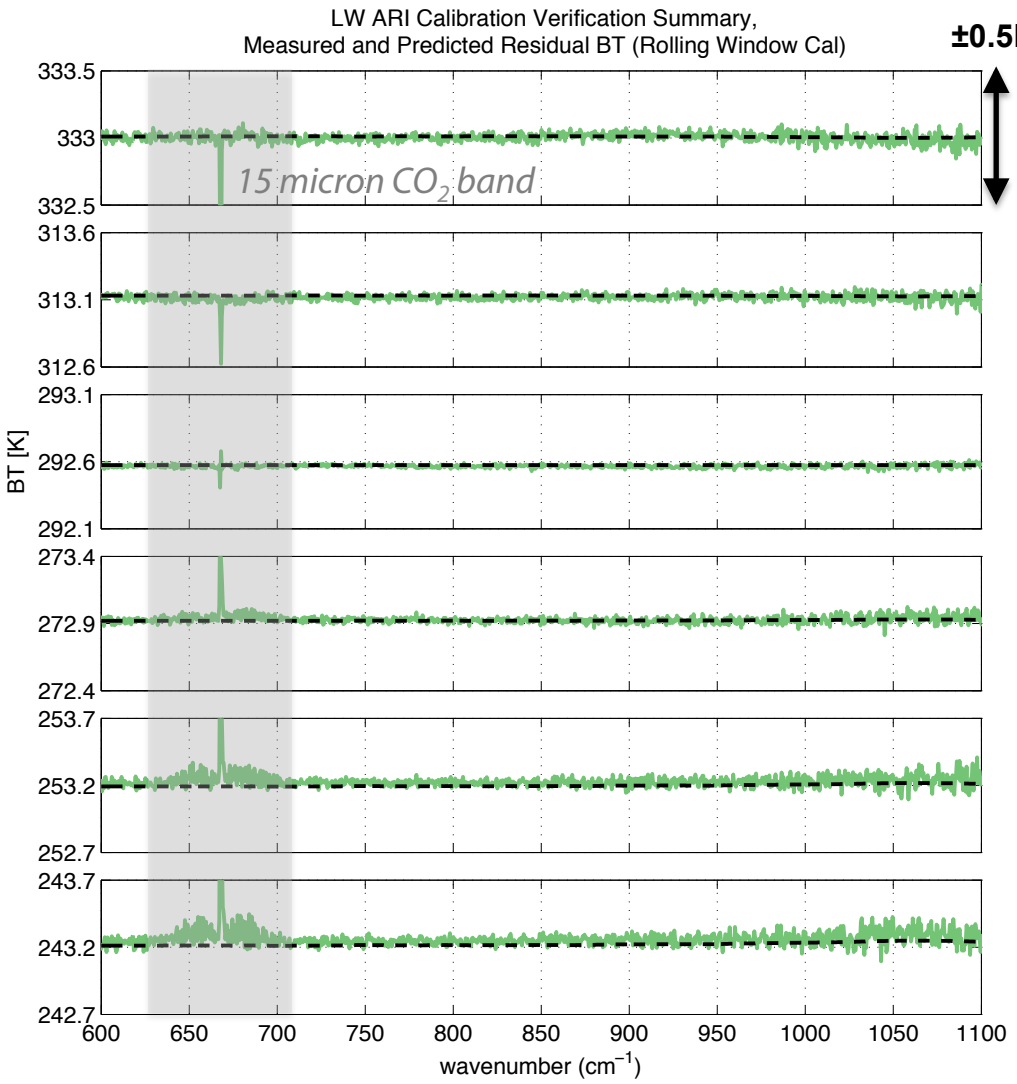


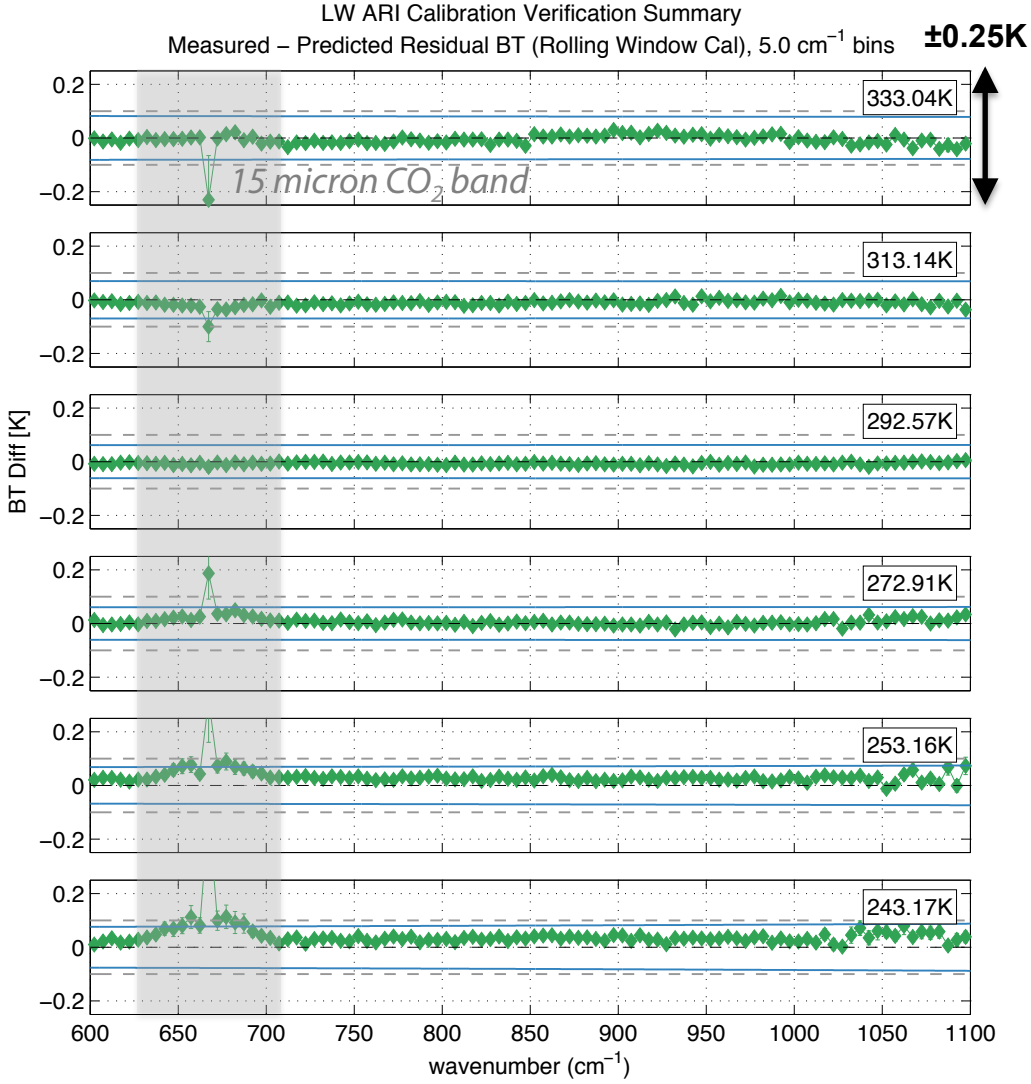
Observed and Predicted



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 testing*

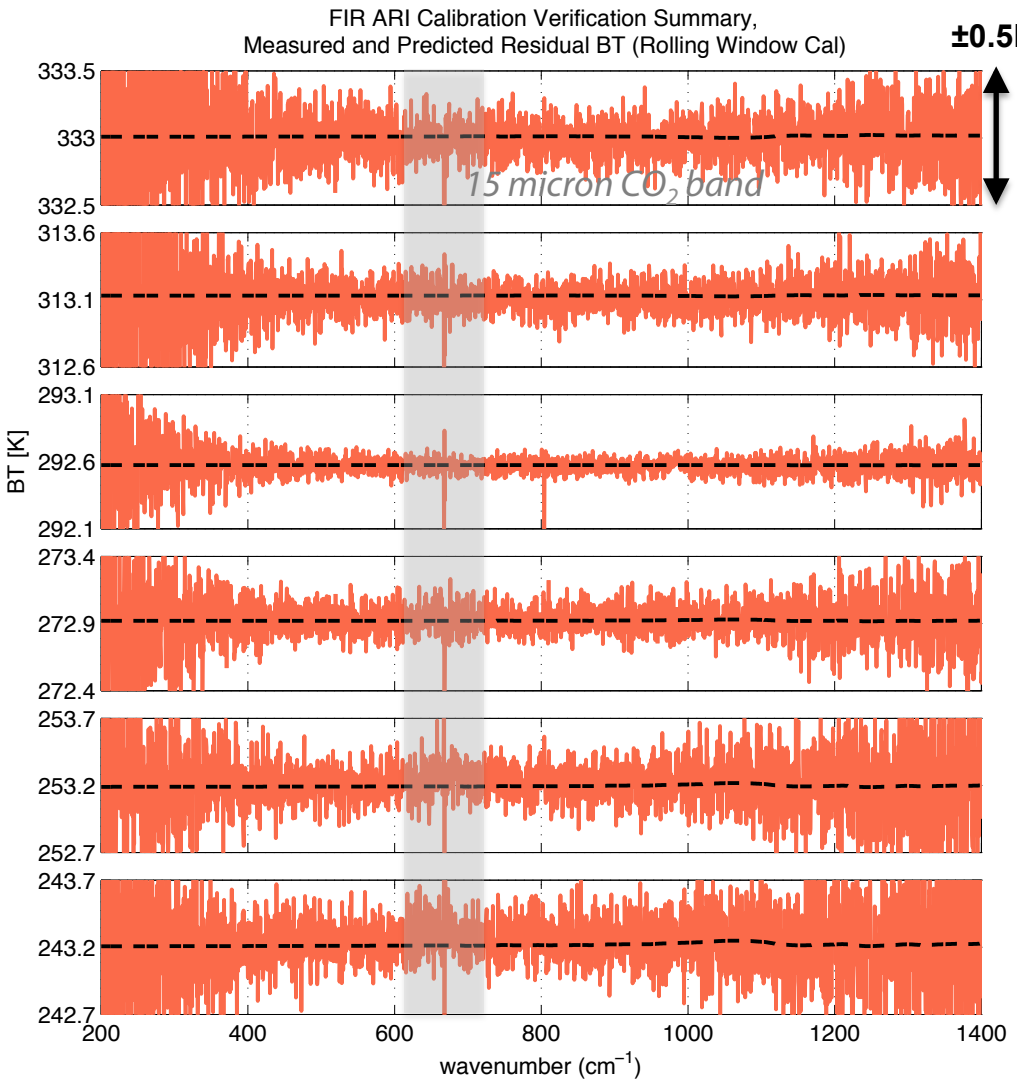
BT Obs BT Pred

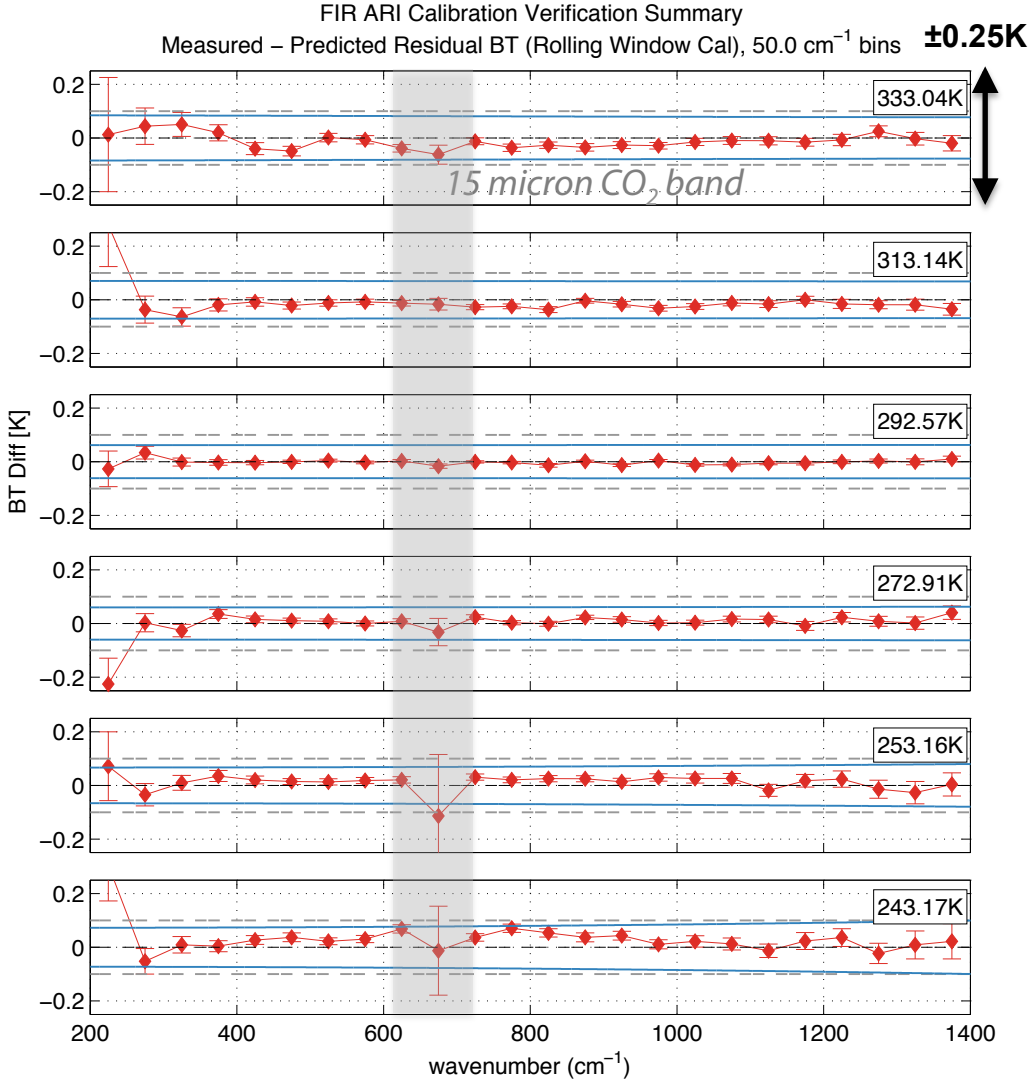
