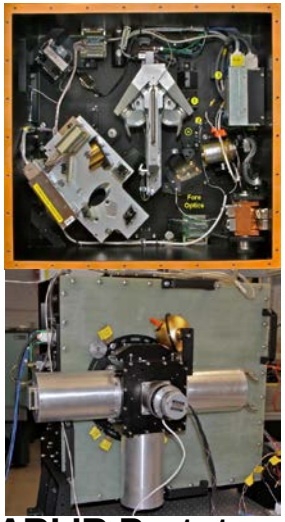
The Absolute Radiance Interferometer (ARI):
Capable of climate Benchmark quality IR measurements from a CLARREO Pathfinder on ISS



ARI IR Prototype

Hank Revercomb, Fred Best, Joe Taylor, Jon Gero,
Dave Tobin, Bob Knuteson, Doug Adler,
Claire Pettersen, Mark Mulligan, Jeff Wong,
Mark Schwarz, and Don Thielman

University of Wisconsin-Madison
Space Science and Engineering Center

20th International TOVS Study Conference
Lake Geneva, Wisconsin, 28 Oct-3 Nov 2015

Key Step US President's FY2016 Budget Request

Includes a Pathfinder mission to kickoff CLARREO!
(Climate Absolute Radiance and Refractivity Observatory)

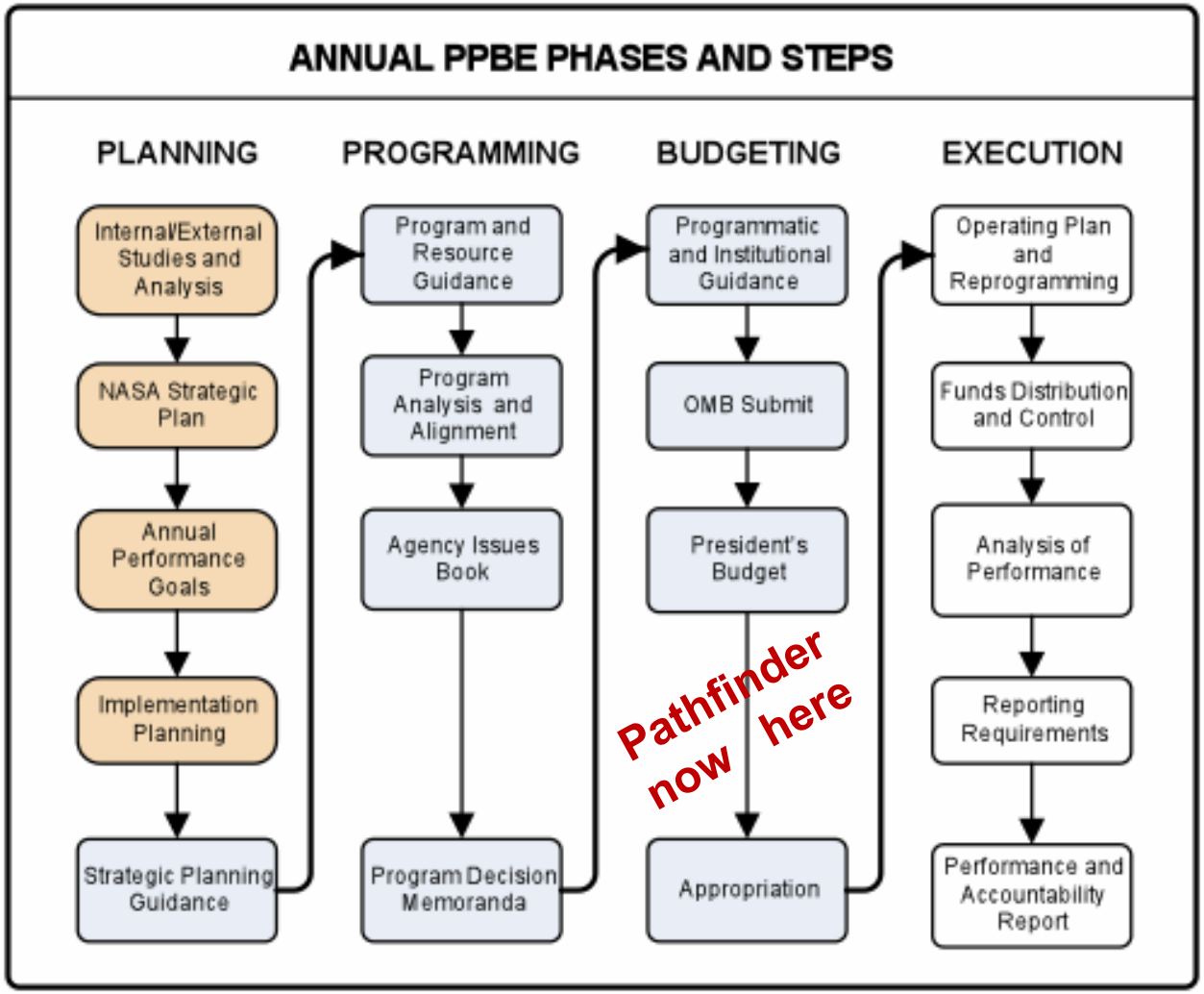
- "The CLARREO Pathfinder mission will demonstrate essential measurement technologies; validate the high accuracy radiometry required for long-term climate studies in support of other Decadal Survey and land imaging missions; and initiate measurements that will benchmark the shortwave reflectance and 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)**

NASA PPBE Milestone Accomplished

(Planning, Programming, Budgeting, and Execution)

- Approach and Grass Roots Cost Estimates for the IR from U of Wisconsin-SSEC and RS inputs from U of Colorado LASP were provided in support of a credible plan to perform the Pathfinder ISS mission under assumed constraints and budget
- The NASA PPBE Milestone qualifies the LaRC CLARREO project to implement the Pathfinder, if it is part of the final FY2016 appropriations

NASA PPBE Process Diagram

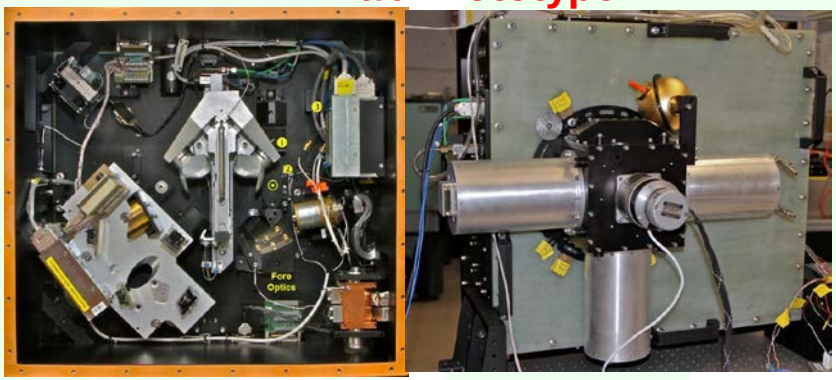


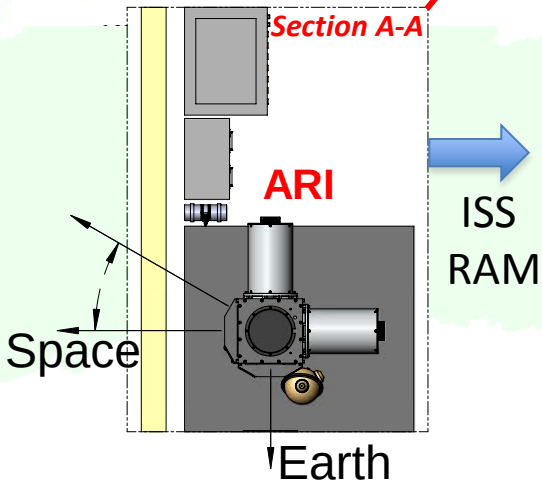
Topics

1) **ISS Pathfinder**

2) **Absolute Radiance Interferometer (ARI) CLARREO Prototype update**

ARI Lab Prototype



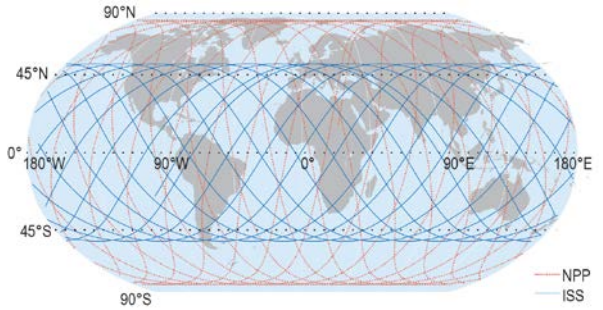


Value of an ISS Pathfinder Mission

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.

The key components supporting the above are

• **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.



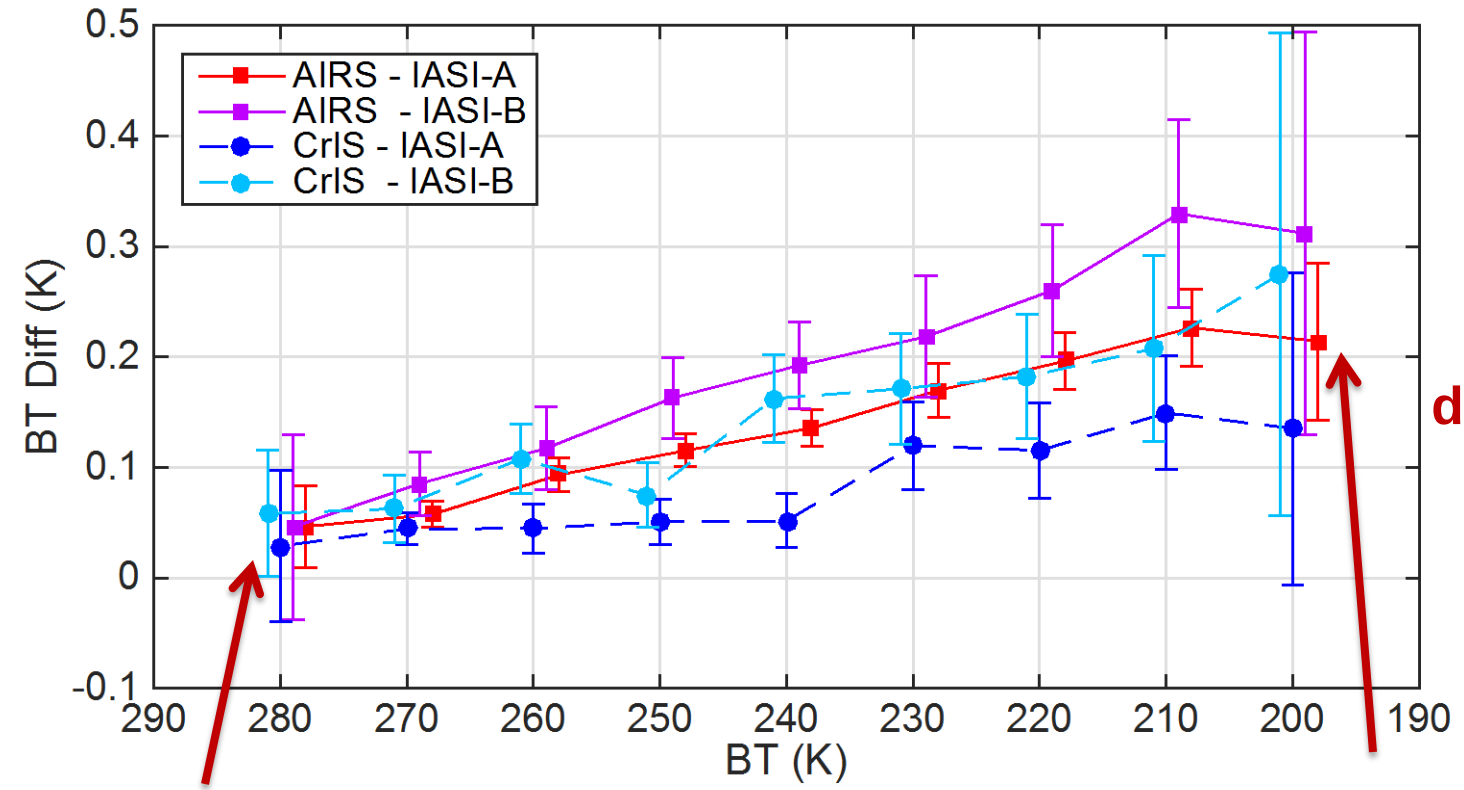
• **Sampling Requirements:** Needs for an **initial benchmark** (unbiased temporal and spatial sampling) are met by ISS below 52 degrees latitude.

