CLARREO Advances in Infrared Spectral Calibration Accuracy

1. NASA Langley (R. Cageao – NASA LaRC)
   Infrared Calibration Demonstration System

2. NIST (R. Cageao – NASA LaRC)
   Mid- to Far-IR Surface Reflectivity and
   Blackbody Cavity Radiance Standards

3. U. of Wisconsin (D. Tobin – UW SSEC)
   Absolute Radiance Interferometer (ARI) and
   On-orbit Verification and Test System (OVTS)

NASA Langley Research Center

CLARREO Infrared Calibration Demonstration System (IR CDS)

GSICS GDWG+GRWG Conference

March 4, 2013

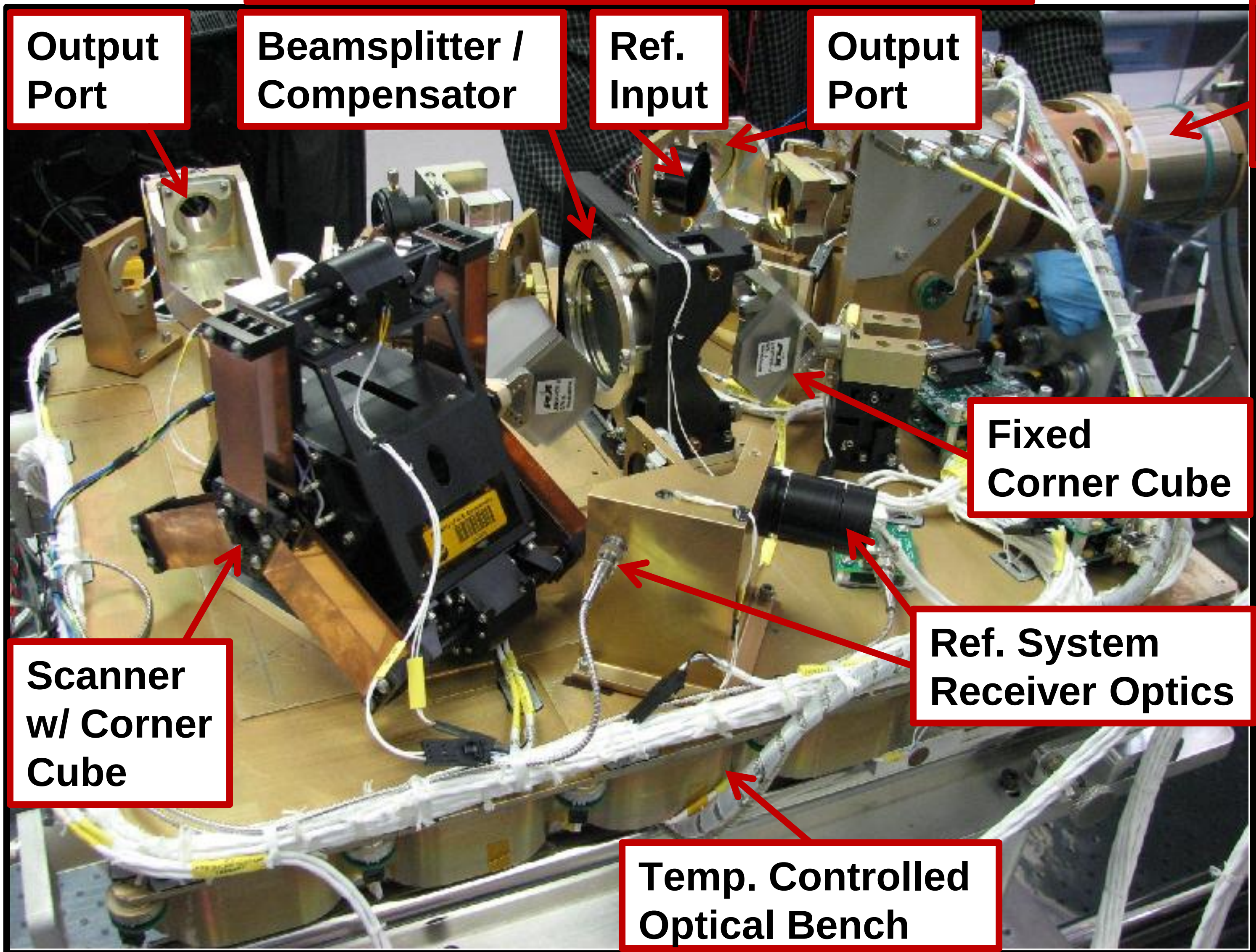
Marty Mlynczak
Dave Johnson
Rich Cageao

The CLARREO IR CDS is a Compact, Demonstration, Four-Port Fourier Transform Spectrometer

Mid- to Far-IR (5-50μm) with Resolution $0.5 cm^{-1}$
Measure brightness temperatures accurate to 0.1K (k=3), for 200 – 320K scenes (CLARREO Req.)

- **Characterize Systematic Radiance Measurement Uncertainty**
  Refine the Instrument Performance Model
- **Develop a Cost-Effective Instrument Design**
- **Flexible and Modular Instrument Design Testbed**
  Operating in a Controlled Thermal and Acoustic Environment