Observed and Predicted

Obs – Pred Combined RU ± 0.1K

Residual

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





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

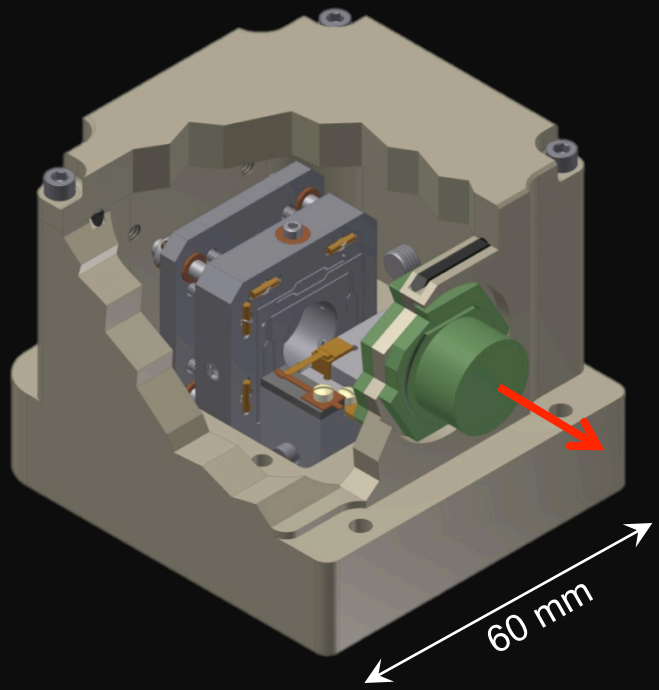
BT Obs BT Pred

Observed and Predicted

Obs – Pred Combined RU ± 0.1K