• **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**.

Current Sounders Show Significant Differences

Mean Simultaneous Nadir Overpass (SNO) differences for 910-930 cm^{-1}



0.050 K Agreement

>0.3 K relative differences

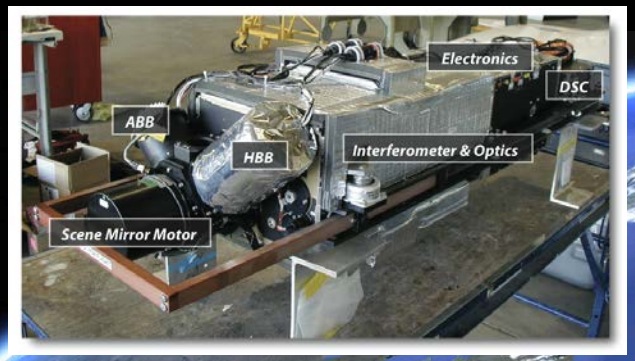
Error-bars represent statistical matchup uncertainty, not sensors uncertainty

SNOs: AIRS-IASIA, CrIS-IASIA
AIRS-IASIB, CrIS-IASIB

ARI would establish an absolute reference to better than 0.1K!

Current Approach to absolute assessment:
SNPP Calibration Validation Campaign 2015

- Seven ER-2 science flights were conducted during the March 2015 airborne calibration validation campaign. Flights were based out of Keflavik Iceland with flights over the Greenland ice sheet.
- The Scanning-HIS has a clear calibration traceability to NIST and many valuable satellite underflight datasets were collected.

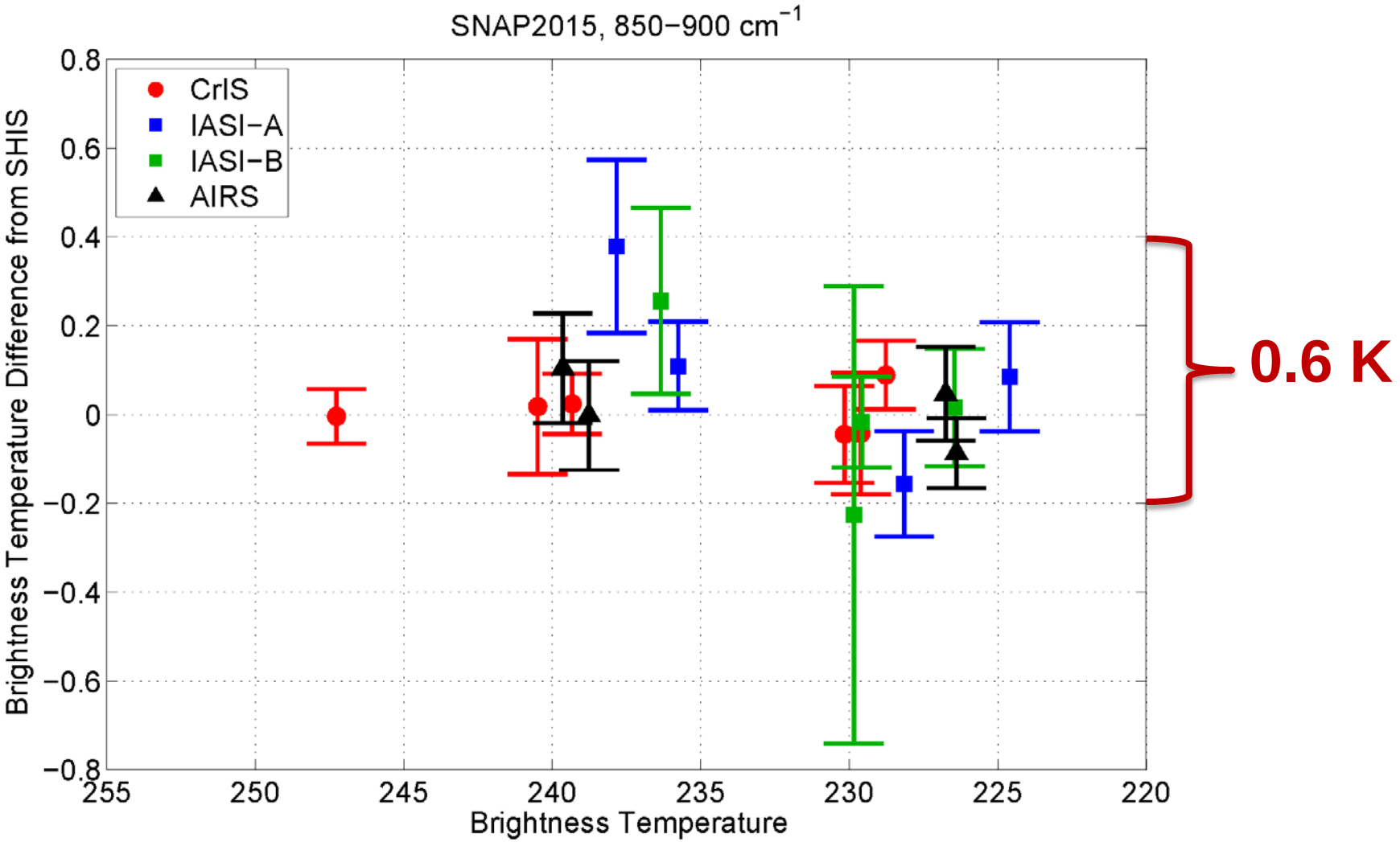


IFOV:	100 mrad (2km @ 20km, nadir)
Scene Coverage:	Programmable 45° scene mirror nadir ± 40° typical
Spectral Coverage:	LW (HgCdTe), 580 - 1180 cm^{-1} MW(HgCdTe), 1000 - 1820 cm^{-1} SW (InSb), 1750 - 3000 cm^{-1}
Spectral Resolution:	0.5 cm^{-1}