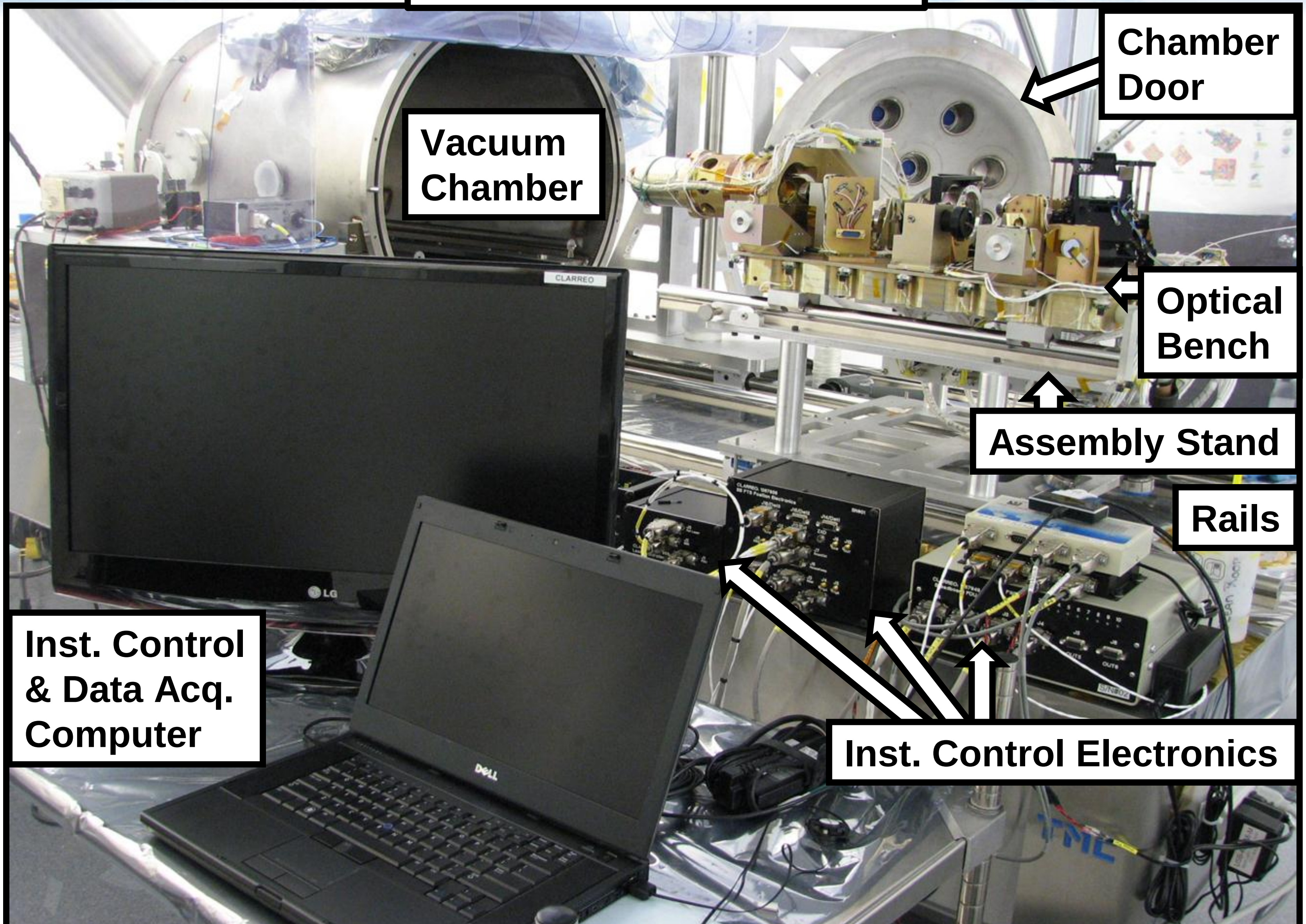
IR CDS Optical Bench



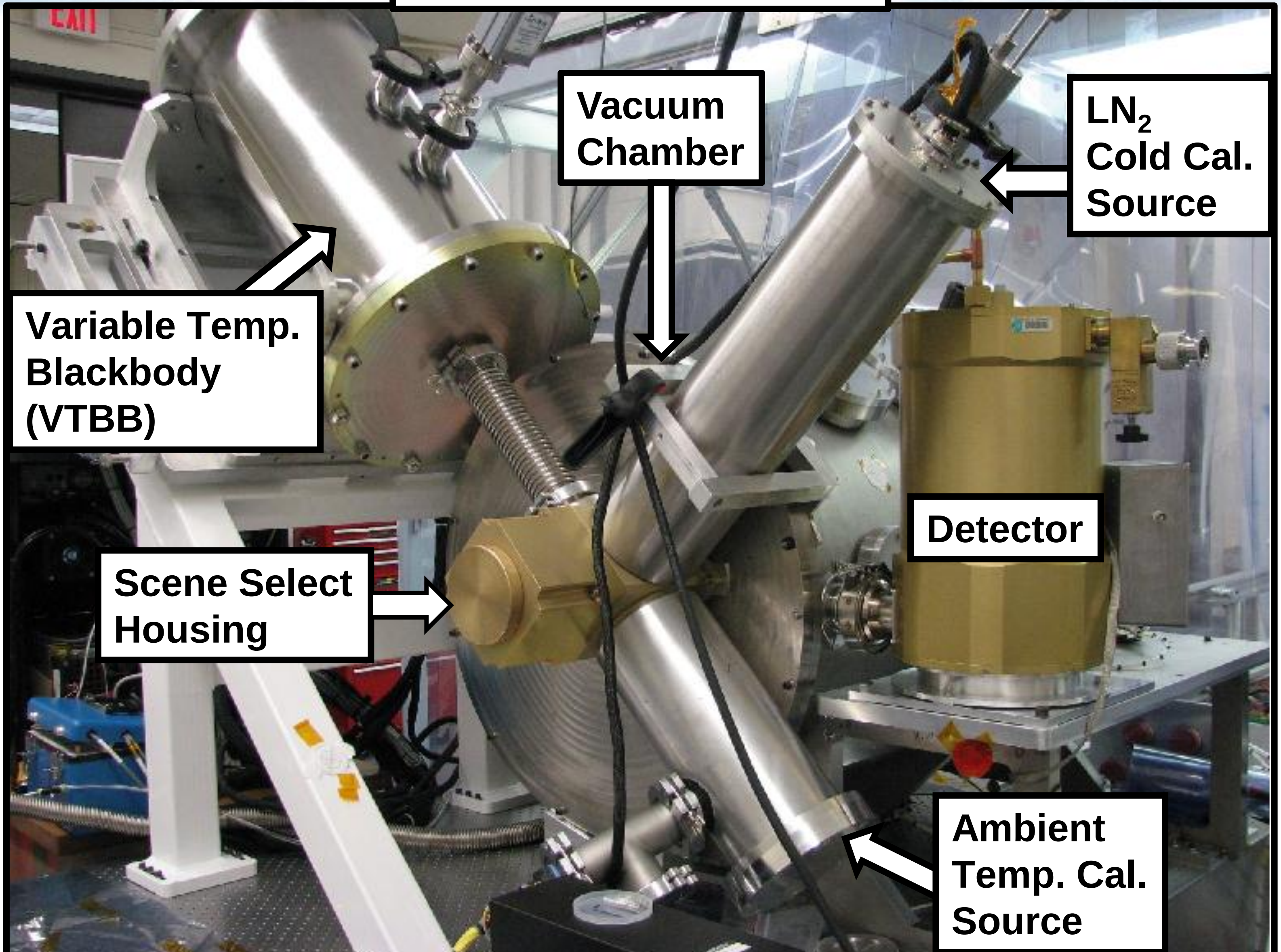
CLARREO

Climate Absolute Radiance
& Refractivity Observatory

IR CDS System



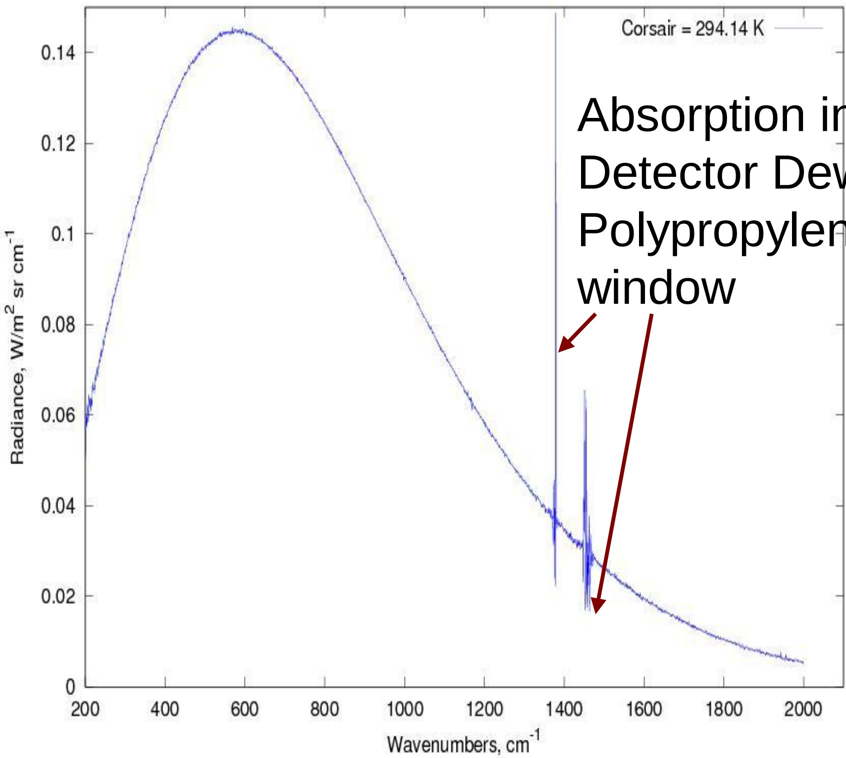
IR CDS Sources



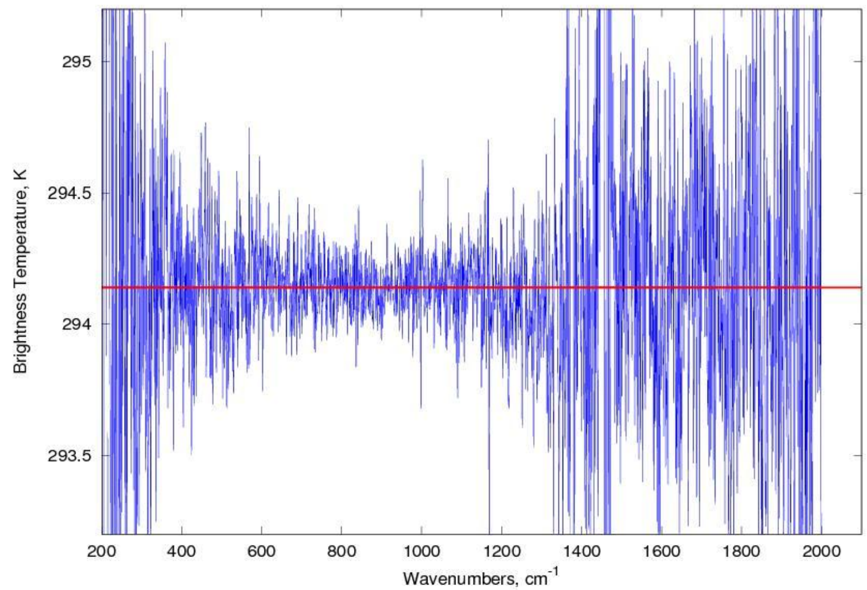
Characteristics of the Current IR CDS Design

- Stacked/Planar Optical Ray Trace
- Cassini CIRS Linear Voice Coil Corner Cube Translation Stage
- Frequency Stabilized Position Reference Nd-YAG Laser
- Optical Bench Thermally and Acoustically Isolated in a Vacuum
- Temperature of Optical Bench Controlled at 30C
- Thermistors Calibrated and Traceable in a 1mK Standard Bath
- Two Output Ports for Bolometer and Pyroelectric Detectors
- Cold (LN_2) and Ambient Temperature Calibration Sources
    - Cavity Reflectances Measured at 4 & 10.6um at NIST
- VTBB has Hg/H_2O/Ga PCM & 9.6μm QCL Emissivity Monitor

IR CDS Measured VTBB Radiance



Single Spectrum Brightness Temp.



Brightness Temp. Bias < 0.05K

(Noise ~0.15K rms, 600 – 1200 cm^{-1})

IR CDS Progress

Achieved:

- **Optical Bench Optics Temp. Stability 30mK (1 hr.)**
- **Preliminary System Operation Analysis**
  - **Design Upgrade Decision Inputs**
  - **Measurement Uncertainty Estimate**
- **Software Development**
  - **Instrument Responsivity Model**
  - **Observed Blackbody Radiance Model**
  - **Multiple-Scattering Angle Emissivity Modeling (Virial Inc.)**

Planned:

- **Installing Pyroelectric Detector and Stable Amplitude Ref. Laser**
- **Radiometric Accuracy Assessment w/ Current Design: late-Mar.**
- **Measurement Uncertainty Report: May 2013**

Climate Absolute Radiance
& Refractivity Observatory

NIST

Mid- to Far-IR Surface Reflectivity and Blackbody Cavity Radiance

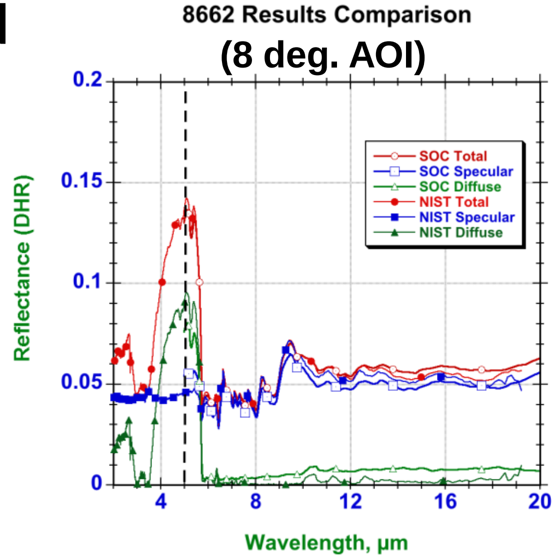
GSICS GDWG+GRWG Conference
March 4, 2013