Residual

Current Work: QCL integration, OSRM with QCL, and OCEM-QCL Testing



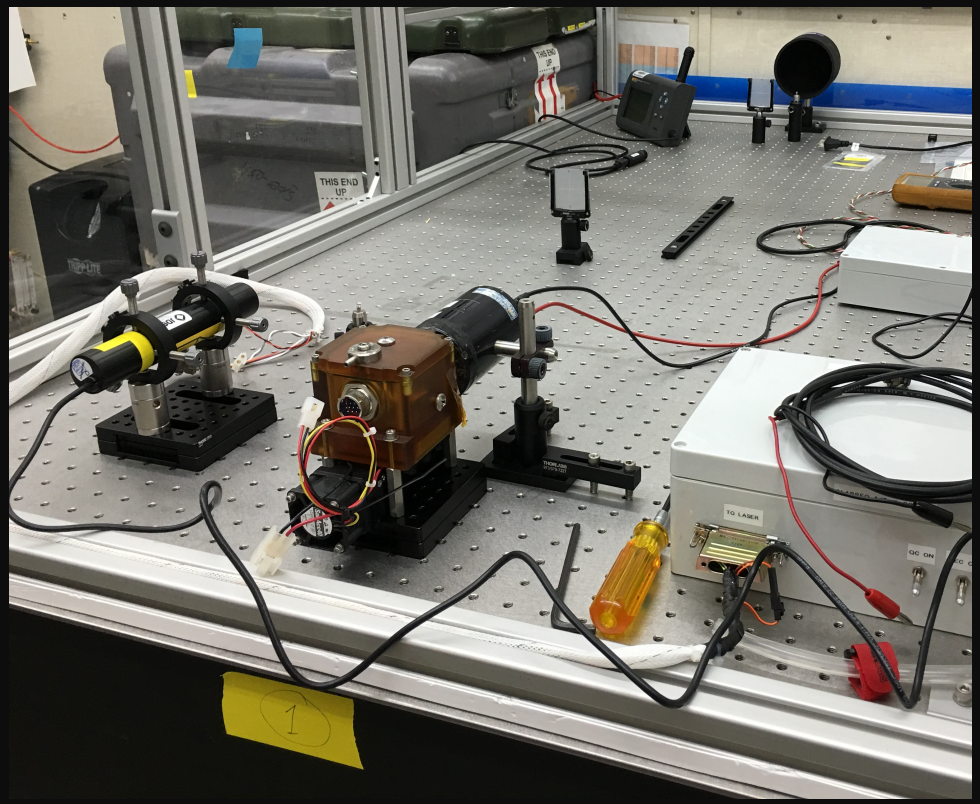
Output:
9.5 μm
80 mW

- 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 during the Instrument Line Shape (ILS) measurement while viewing the Integrating Sphere