Google Earth

Joe Taylor et al., talk 12.06

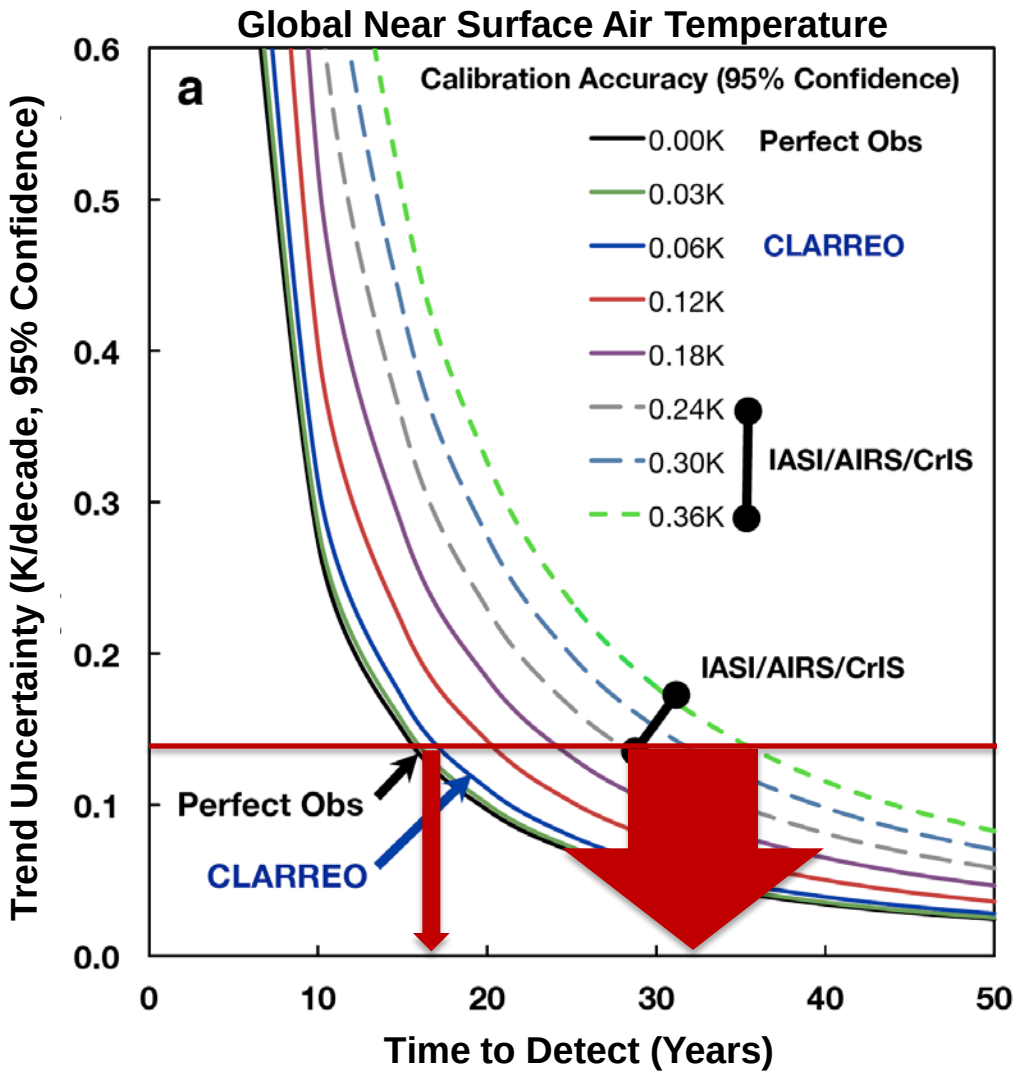
PRELIMINARY LW window differences



See Joe Taylor, Poster 6.8 for much more information

ARI Accuracy Offers Substantially Reduced Time to Detect Global Climate Change

Achieving Climate Change Absolute Accuracy in Orbit,



Example with ~ factor of 2 shorter Time to Detect

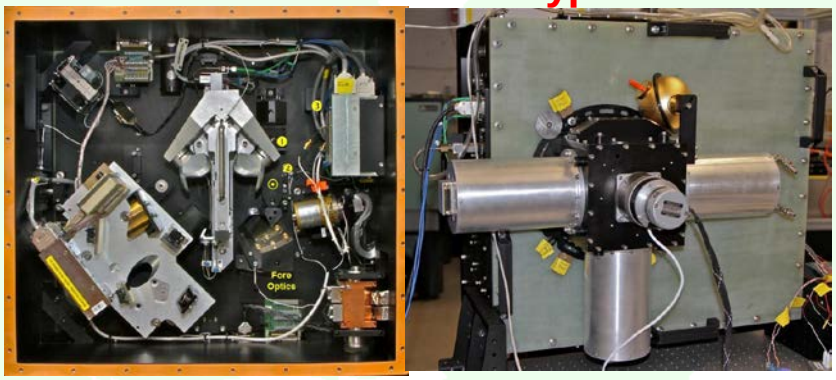
Wielicki et al., BAMS, 2013

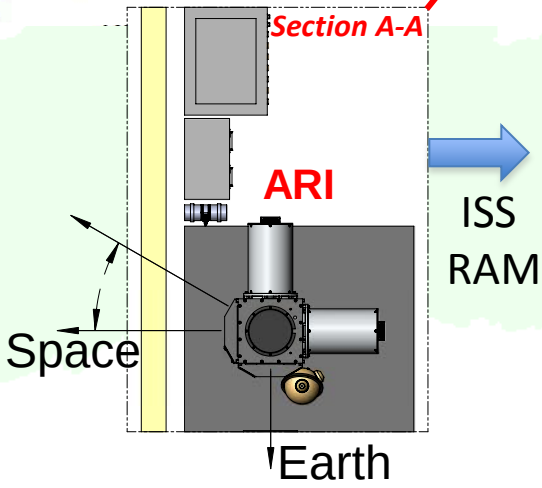
Topics

1) ISS Pathfinder

2) Absolute Radiance Interferometer (ARI) CLARREO Prototype update

ARI Lab Prototype





Key Instrument Performance Specifications

Calibrated Fourier Transform Spectrometer (CFTS)		
Characteristic	**Value**	**Comment**
Bands	3.5 - 5.5 μm	InSb
	5.5 - 9 μm	MCT
	9 - 15 μm	MCT
	10 - 50 μm	Pyroelectric
NEDT (Far-Infrared) @290K	4.0 K	(350-1,000 cm^{-1})
NEDT (Mid-Infrared) @290K	0.3 K	(700-2,000 cm^{-1})
Spectral Resolution (Δν)	0.625 cm^{-1}	Unapodized
Radiometric Accuracy	0.07 K	3σ
Spectral Calibration @ 735 cm^{-1}	≤1 ppm	(Verified on orbit using atmos. line)
Instrument Lineshape width	<1% Δν	knowledge
Ground Footprint	40 km	For 390 km orbit
Field-of-View	104 mrad	ifr divergence as mrad
Viewing Geometry	Nadir	
Optical Throughput	0.0084 cm^2 -sr	
Maximum OPD	± 0.8 cm	Two-sided interferogram
OPD Scan Rate	0.4 cm/second	
Metrology Laser Wavelength	1.55 μm	
Samples per Interferogram	10323	
Bits per Sample	16	
Mean Data Rate	0.132 Mbps	33 Kbps/band X 4 bands
Time per Interferogram	2-4 sec	
Scan Mirror Retrace	1 second	
Time per Sequence	20 seconds	ABB, Space, Earth, OVTS
Ground Sample Spacing	145 km	
ABB Temperature Range	268 to 303K	3σ
ABB Temperature Uncertainty	<45 mK	3σ
ABB Cavity Max Temp. Gradient	0.1 K	
ABB Emissivity	0.999	
ABB Emissivity Uncertainty	<0.001	3 to 50 μm 3σ

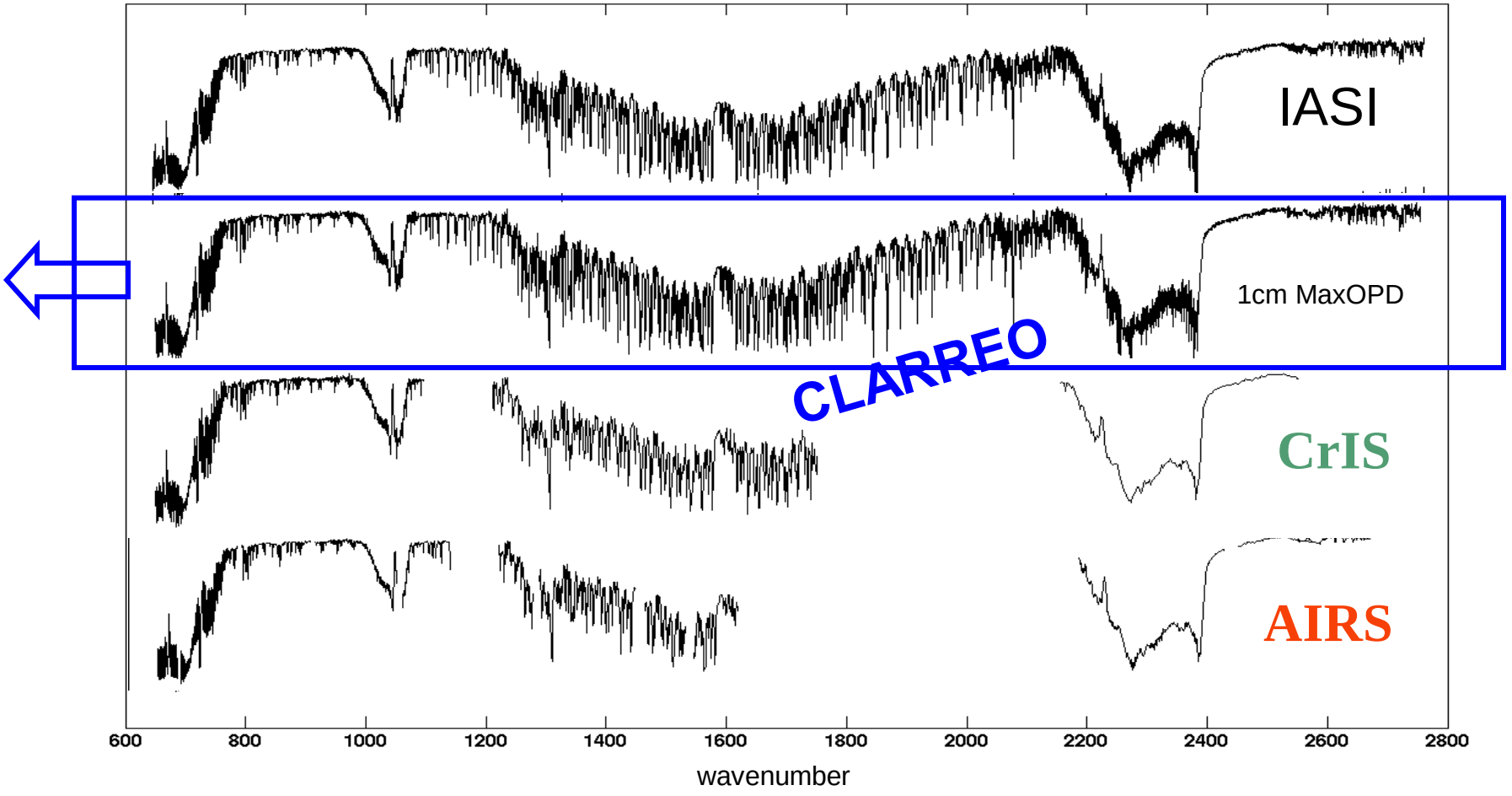
On-Orbit Verification and Test System (OVTS)		
Characteristic	**Value**	**Comment**
On-Orbit Absolute Radiance Standard (OARS)		
Blackbody Radiance Uncertainty	<0.07 K	3σ
Aperture Diameter	30 mm	
Temperature Range	228 to 313K	
Temperature Stability	50 mK/min	While viewing
OARS Cavity Max Temp. Gradient	0.1 K	
Absolute Temp Calibration	29.76 °C	Gallium (302.41K)
	0.00 °C	Water (273.15K)
	-38.83°C	Mercury (234.32K)
Melt Temperature Calibration Uncert.	5 mK	3σ
Emissivity	>0.999	3-50 μm
Emissivity Uncertainty	<0.0006	3σ
Heated Halo Emissivity Meas.Uncert.	<0.0006	3σ
Heated Halo Temperature	343K	
Heated Halo Temperature Knowledge	<268K	
View Factor (Cavity to Halo)	F>0.6	
Quantum Cascade Laser (QCL) for Emissivity & Instrument Line Shape (ILS)		
ILS Measurement Uncertainty (Dn/n)	2 ppm	3σ
QCL Wavelenght	9.5 μm	
QCL Linewidth	0.001 cm^{-1}	
QCL Wavelength Stability	0.1 ppm	
QCL Emissivity Meas. Uncertainty	<0.001	3σ
QCL Power Meas. Uncertainty	5%	Using calorimetry

Spectral Requirements

Spectral Coverage & Resolution:

