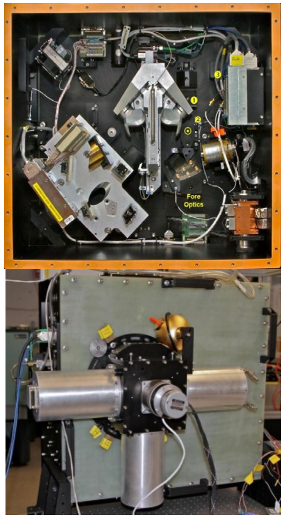
Rationale for Flight of an Infrared SI Reference Sensor for Climate Data Uncertainty Quantification



ARI IR Prototype

Hank Revercomb,
Joe Taylor, Fred Best, David Tobin,
Jon Gero, Robert Knuteson

University of Wisconsin-Madison
Space Science and Engineering Center

ITSC, Climate Session 6.03
Virtual, 28 June 2021

Infrared SI Reference: ARI
Absolute Radiance Interferometer

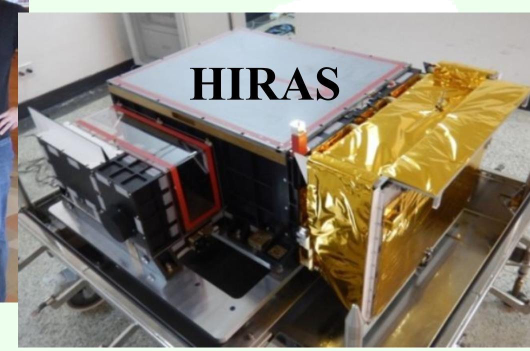
- **A. CLARREO Background**
- **B. Why ARI is Needed Now**
- **C. The ARI Approach**
- **D. A Pathfinder Mission**

1330 orbits

EOS Aqua

Suomi NPP & JPSS

0930 MetOp orbit



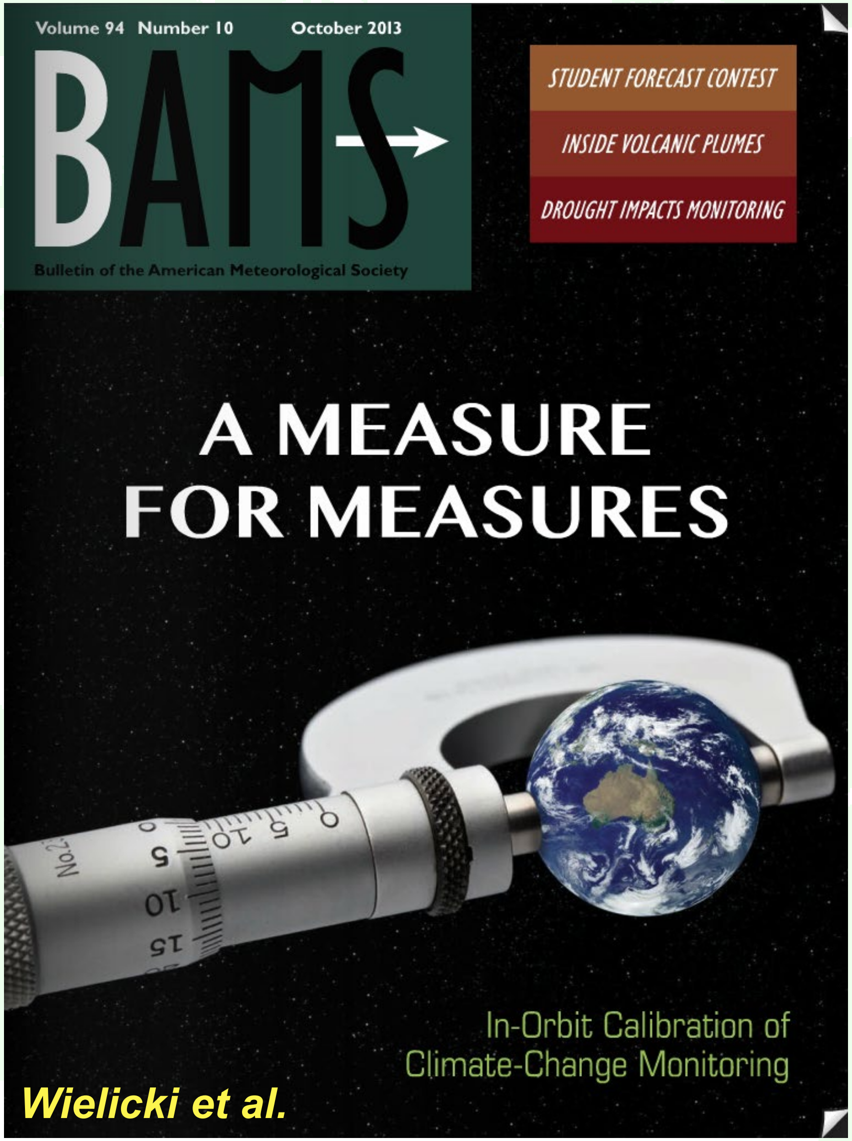
0530 FY3E orbit

+ FORUM

A. NASA CLARREO Background

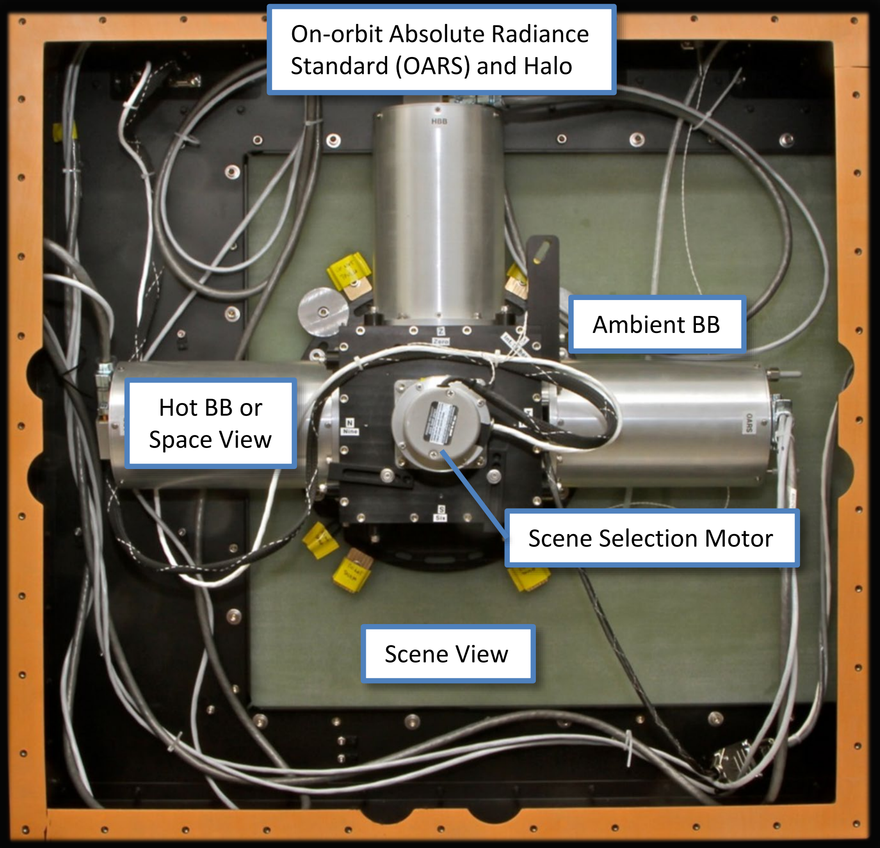
(Climate Absolute Radiance and Refractivity observatory)

- **2008-2010 CLARREO** –following the 2007 DS, NASA assigned mission responsibility to Langley Research Center (LaRC)
  - Science Team formed and mission detailed
  - Mission Confirmation Review passed Nov 2010
  - IR and Reflected Solar (RS) instruments developed under NASA Instrument Incubator Program (IIP) and LaRC calibration system studies
- **2011 CLARREO** –funding profile removed from the president's budget on 14 February
- **2011-15 CLARREO** – Science Team studies continued (Wielicki et al., BAMS, Oct 2013)
- **2012-2014 New Instrument Technologies**
  Achieved TRL 6 under NASA IIP / ESTO:
  LASP for RS and UW-SSEC & Harvard for the IR
- **2016- IR & RS Pathfinders in President's budget**
  Reflected Solar Pathfinder launch planned
  IR not yet supported

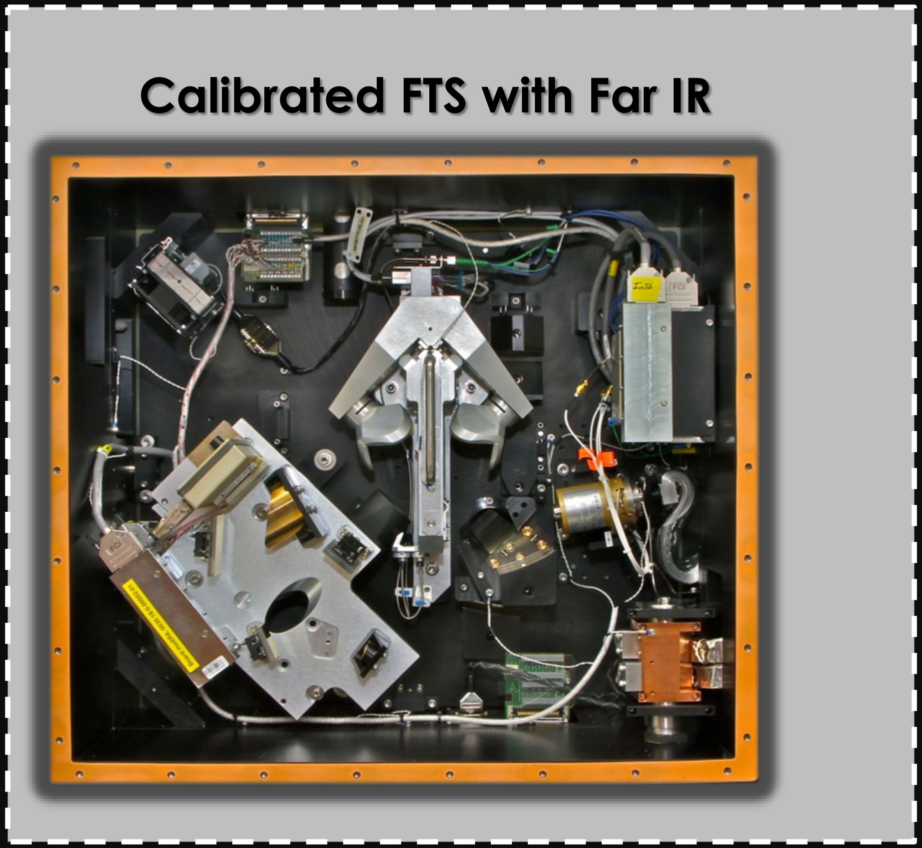


CLARREO Absolute Radiance Interferometer (ARI) IR Prototype

On-orbit Verification & Test System*



Shown without integrating sphere



Dashed line indicates OVTS enclosure envelope.

