A New Class of Advanced Accuracy Satellite Instrumentation for Earth Observation

(UW-Harvard project, NASA Instrument Incubator Program)

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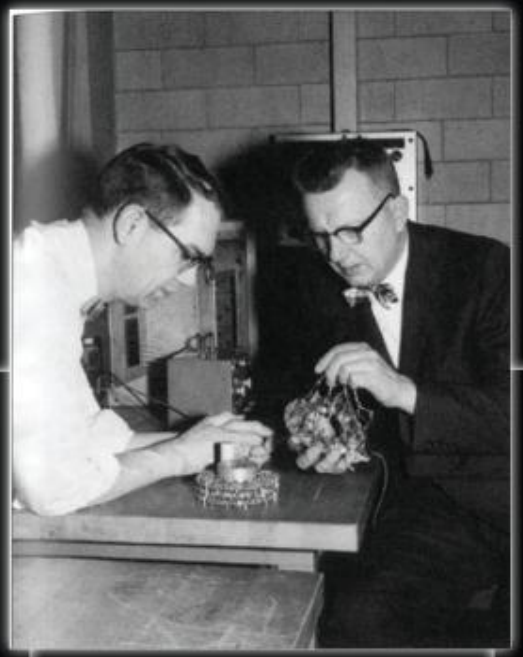
Space Science and Engineering Center

2011 Workshop on Far-Infrared Remote Sensing
University of Wisconsin-Madison
Pyle Center, 8-9 November 2011

The need for high spectral resolution observations for Climate benchmarking (a la CLARREO) motivates the drive for High accuracy

- For climate, we have been making broadband total radiance and flux measurements for 50 years, starting with Verner Suomi and Robert Parent's 1st experiment to look at the Earth from space
- To unequivocally resolve key climate trends on the decadal time scale, we need a new approach with higher information content
- Spectrally resolved IR radiance measurements combined with **SI-traceable on-orbit standards** can deliver the needed information content with proven accuracy
  (when sampling biases are controlled by orbit choice)
- Broad spectral coverage, **including much of the Far-IR**, is important for optimizing information content

October 1959 - October 2009



Suomi/Parent Radiometer

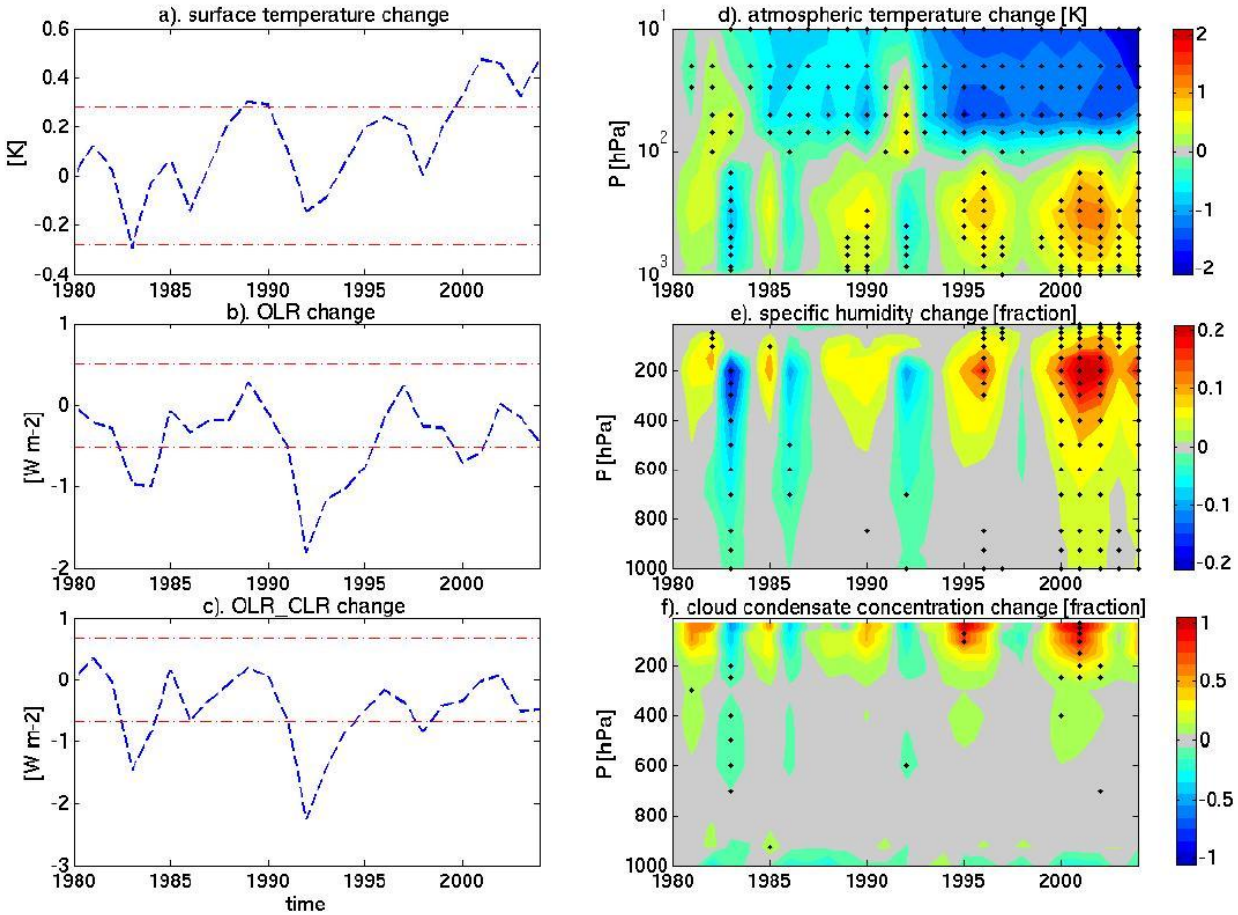
Explorer VII

50 YEARS

50 years celebrated 2 November 2009, Madison, Wisconsin

CM2 25-yr Annual Mean Trends

Yi Huang, McGill University



Note OLR insensitivity to trends in T, WV, and Clouds

Black dots indicate changes > 3 x standard deviation of unforced means

IR Accuracy Requirements for Climate Benchmarking

Radiance Accuracy: <0.1 K 2-sigma brightness T for combined measurement and sampling uncertainty for annual averages of 15° zones (each <0.1 K 3-sigma) to approach goal of resolving a climate change signal in the decadal time frame

On-orbit Verification and Test: Provide an On-orbit Absolute Radiance/Brightness Temperature Standard with an accuracy of <0.1 K 3-sigma to provide SI traceability of on-orbit measurements

Topics: IR Measurement Science

- Background on IR Accuracy: Calibration and Validation of current sounders supports 0.1 K 3-sigma being achievable for CLARREO
- NASA Instrument Incubator Program (IIP) achievements demonstrate
  On-orbit Verification and Test System

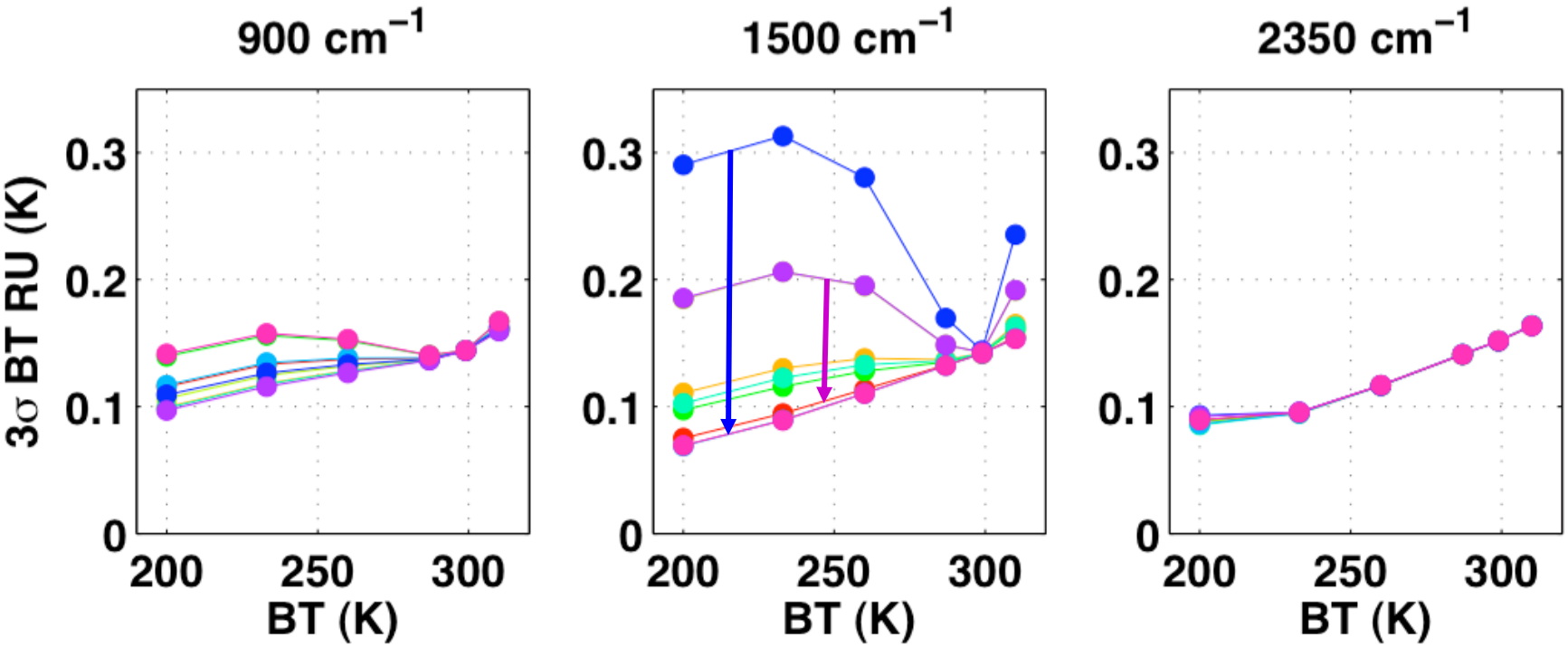
Current System Capabilities

- **New High Resolution IR Sounders:** AIRS, IASI, CrIS…
  - Tremendous advance in information content & accuracy
  - Huge advance for climate process studies, offering
    - High vertical resolution T and WV profiling
    - Trace gas distributions
    - Cloud and surface properties
  - Provide a solid foundation for CLARREO IR feasibility
  - <u>But, not optimized for unequivocal decadal trending</u>
    - Biased diurnal sampling
    - Inconsistent and incomplete spectral coverage among platforms
    - Accuracy can be improved (by factor of 4-5)
    - SI traceability post-launch limited to aircraft inter-comparisons
      (sounder-to-sounder comparisons useful, but do not have direct, timely connections to International Standards)