Harvard University

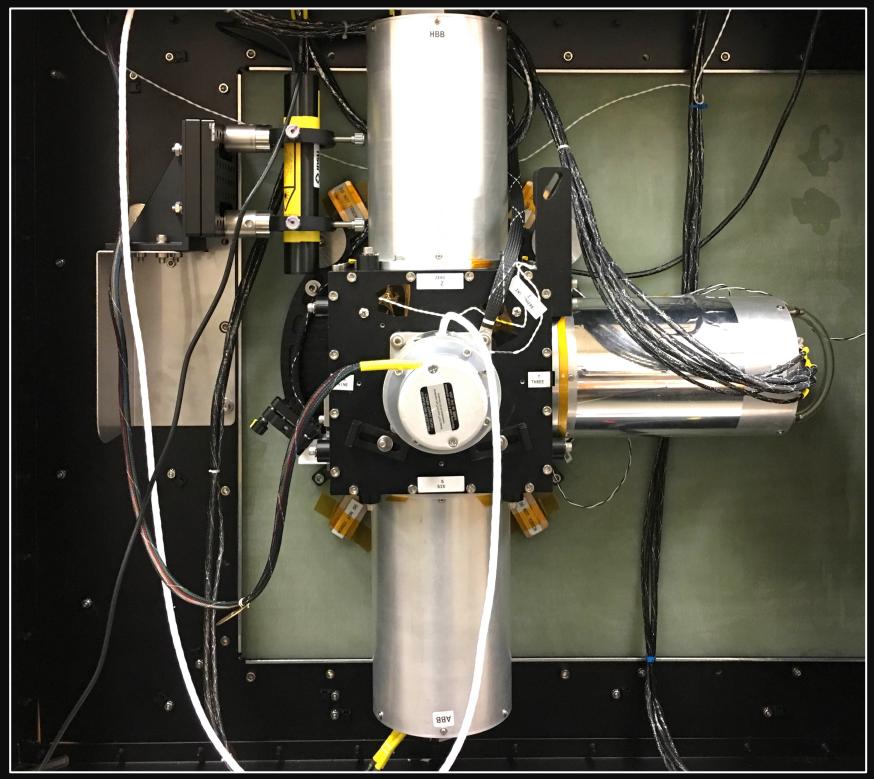
QCL Testing: Bore-sight with HeNe

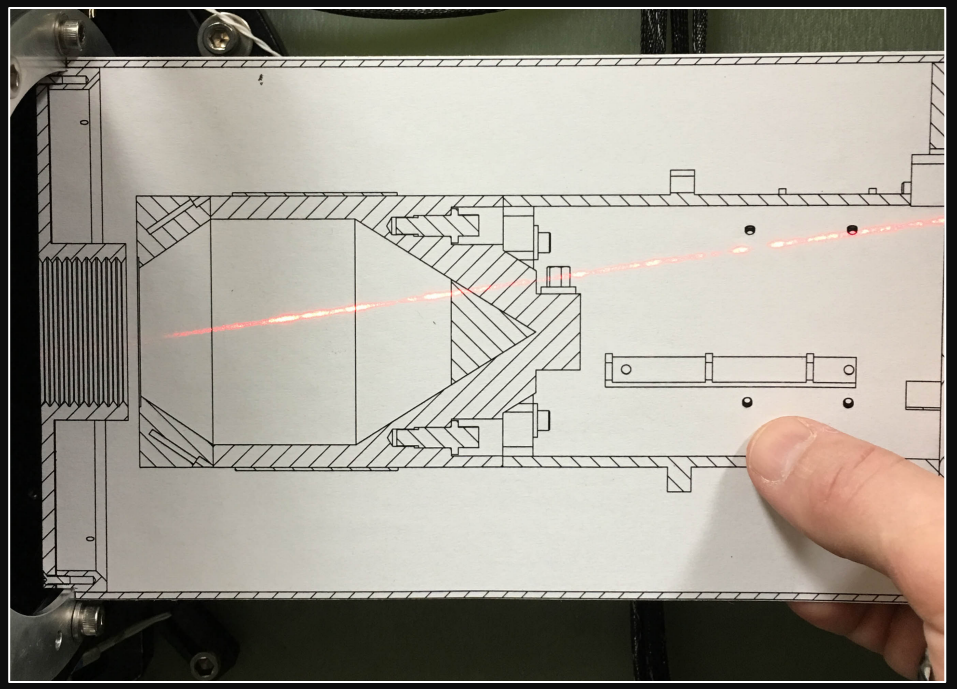
- Magnetic locking kinematic bases, combination of custom and COTS opto-mechanical elements
- Bore-sighted from approximately 10 – 180 cm



OCEM-QCL Testing: Positional Dependence

- Direct injection of laser into blackbody via tip-tilt mirror
- Measurements to be made at a range of positions across the cone of the blackbody