From Taylor, et al., 2016

Other Spectrally Resolved Climate Radiation Missions

- Solar Reflectance
  - CLARREO Solar Pathfinder, NASA, 2023
  - TRUTHS, ESA, 2026-28
  - LIBRA, China [Earth-Moon Imaging Spectrometer (EMIS), Total Solar Irradiance (TSI), and Solar spectral Irradiance Traceable to Quantum benchmark (SITQ)] as part of Chinese Space-based Radiometric Benchmark (CSRB) project, 2025-32 launch
- Infrared Emission
  - FORUM, ESA, 2026
  - LIBRA, China [Infrared Spectrometer (IRS)]

Proven ARI-based CLARREO IR uncertainty of < 0.1 K T_B k=3 for SI benchmarking exceeds other proven capabilities

Infrared SI Reference: ARI
Absolute Radiance Interferometer

A. CLARREO Background

B. Why ARI is Needed Now

C. The A

Climate Requires Higher, Proven, Accuracy and Information Content

EOS Aqua

Suomi NPP & JPSS

0930 MetOp orbit

0530 FY3E orbit

+ FORUM

Key Drivers for Climate Radiance Observing

from Jim Hansen and CLAREO

- **Greenhouse Forcing:** Order 3.5 W/m^2
- **Earth Radiative Imbalance:** Order 1 W/m^2
- **Large Scale Temperature Trends:** 0.1-0.2 K per decade
- **Time-to-Detect Trends: >** 1-2 decades (limited by natural variability)

To begin to resolve factors on the scale of the Radiative Imbalance from Satellite radiances, an order-of-magnitude higher accuracy is required for well-sampled global data

Times-to-Detect are minimized by similar accuracy improvement

Interpreting radiation in terms of physical properties and feedbacks is greatly enhanced by high spectral resolution

Radiometric Uncertainty (RU)

To connect to Key Drivers (Slide 7) expressed as Fluxes (W/m2), we make use of some simple "Rule of Thumb" arguments

For Earth emitted spectral measurements, we define RU <u>in units of Brightness Temperature (T_b) uncertainty at scene T_b</u>, because:

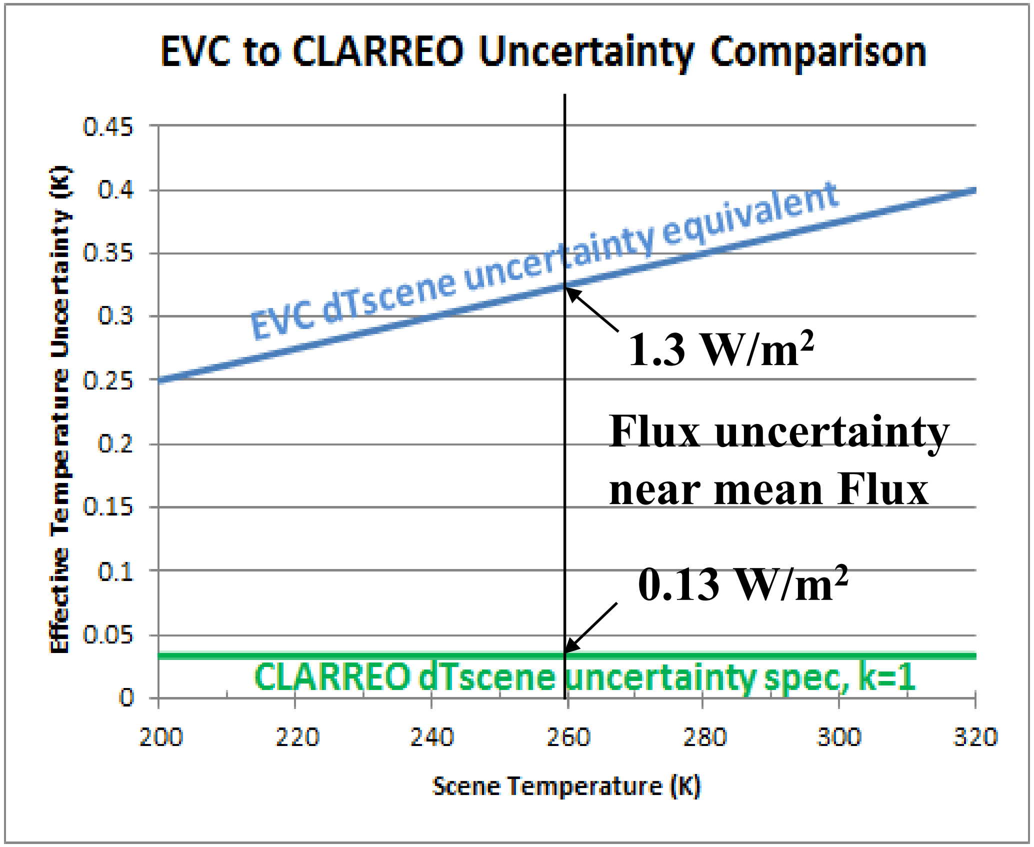
1. **RU expressed as this physical property is easy to think about and conceive of how it can arise**
2. **An RU only weakly dependent on wavelength is achievable**
3. **An RU only weakly dependent on scene T is achievable**

These properties then allow simple comparisons to be made between the expected performance of (1) the CLARREO ARI, (2) broadband climate instruments like CERES (or its Libera replacement) and (3) the Key Drivers (Slide 7)

CLARREO Spectrally Resolved Uncertainties

~ an order of magnitude lower than CERES-type LW total RU

- Earth Venture Continuity (EVC) LW Total Uncertainty (threshold): **% Flux < 0.5 k=1**
- CLARREO LW Uncertainty: **Brightness T at Scene T_b < 0.1 K k=3**



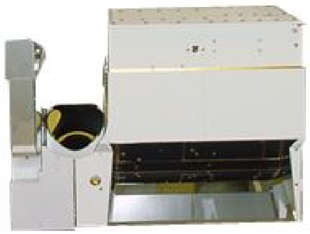
CLARREO ARI will be valuable in reducing the uncertainty of future Earth Radiation Budget Observations

Earth imbalance ~ 1 W/m^2
Greenhouse forcing ~ 3.5 W/m^2

Simple Unit Conversion $dF/F = 4\ \sigma\ T^3\ dT/\ \sigma\ T^4$, where T is an effective scene temperature implying $\mathbf{dT = (\delta F/F)\ T/4 = T/800}$

CrIS RU Estimates Compared to ARI

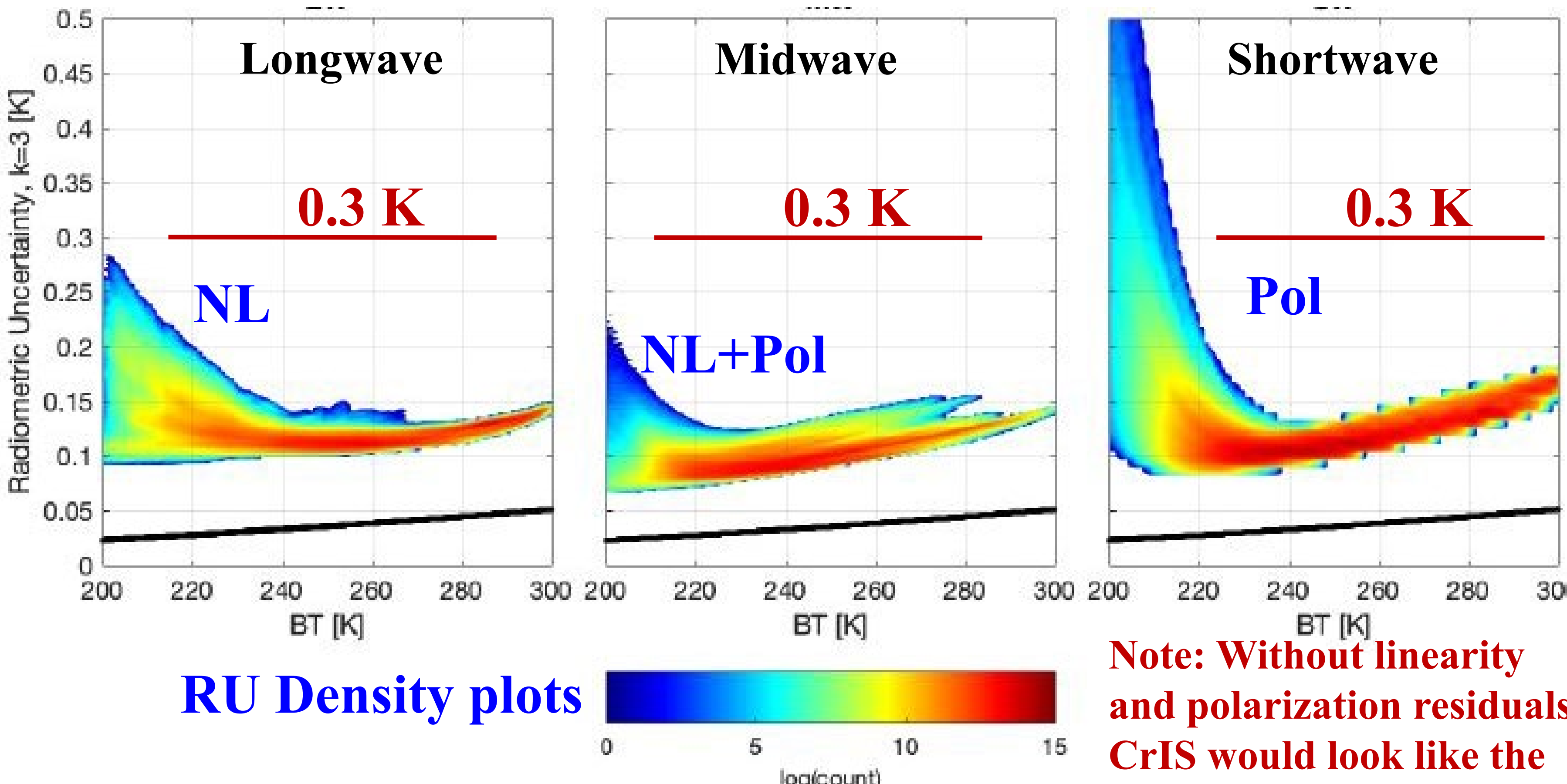
(3-sigma)



Cold T dominated by correction residuals for

(1) Non-linearity (NL)