CrIS FM1 In-flight Radiometric Uncertainty:

versus scene temperature for all FOVs for ~mid-band spectral channels

Generally < 0.2 K 3-sigma for all scene temperatures

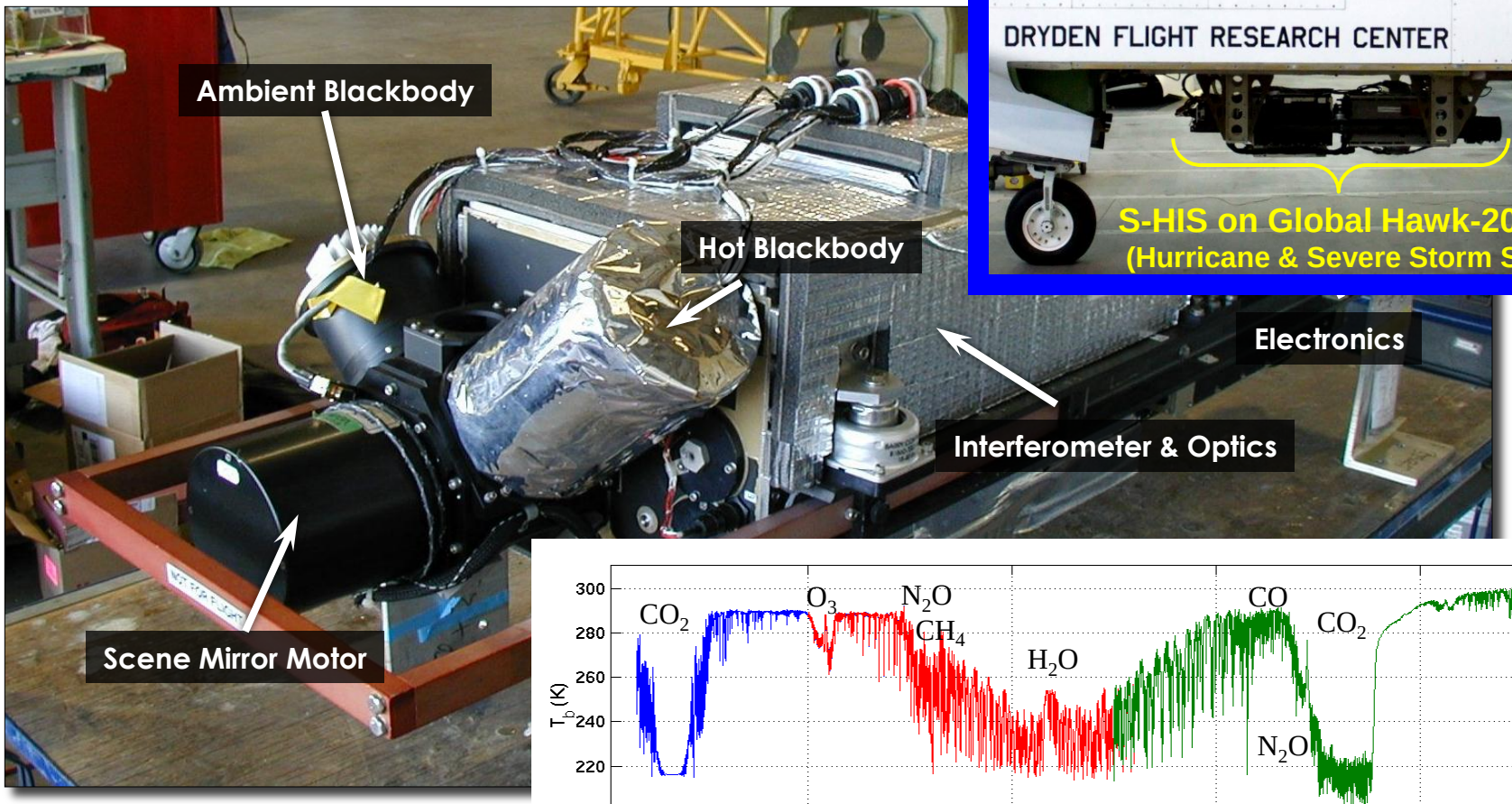


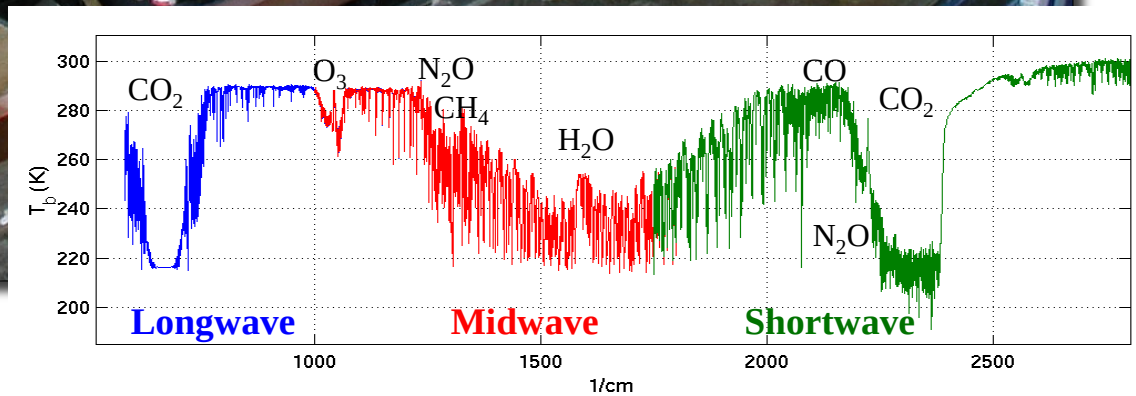
Non-linearity causing prominent FOV dependence (color coded) will be reduced significantly by in-flight FOV inter-comparisons

Tobin, D., J. Taylor, L. Borg, H. Revercomb, 2010: Expected On-orbit Radiometric Performance of the CrIS and comparisons with IASI and AIRS. CALCON Technical Conference, 23-26 August, Utah State University, Logan, UT.

UW Scanning HIS

Provides Sounder Inflight Validation

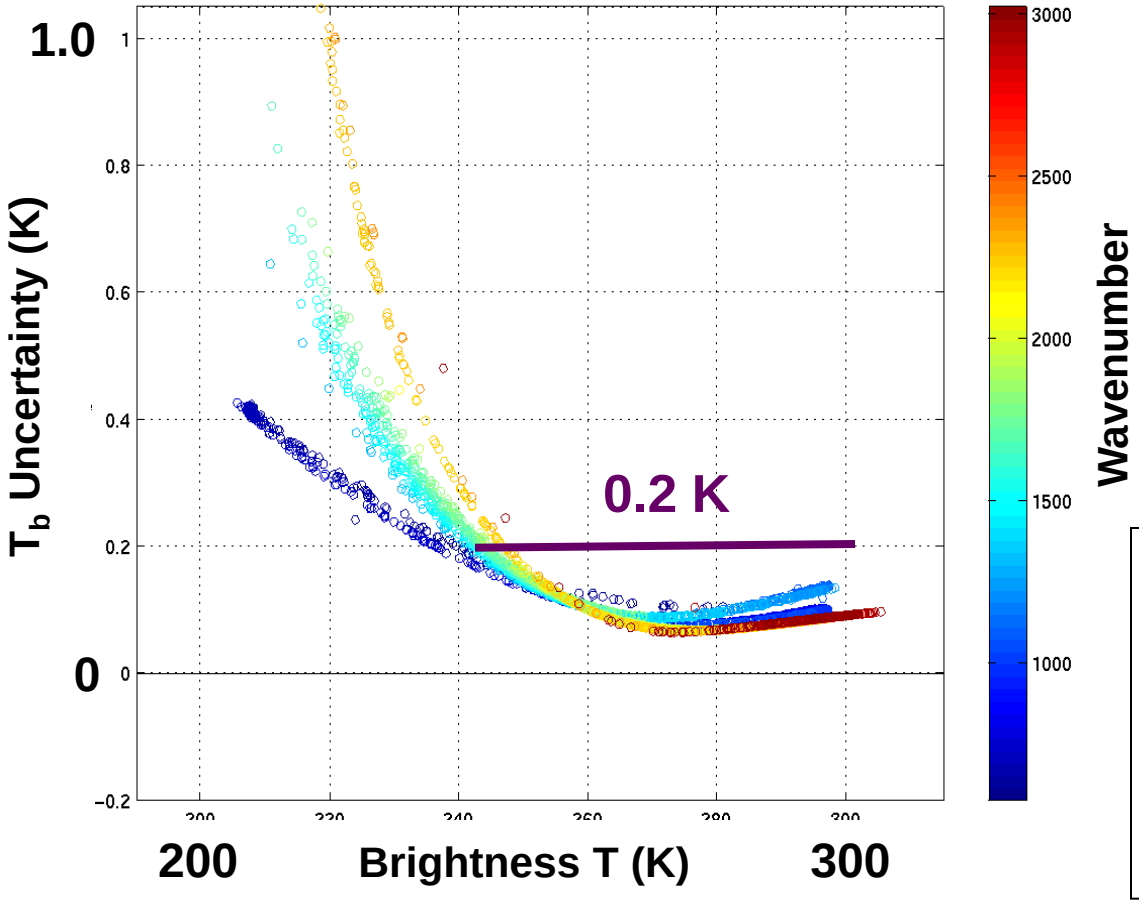




S-HIS Absolute Radiometric Uncertainty

for typical Earth scene spectrum

****Formal 3-sigma absolute uncertainties, similar to that detailed for AERI in Best et al. CALCON 2003**

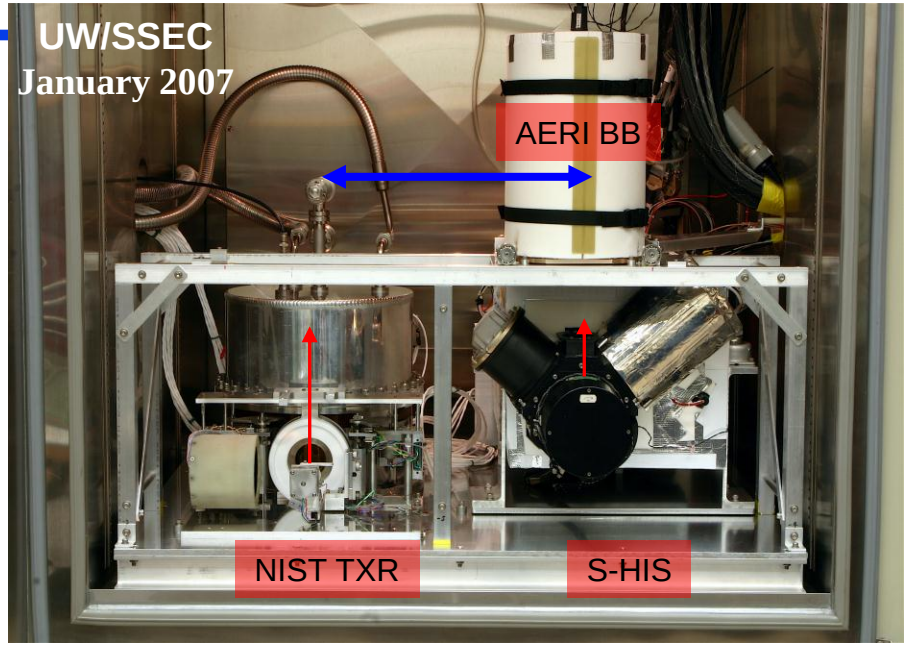


T_{ABB}= 260 K
T_{HBB}= 310 K

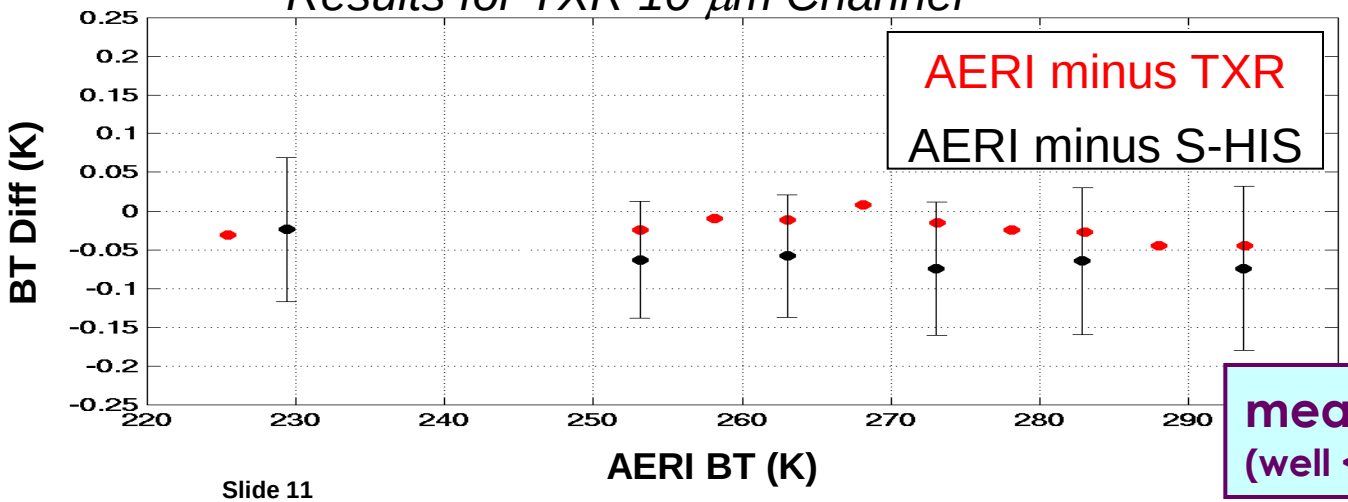
σT_{BB} = 0.10 K
$\sigma \varepsilon_{BB}$ = 0.0010
σT_{refl} = 5 K
10% nonlinearity