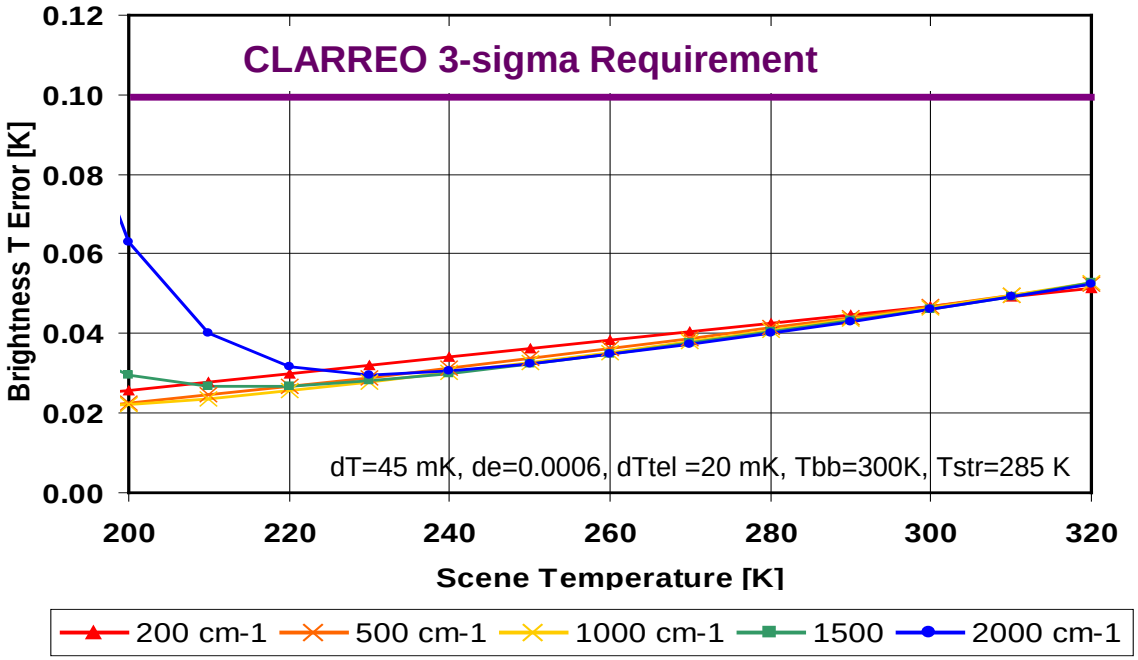
3-50 μm or 200-3000 cm^{-1} with $\Delta\nu$=0.5 cm^{-1}

(includes Far IR to capture most of the information content and emitted energy, & instrument independent scale)



CLARREO IR Accuracy

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



Absolute Radiance Interferometer (ARI):
Definitions of key components of prototype instrument

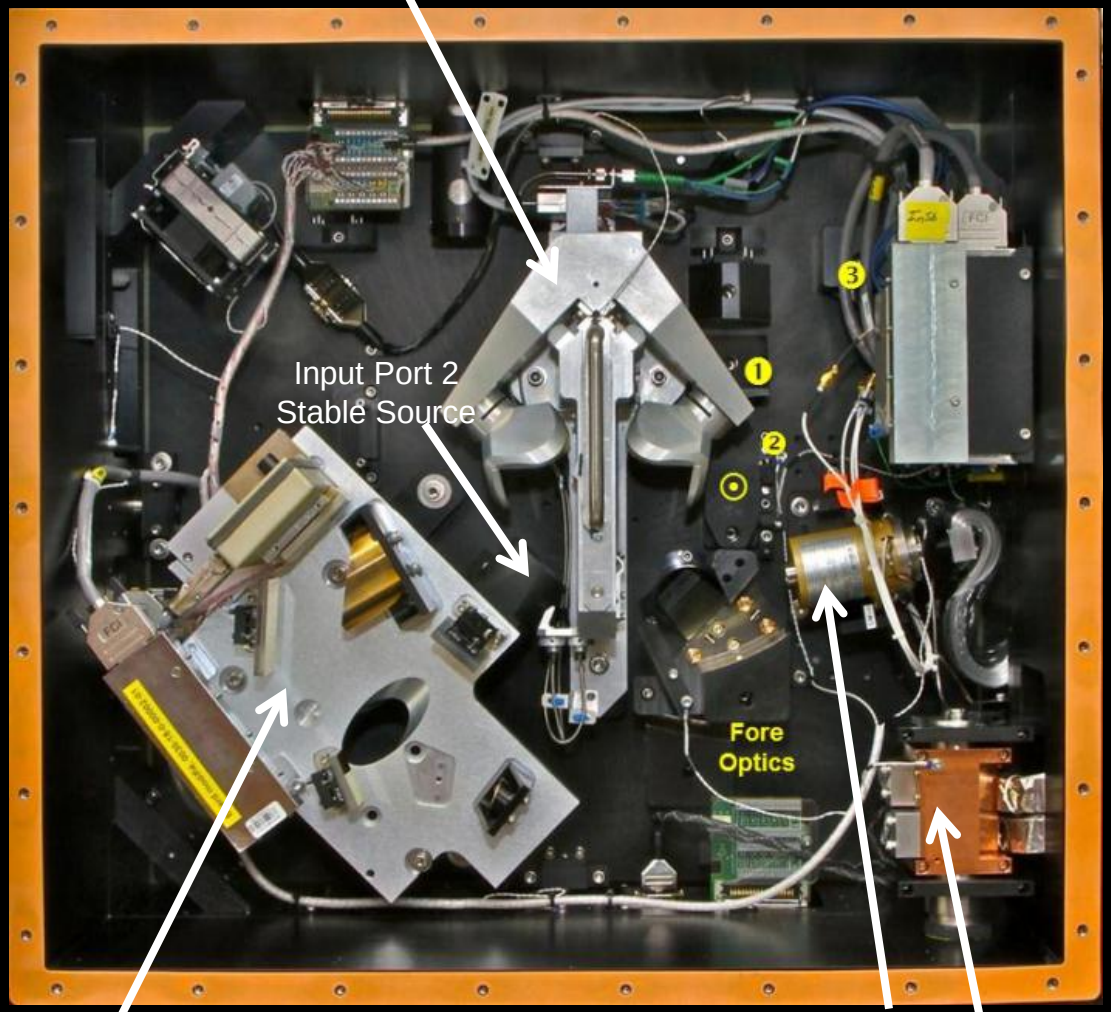
- **Calibrated Fourier Transform Spectrometer (CFTS):**
  - FTS with strong flight heritage from ABB/Bomem, Inc.
  - 3 Spectral bands covering 3-50 μm
  - 2 Cavity Blackbody References for Calibration (1 + Space On-orbit)
- **On-orbit Verification and Test System (OVTS):**
  - ❶ On-orbit Absolute Radiance 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)-Heated Halo using a blackened, 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

SSEC

*Not fully implemented in prototype—demonstrated separately

Absolute Radiance Interferometer (ARI) Prototype

with a short upgrade path to flight



Calibrated FTS

- Corner-cube interferometer used in 4-port to avoid double pass; Strong flight heritage
  - 0.5 cm^{-1} resolution (±1 cm OPD)
  - 1.55 µm diode laser for interferogram sample control & fringe counting
  - 10 cm CsI single-substrate beamsplitter
- Fore optics designed to
  - minimize polarization effects
  - minimize sizes of calibration/ verification BBs & reflectivity sources
  - minimize stray light by providing effective field and aperture stops
  - maximize energy throughput
- 3-50 µm Spectral Coverage
  - Highly linear pyroelectric detector, all reflective aft optics: 10-50 µm
  - Cryo-cooler for MCT & InSb semi-conductor detectors: 3-18 µm

FTS Flight Readiness for CLARREO-like Mission

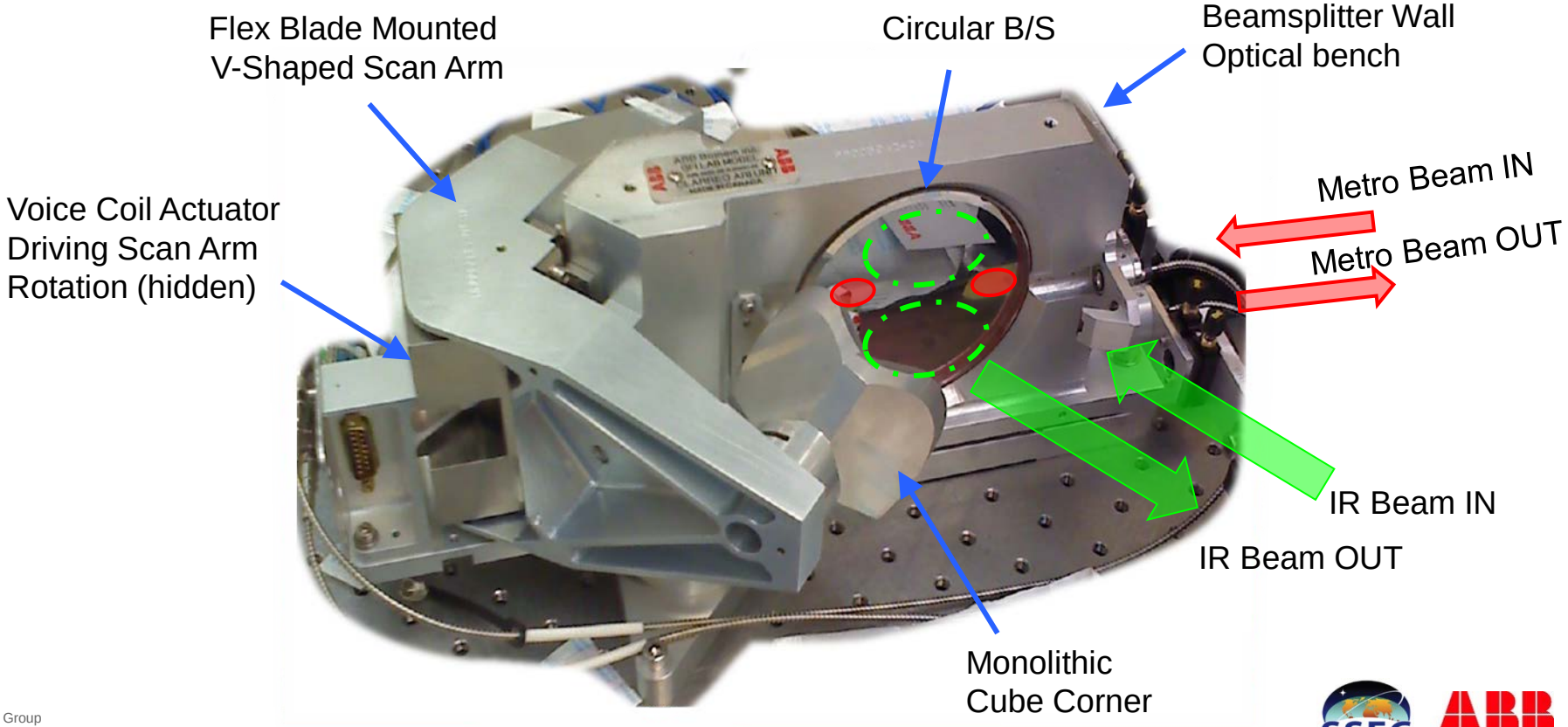
- **Mechanism:** ABB's simple flex blade double pendulum design paired with retro-reflector meets CLARREO resolution with proven reliability and launch protection.
- **Beamsplitter:** CsI is a material with space (lens or window) and commercial heritage at ABB. Its spectral properties provide coverage of the full CLARREO spectral range
- **Metrology:** ABB uses high reliability telecom DFB laser diodes (1310 or 1550 nm) that meet OPD accuracy and lifetime requirements. Redundancy is always implemented, but never used…
- **Actuator:** Simple voice coil is reliable and low cost. Redundant winding can be easily built into design if needed.

Frederic Grandmont, Ph.D.