(2) Polarization (Pol)



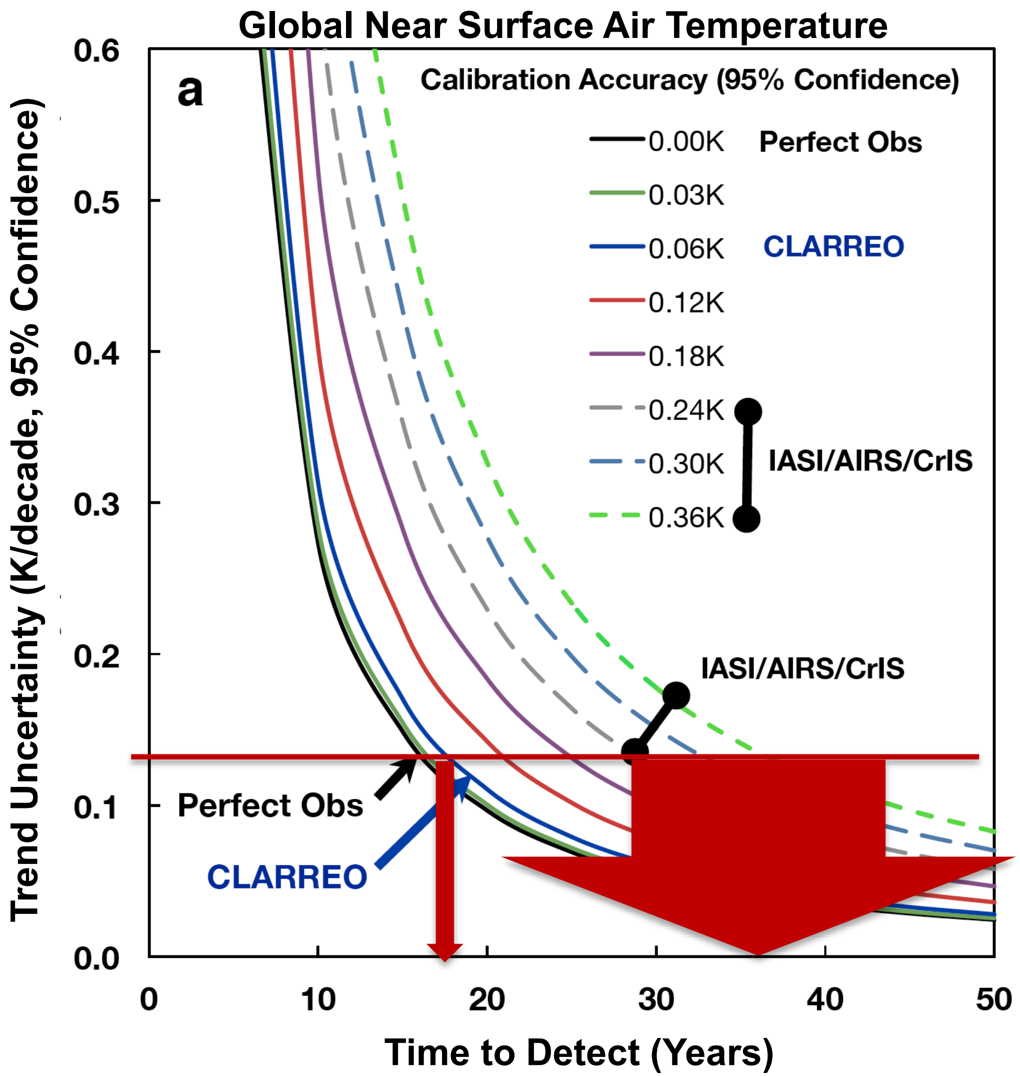
RU Density plots

Note: Without linearity and polarization residuals, CrIS would look like the Lower bound of the SW

Suomi NPP, from Taylor et. al., 2020

CLARREO/ARI Accuracy Offers Substantially Reduced Time to Detect Global Climate Change

Wielicki et al., BAMS, 2013



Expect RU for combined AIRS, IASI, CrIS. HIRAS to be at least 2x CrIS

Example with ~ factor of 2 shorter Time to Detect

Huge Financial benefit shown by Cooke and Wielicki

Infrared SI Reference: ARI
Absolute Radiance Interferometer

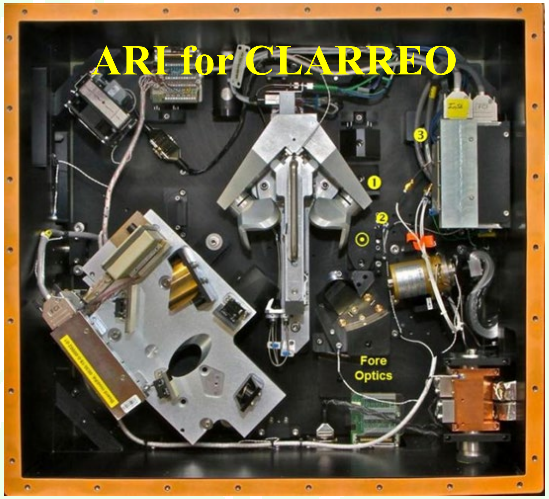
A. CLARREO Background

B. Why ARI is Needed Now

C. The ARI Approach

D. A

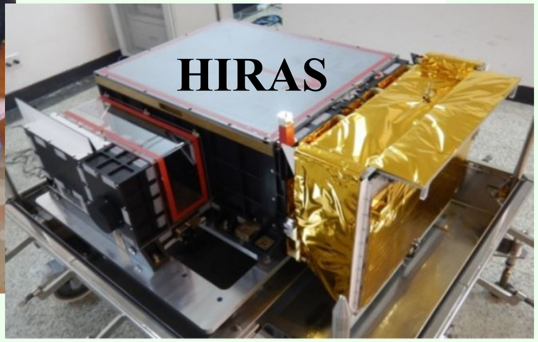
How ARI Achieves Higher, Proven, Accuracy



EOS Aqua

Suomi NPP & JPSS

0930 MetOp orbit



0530 FY3E orbit

+ FORUM

remote sensing

Published 12 June 2020

MDPI

Review

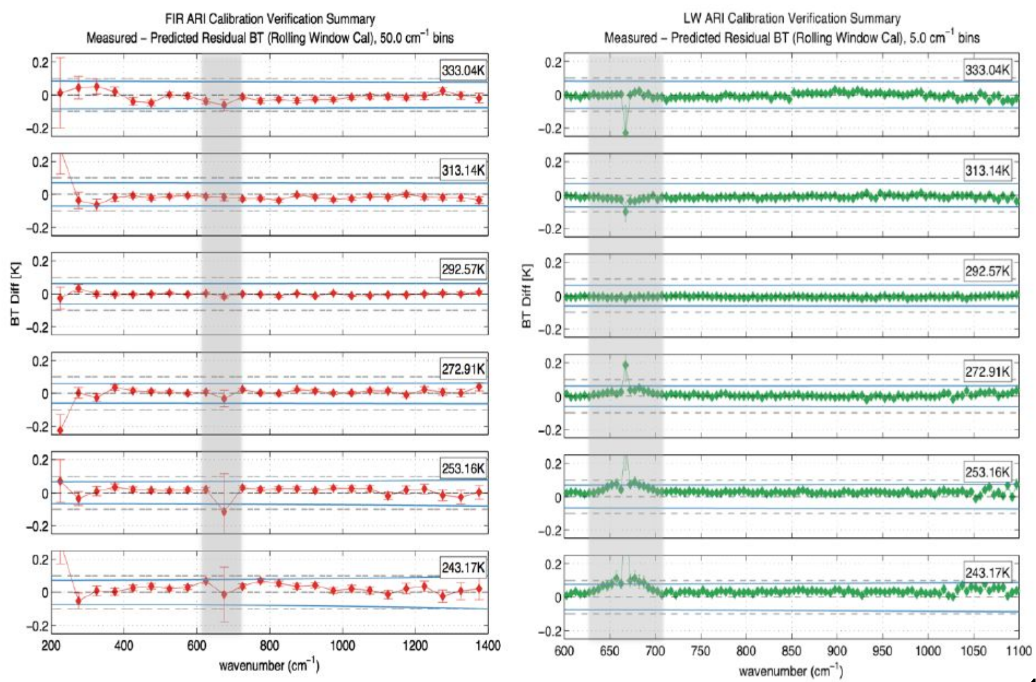
The Infrared Absolute Radiance Interferometer (ARI) for CLARREO

Joe K. Taylor *, Henry E. Revercomb, Fred A. Best, David C. Tobin and P. Jonathan Gero

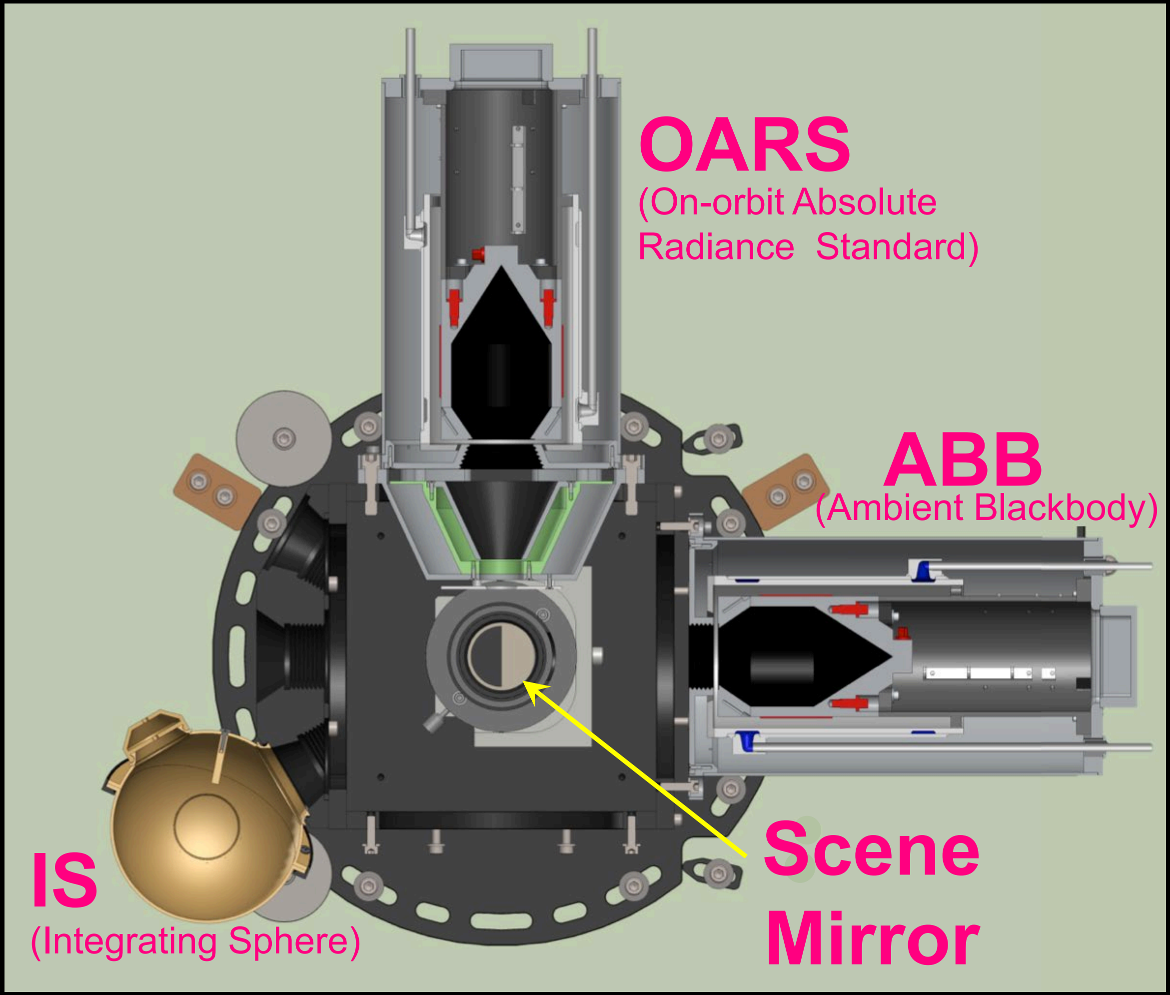
Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53719, USA; hankr@ssec.wisc.edu (H.E.R.); fabest@wisc.edu (F.A.B.); Dave.Tobin@ssec.wisc.edu (D.C.T.); jonathan.gero@ssec.wisc.edu (P.J.G.)