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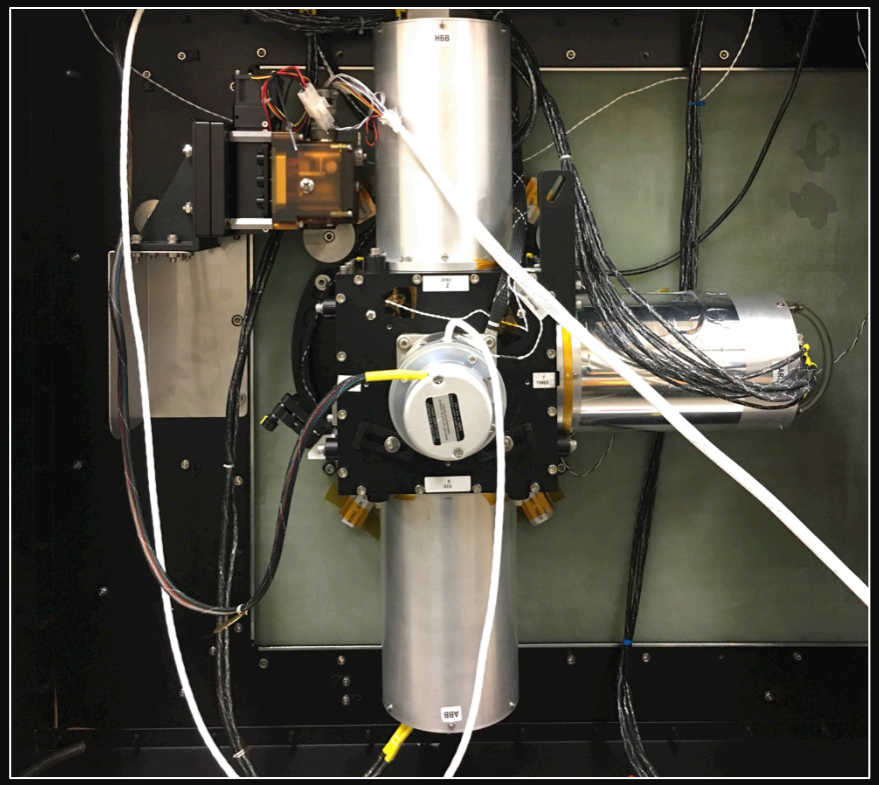
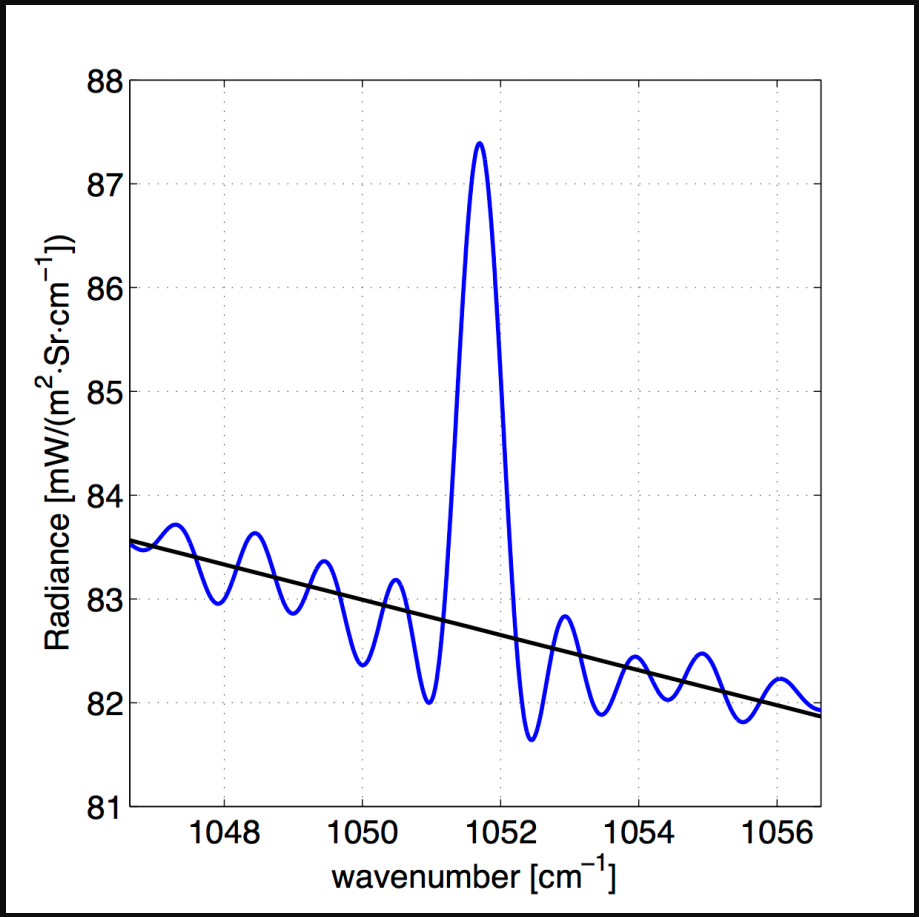
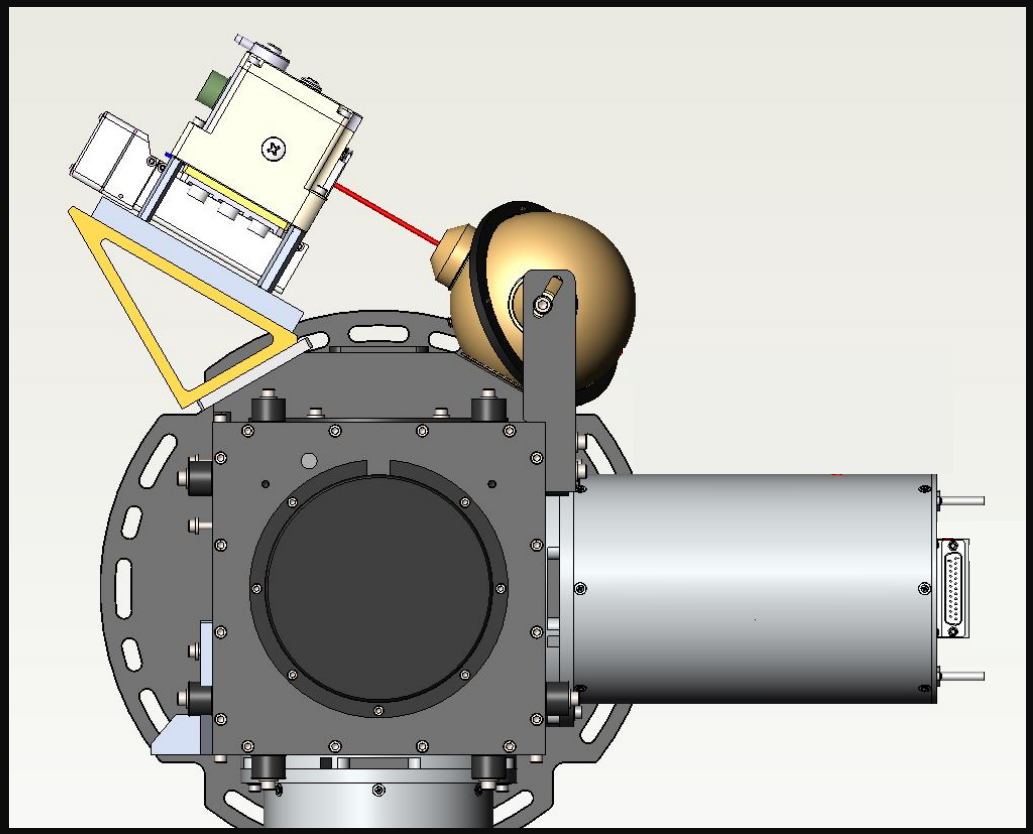
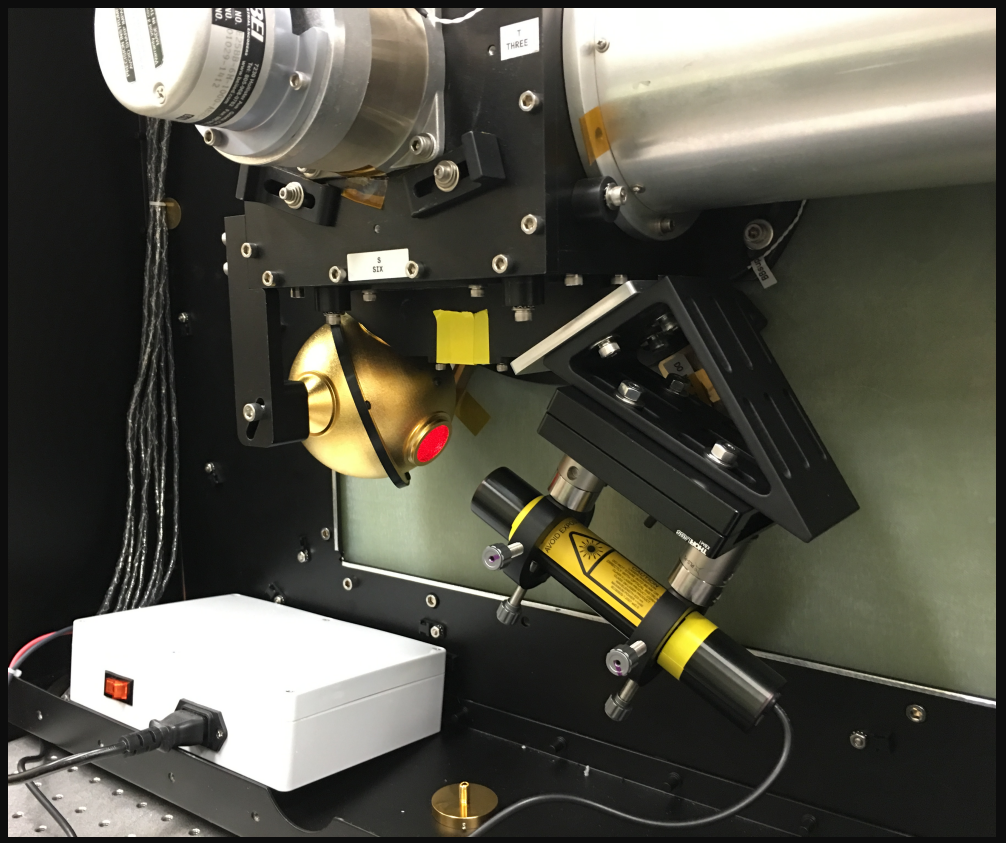