UW S-HIS & AERI Blackbody Absolute Accuracy: The NIST Connection for SI Traceability

End-to-end S-HIS radiance evaluations conducted under S-HIS flight-like conditions with NIST transfer sensor (TXR) such that S-HIS satellite validation & AERI observations are traceable to the NIST radiance scale



Results for TXR 10 μm Channel

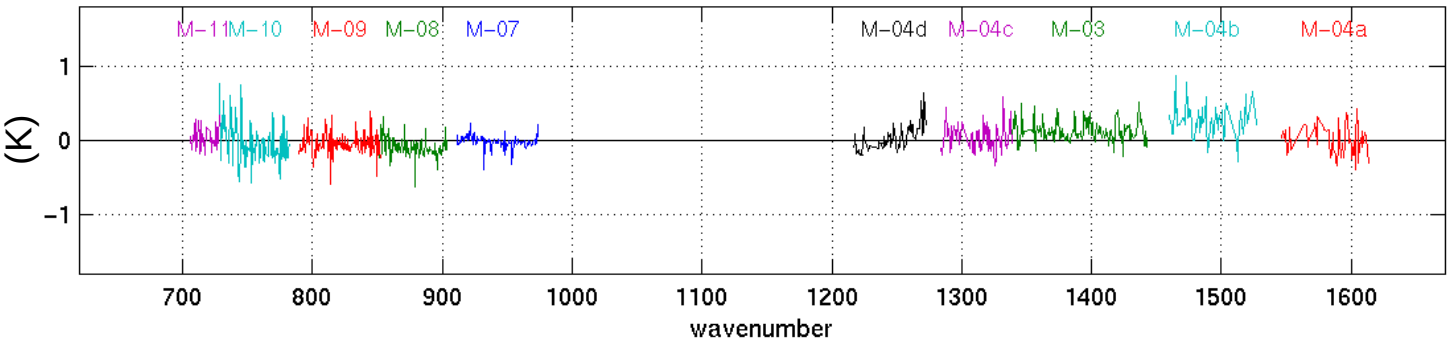


mean = -22 mK

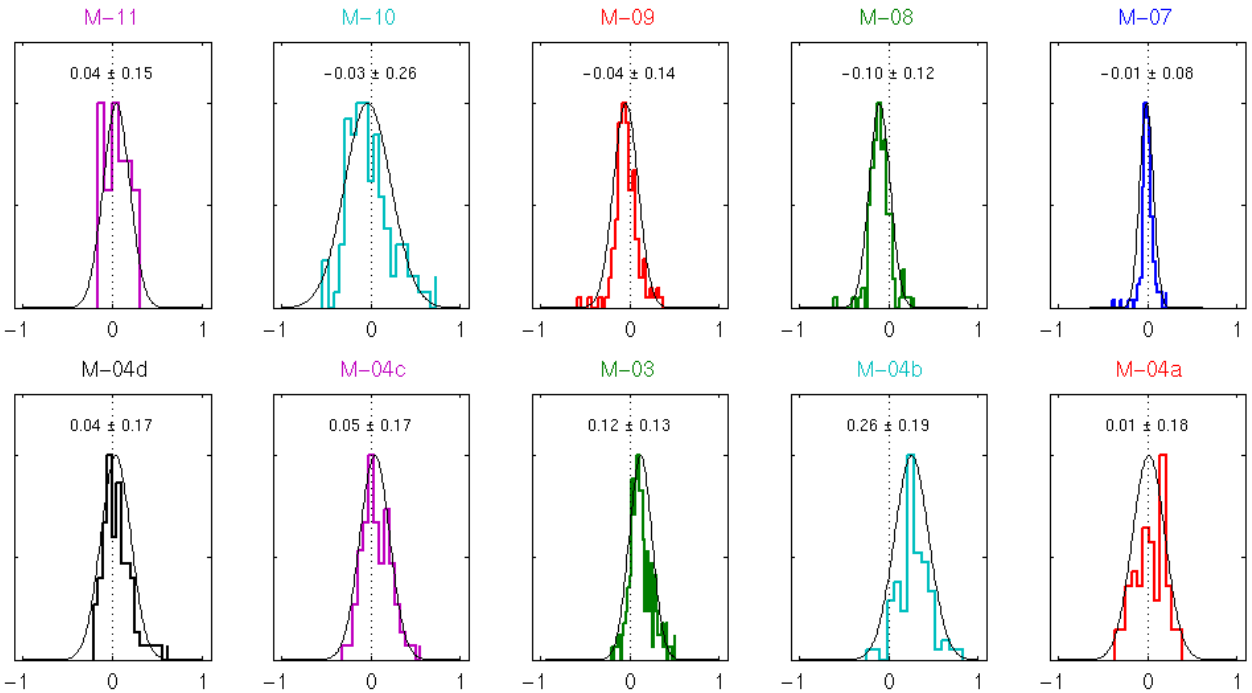
mean = -60 ± 90 mK

mean S-HIS-TXR = 38 mK
(well < 3-sigma uncertainties)

Example S-HIS Validation of AIRS



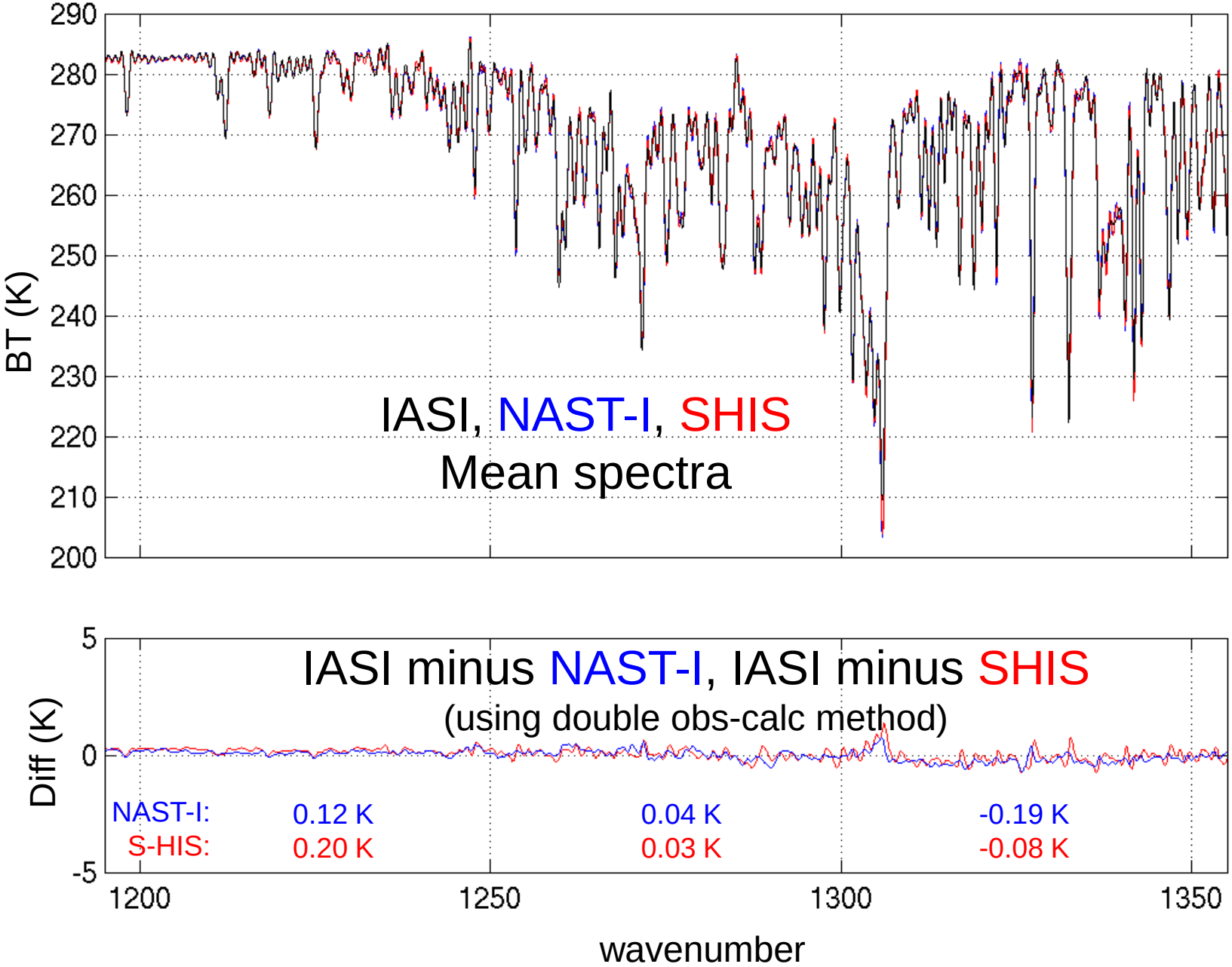
Aircraft is key approach for direct radiance validation of EOS & NPOESS, and will be key to CLARREO validation also



21 November 2002

Tobin, D.C., et al., 2006: *J. Geophys. Res.*, 111, doi:10.1029/2005JD006094.

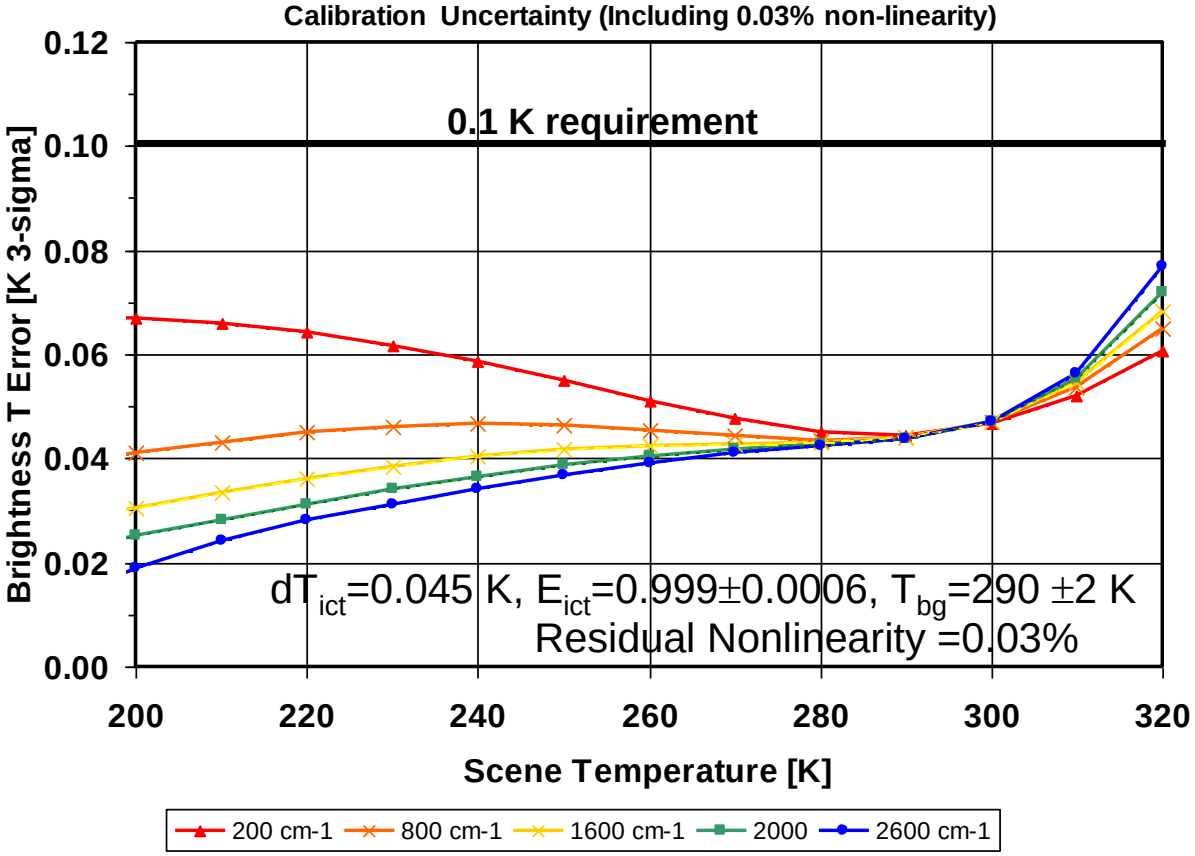
IASI Midwave Validation



IR Measurement Accuracy

< 0.1 K 3-sigma brightness T accuracy is achievable by applying proven techniques with simplified instrument design