* Correspondence: joe.taylor@ssec.wisc.edu

Please consult Taylor et. al. for a detailed description of the expected accuracy of better than 0.1 K k=3

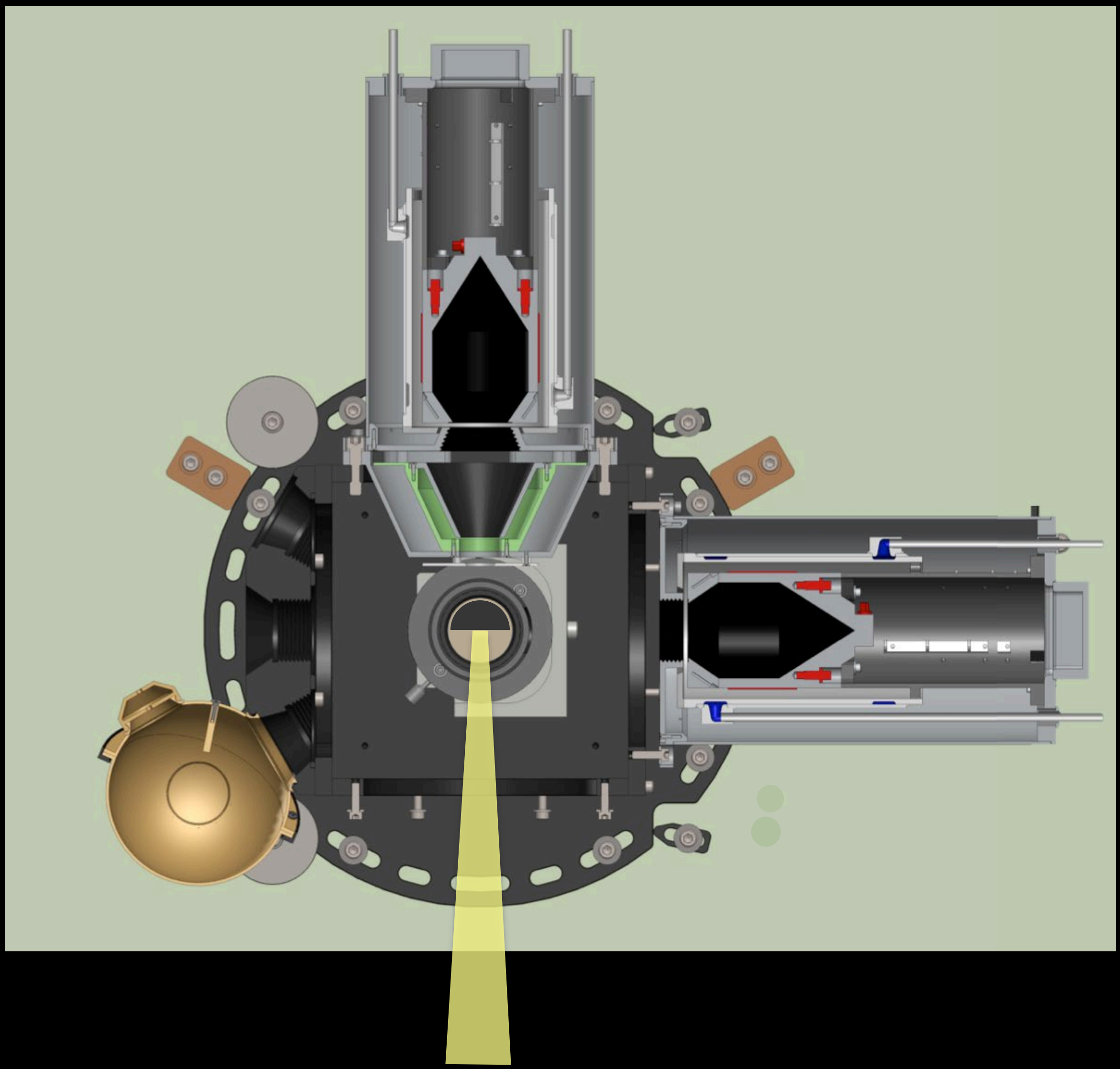


ARI Front-End Key Elements

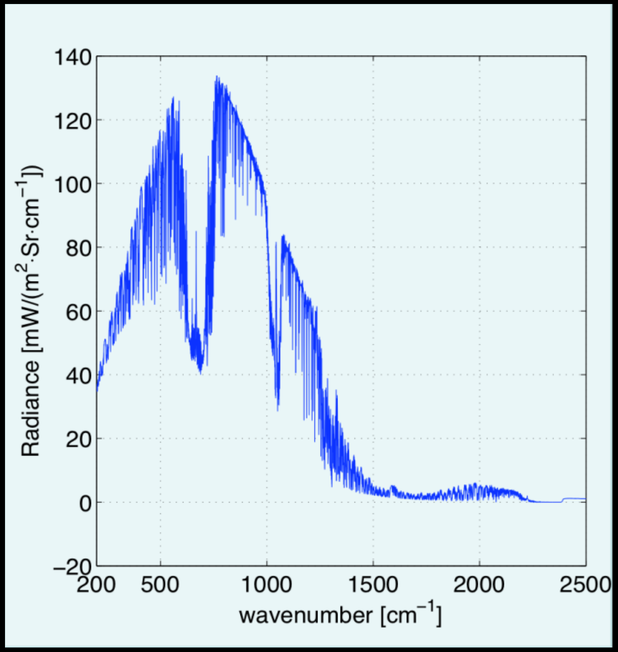


Following views illustrate ARI concepts

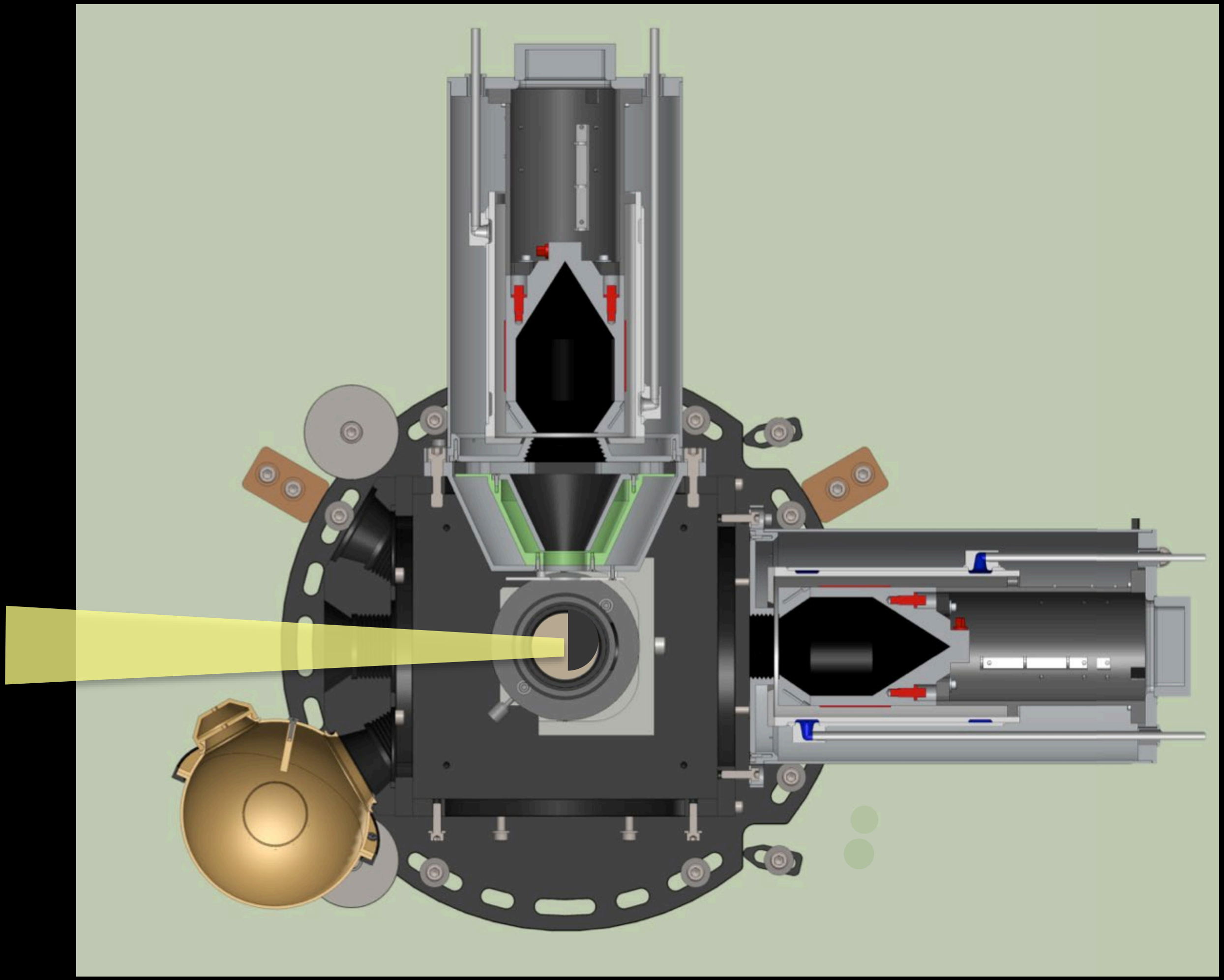