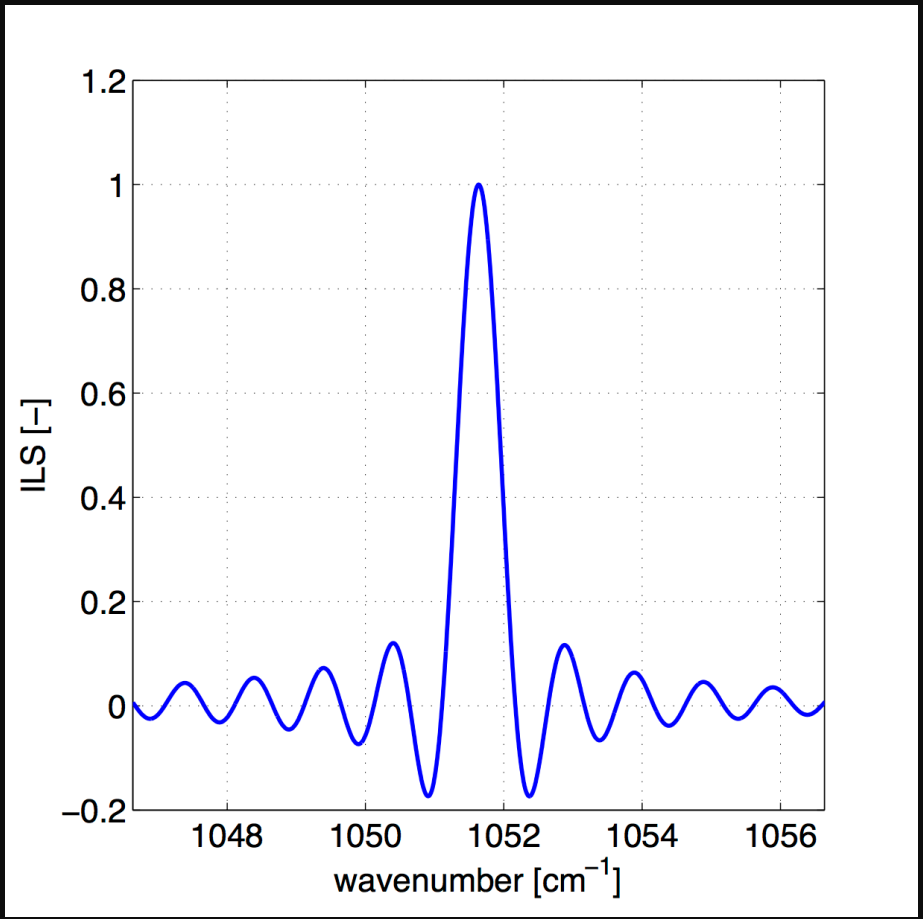
OSRM-QCL Testing: Direct Injection Configuration





- Comparison with CO_2 laser based ILS results
- Reference ILS for measurements completed using laser injection via SSM

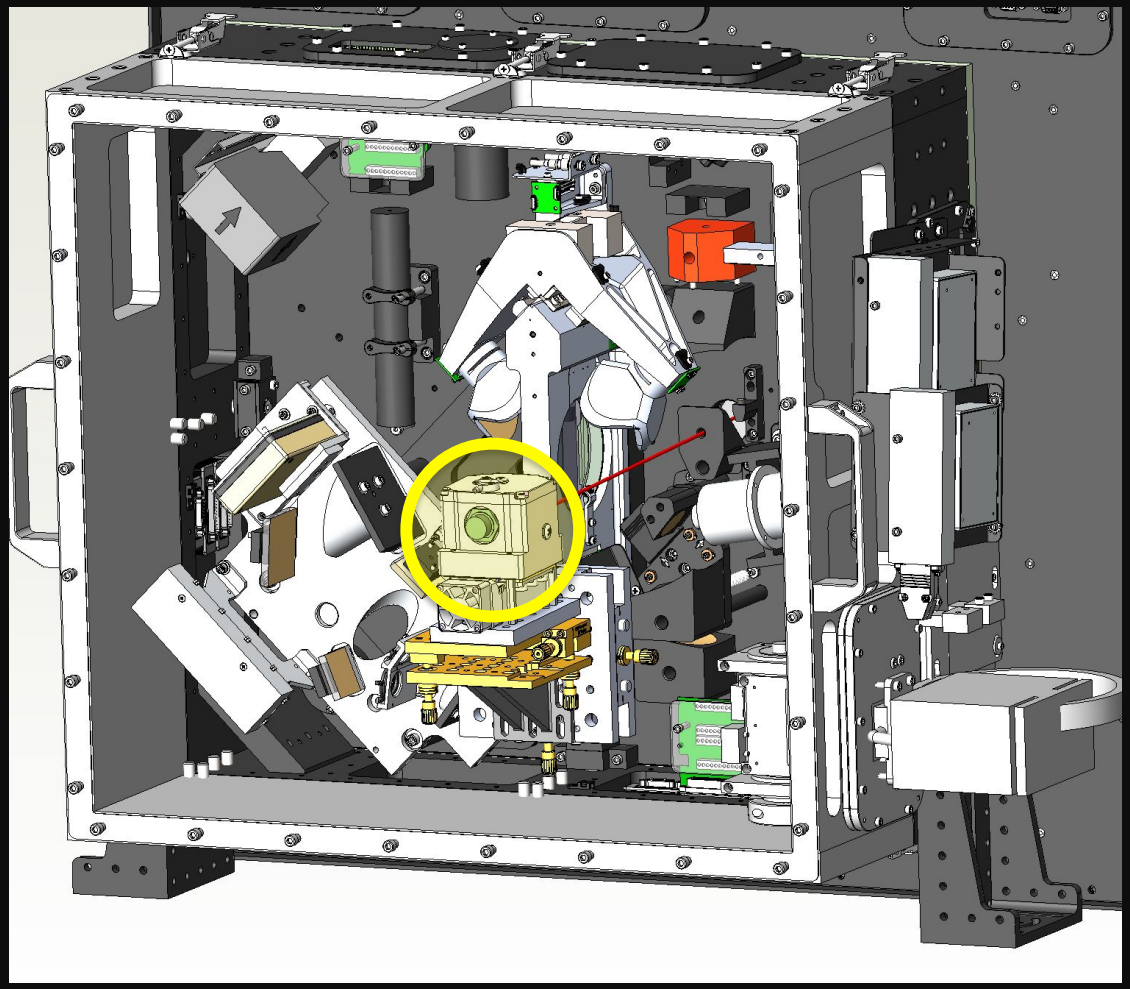
OSRM-QCL Testing: Direct Injection Configuration