SSEC

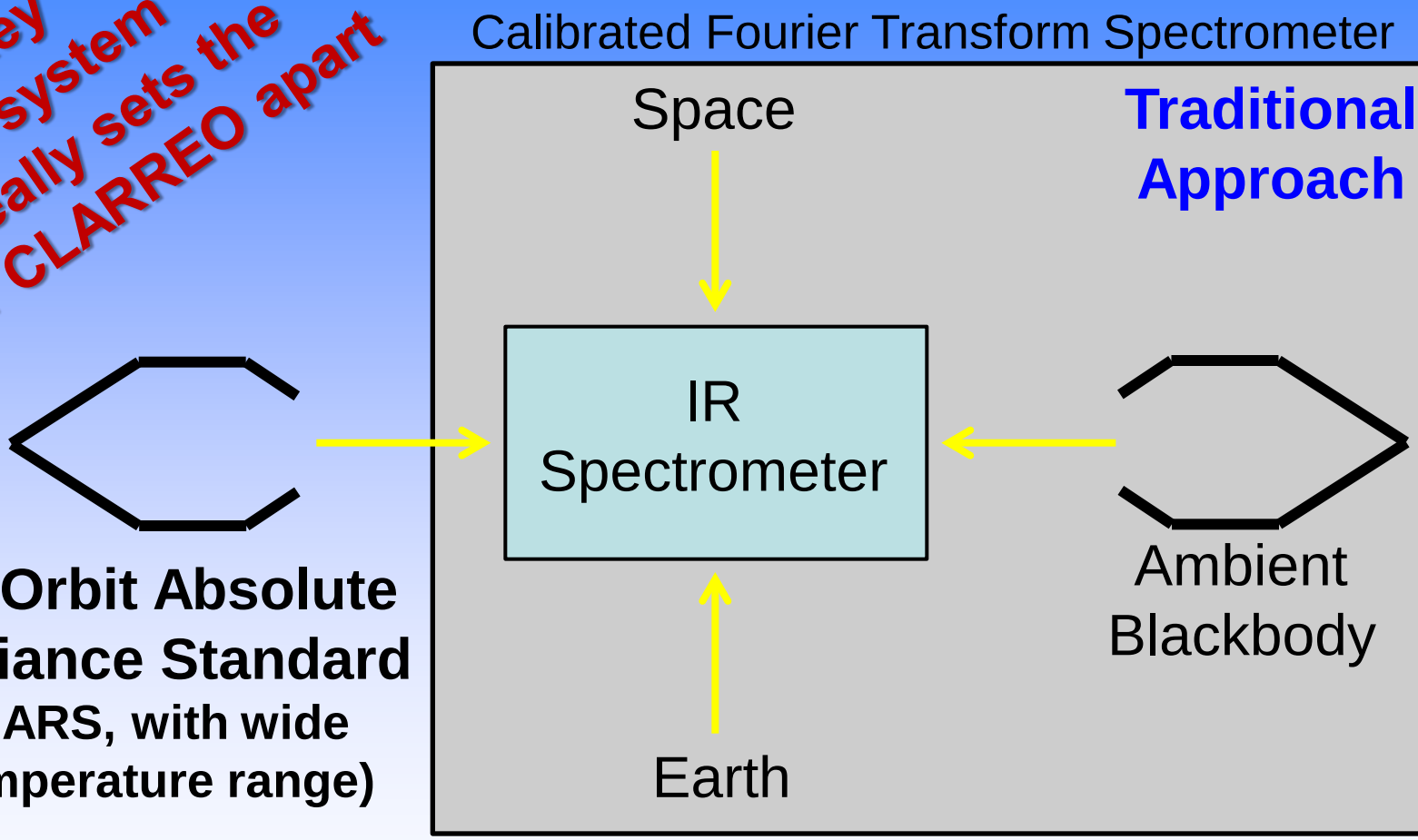
FTS Flight Readiness for CLARREO-like Mission

- Mirrors: New monolithic all metallic cube corner exceeds CLARREO optical quality requirements. By far the most robust design to be flown in space (result of 7 years of development at ABB)



On-Orbit Verification and Test System

A key new system that really sets the ARI for CLARREO apart



On-Orbit Absolute Radiance Standard
(OARS, with wide Temperature range)

OVTS Provides On-Orbit, End-to-End Calibration Verification & Testing Traceable to Recognized SI Standards

Absolute Radiance Interferometer (ARI) Prototype

with a short upgrade path to flight

On-orbit Verification and Test System (OVTS) Technologies

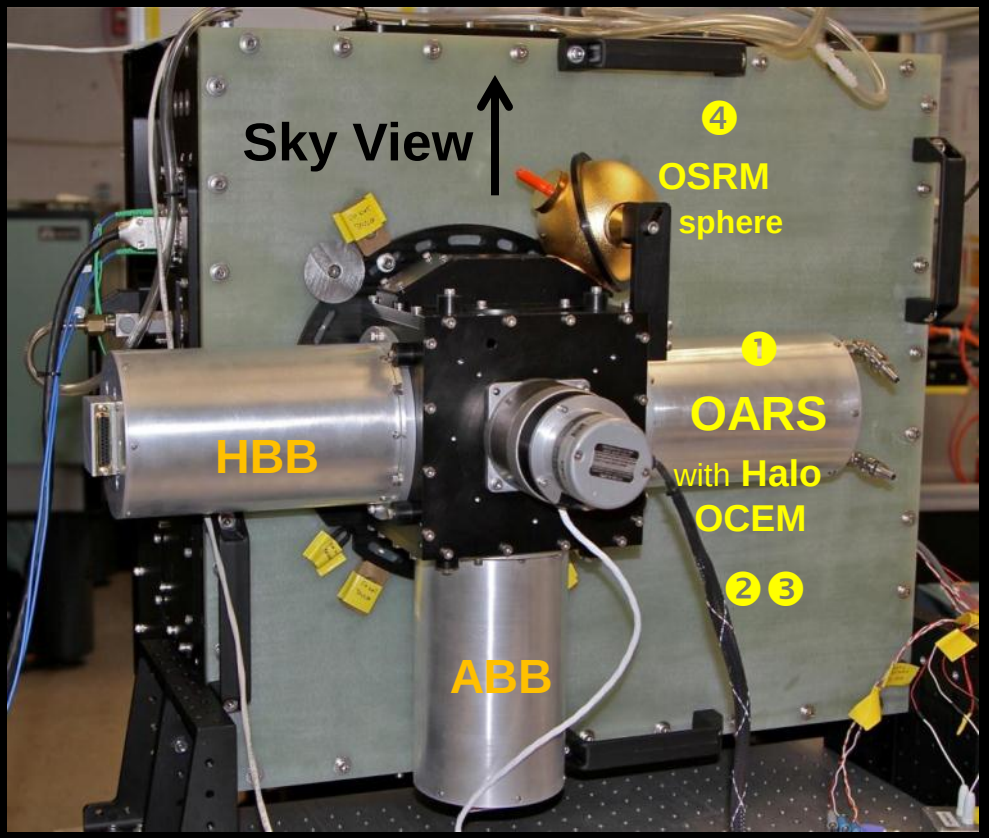
❶ On-orbit Absolute Radiance Standard (OARS) cavity blackbody using three miniature phase change cells to establish the temperature scale from -40, to +30 C to better than 10 mK

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*

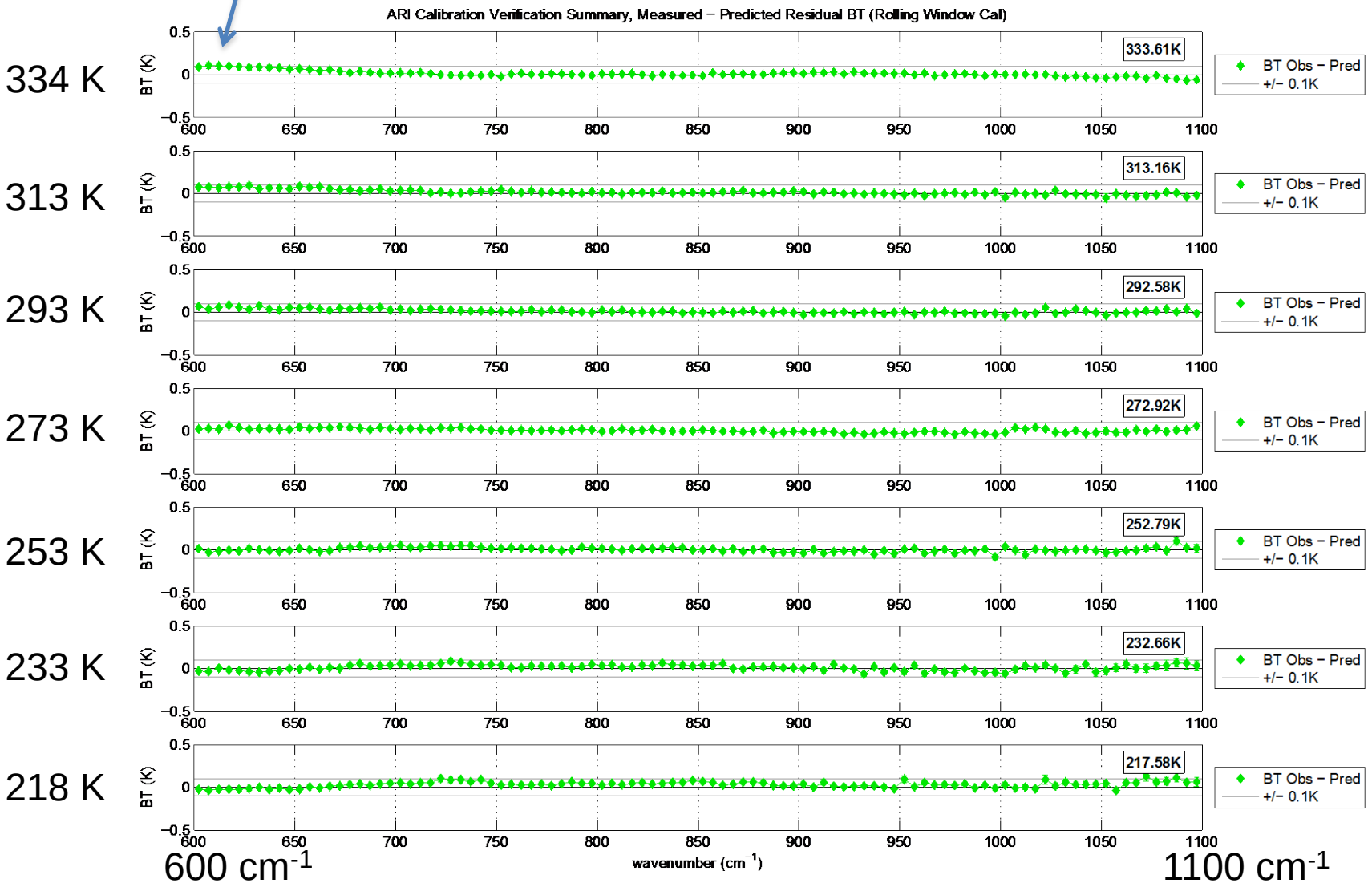
Brightness Temperature Accuracy Verified to < 0.1 K