(nadir only, high S/N not needed, can avoid polarization errors & minimize non-linearity)



Expected Calibration Accuracy

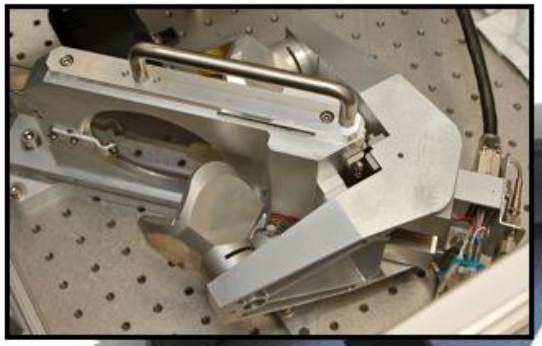
Equally achievable in Far-IR

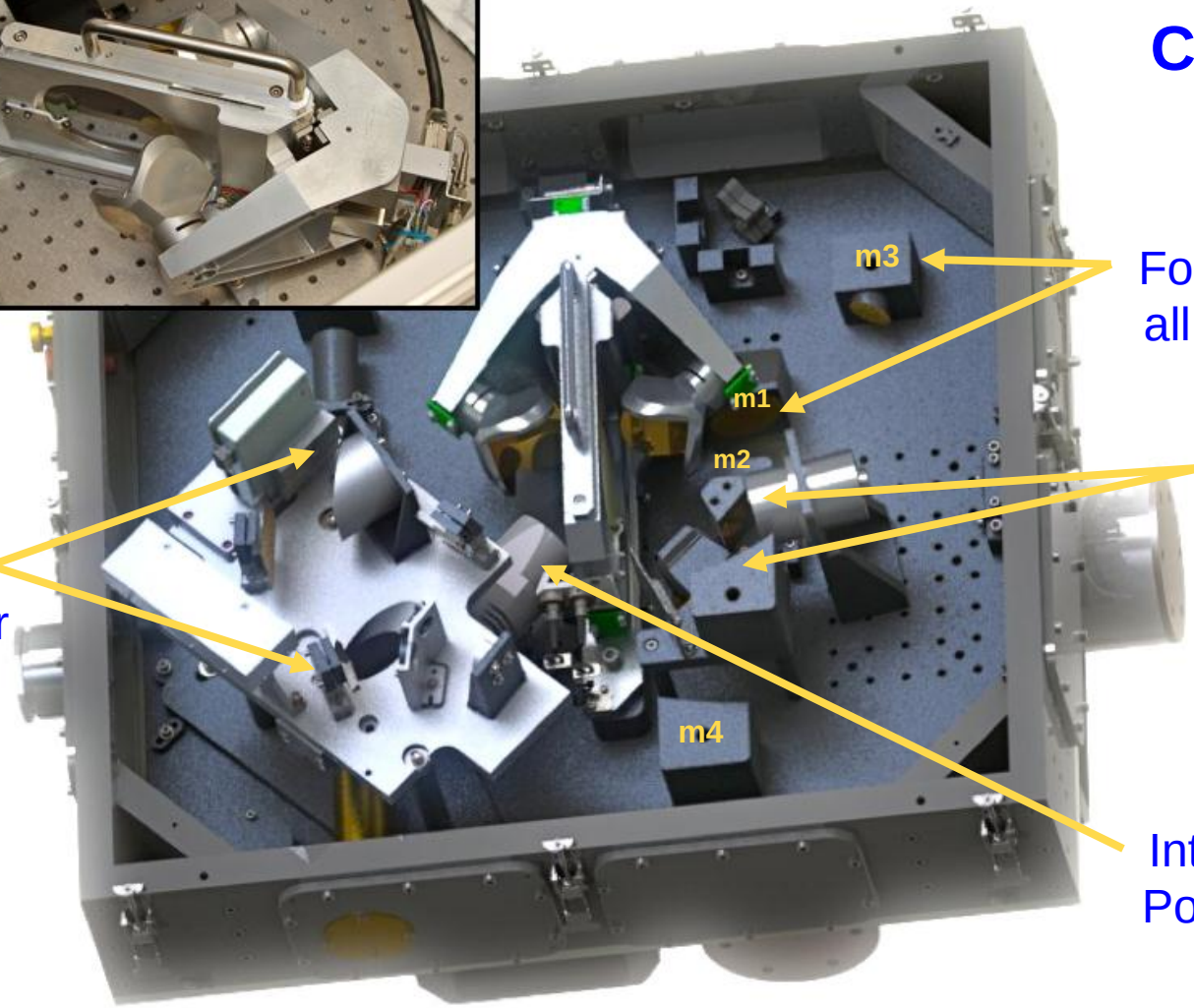
Topics: IR Measurement Science

- **Background on IR Accuracy: Calibration and Validation of current sounders supports 0.1 K 3-sigma being achievable for CLARREO**
- **NASA Instrument Incubator Program (IIP) achievements demonstrate On-orbit Verification and Test System**

Flight-like Breadboard Configuration

ABB Interfero-meter (corner cube, wishbone, CsI beam-splitter)





Calibrated FTS

Fore Optics-all reflective

Cryogenic Detector/ Dewar & Aft Optics

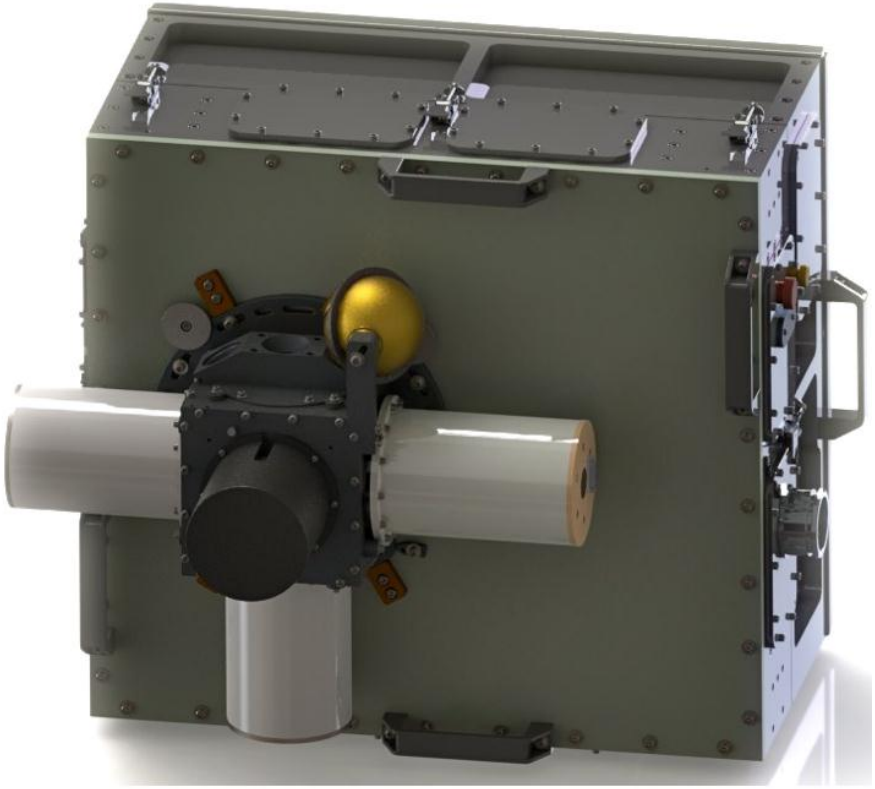
Pyroelectric Far IR Detector & all reflective Aft Optics

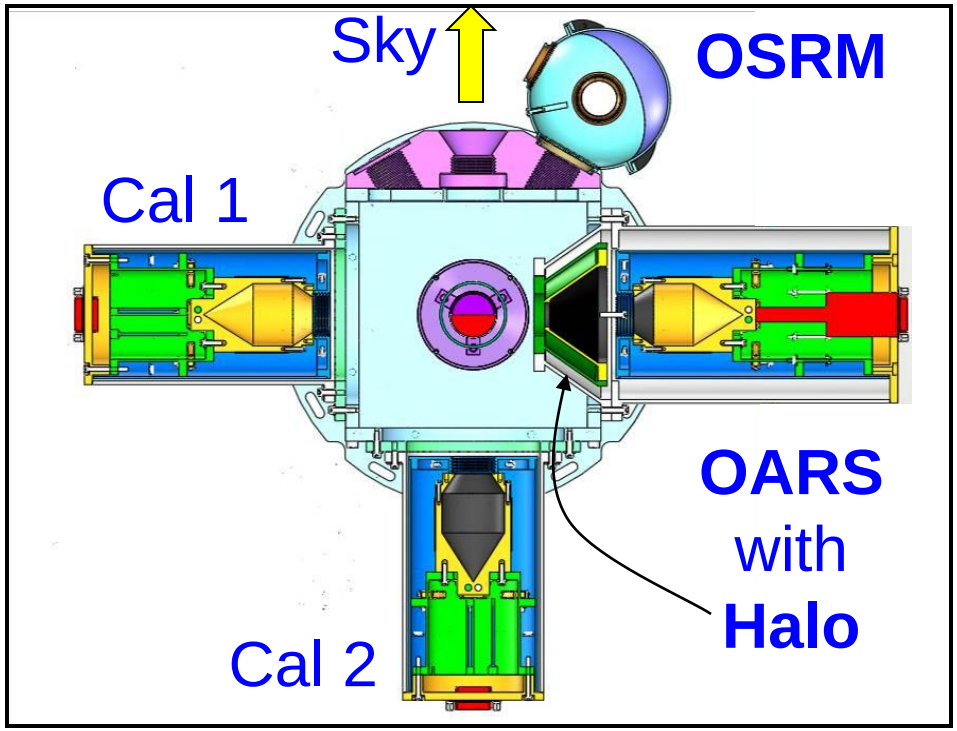
Internal Input Port 2 Source

see Joe Taylor's talk

Taylor, J.K., et al., 2011: NEWRAD
Taylor, J., et al. 2010: *SPIE*

On-Orbit Verification & Test System





- **3 cm aperture Sources**
- **45° Gold Scene Select Mirror**
- **2 Blackbodies for Calibration**

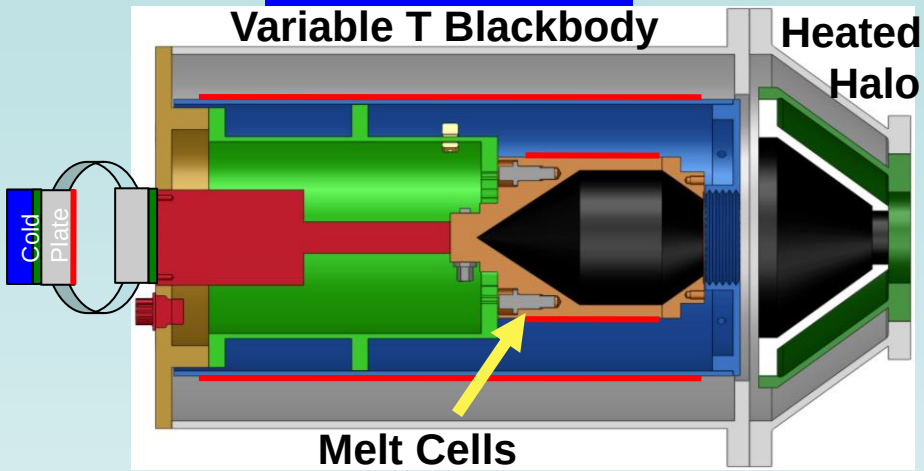
OARS: On-orbit Absolute Radiance Standard