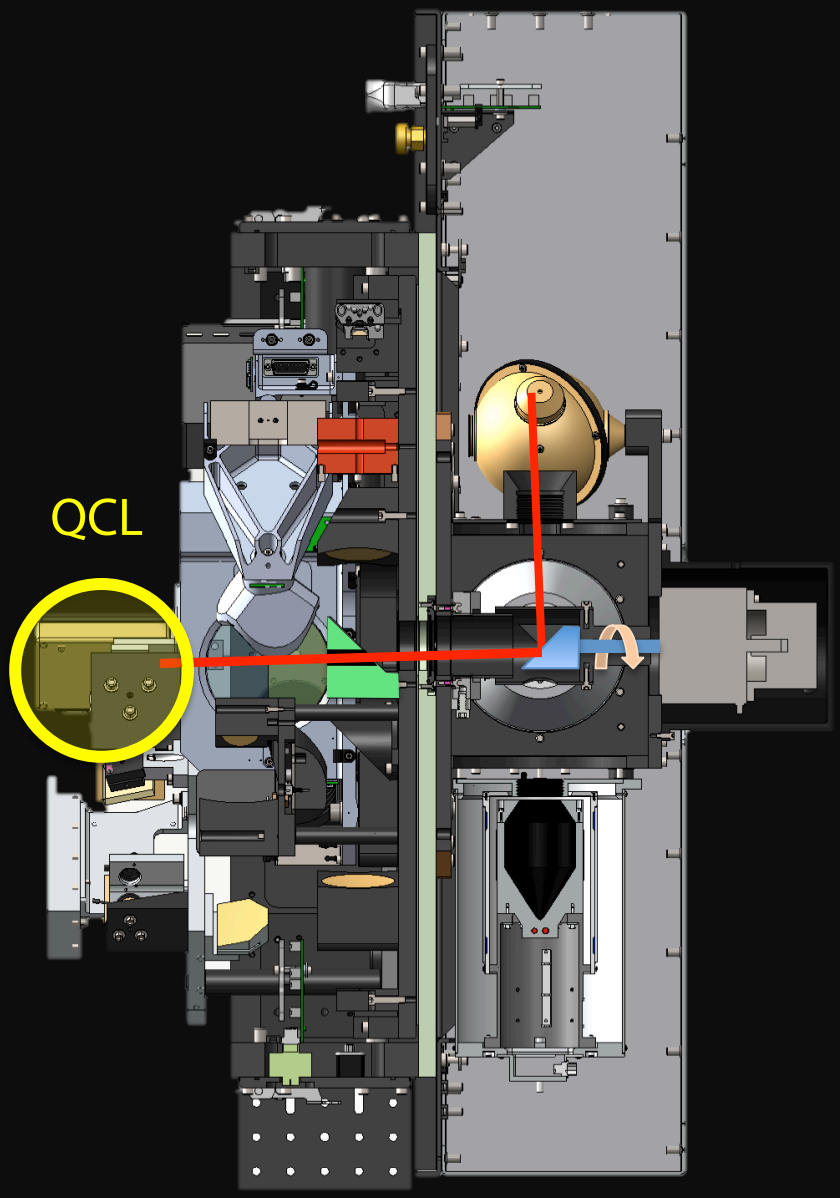
- Compare with CO_2 laser based ILS results
- Reference ILS for measurements completed using laser injection via SSM

OSRM-QCL and OCEM QCL: Injection via SSM

The QCL is reflected of of 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

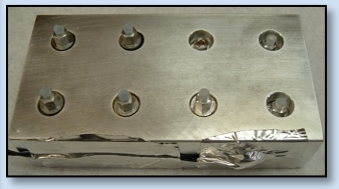


Conclusion

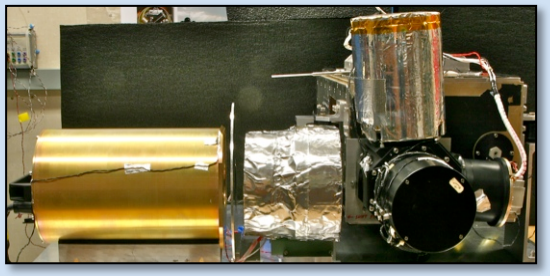
- A CLARREO IR Pathfinder would provide
  1. economical risk reduction for the full CLARREO mission,
  2. a chance to improve the overall accuracy of operational environmental satellite capabilities, and
  3. leverage them to start a global benchmark record.
- The ARI and OVTS have passed NASA ESTO TRL assessments and laboratory test results show that it meets CLARREO mission performance requirements
- The demonstration has been accomplished with a design that is representative of a flight instrument, and makes use of components with strong space flight heritage (direct analogs with high TRL), with a short path to a full flight prototype
- The RS Pathfinder effort is underway
- The IR Pathfinder is in limbo
- The full mission remains in “Extended pre-Phase A”

ARI Technology Development

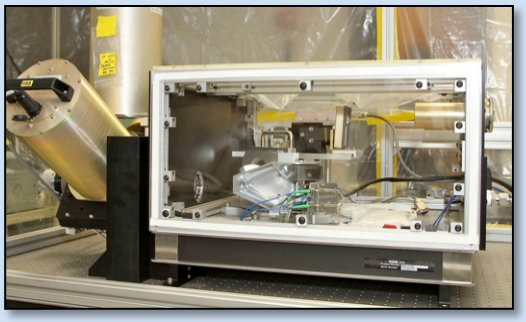
Miniature Phase Change Cell (MPCC)



MPCC Component Integration,
Characterization and Accelerated Life Testing

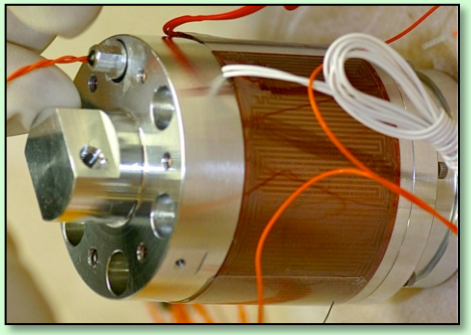


Heated Halo Generation-1 (Breadboard Halo,
AERI BB with Scanning HIS Aircraft FTIR)