(CFTS calibrated - OARS verification)

MCT

Correction of field stop problem removes this error

Error bars only include statistical error in measurement

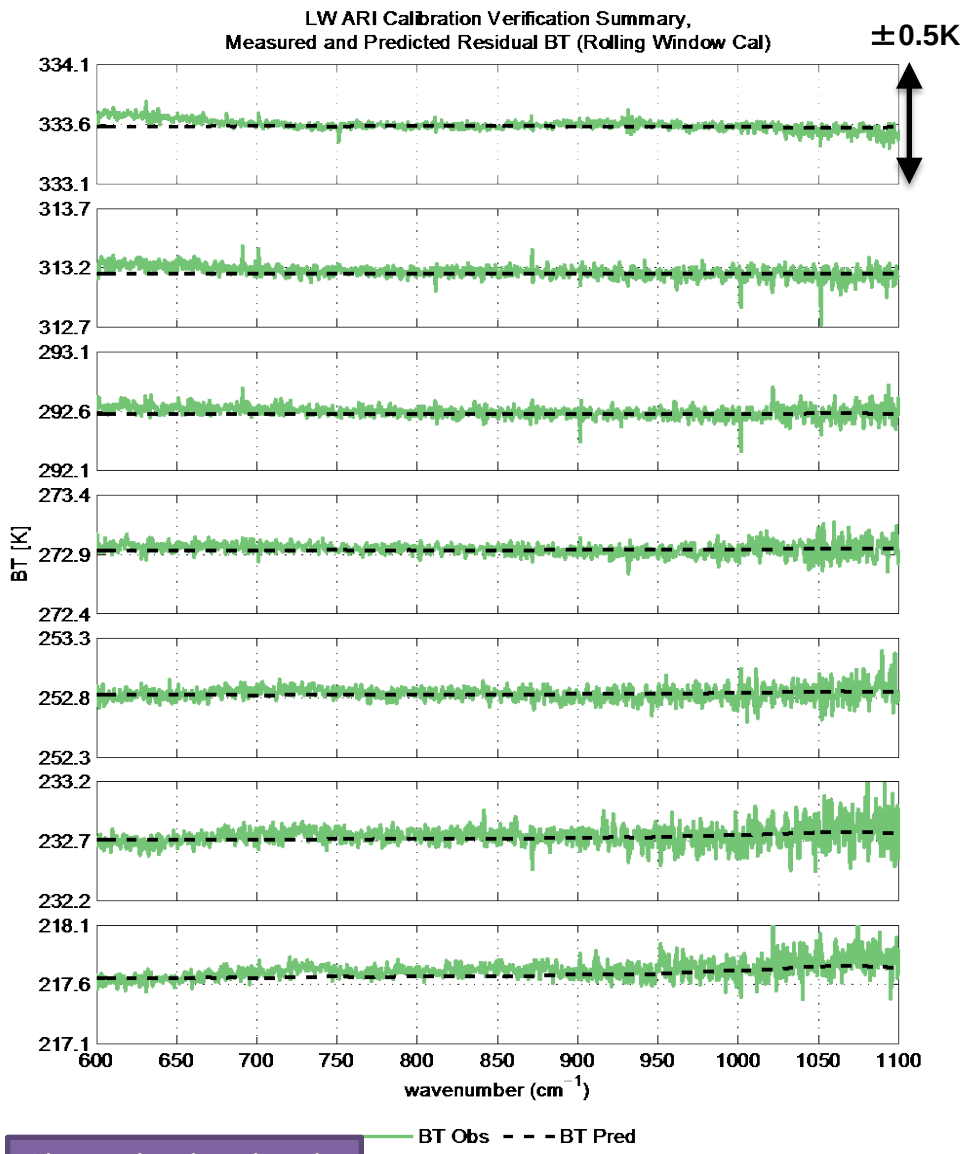


Spectral Averaging Bin Width is 5 cm^{-1}

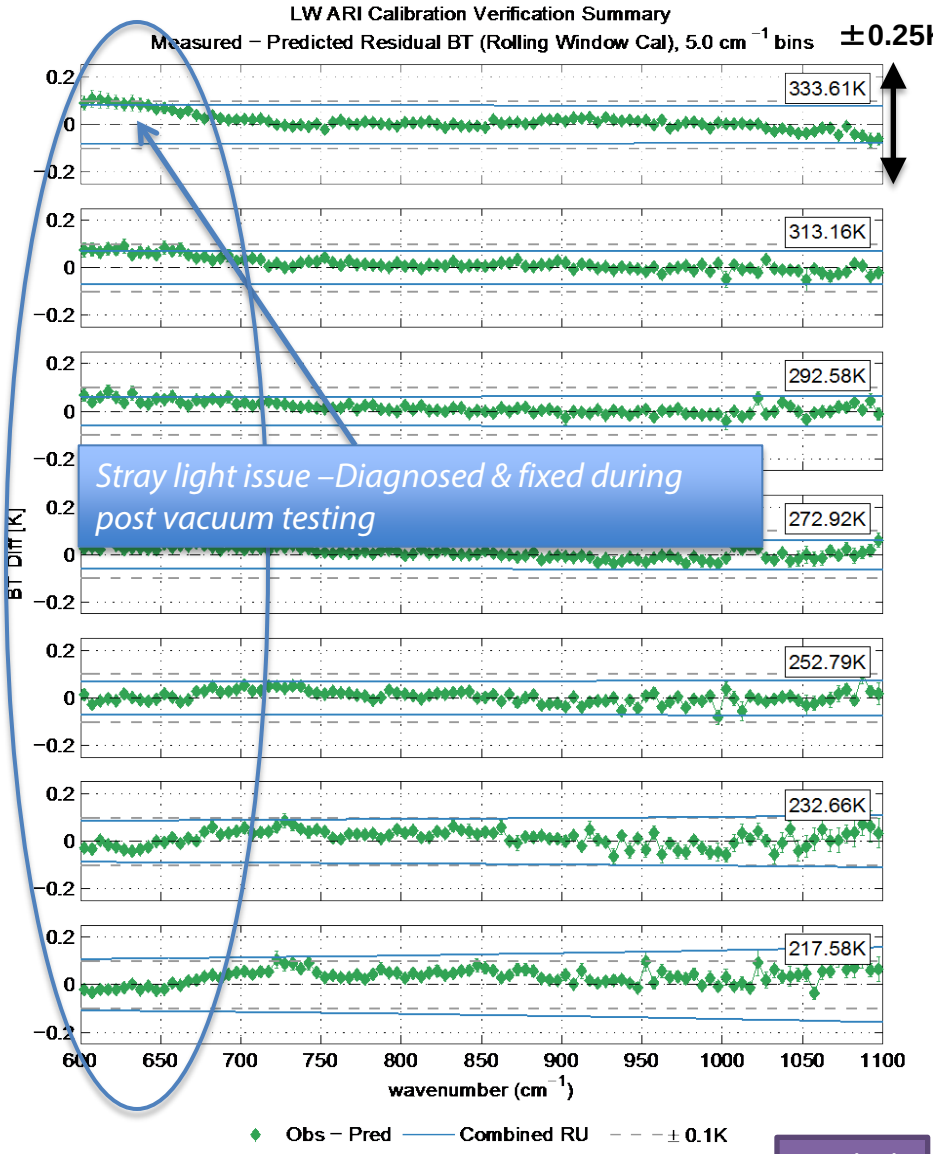
Original Vacuum Data Collect shown before