Calibrated FTS: Earth View-Nadir only



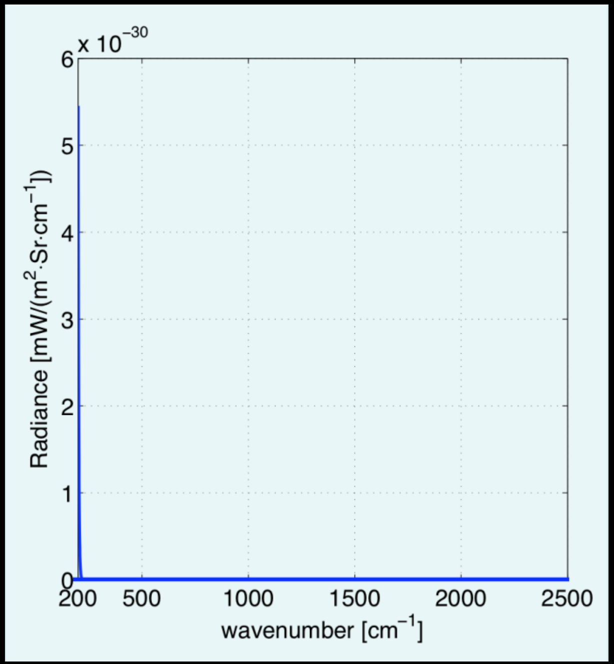
Earth view taken
every 20 seconds



Calibrated FTS: Space Calibration View



Space view taken
every 20 seconds



Calibrated FTS: Ambient Blackbody (ABB)

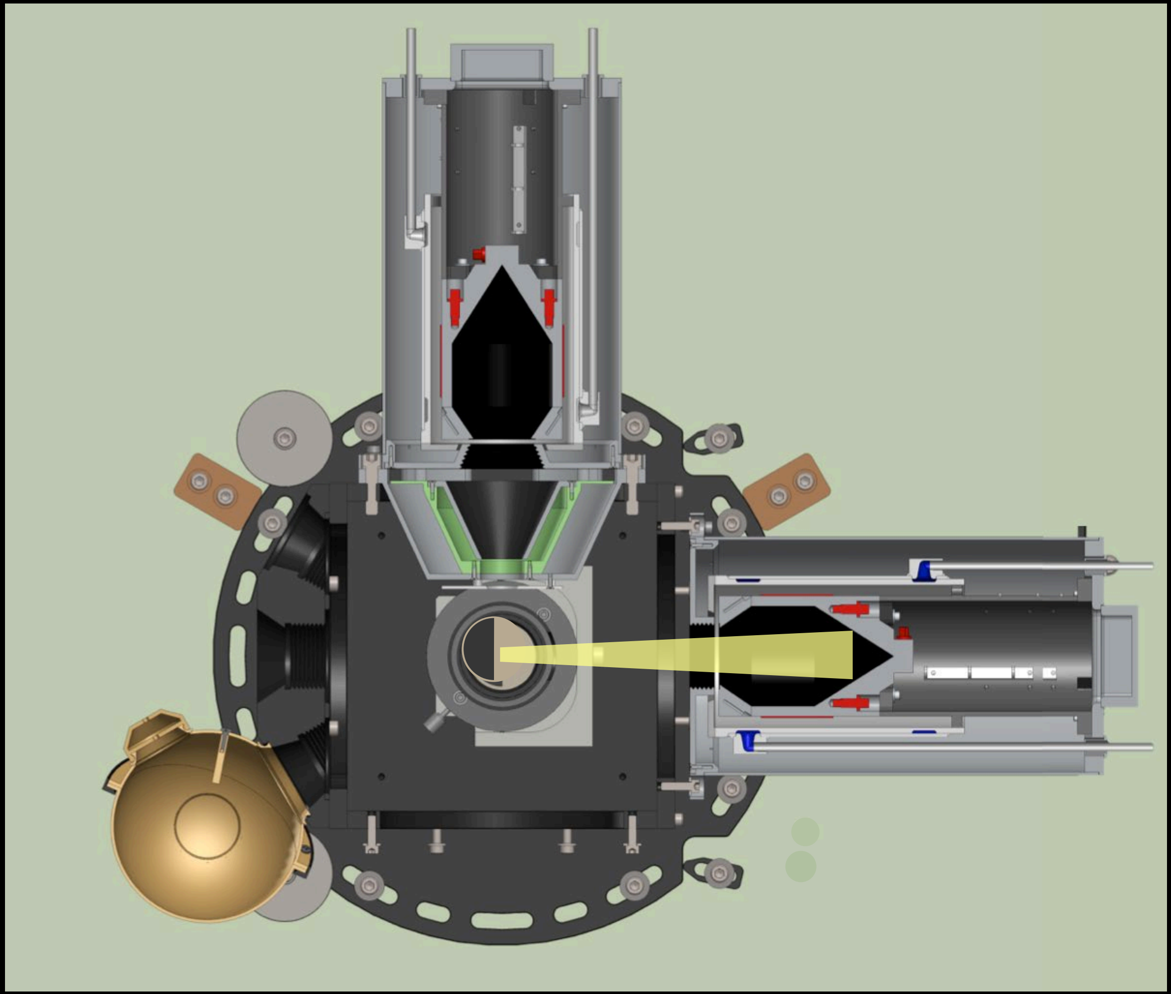
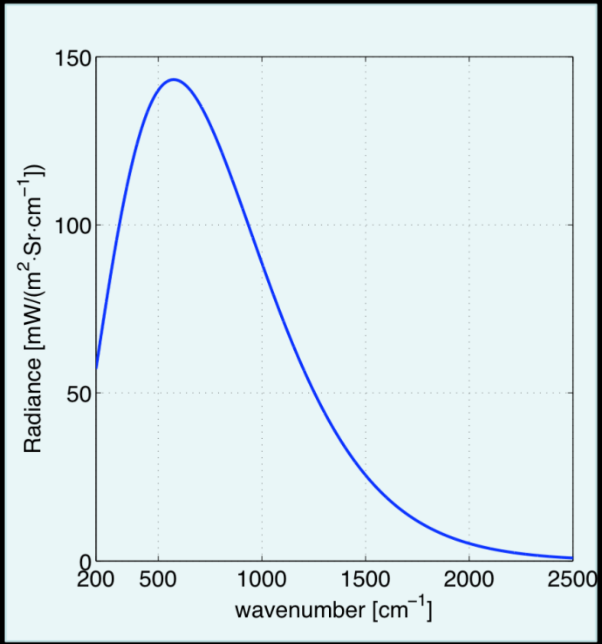
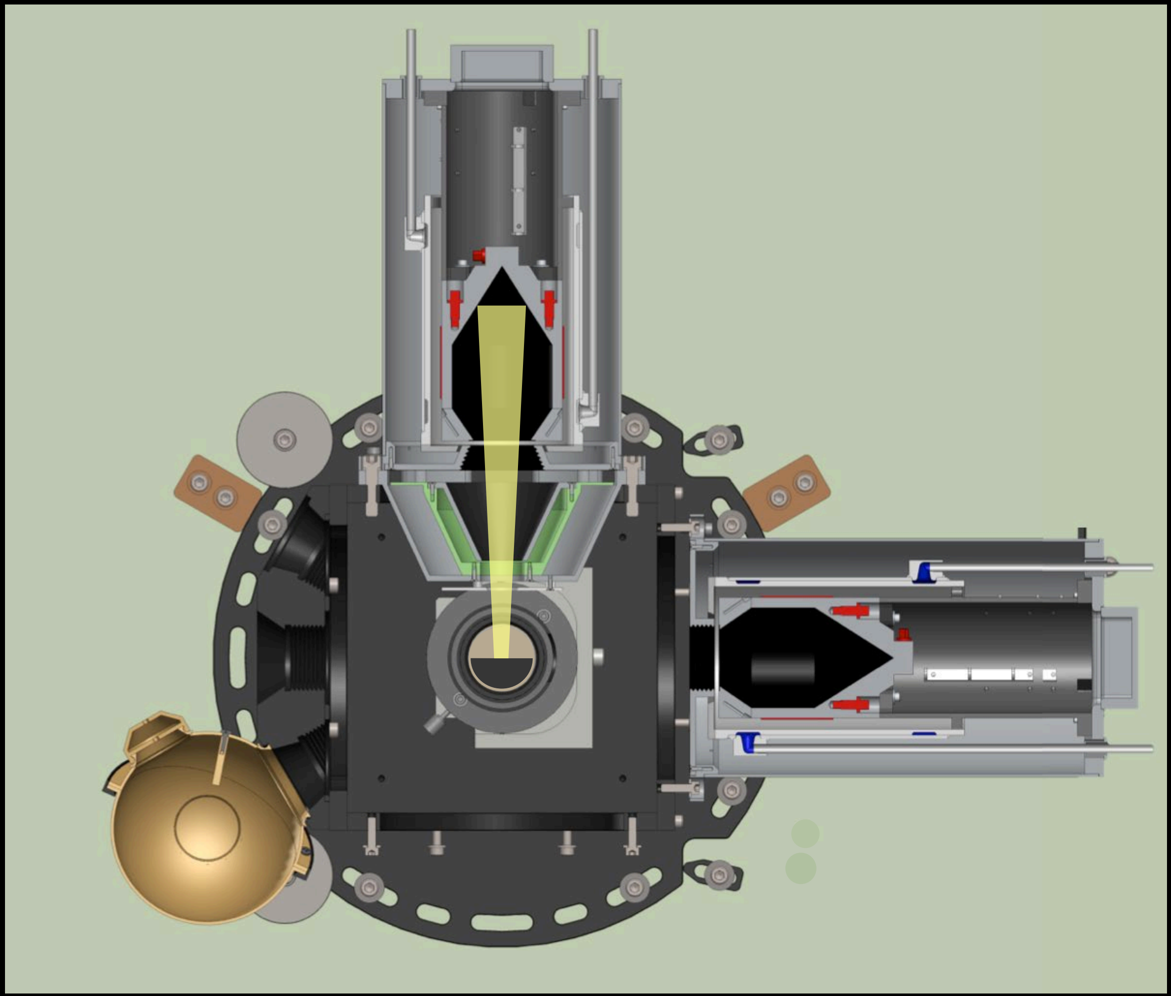