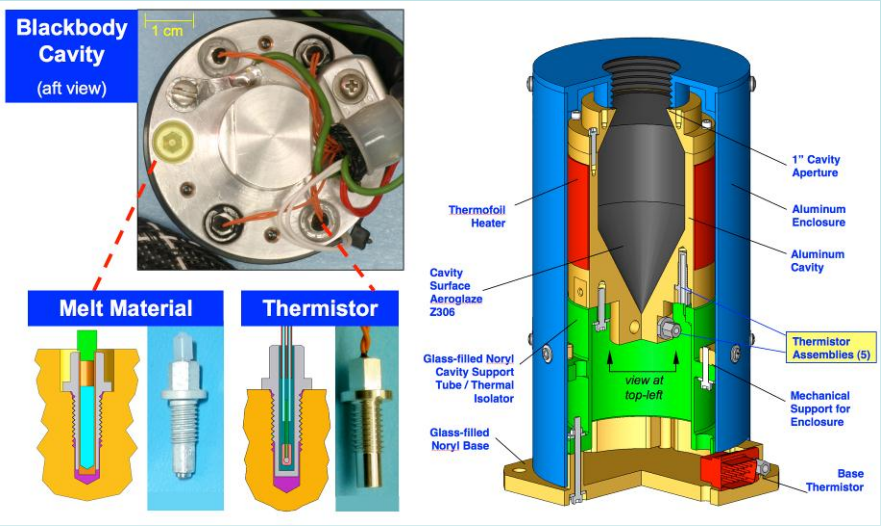
OSRM: On-orbit Spectral Response Module (QCL source)

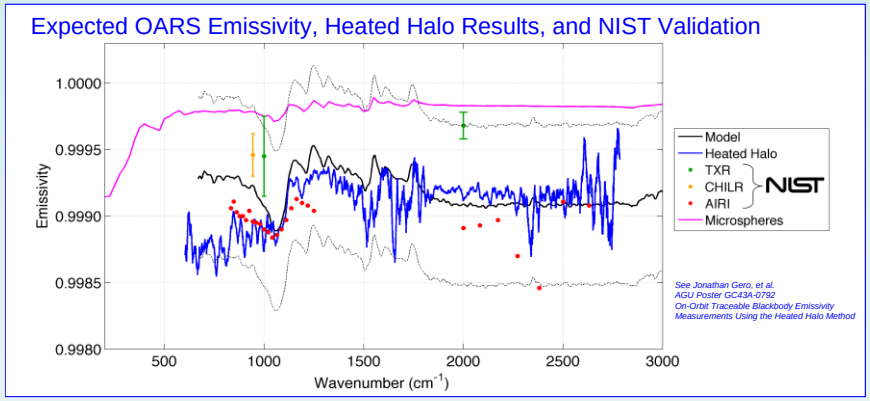
On-Orbit Absolute Radiance Standard

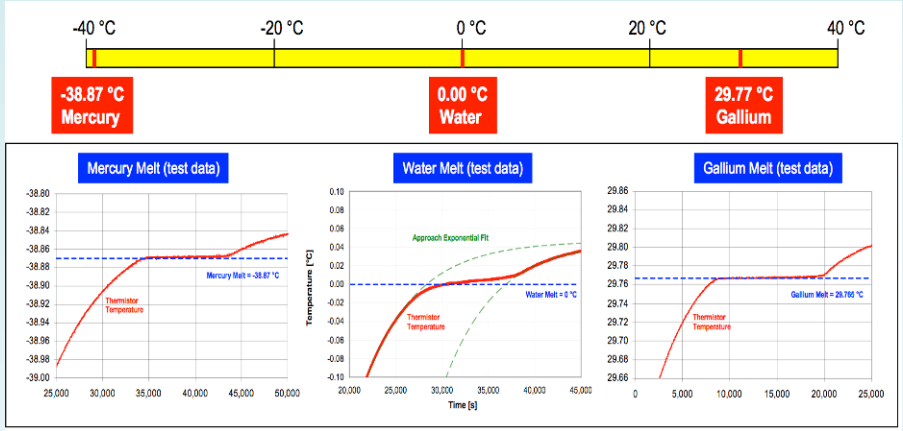
allowing calibration testing throughout mission

OARS









High Emissivity, Measured On-orbit with halo and QCL source

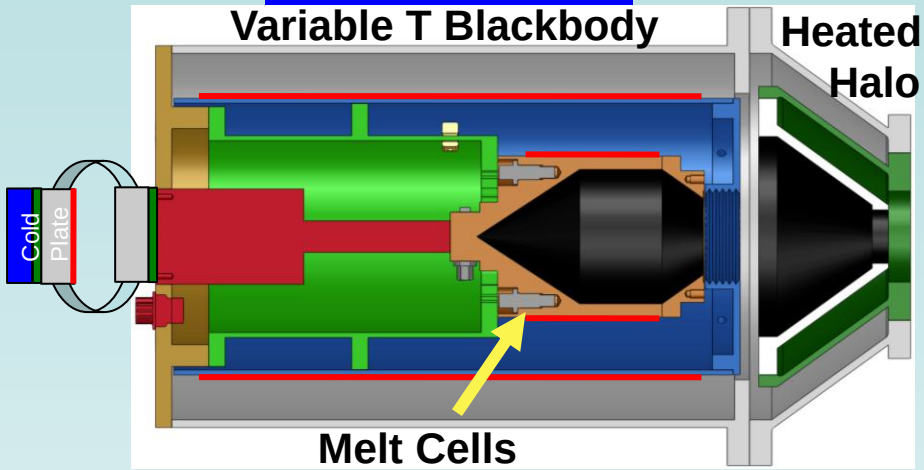
Absolute Temperature Calibration Using Multiple Phase Change Materials

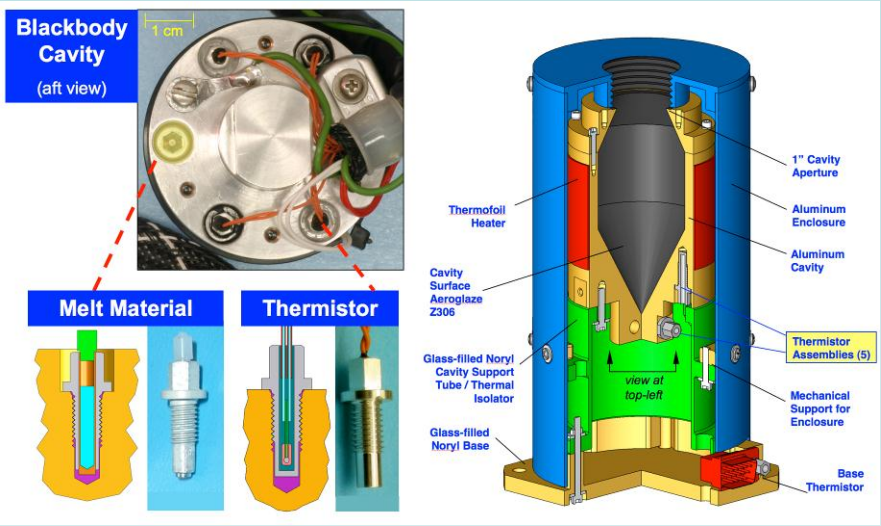
see Jon Gero's talk

On-Orbit Absolute Radiance Standard

allowing calibration testing throughout mission

OARS

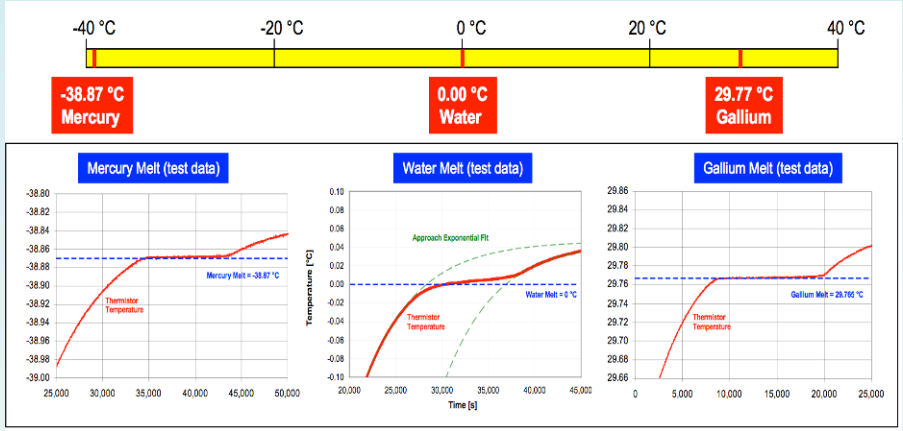




Best, F.A., D.P. Adler, S.D. Ellington, et al., 2008: *Proc. SPIE*, 7081, 70810O.

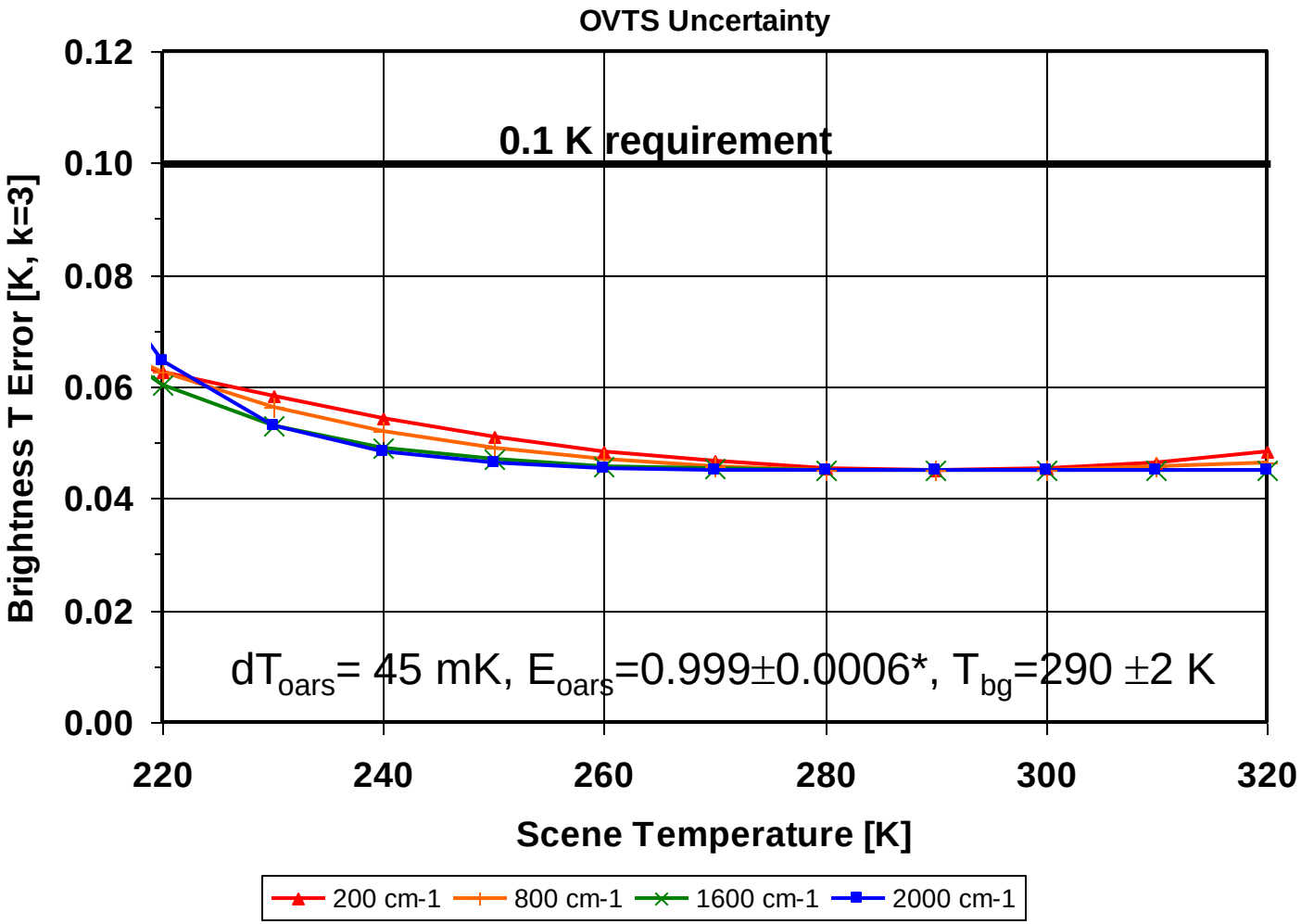
Best, F.A., D.P. Adler, C. Petterson, H.E. Revercomb, J.H. Perepezko, 2010: *Proc. SPIE*, **7857**, 78570J: doi:10.1117/12.869564.