Demonstration of Required Radiometric Accuracy, LW MCT

Original Vacuum Data Collect



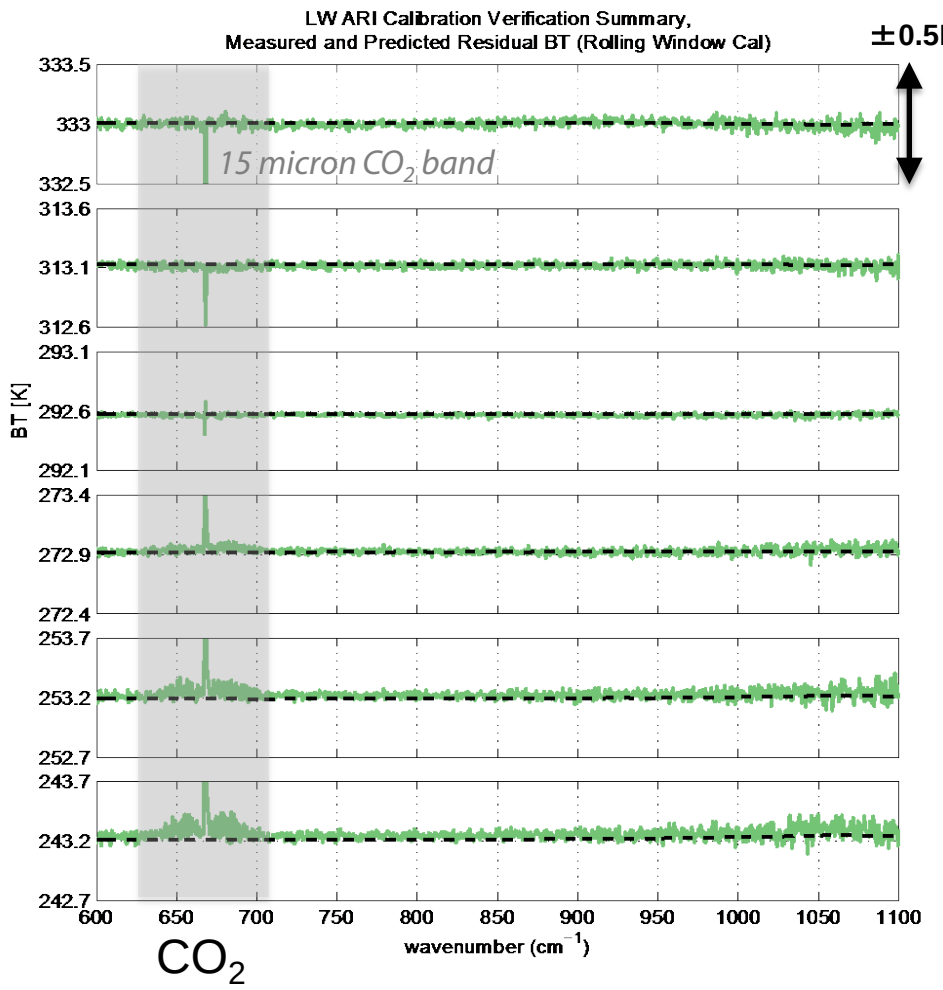
Observed and Predicted

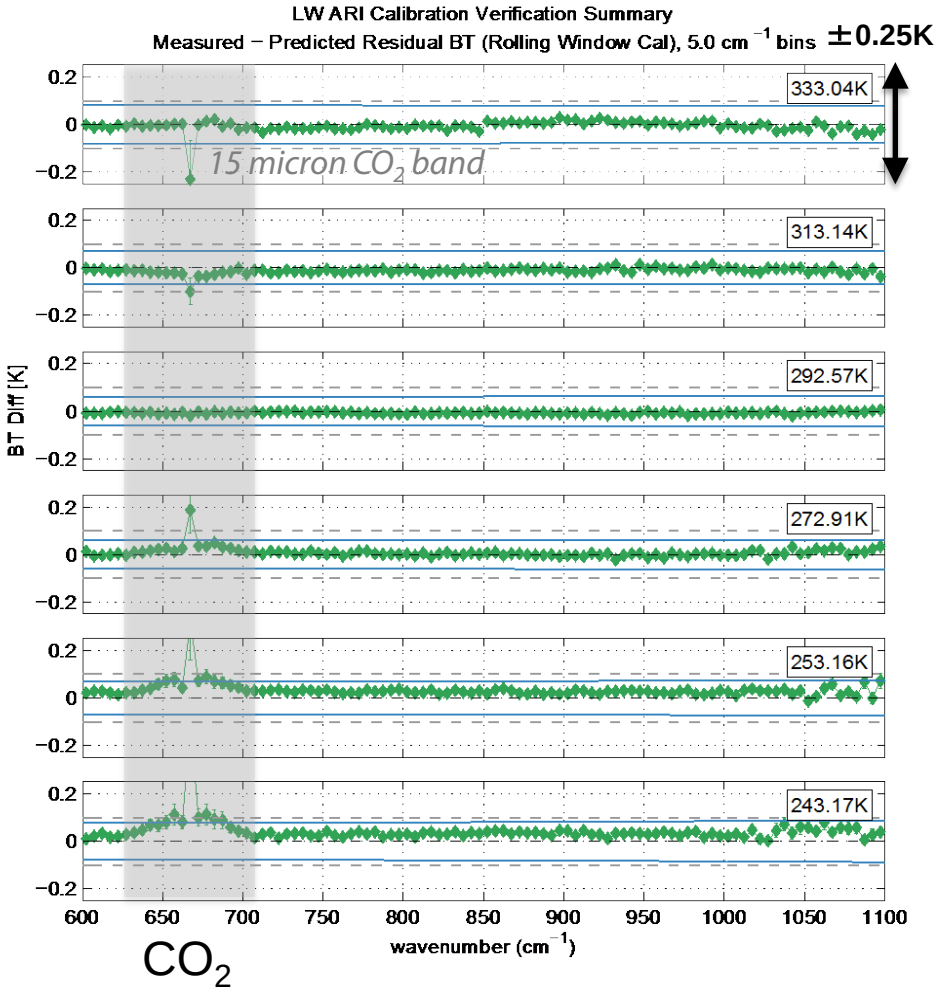


Residual

Demonstration of Required Radiometric Accuracy, LW MCT

New 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

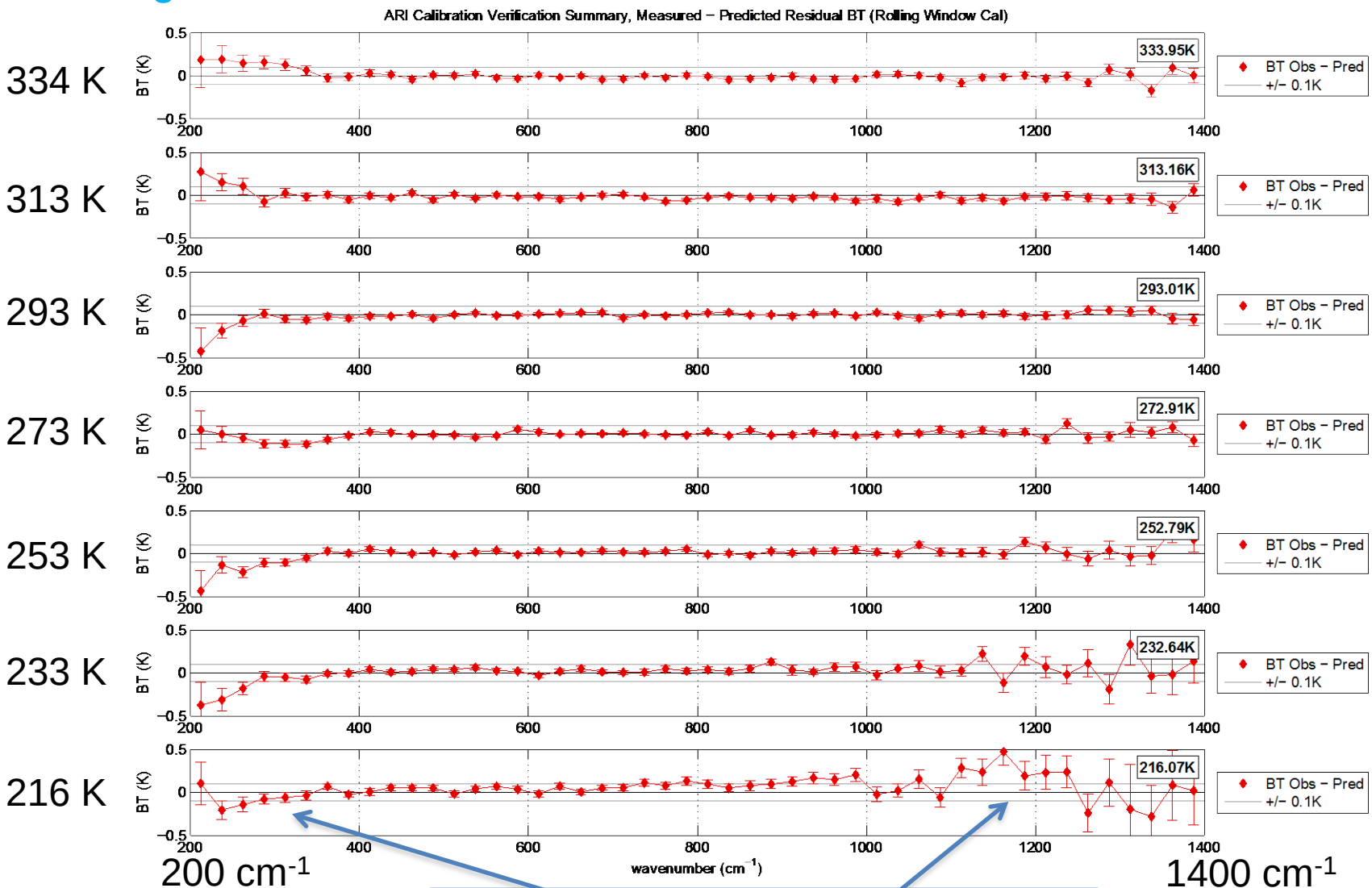
Brightness Temperature Accuracy Verified to < 0.1 K

(CFTS calibrated - OARS verification)