ABB view taken
every 20 seconds



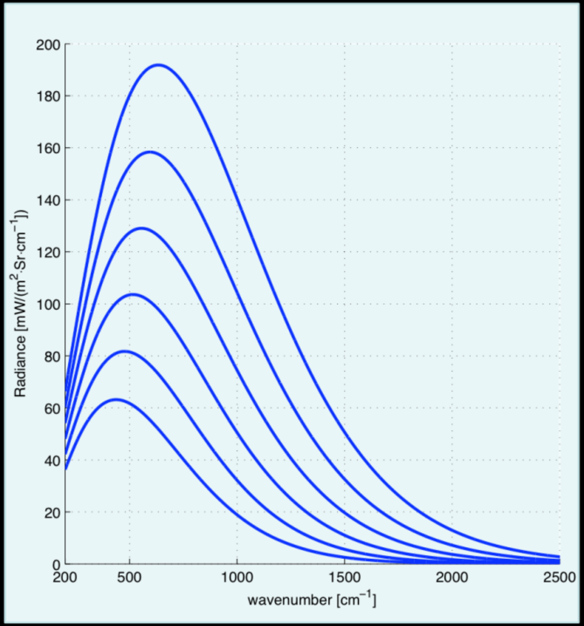
Emissivity > 0.997

OVTS: Variable Temperature OARS View
(On-orbit Verification and Test System)



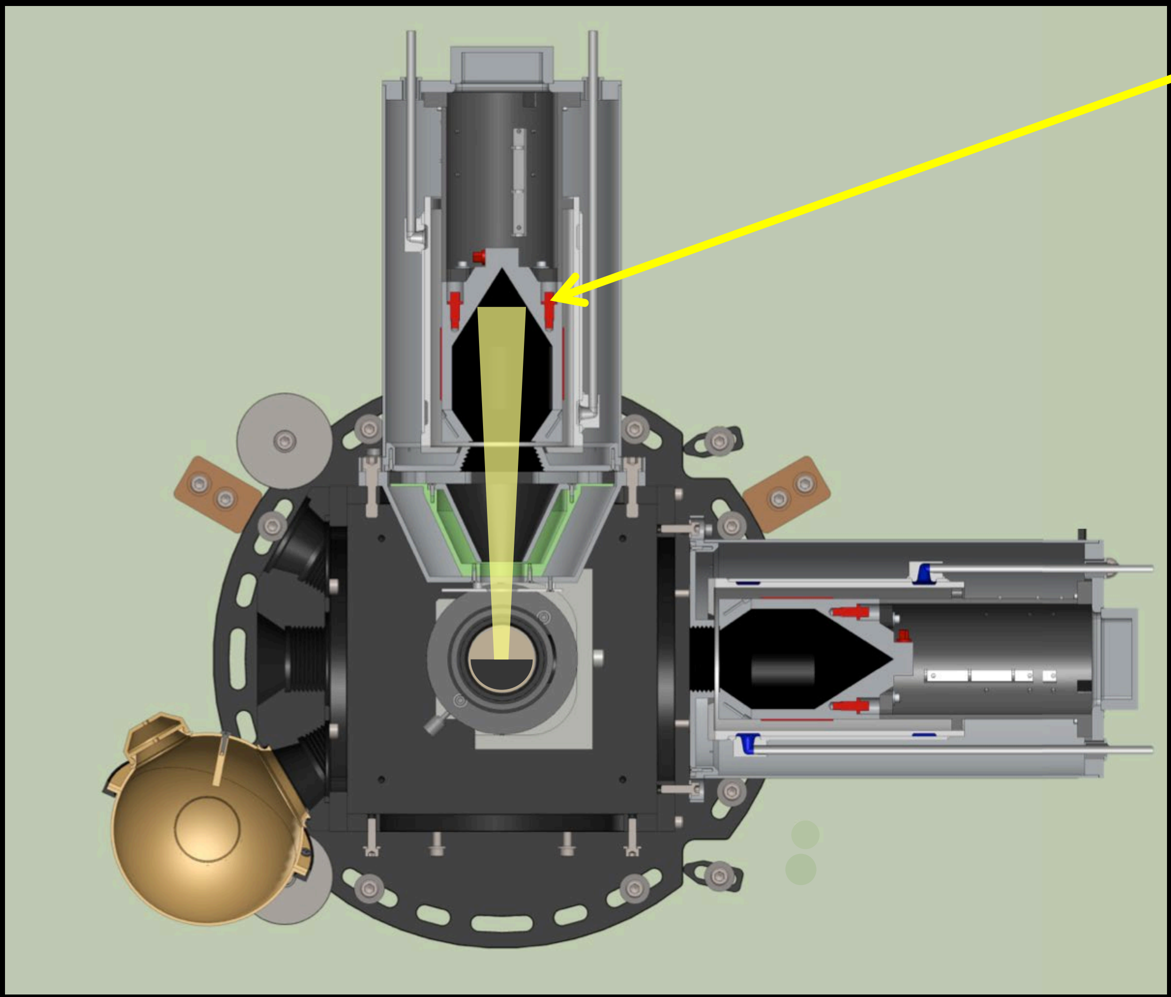
Controllable to a wide range of temperatures to verify absolute radiance and instrument linearity

Si-traceable without long-term stability assumptions



Emissivity > 0.997

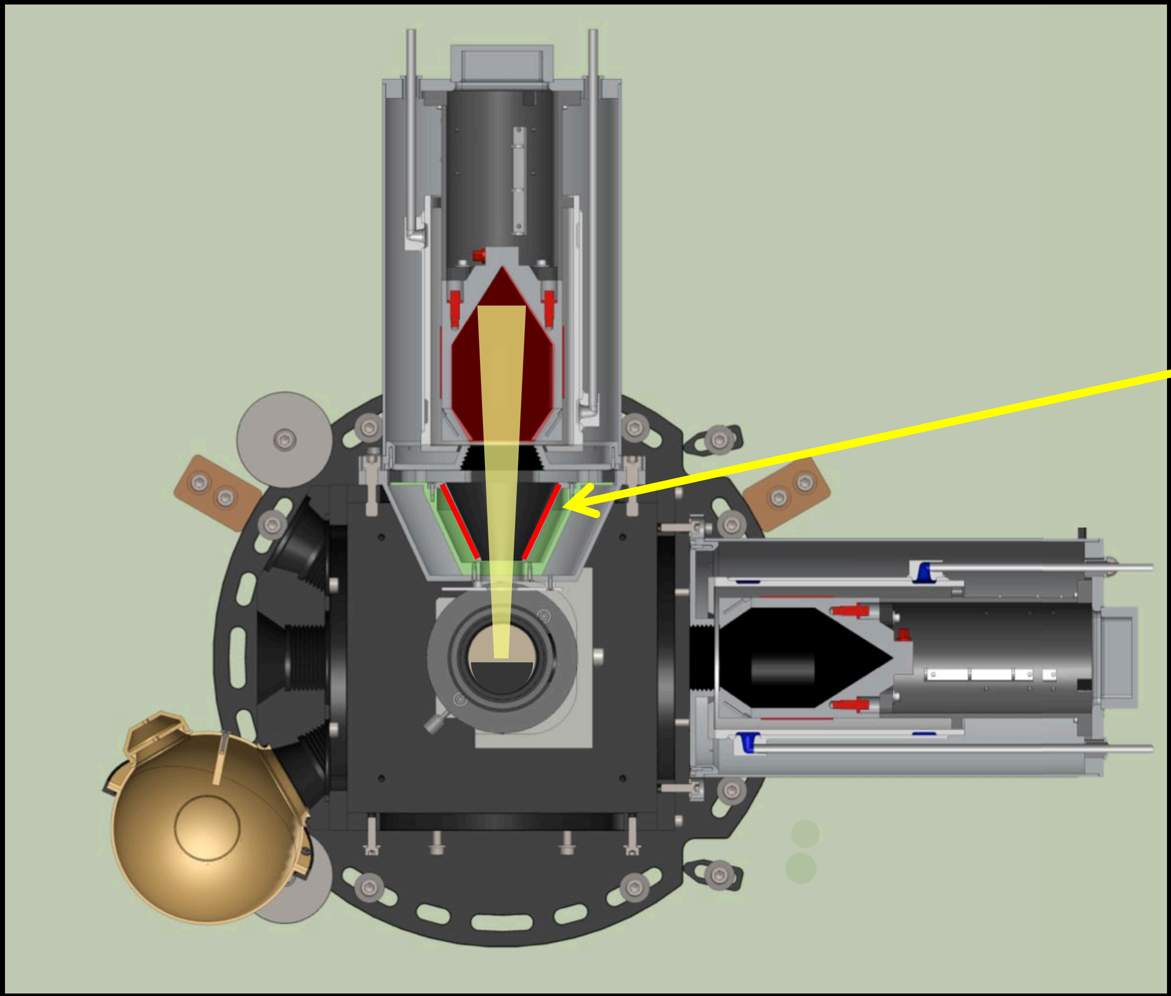
OVTS: Thermistor Temperature Calibration



The OARS has miniature phase change cells containing Ga, H_2O, and Hg, used for periodic temperature calibration at 30, 0, and -38 °C