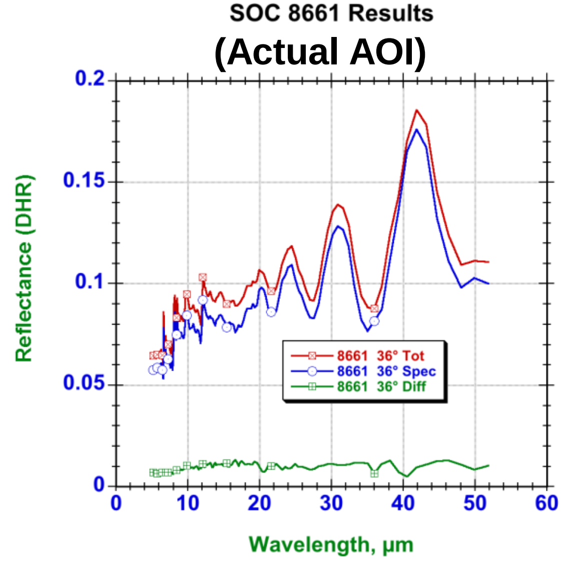
(with inputs from)
Joe Rice
Leonard Hanssen
Sergey Mekhontsev

1) Measure Paint Sample Properties to Model Cavity Reflectance

Near Normal Specular and Diffuse BB Paint Sample Reflectance: NIST and Surface Optics (SOC) Differences, 8 – 20µm

NIST Extending Meas.: Total Reflect. to 50µm, Diffuse Reflect. to 25µm

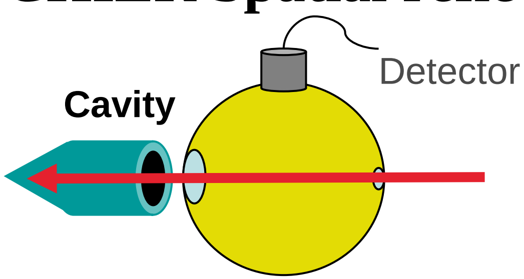




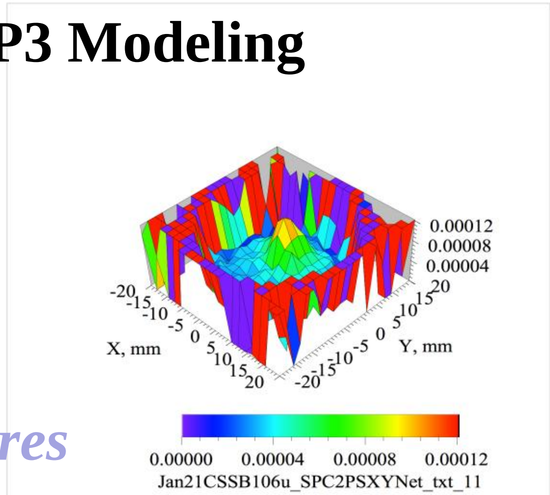
2) Measure Cavity Reflectance

Spot Check Cavity Emissivity for 5 – 50µm STEEP3 Modeling

NIST CHILR Spatial reflectance @ 4, 10.6, *23* µm



$$R = \frac{V_{sc} - V_{ap}}{V_r - V_{back}} R_r$$

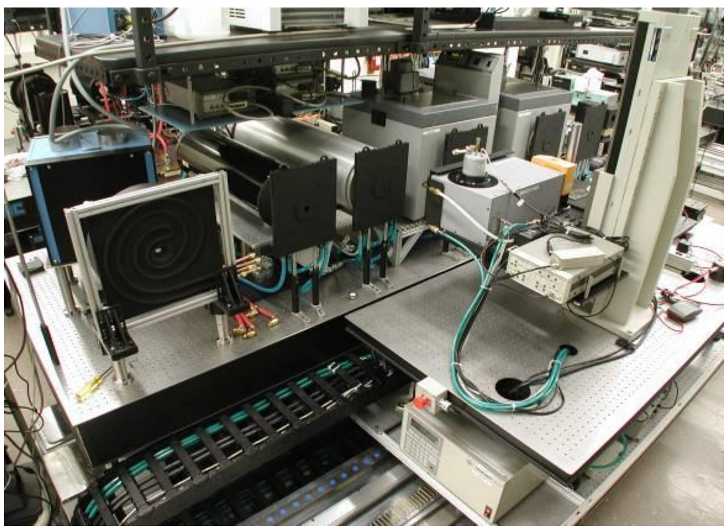


Longer Wavelength Sources & Reflective Integ. Spheres

3) Compare Modeled Cavity and Measured Radiances

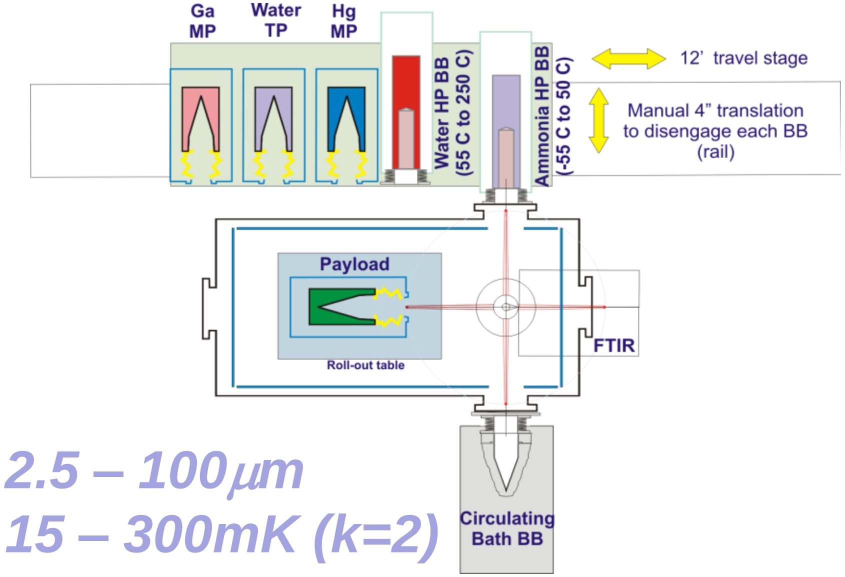
Measured Blackbody Cavity Spectral Radiance

AIRI - Advanced IR Imaging Lab



2.5 – 14.8μm
20 – 50mK (k=2)
[420 – 220K]

CBS3 – Controlled Background Spectroradiometry



2.5 – 100μm
15 – 300mK (k=2)
[300 – 190K]

(Designs developed, awaiting funding)

IR Absolute Radiance Interferometer (ARI) with On-orbit Verification and Test System (OVTS) prototype demonstrates 0.1 K capability

(UW-Harvard project, NASA Instrument Incubator Program)

Hank Revercomb, Fred Best, Joe Taylor,
Jon Gero, Doug Adler, Claire Petersen,
John Perepezko, Dave Hoese, Ray Garcia,
Bob Knuteson, Dave Tobin

University of Wisconsin-Madison
Space Science and Engineering Center

Absolute Radiance Interferometer (ARI):
Definitions of key components

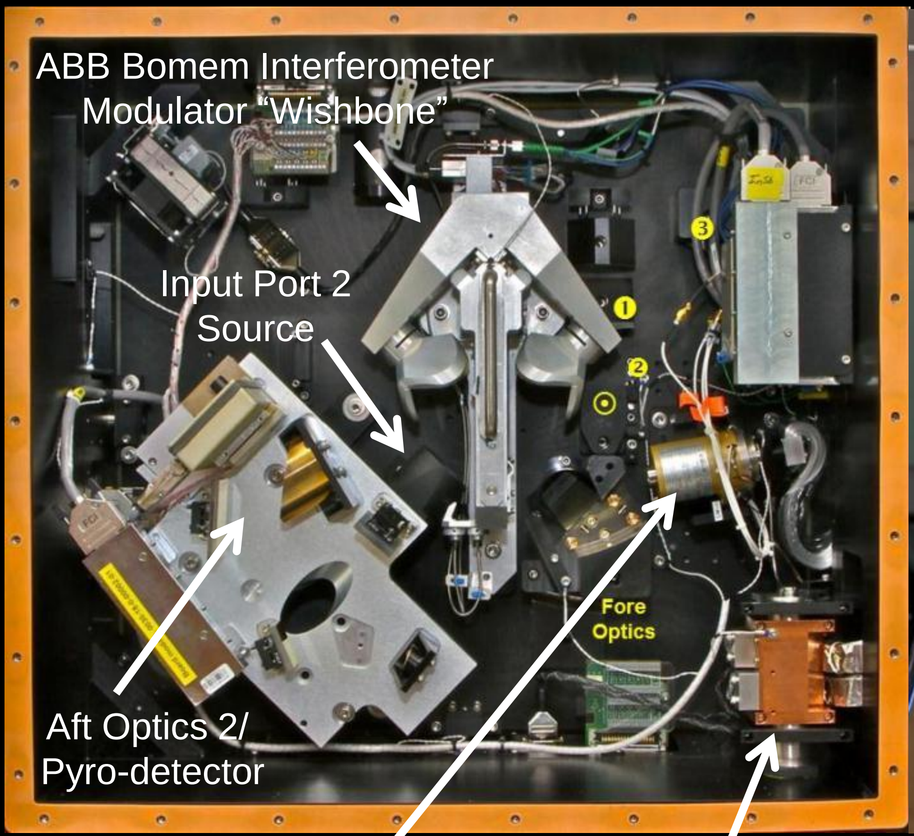
- **Calibrated Fourier Transform Spectrometer (FTS):**
  - FTS with strong flight heritage
  - 3 Spectral bands covering 3-50 µm
  - 2 Cavity Blackbody References for Calibration
- **On-orbit Verification and Test System (OVTS):**
  - ❶ On-orbit Absolute Radiance Standard (OARS) cavity blackbody using 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