see Fred Best's talk



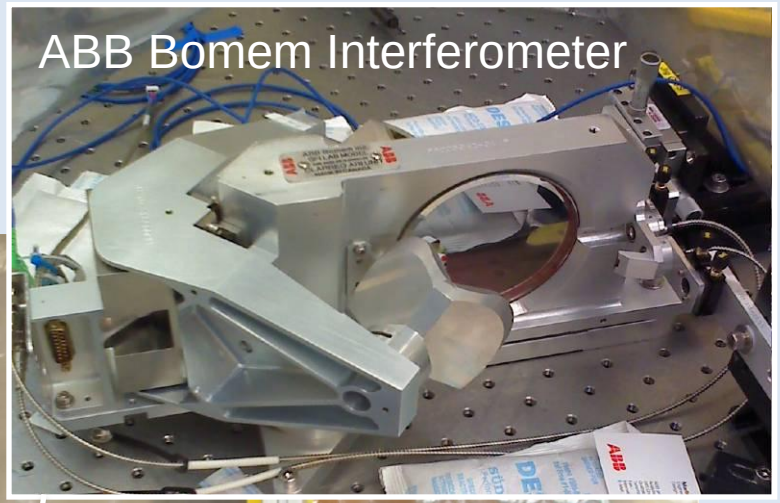
Absolute Temperature Calibration Using Multiple Phase Change Materials

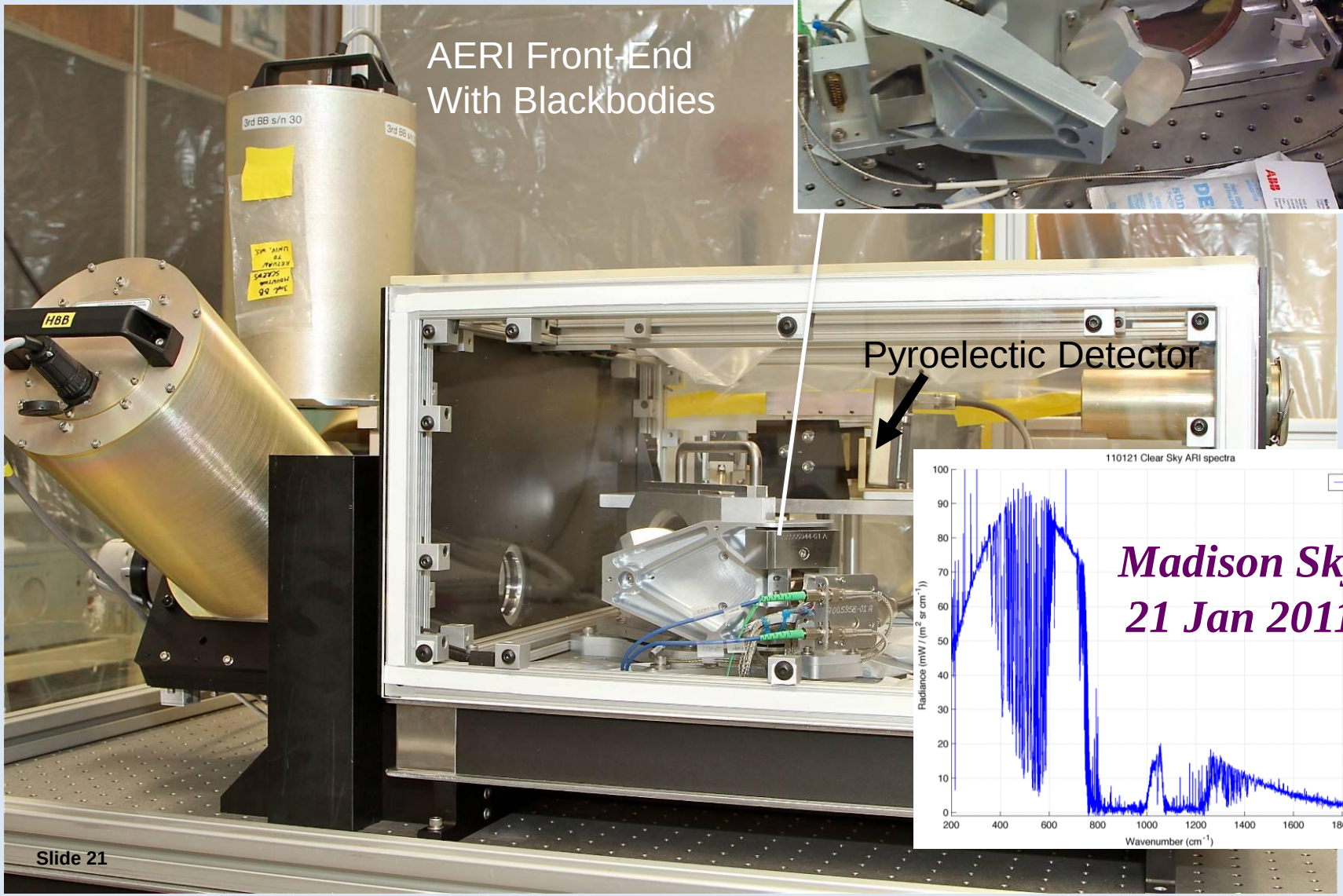
On-orbit Verification Uncertainty

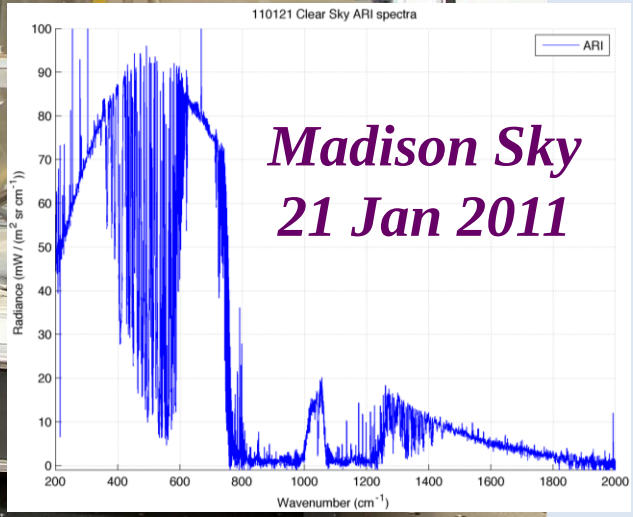


*uncertainty for low T, high wavenumbers reduced via T/V Testing with high E references