Establishing a fundamental T scale on-orbit

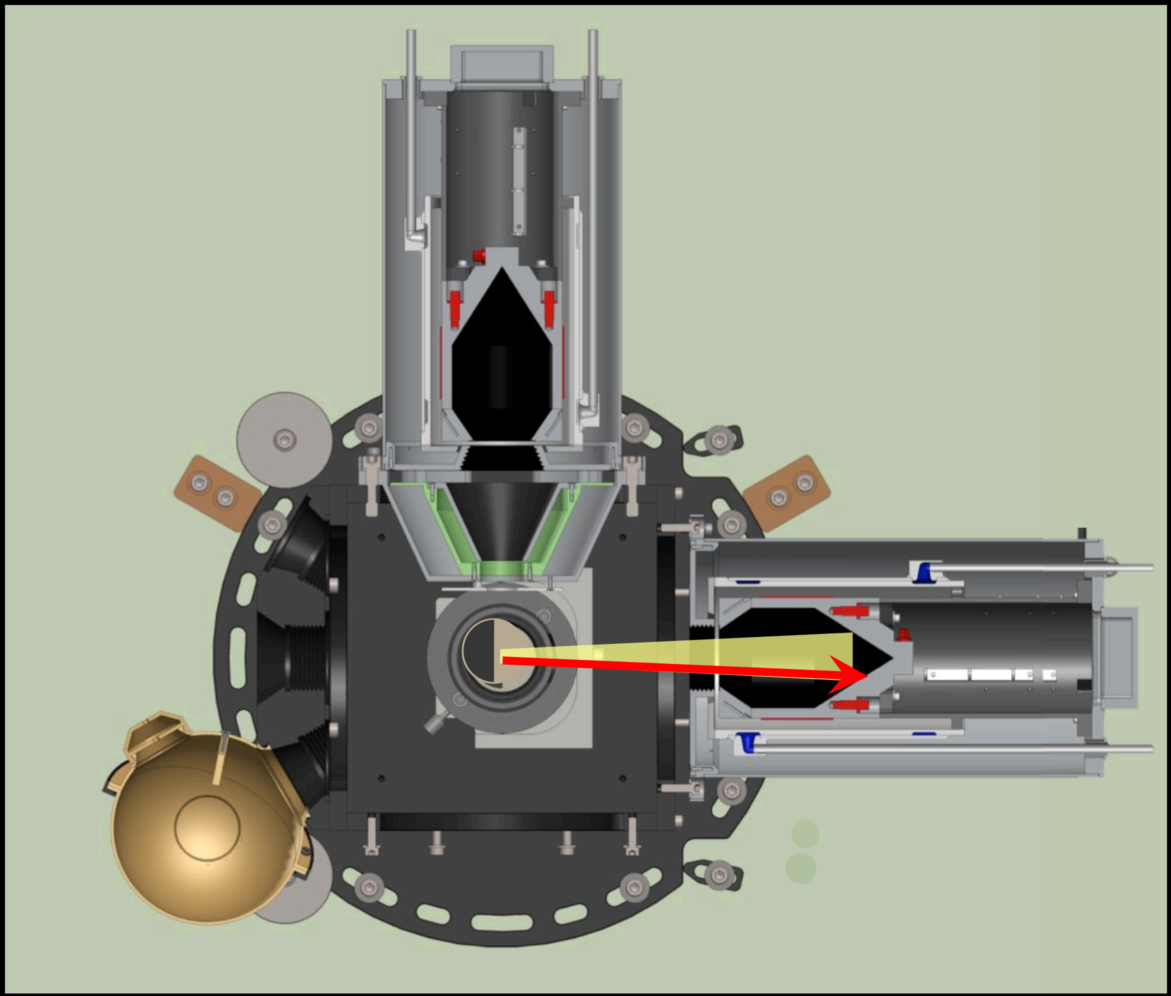
OVTS: OARS Spectral Emissivity – Heated Halo

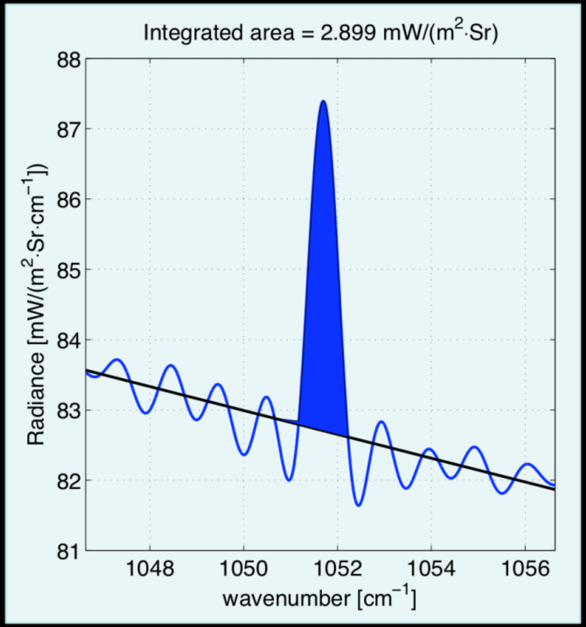


The Heated Halo is used periodically for measuring the blackbody cavity spectral emissivity

Quantifying any unexpected degradation to better than 0.1 %

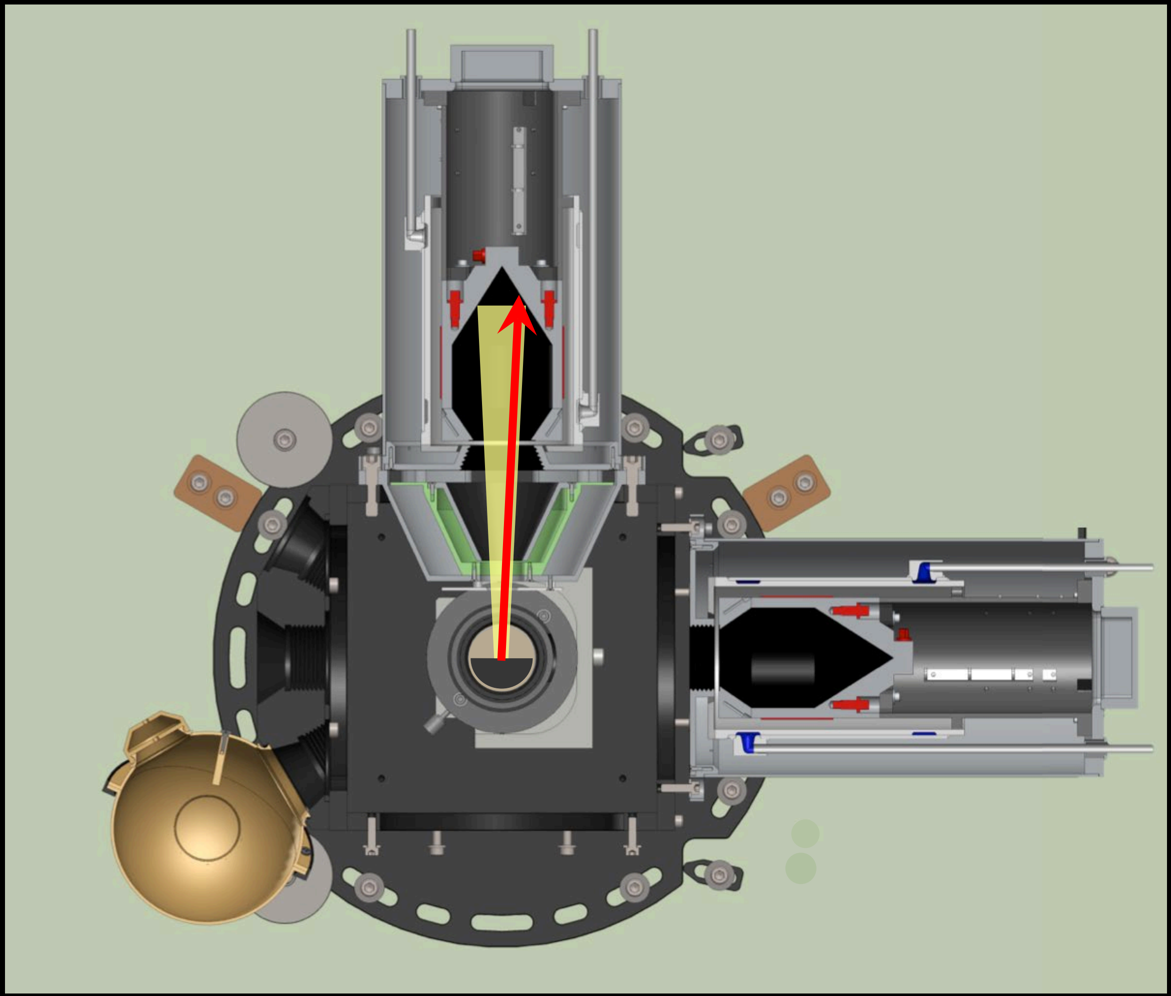
OVTS: ABB Emissivity – QCL 9.5 μm Source

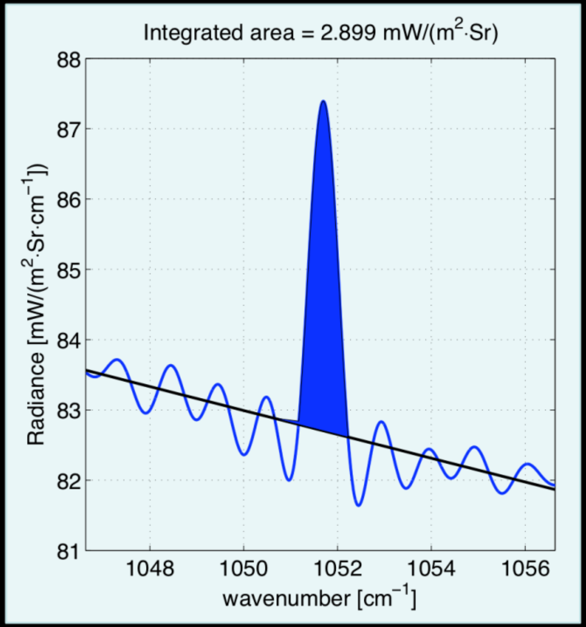




Compares ABB to OARS emissivity

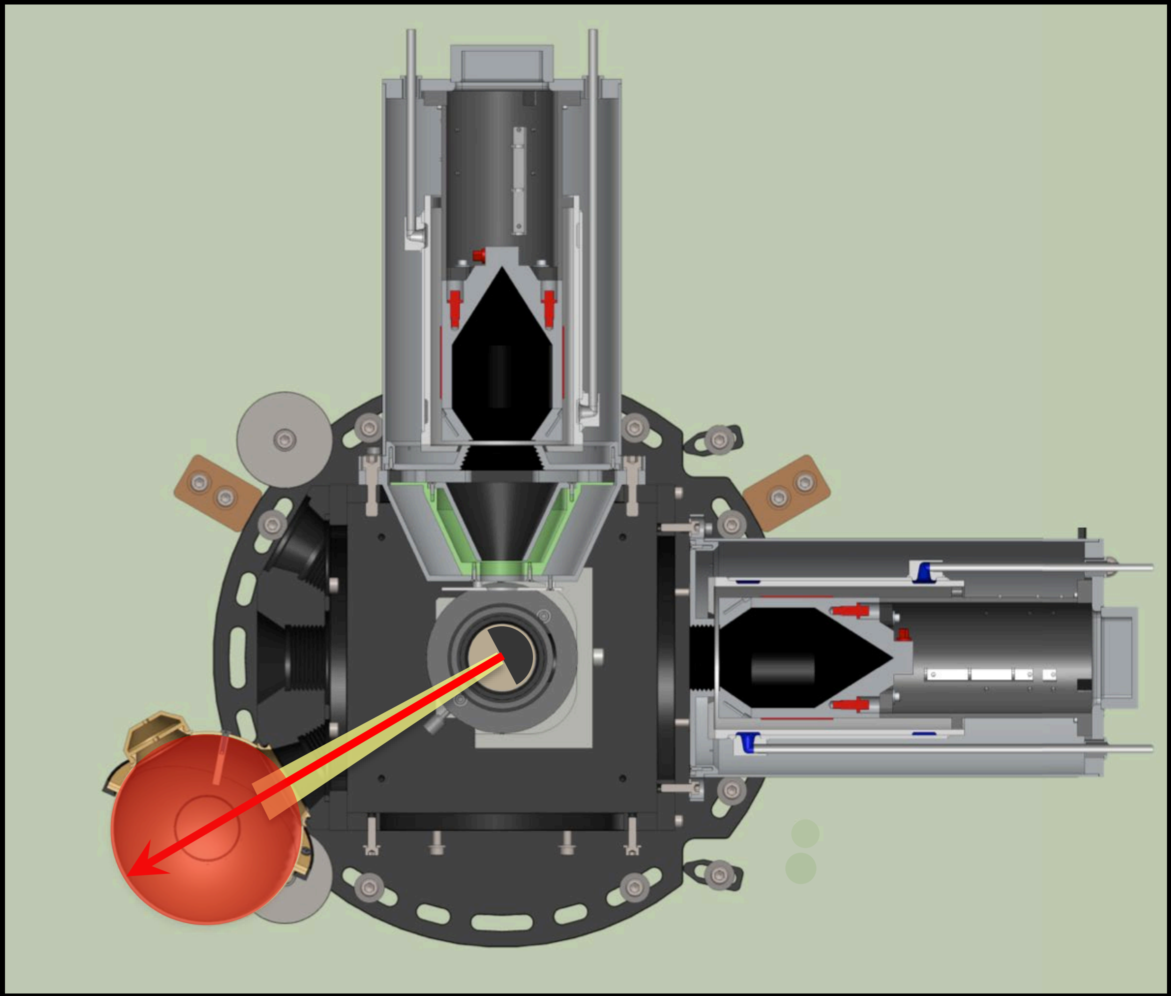
OVTS: OARS Emissivity – QCL 9.5 μm Source