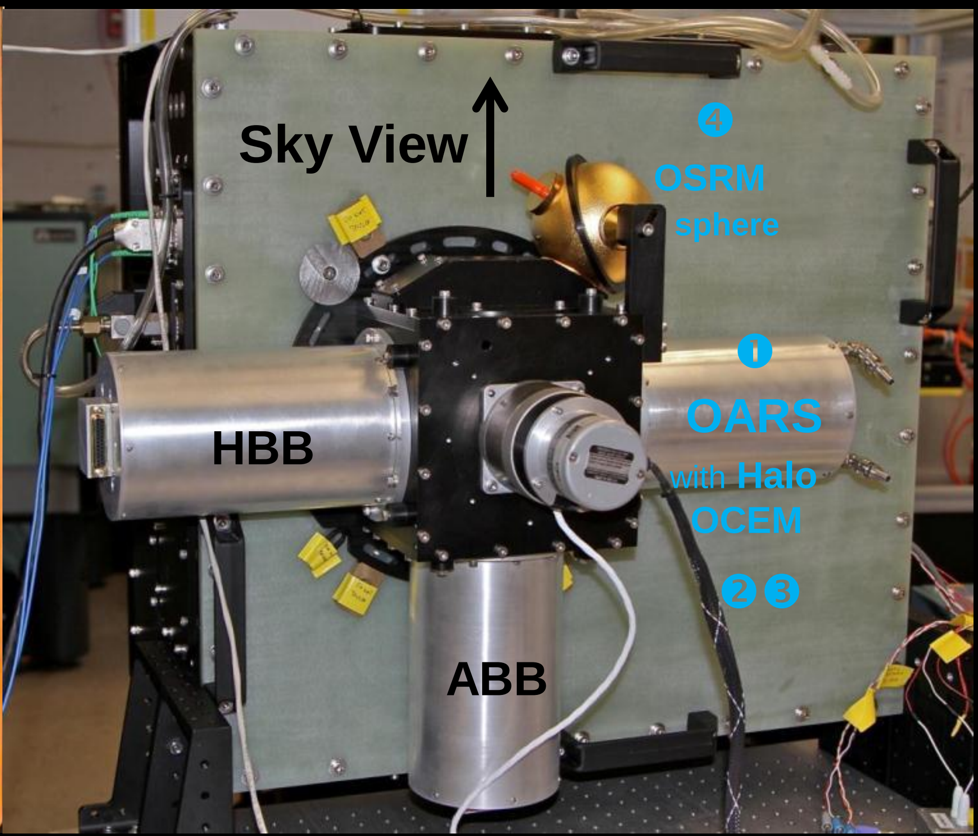
*Not fully implemented in prototype—demonstrated separately

UW Absolute Radiance Interferometer (ARI) Prototype

components of Calibrated FTS

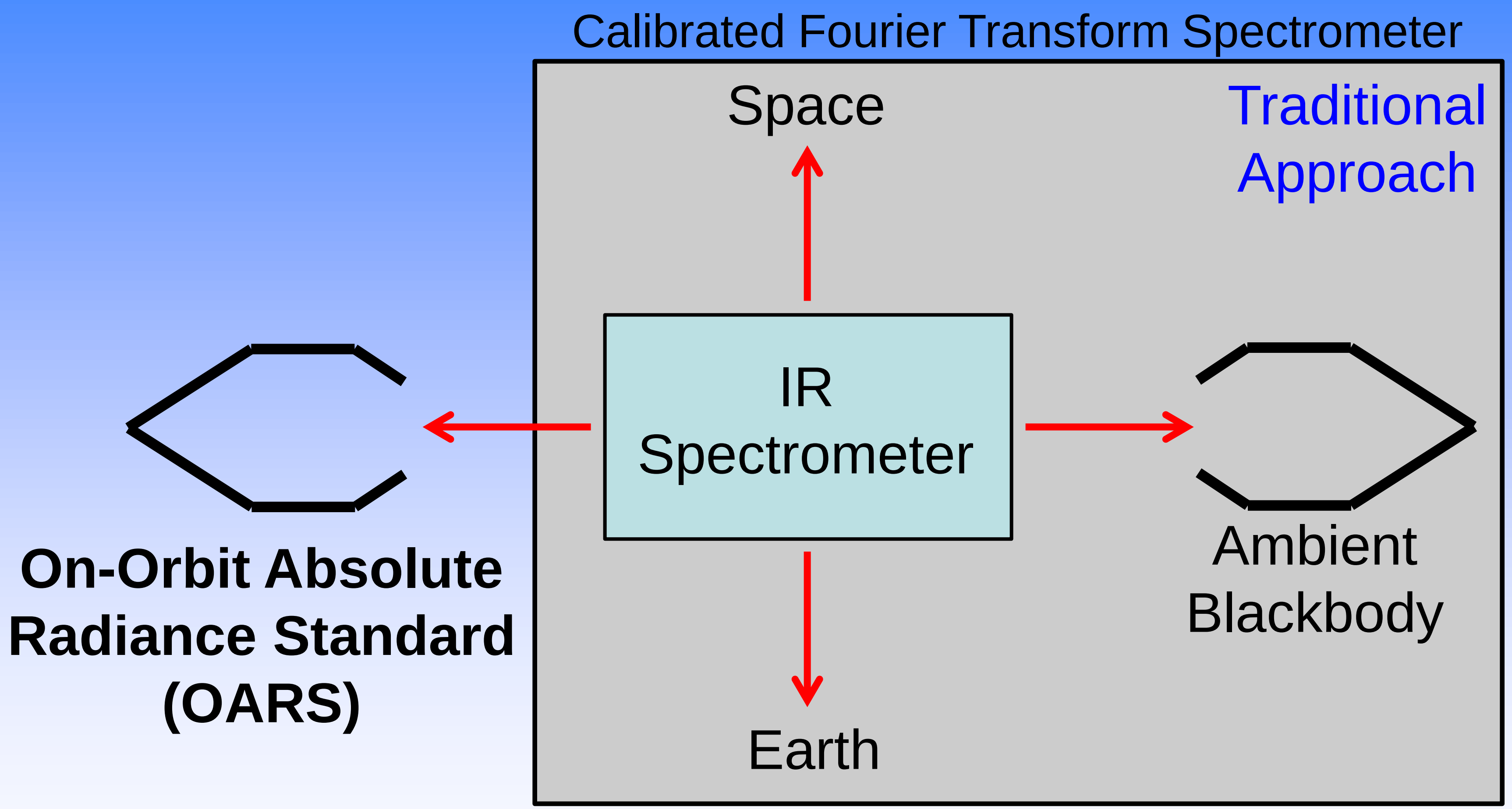
On-orbit Verification & Test Sources & Calibrated FTS Blackbodies (HBB & ABB)





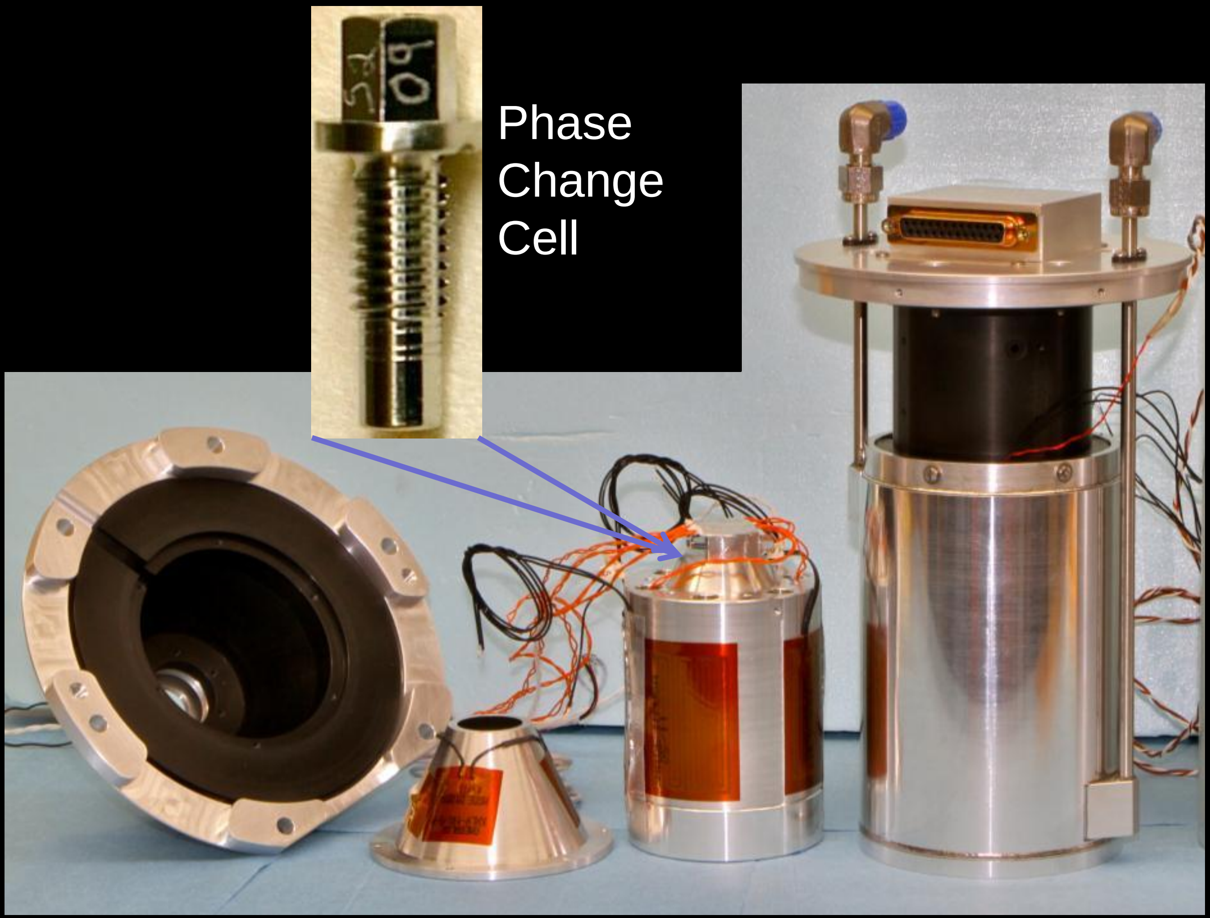
Aft optics 1 (MCT/InSb)
Sterling Cooler Compressor