DTGS

Original Vacuum Data Collect shown before

Error bars only include statistical error in measurement

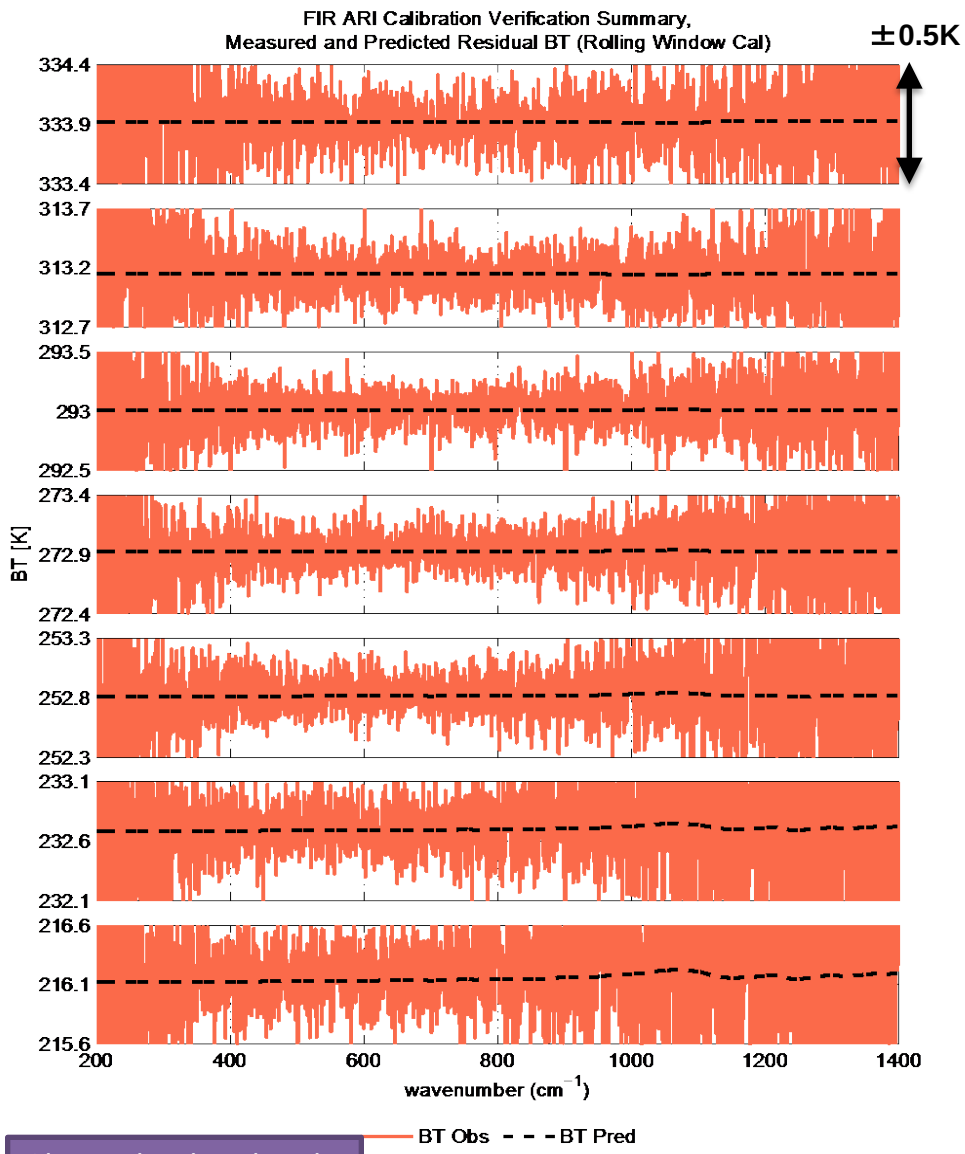


Bin averaged result subject to low SNR at band edges

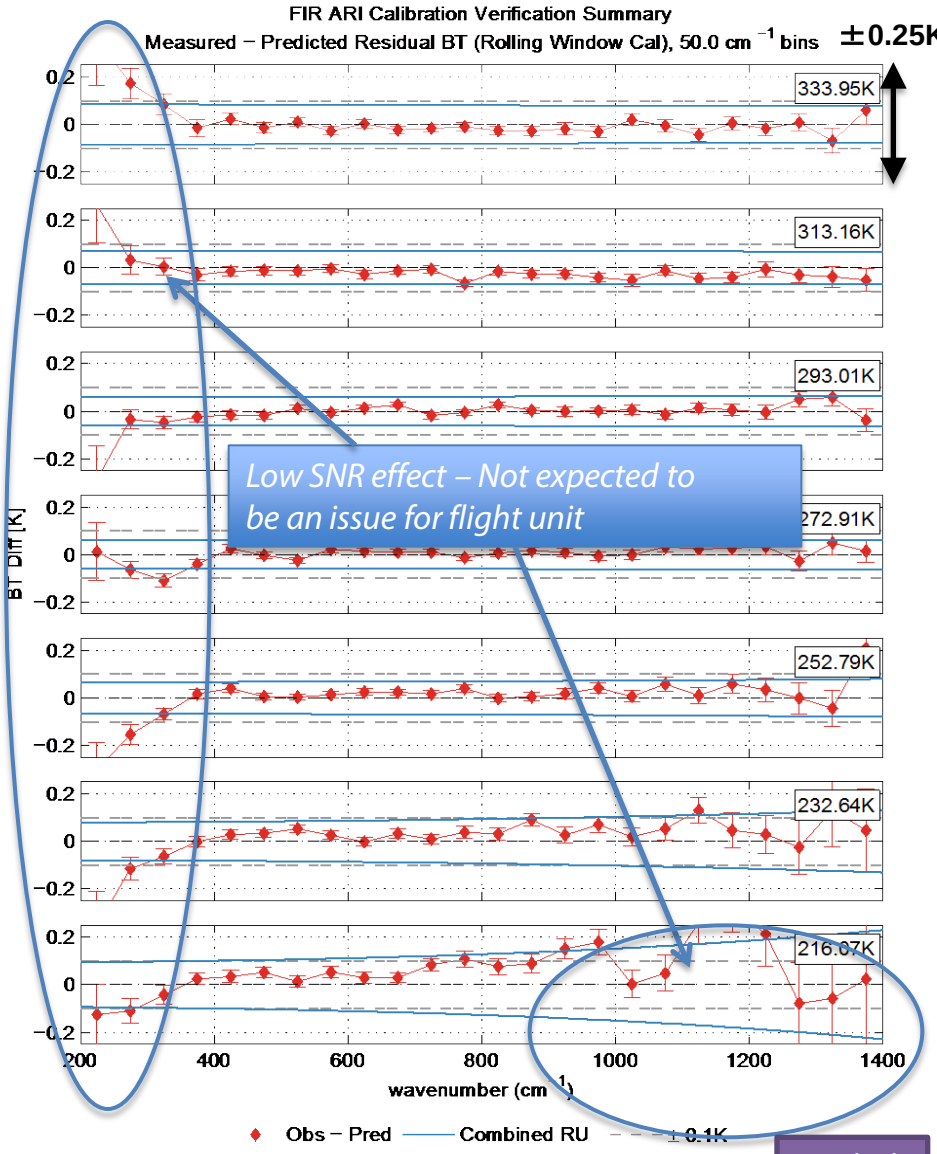
Spectral Averaging Bin Width is 25 cm^{-1}

Demonstration of Required Radiometric Accuracy, DTGS

2015 Data Collect – Dry Air Purge



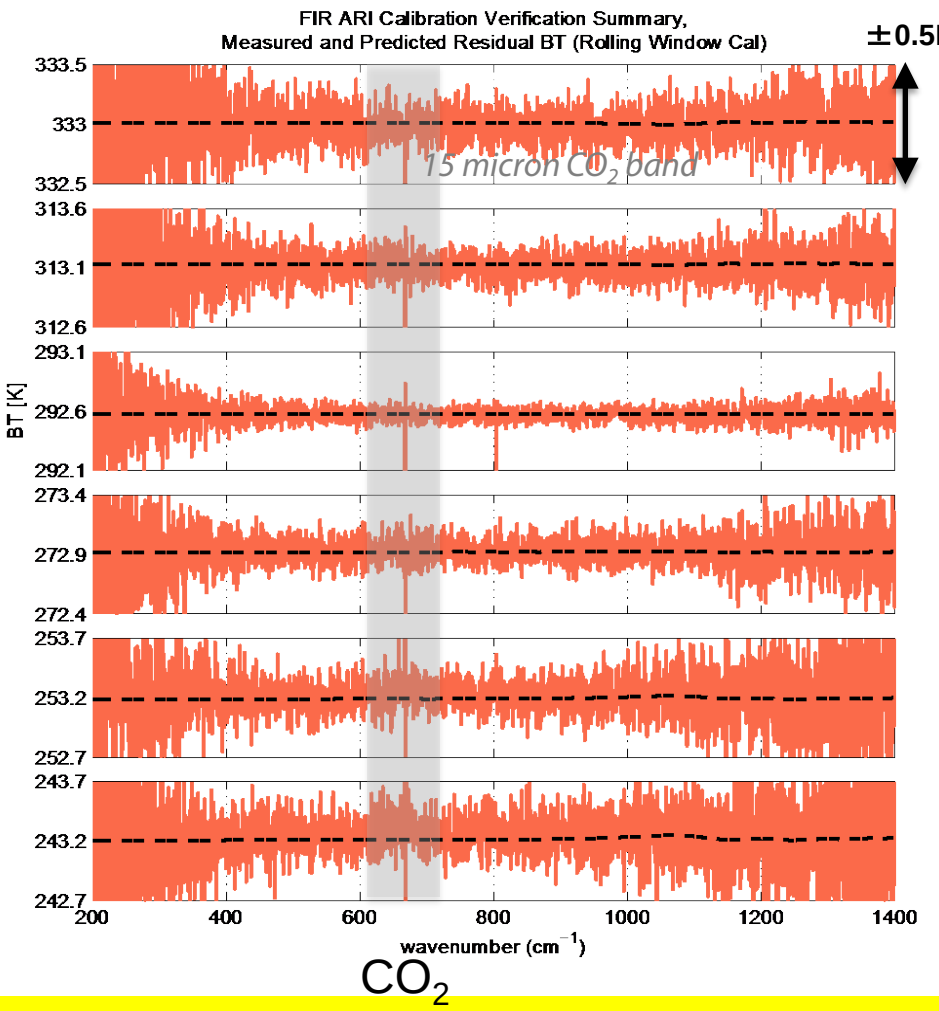
Observed and Predicted

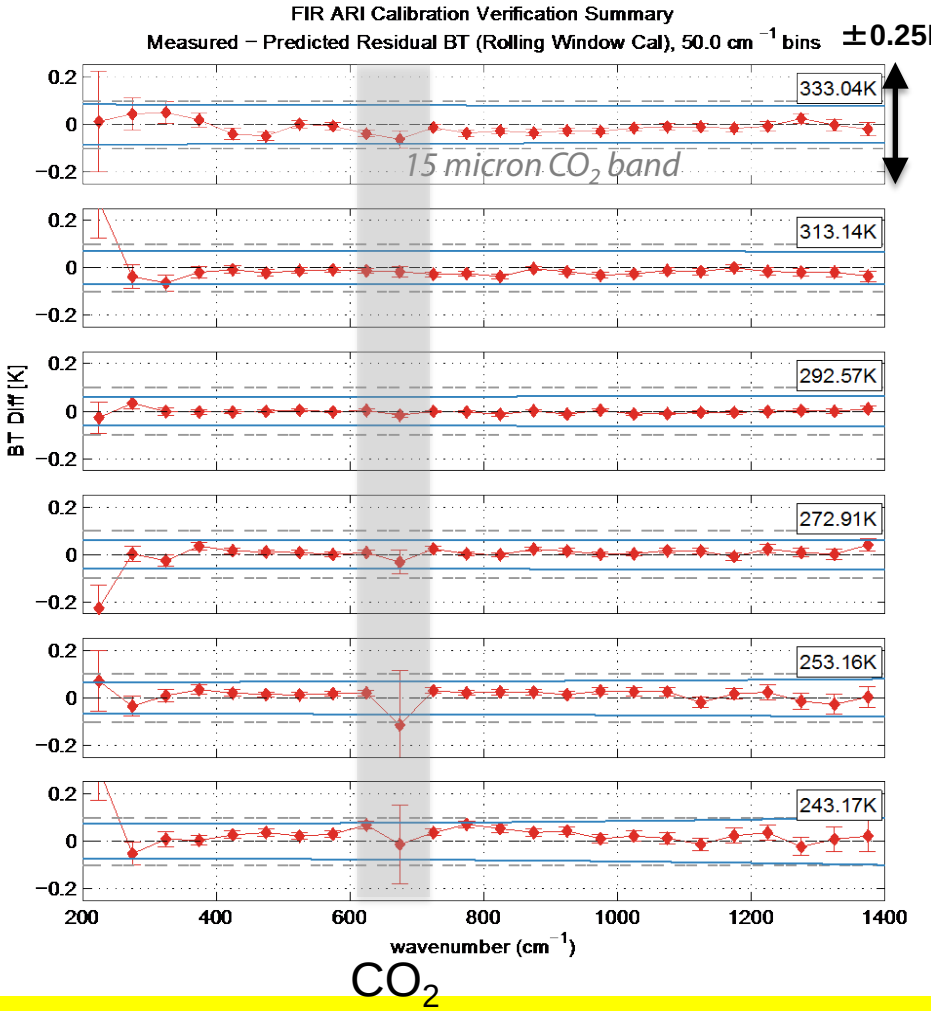


Residual

Demonstration of Required Radiometric Accuracy, DTGS

New 2015 Data Collect – Dry Air Purge





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

Observed and Predicted — BT Obs – – – BT Pred

Residual — ♦ Obs − Pred — Combined RU – – – ± 0.1K

Summary

- **CLARREO pathfinder on ISS** would provide economical risk reduction for the full CLARREO mission and a chance to improve the overall accuracy of operational environmental satellite capabilities and leverage them to start a global benchmark record. **And it is now in the FY2016 President's Budget Request and satisfied the NASA PPBE process**
- **CLARREO IR Flight Prototype, ARI** has passed ESTO TRL assessments and laboratory test results have demonstrated the capability to meet full CLARREO mission performance requirements
- **US 2017 NRC Decadal Survey White Papers Due Today:** Several white papers arguing for the importance of proceeding with the full CLARREO Mission are being submitted

Let's hope the Pathfinder stays in the FY2016 Budget and that a commitment is soon made to the full mission!