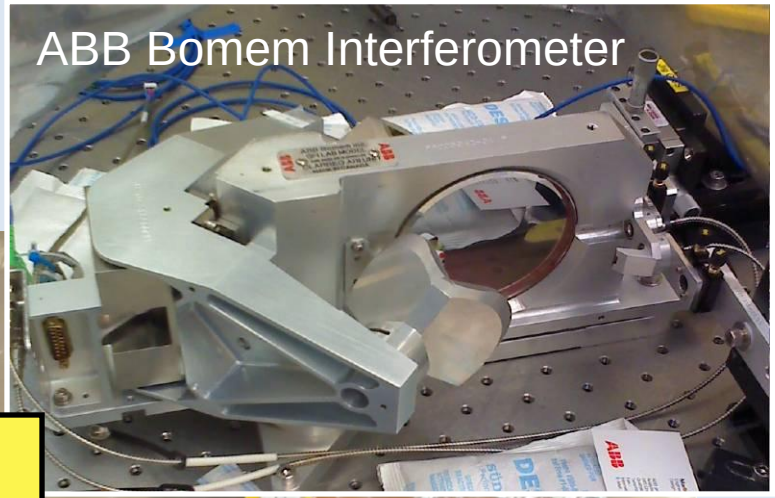
UW Breadboard ARI-1 Results Summary

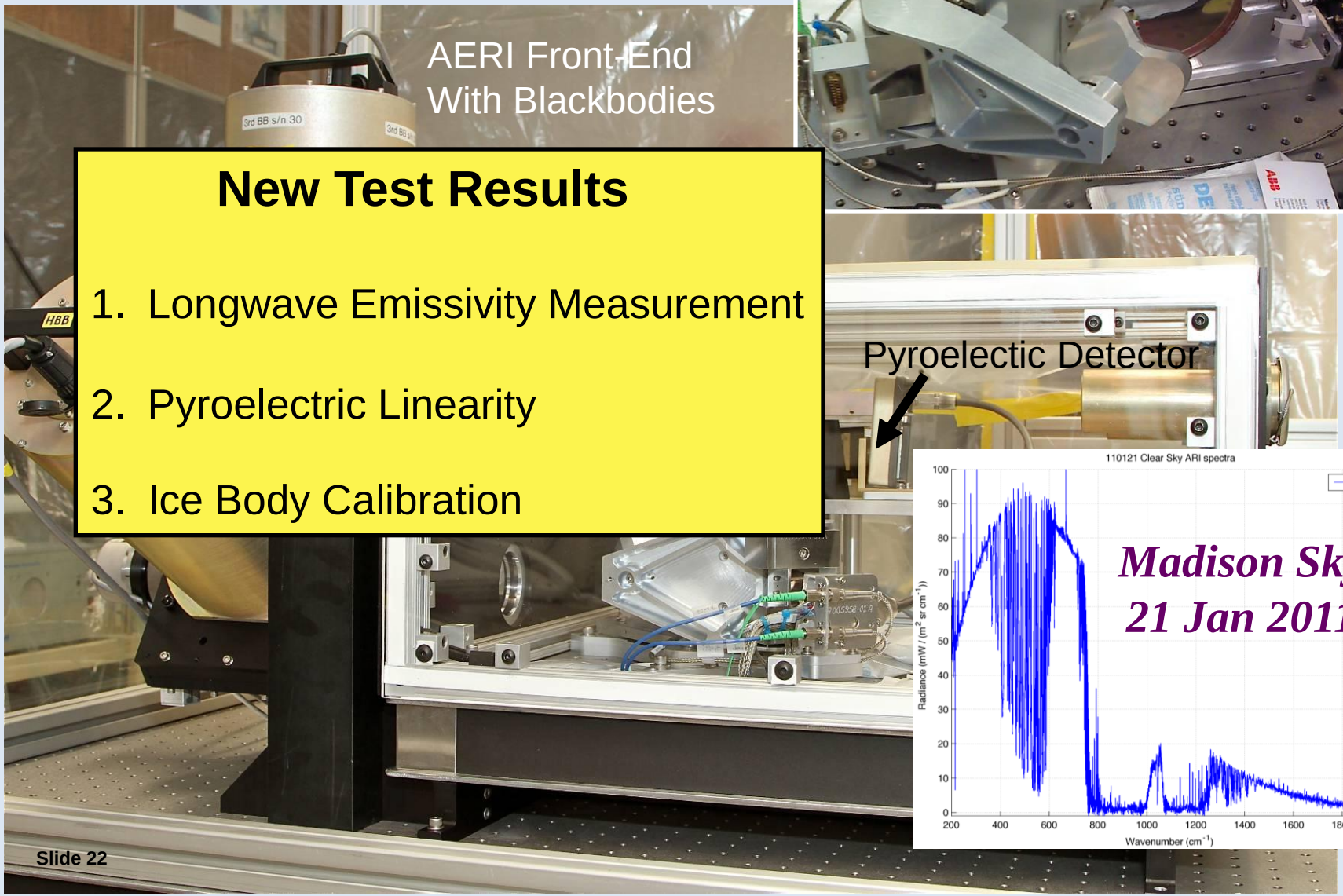






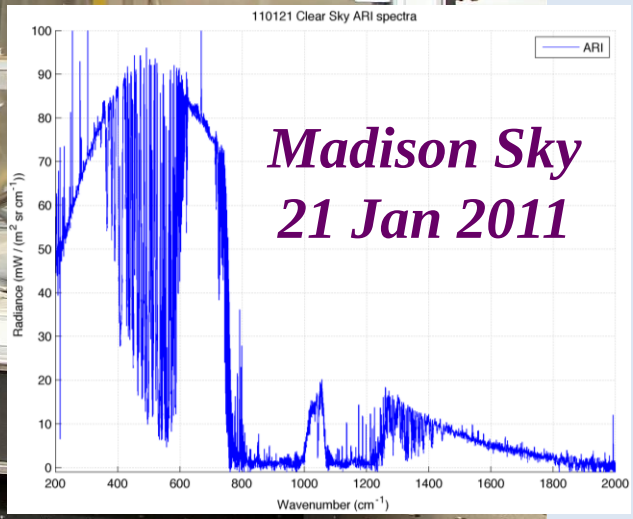
UW Breadboard ARI-1 Results Summary



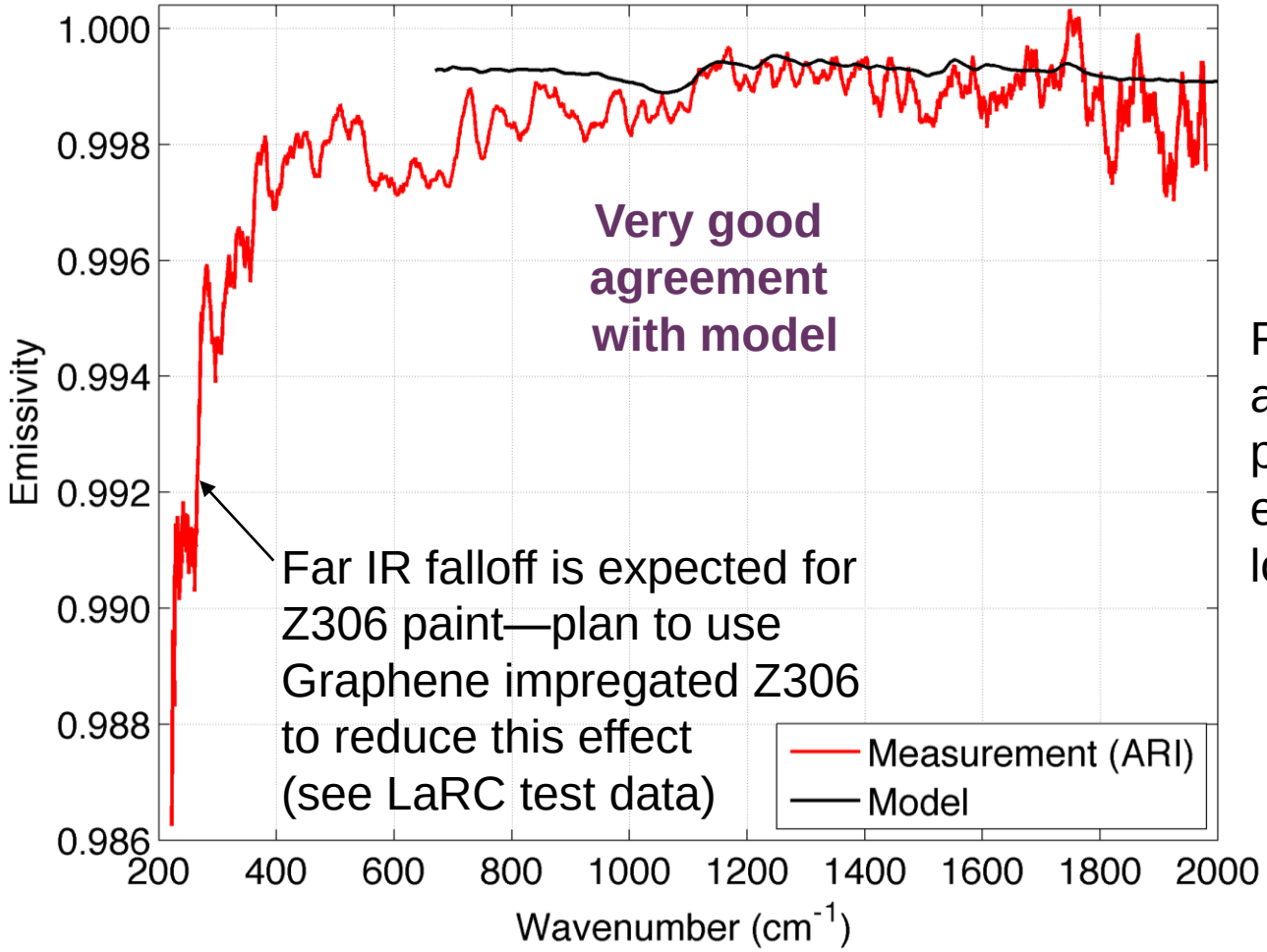


New Test Results

1. Longwave Emissivity Measurement
2. Pyroelectric Linearity
3. Ice Body Calibration



AERI BB Emissivity (Halo, ARI-1)



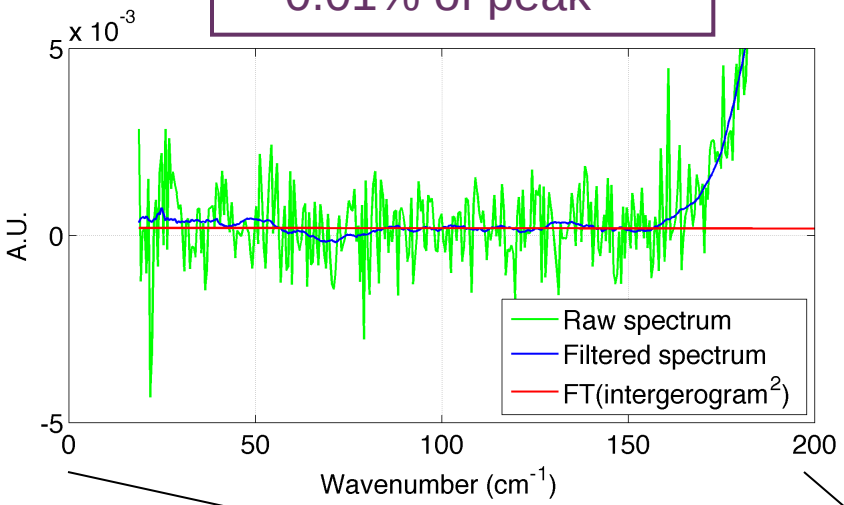
Responsivity averaged to prevent bias errors from low S/N

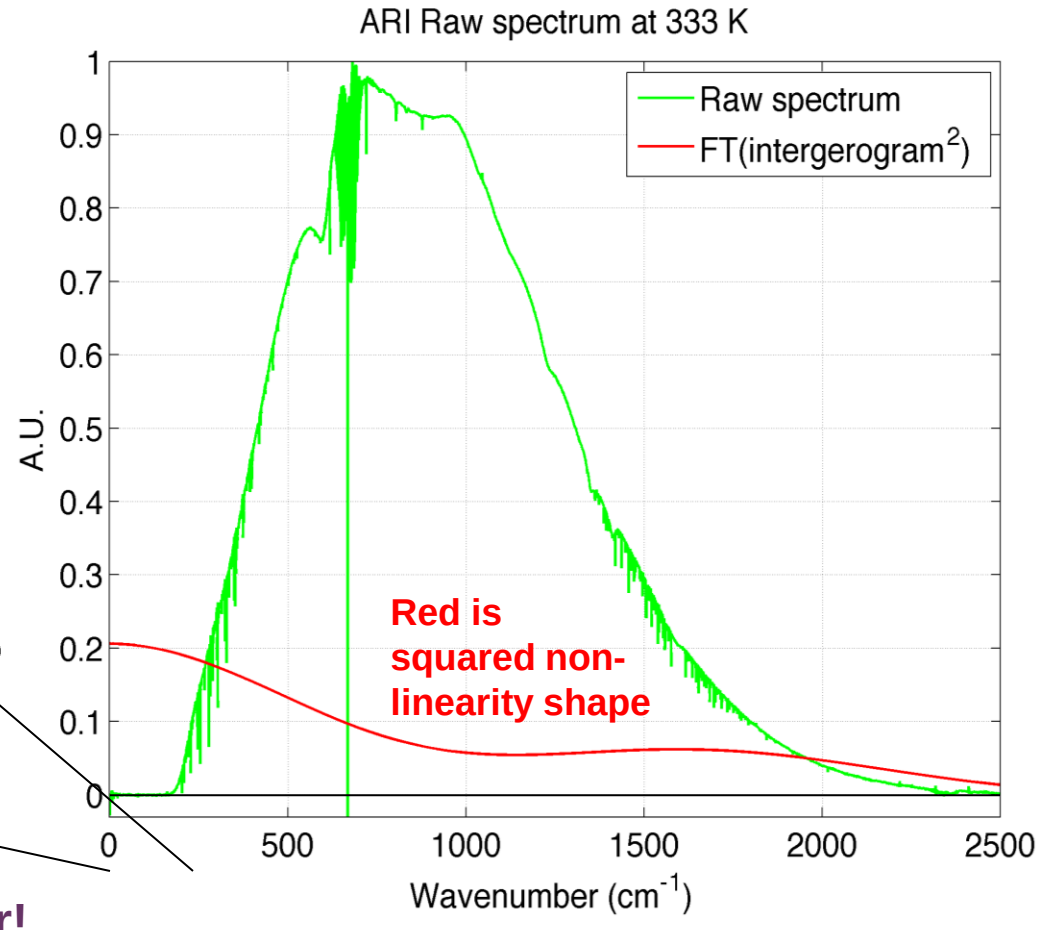
Shows that excellent measurements are possible even with pyroelectric noise level

see Jon Gero's talk

Pyroelectric Linearity

Out of band estimate:
0.01% of peak

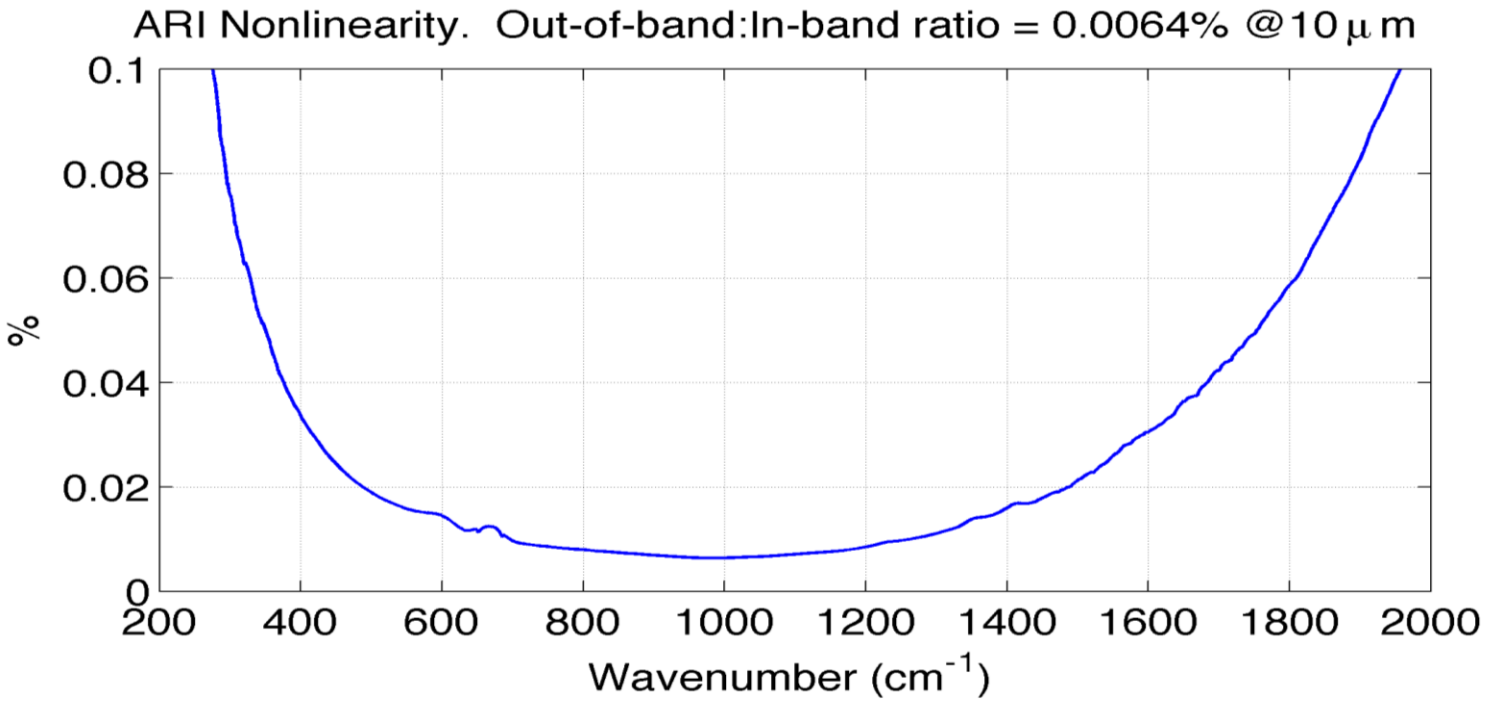




Pyro & electronics are very linear!