On-Orbit Calibration Verification



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

On-orbit Absolute Radiance Standard OARS

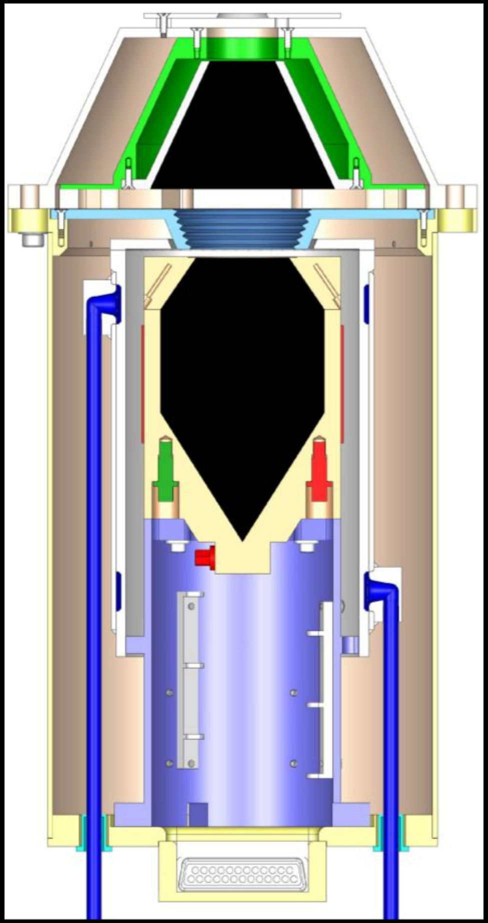


Heated Halo
& Halo Insulator

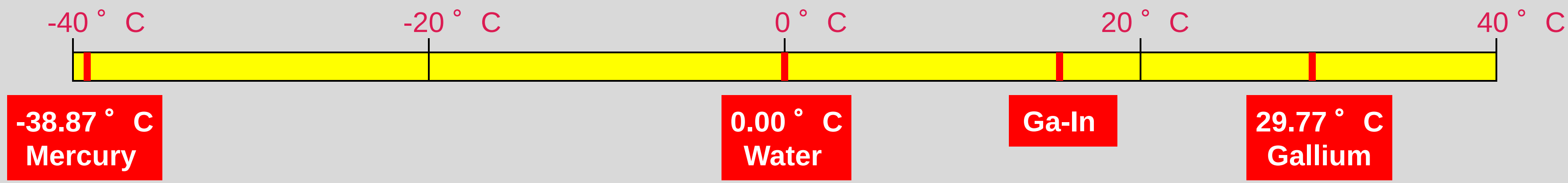
Cavity

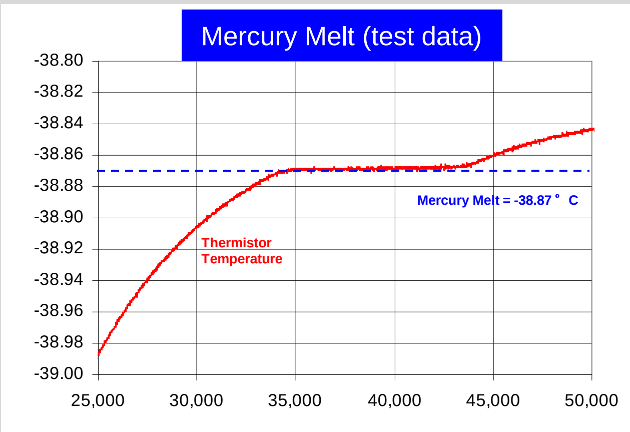
Inner Shield
& Isolator

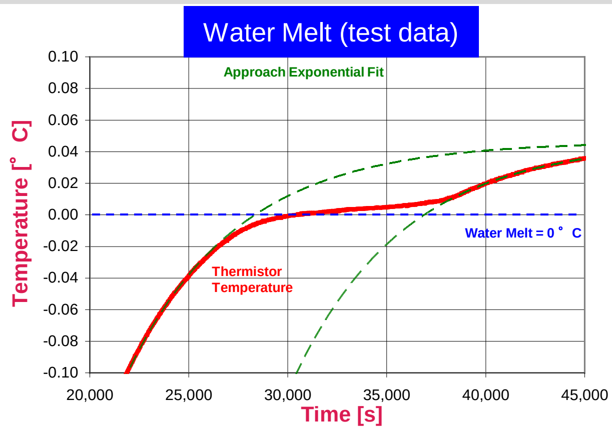
Assembly Diagram

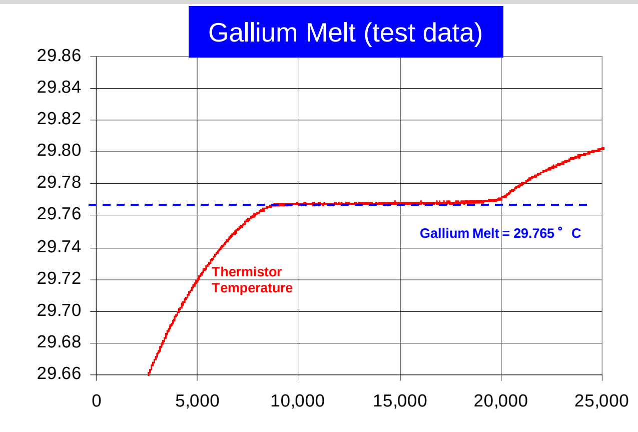


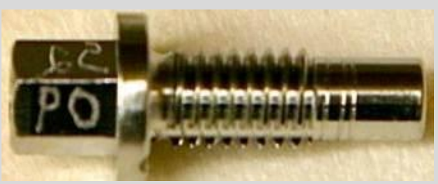
Melt Signatures Provide Temperature Calibration



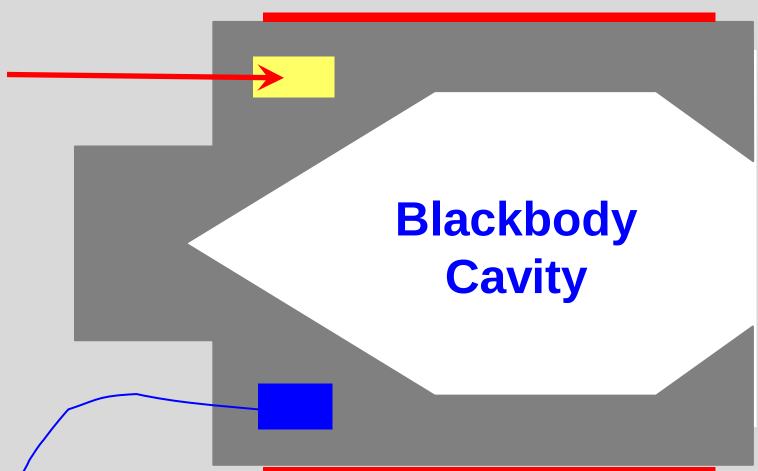








Phase Change Cell
(Ga, H_2O, or Hg)