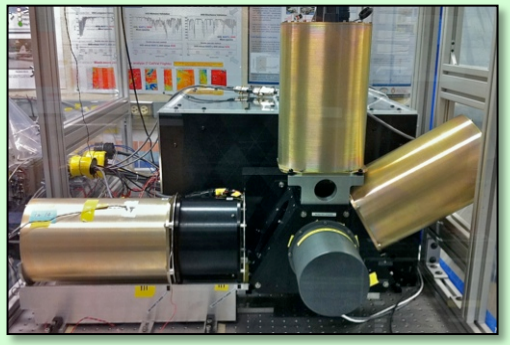


Absolute Radiance Interferometer (ARI) Breadboard

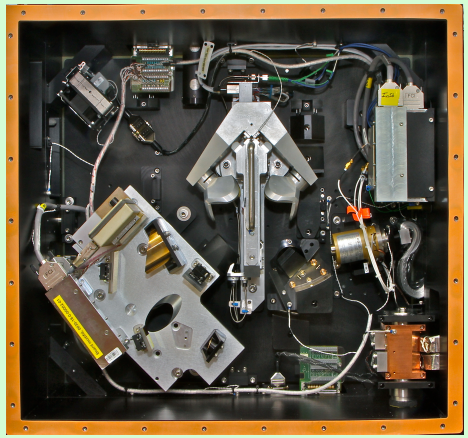
TRL 4



Integration of MPCC into Breadboard
Blackbody for Thermal Testing

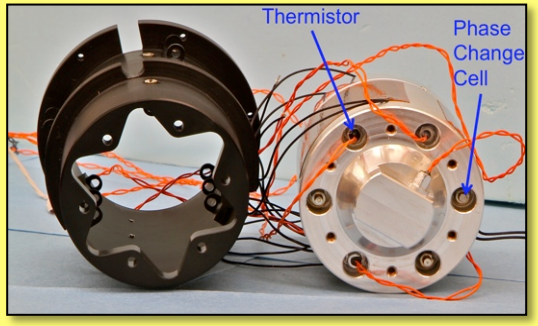


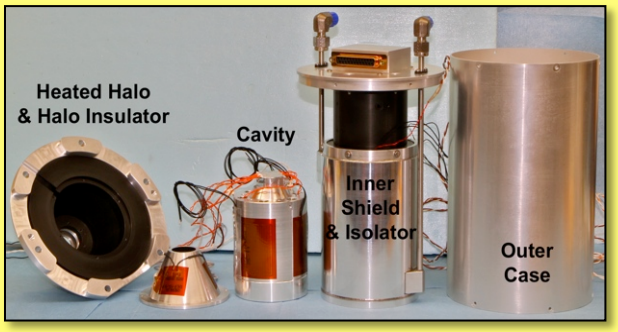
Heated Halo Generation-2 (Large Conical
Halo, AERI BB with ARI Breadboard FTIR)



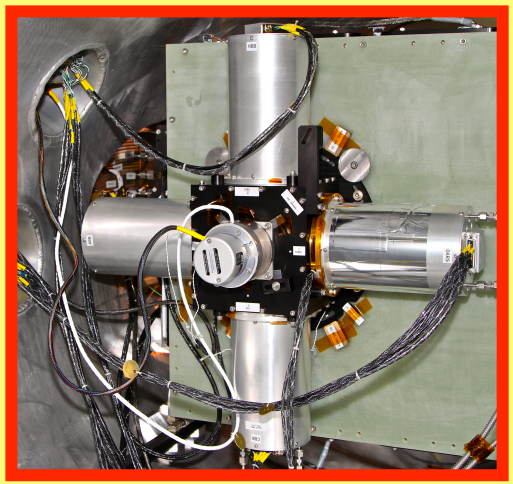
Absolute Radiance Interferometer Prototype

TRL 5





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



ARI Prototype Tested in Vacuum

TRL 6

Ready for Flight Program

BACK-UP MATERIAL

Requirements on Quality, Instrument Specifications, and Measurement Approach

Science Objectives	Scientific Measurement Requirements: Observables	Scientific Measurement Requirements: Data Products	Instrument Requirements: Instrument Functional Rqmt	Instrument Requirements: Projected Performance	Mission Functional Requirements
Benchmarking Radiance for Climate Change: provide a benchmark of the thermal infrared radiance spectrum against which similar futhre observations can be compared to infer atmospheric change with credibility	Thermal infrared upwelling radiance, spectral range 200 to 2000 cm^{-1}, spectral resolution 1.0 cm^{-1}, with sampling adequate to achieve <0.1 K (k=2) accuracy in zonal, annual averages for 15° latitude bins	Example Products include: spectral radiance (or brightness T) temporal and spatial means and higher moments (standard deviation, skewness, kurtosis) & distribution functions for spatial bins of 10°-15° zonal, 15° x 30° lat x lon, and climatological regions over monthly to annual time scales. Similar climate products directly related to physical properties (temperature and water vapor profiles, lapse rates, CO2 and other trace gases, cloud properties) from application of fingerprinting and linearized retrieval techniques	Radiometric Calibration: 0.1 K (k=3)	<0.07 K (k=3) for all wavelengths and scene temperatures	Orbit: One precessing 90° polar orbit for global coverage (full CLARREO Mission), and 52° ISS orbit combined with intercalibration (Pathfinder Misson) Nadir pointing: control <2° knowledge <0.2° Sampling: Interferograms collected continuously every 5 sec. -- scene mirror used to sequence through a calibration cycle every 20 sec. (Earth, Space, Ambient Blackbody; and view of OVTS) Thermal environment: Provide a temperature of 223 K or below for OARS heat sink, and an optical bench temperature of 303 ±5 K with stability of <0.05 K/min Mission life: 5-year Unobstructed FOVs: Provide for nadir Earth viewing and two space views: one at 90°, 180° or 270° measured from Nadir normal to orbit plane, and one at 135° or 225° Mass: 138 kg power (ave): 116 W Data Rate: 132 kb/s
			Spectral Resolution (Δnu): <1 cm^{-1}	0.625 cm^{-1} maximum OPD=0.8 cm	
			Spectral Coverage: 200-2800 cm^{-1}	200-2800 cm^{-1}	
			Spectral Calibration: 1ppm	<1ppm	
			Instrument lineshape (ILS): <1% of Δnu	<1% of Δnu	
Benchmarking Radiance for Climate Forecast testing: provide a benchmark of the themal infrared radiance spectrum against which future similar observations can be compared to infer longwave forcings and longwave feedbacks for testing climate models	Thermal infrared upwelling radiance, spectral range 200 to 2000 cm^{-1}, spectral resolution 1.0 cm^{-1}, with sampling adequate to achieve <0.1 K (k=2) accuracy in zonal, annual avrages for 15° latitude bins		Footprint Diameter: 25-100 km	40 km	
			Sampling Intervals: <250 km	145 km	
			NEdT Mid-infrared: 0.5 K at 290 K for 650-2300 cm^{-1} (state-of-the-art acceptable for 2300-2800 cm^{-}	<0.3 K for 700-2300 cm^{-1} <0.5 K for 650-700 cm^{-1}	
			NEdT Far-infrared: 5 K at 290 K for 350-1000 cm^{-1} (state-of-the-art acceptable for 200-350 cm^{-1})	<3 K for 450-1000 cm^{-1} <4 K for 350-450 cm^{-1}	
Benchmarking Radiance for Intercalibration: provide a benchmark of the thermal spectrum that can provide reference intercalibration for other sensors	Thermal infrared upwelling radiance, spectral range 650 to 2800 cm^{-1}, spectral resolution 1.0 cm^{-1}, sampling sufficient to provide single channel intercalibration uncertainty for operational sounders of 0.1 K (k=3) in 6 months	GSICS intercalibration of operational sounders for weather and climate process studies	OVTS radiance accuracy requirement: 0.1 K (k=3)	<0.07 K (k=3) for all wavelengths and scene temperatures	
			OVTS calibration temperature accuracy requirement: 0.01 K	0.005 K	
			OVTS Emissivity accuracy requirement: 0.1%	0.06%	
			OVTS lineshape width measurement accuracy: 0.5% of Δnu	<0.3% of Δnu	
		Second climate benchmark covering ±82 latitude constructed using intercalibrated CrIS on Suomi NPP/JPSS, IASI on MetOp, and GIIRS on China's FY3	Operate continuously for at least 6 months for intercalibration and a goal of 5 years for benchmarking climate change	5 years	