(Dry air purge, ~50 hour dwell)

Pyroelectric Linearity: Estimate



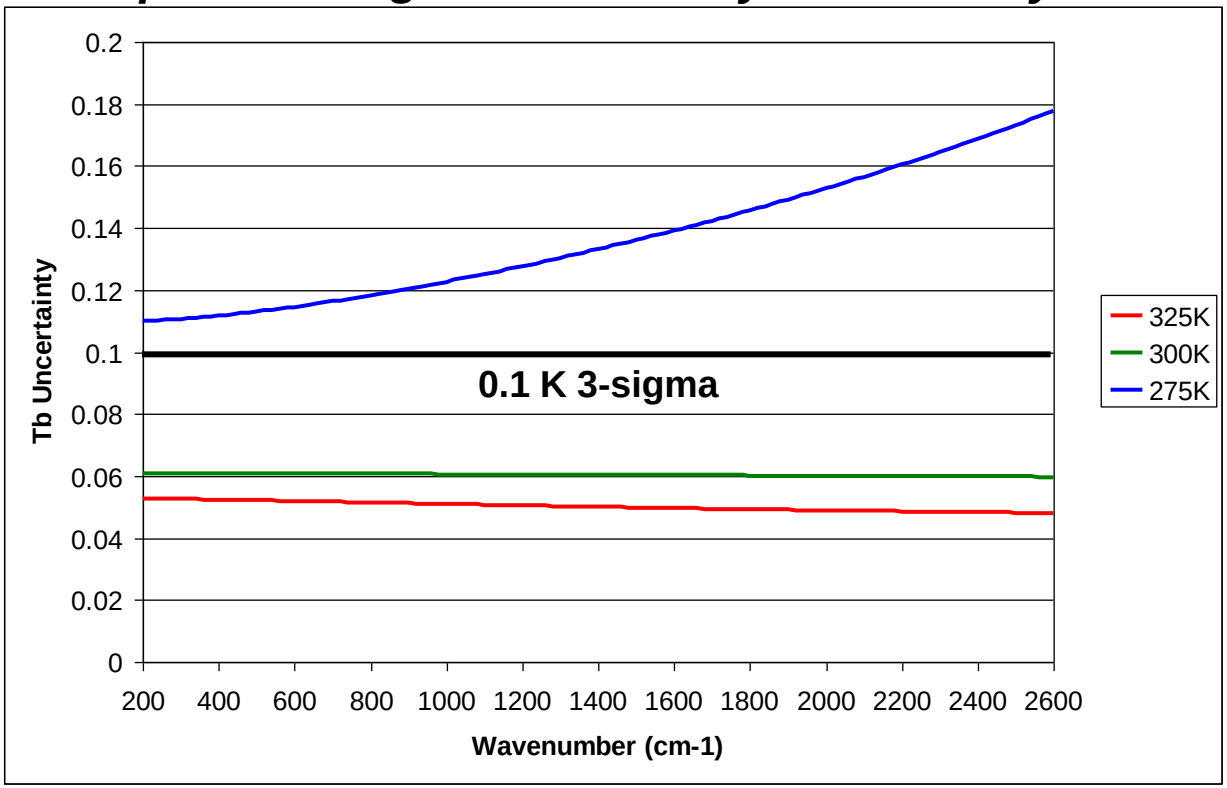
Rough quantitative estimate shows high degree of linearity even for raw spectrum—effects on calibrated spectra are smaller

Pyroelectric detector is well suited to CLARREO

Ice Body Calibration Test

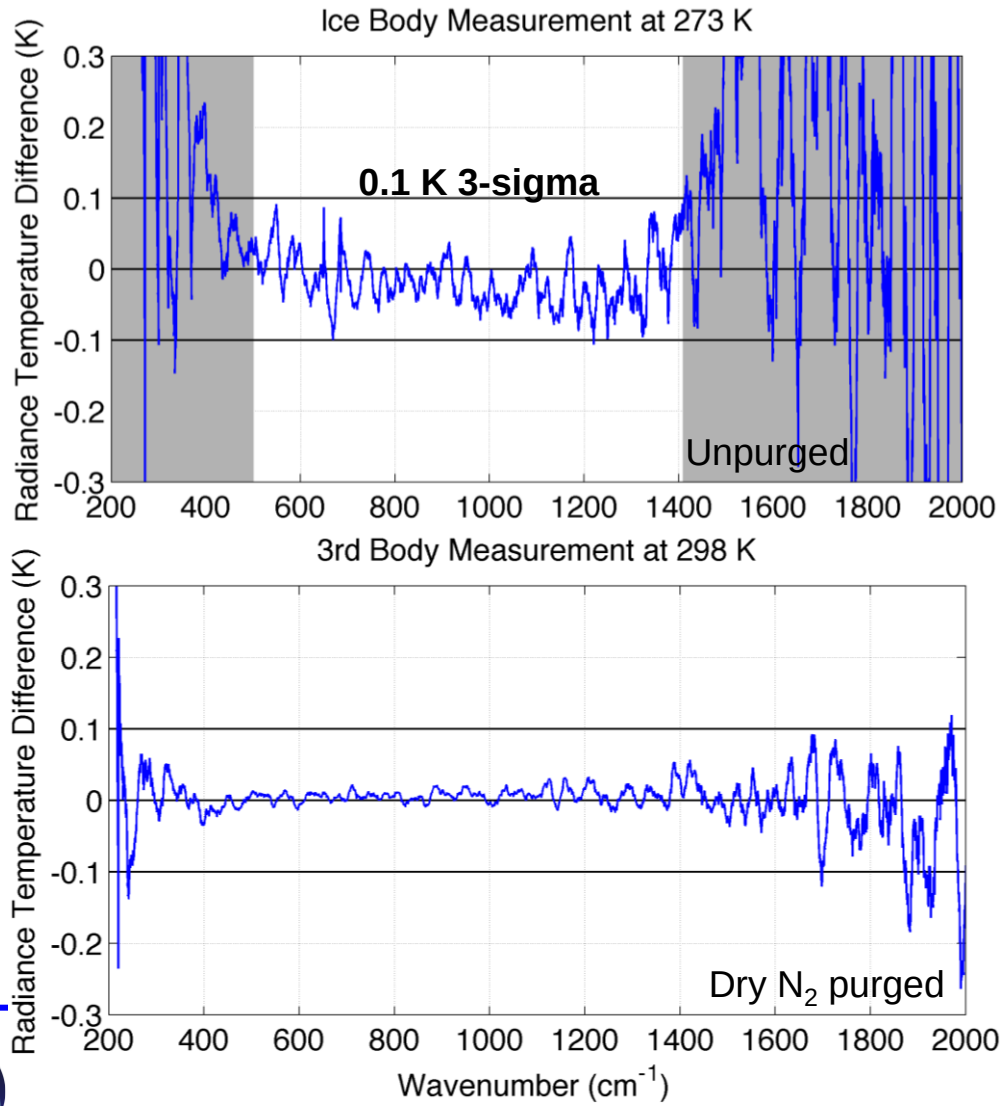
- **Demanding ambient lab test**
- **Calibration Blackbody T's: 298 K & 317 K**
- **Extrapolating to 273.15 K**

Expected 3-sigma Uncertainty for Ice Body Test



Same Blackbody characteristics would give < 0.1 K 3-sigma accuracy with a space view on-orbit

Ice Body Calibration Test Result



- **Expected Accuracy is realized**
- Grayed area is affected by room water vapor
- Extrapolating enhances noise (see 298 K comparison)

12 hours test time

Conclusions

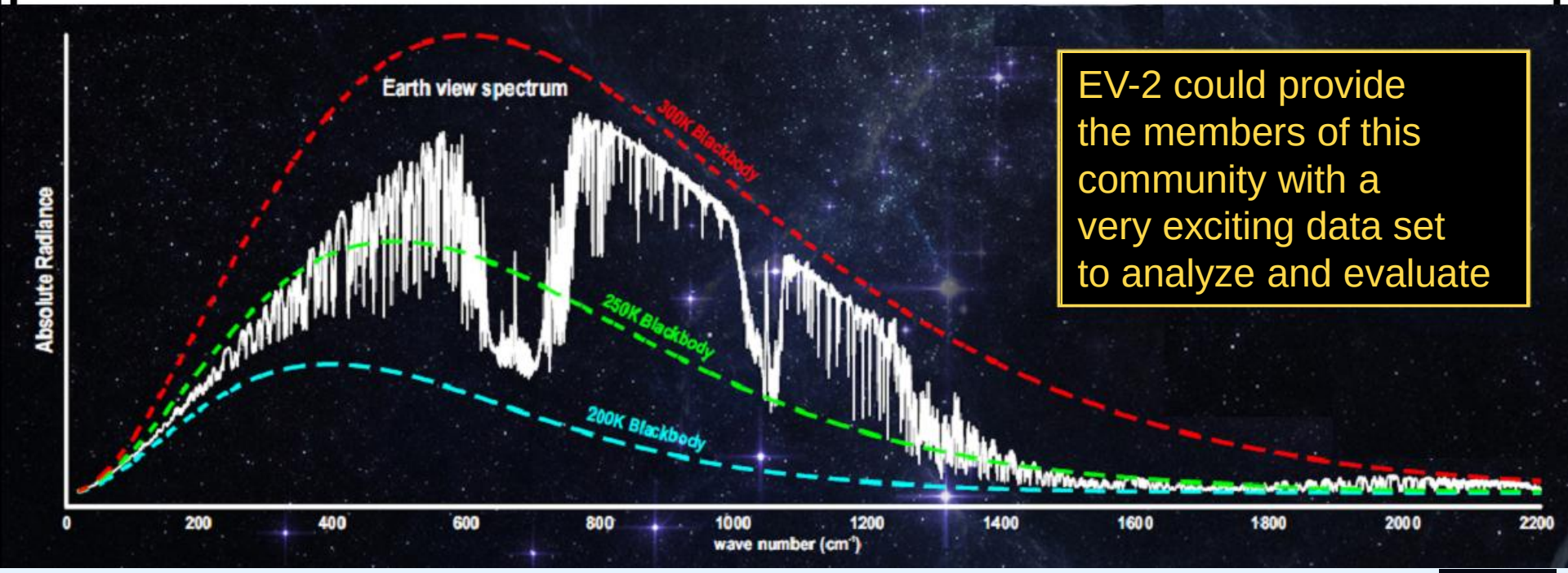
- **Proven results from high spectral resolution measurements and the recent UW/Harvard IIP developments demonstrate readiness for an IR Climate Benchmark Mission**

- **NASA Earth Venture-2 provides the first opportunity for getting this compelling mission into space**

Science and Society: High Accuracy Measurements for Climate and Weather

Mission Overview

Named for the god of sky and weather, law, order, and fate, the Zeus mission will harness advances in the physics of high accuracy measurements from Earth orbit to establish a benchmark observation of global climate.
Zeus will observe spectrally resolved infrared radiances from a 90° polar orbit, creating a dataset with high information content.



EV-2 could provide the members of this community with a very exciting data set to analyze and evaluate

Jim Anderson, PI

Element I

NASA Science Mission Directorate:
Advance Earth system science to meet the challenges of climate and environmental change.
1. How is the Earth system changing? (characterize)
2. What are the sources of change? (understand)
3. How will the Earth system change in the future? (predict)

Element II

NRC Decadal Survey Tier 1:
Address climate prediction, sea level rise, and climate-weather coupling.
1. Need for benchmark climate record that is global, accurate in perpetuity, tested against independent strategies.
2. Development of tested and trusted operational climate forecast.
3. Disciplined decision structures that assimilate accurate data and forecast.

Element III

NRC Decadal Survey Venture Class:
Restore more frequent launch opportunities to facilitate innovative ideas and technologies. Create a new Venture Class low-cost research and applications mission.

Element IV

NASA Instrument Incubator Program:
Develop an extensive infrastructure, leading to the production of the Engineering Demonstration Unit for the Zeus high accuracy calibrated interferometer and on-orbit verification system.

4 Major Elements have set the stage for Zeus