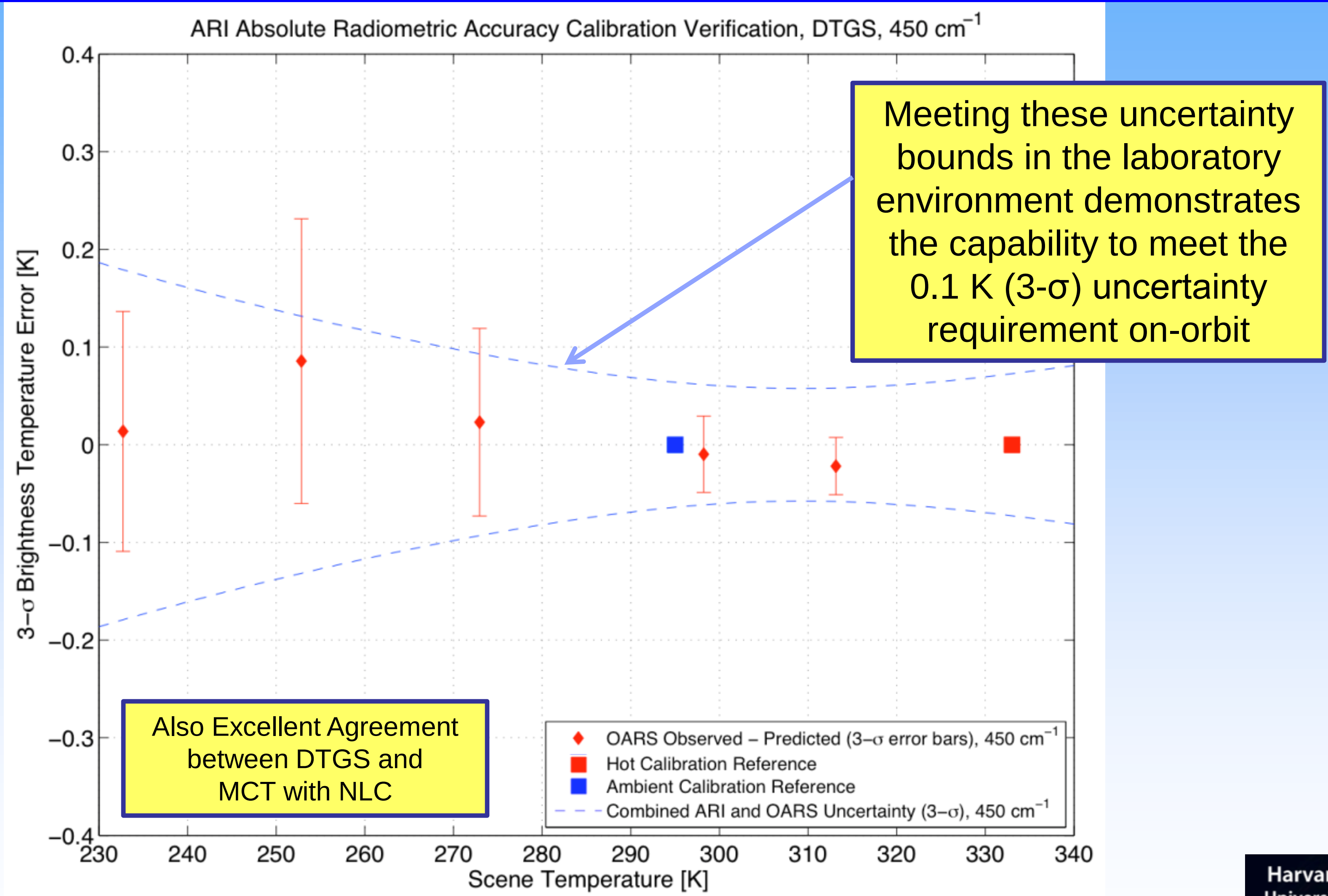


Plateaus (shown in plots) provide known temperatures to better than 10 mK

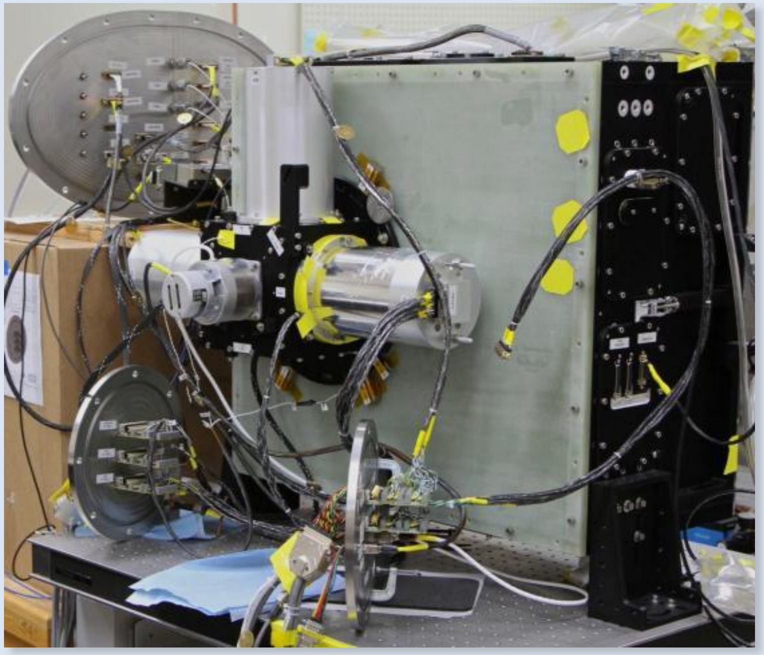
Thermistor (plotted above)

Sample Radiometric Calibration Verification

DTGS (450 cm^{-1})



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 March/April).

Summary

CLARREO IR Spectral Calibration Accuracy

- Have Developed Systems that can Provide On-orbit Traceability to Fundamental Physical Standards
- NIST is Developing Methods and Standards for Mid- and Far-IR Reflectivity and Radiance Measurements
- 0.1K (k=3) Brightness Temperature Accuracy has been Demonstrated in a Laboratory Environment
- Independent and Collaborating Efforts at our Institutions, which are Regularly Reviewed

Backup Slides

IR CDS Acknowledgements

Engineering and Technical:

LaRC: Nurul Abedin, Ashley Alford, Jennifer Allen, Chuck Antill, Dick Bender, Charlie Boyer, Frank Boyer, Rich Cageao, Bill Culliton, Barry Dunn, Glenn Farnsworth, Mick Hartzheim, Ron Huppi, Peter Huynh, Dave Johnson, Cathy Kern, Paul Manhart, Joe McKenney, Johnny Mau, Wade May, Mark Motter, Willie Munden, Ben Nickless, Joe O'Connell, Jim Osmundsen, Irene Pang, Steve Pennington, Tamer Refaat, Don Robinson, Ray Seals, Tory Scola, Tim Shekoski, Katie Smith, Chris Thames, Joe Walker, Tim Wood

GSFC: Ken Blumenstock, Tom Capon, Alex Cramer, Don Jennings, Ken Lee, Brendan McAndrew

Management:

LaRC: Rosemary Baize, Kevin Brown, Jerri Carter, Jim Corliss, Mary Dijoseph, Don Garber, Mike Gazarik, Nicole Hintermeister, Susie Johnston, Alan Little, Bill Luck, Ken Parkinson, Steve Sanford, Jo Sawyer, Don Shick, Dave Young

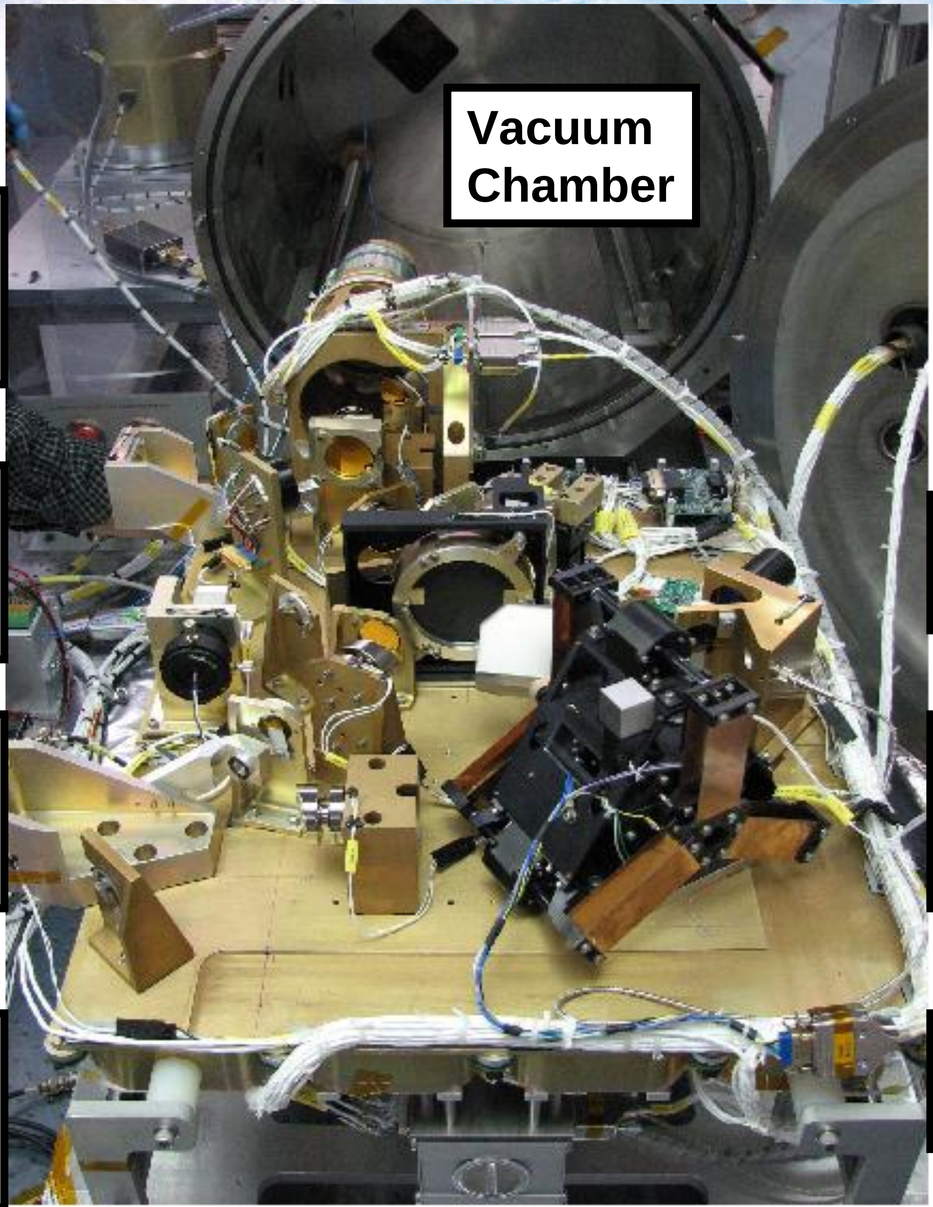
Science:

Ron Huppi, Don Jennings, Dave Johnson, Marty Mlynczak, Bruce Wielicki

SDL CORSAIR IIP VTBB Acknowledgements

Engineering:

SDL: Gail Bingham, Harri Latvakoski, Seth Topham, Mike Watson, Mike Wojcik

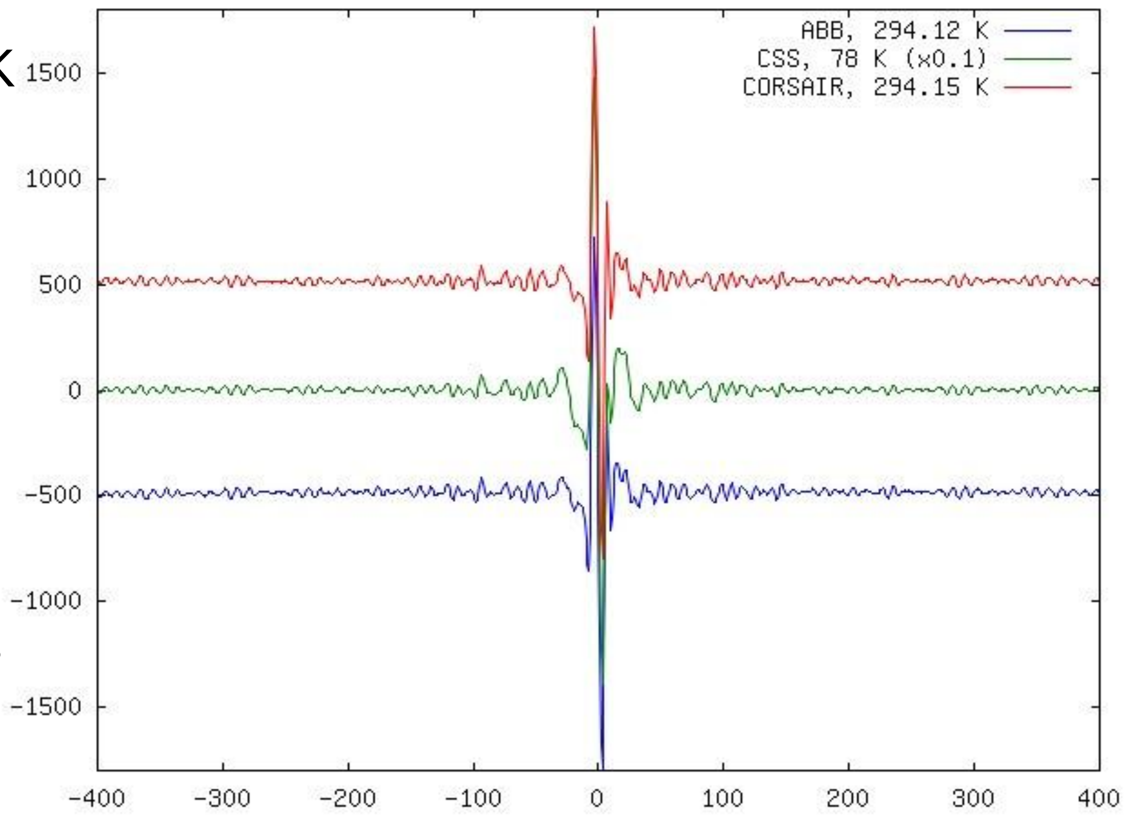

Vacuum Chamber
Scene Motor & Mirror
Dual Output Ports
Au Coated OAP's & Flat Mirrors
IR Beam and Control / Reference Interferometers
Beamsplitter / Compensator
Scanner w/ Corner Cube
Temp. Controlled Optical Bench

Internal reference ~303 K

CSS interferogram divided by 10 to fit on same scale.

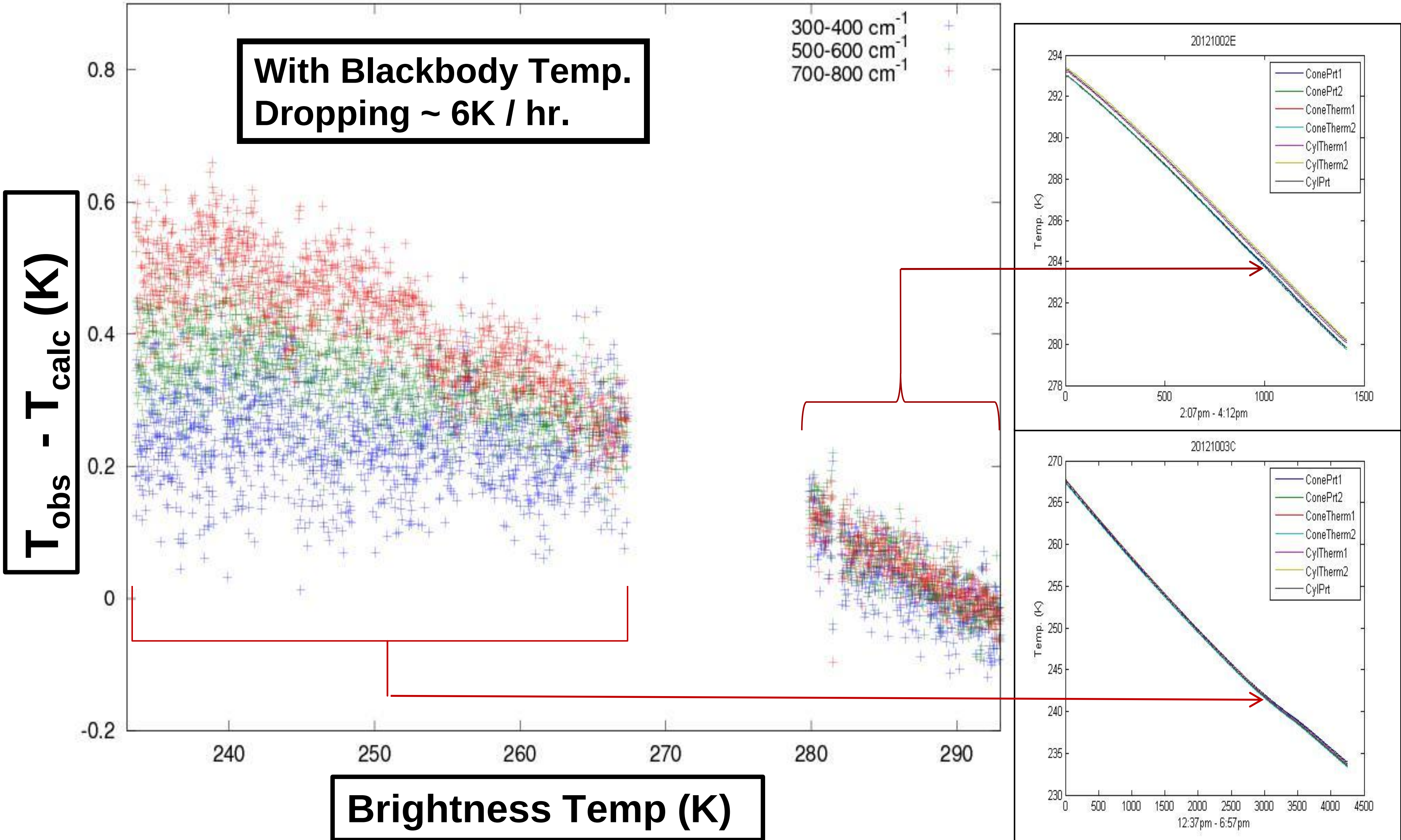
Individual interferograms offset by 500 for clarity.

Only the central region is shown.

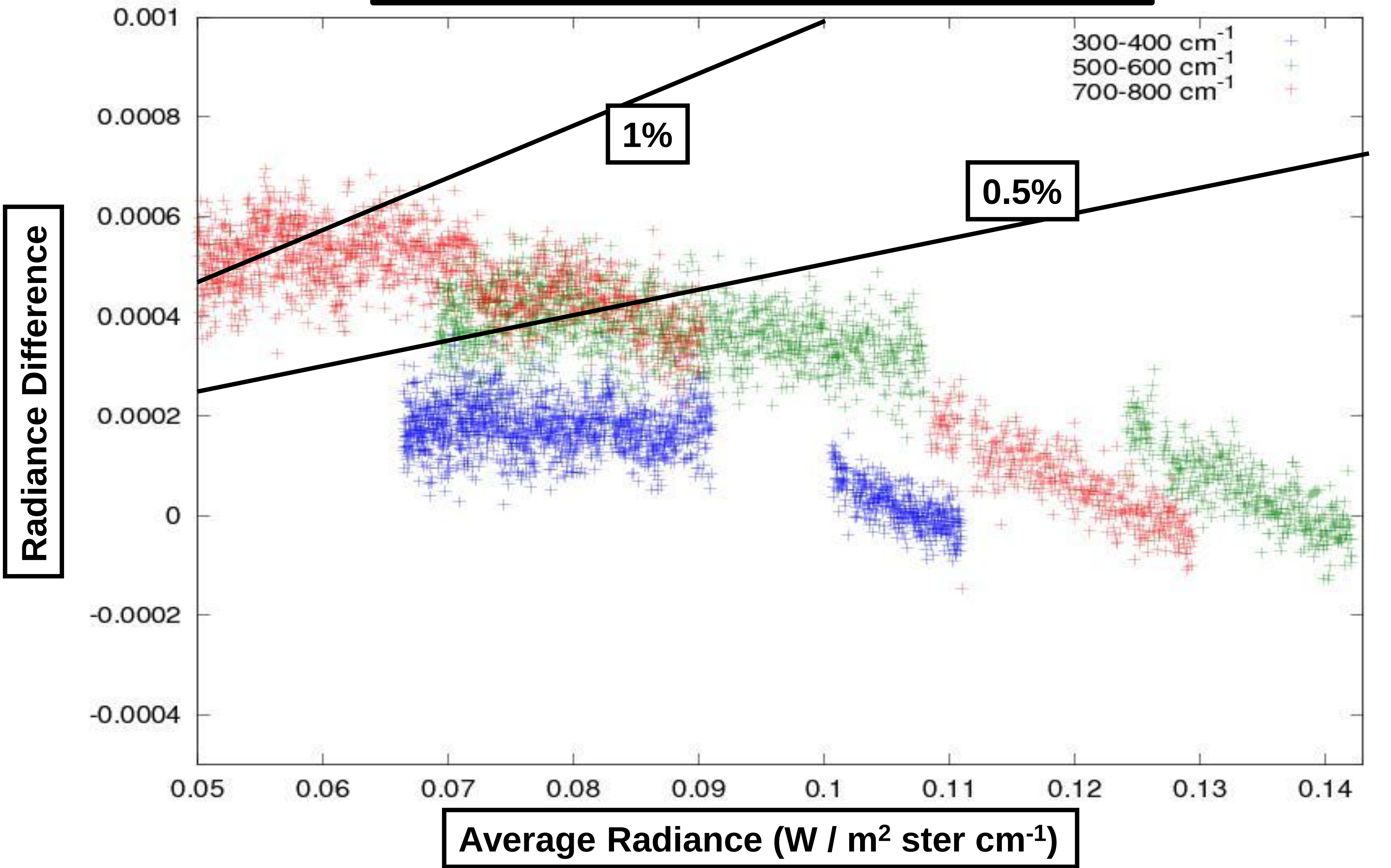


Climate Absolute Radiance
& Refractivity Observatory

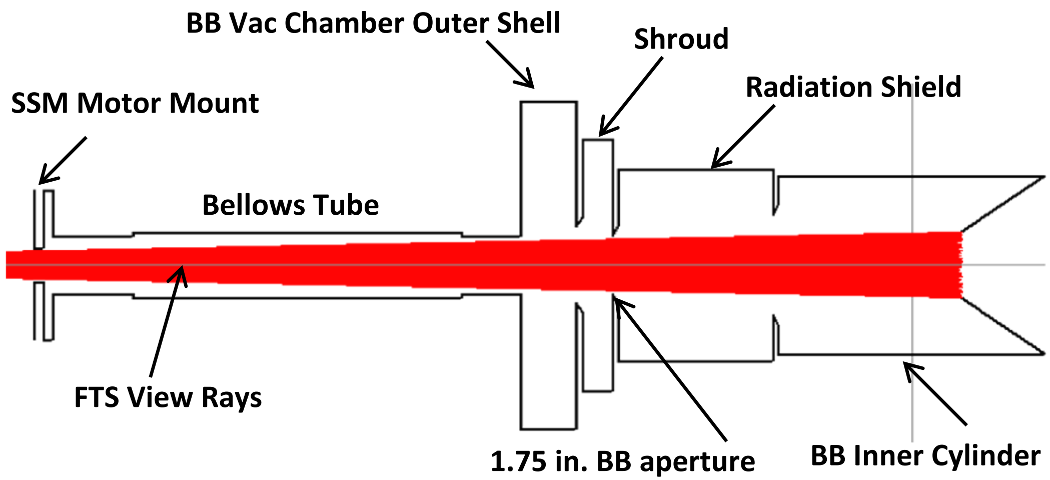
IR CDS Operational Analysis



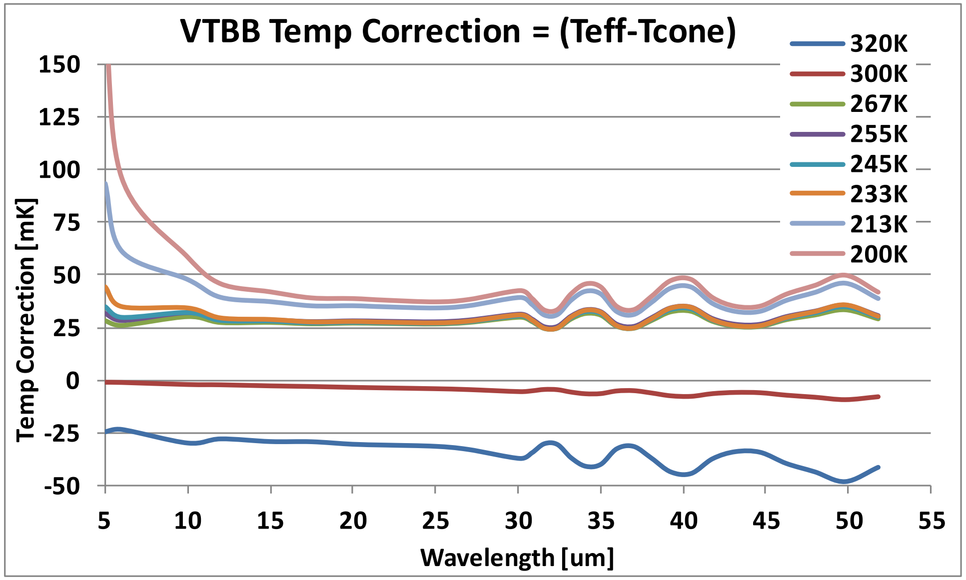
IR CDS Operational Analysis



- Model includes all important geometry
  - BB cavity is Z302 glossy black paint
  - All else is semi-rough Al



- STEEP3 results for 8 temperatures indicate significant variations in temp corrections



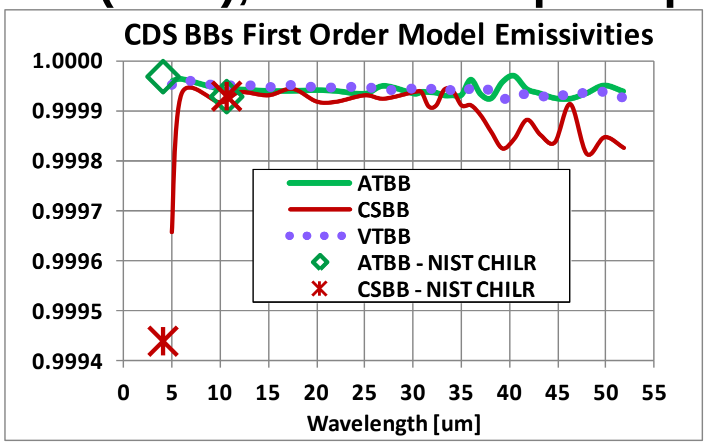
- **IR CDS measurement of target radiance requires accurate knowledge of the blackbody (BB) radiances:**

$$(1) \quad L_{bb}(\lambda, T_{bb}) = \varepsilon_{bb} P(\lambda, T_{bb}) + (1 - \varepsilon_{bb}) P(\lambda, T_e)$$

- **Effective emissivity of BB is evaluated by:**
  - **Meas. of cavity reflectance at 4 and 10.6 µm (NIST)**
  - **Modeling of cavity emissivity over wavelength range**
  - **Comparison of model results with cavity reflectance measurements**

L = *spectral radiance*
bb = *blackbody*
ε = *emissivity*
P = *Planck equation*
λ = *wavelength*
T = *temperature*
e = *surrounding environs*

- **First Order Model (FOM), from basic principles:**

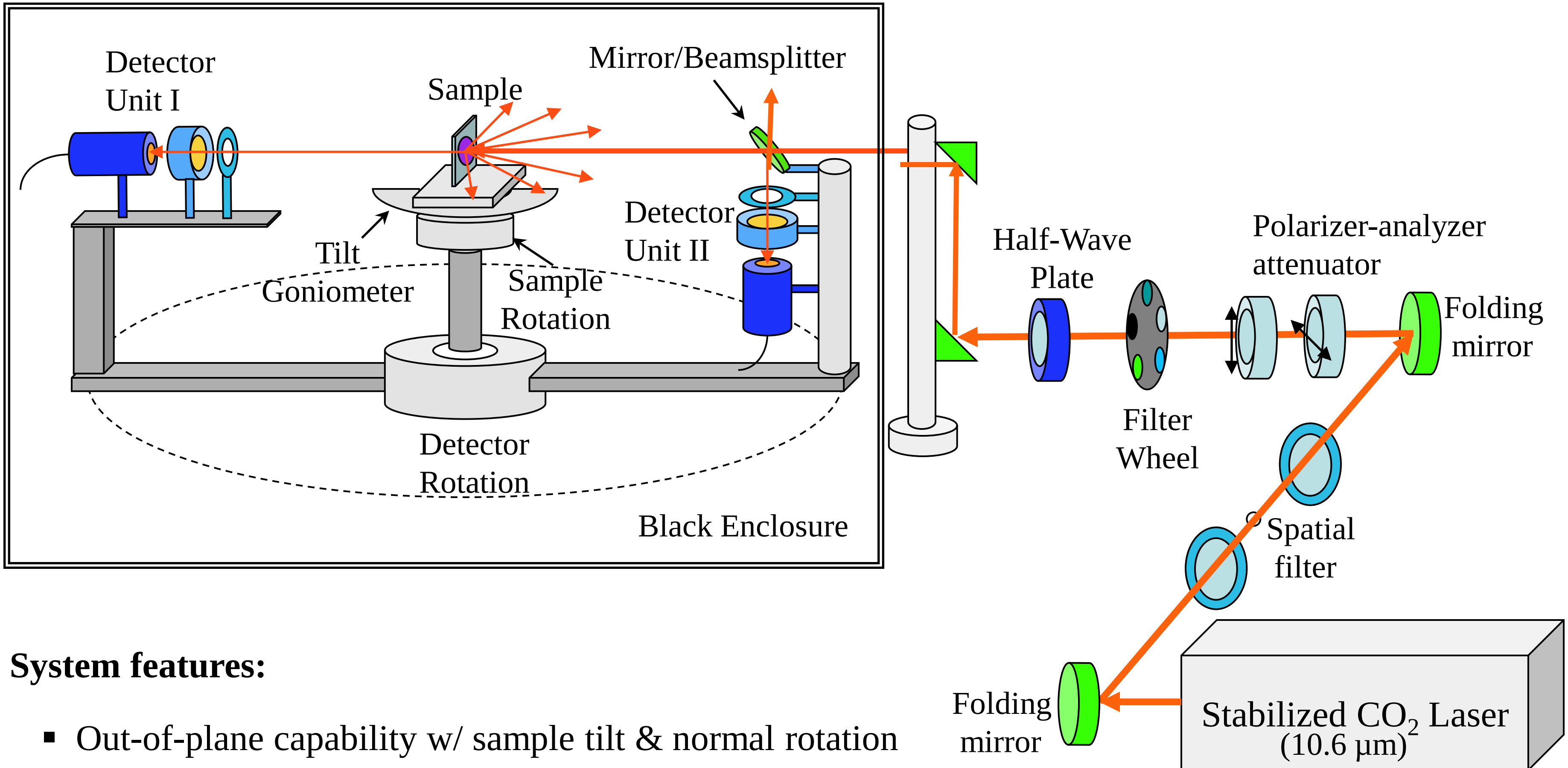


ATBB – Ambient Temp BB
CSBB – Cold Source BB
VTBB – Variable Temp BB

Good agreement with NIST CHILR results

- **Commercial software from Virial International, Inc. (VII)**
  STEEP323 for axially symmetric cavity - conical back of BB
  INCA333 for inclined plane back of BB
  Modeling based on measured paint coupon 5 – 50um reflectance

FTIS: BRDF Experimental Setup



System features:

- Out-of-plane capability w/ sample tilt & normal rotation
- Retro-reflection setup w/ beamsplitter
- Set of interchangeable sample mounts
- Mueller Matrix w/linear polarizers & retarders
- 1.32, 3.39, 0.78 µm, 1 - 5 µm tunable lasers in process to be added