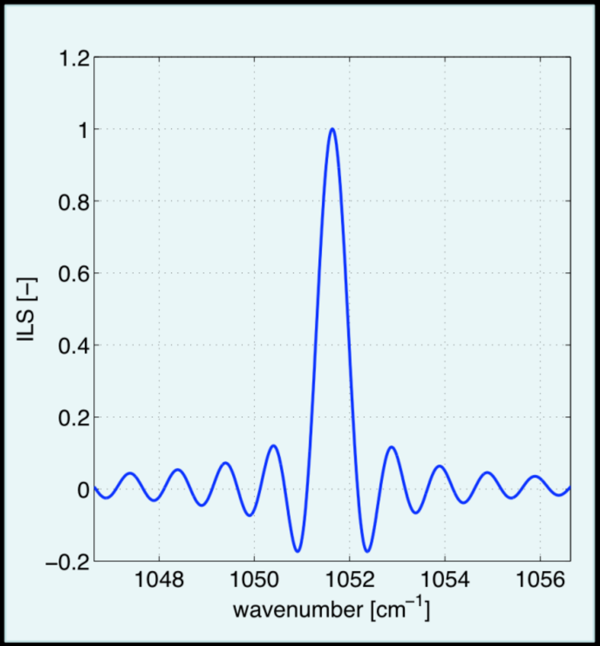


Compares ABB to OARS emissivity

OVTS: Instrument Line Shape – QCL Source

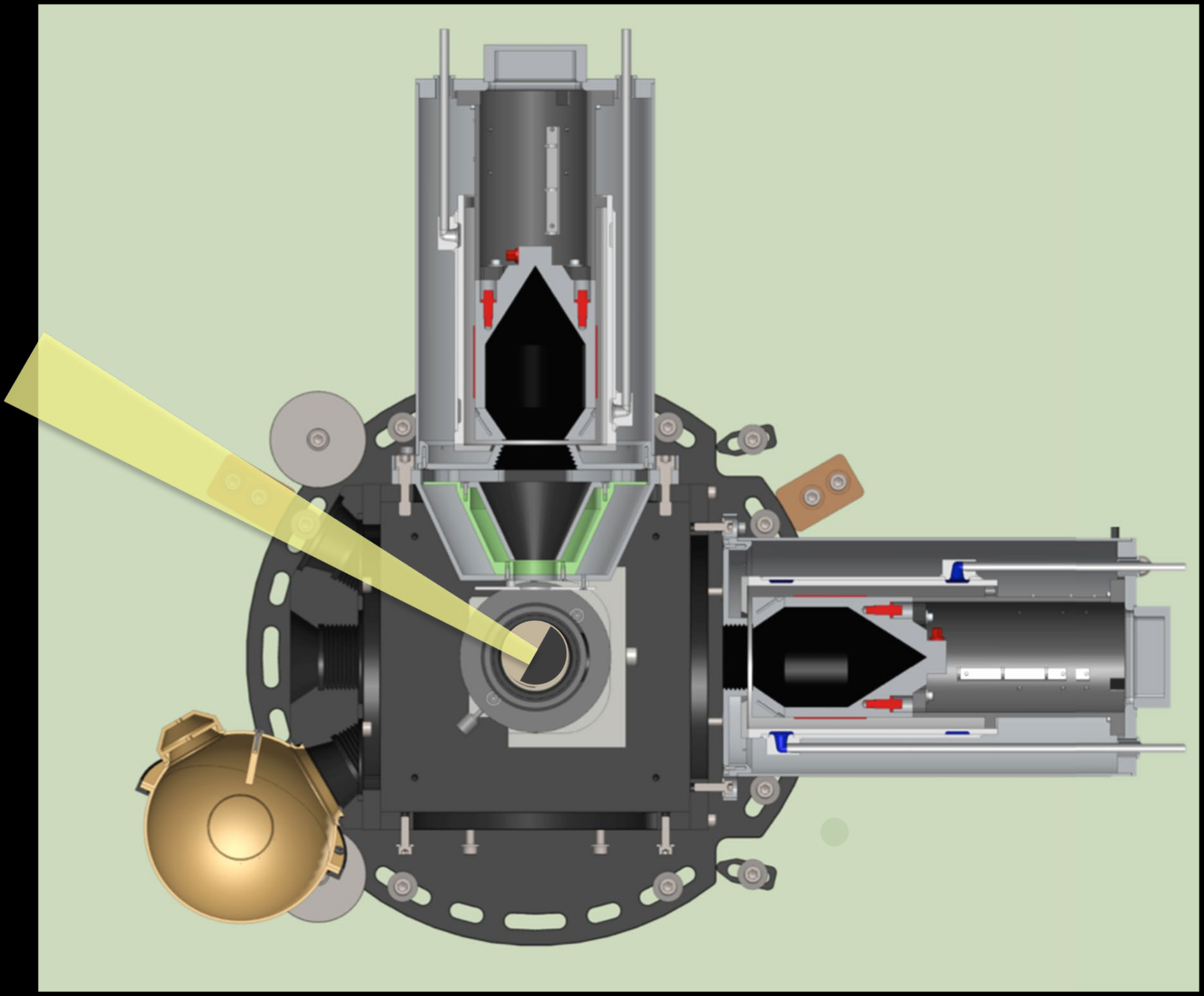


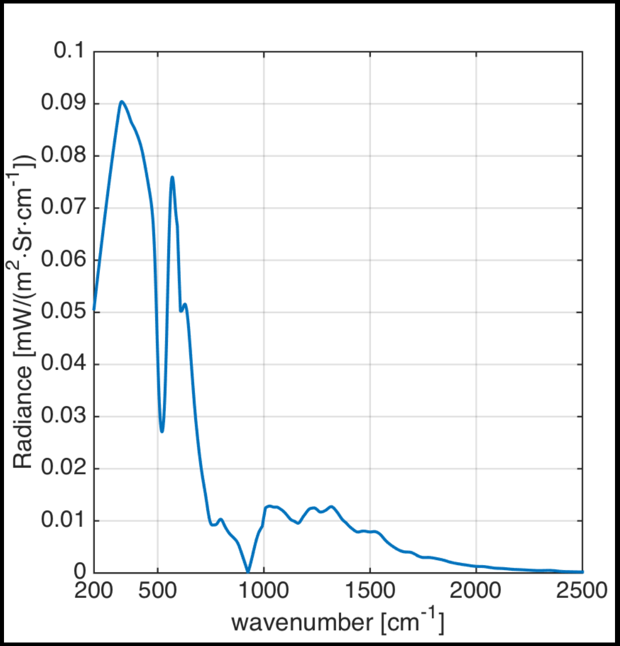
Spectral ILS monitor
Supports SI-traceability



OVTS: Space-2 View

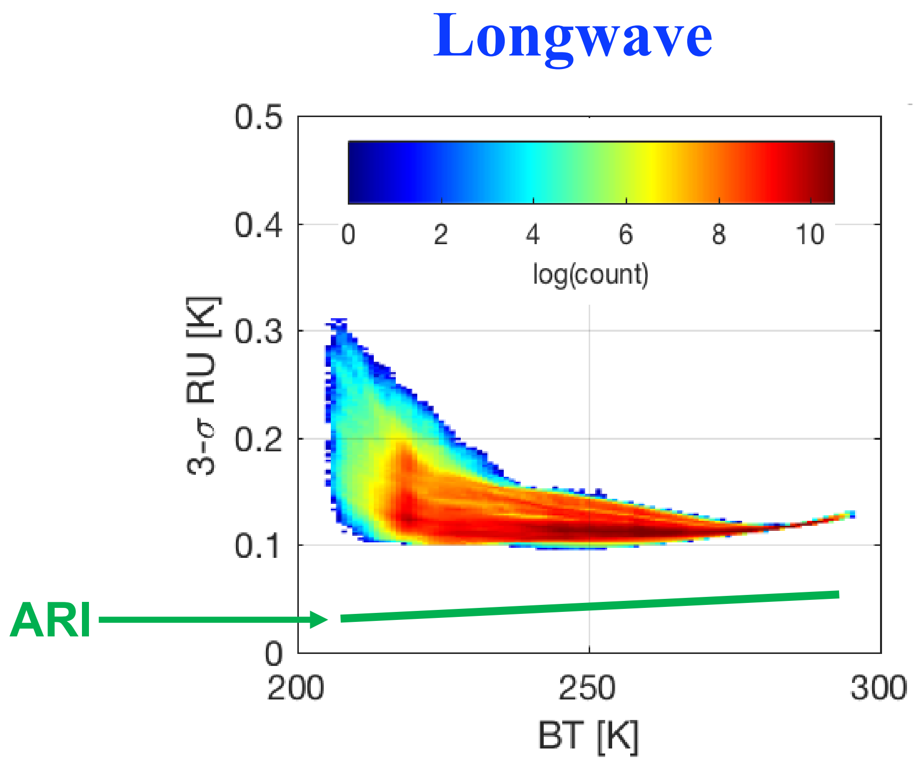
Used to characterize polarization*





*Instrument design provides Earth viewing immunity to polarization

ARI compared to CrIS On-Orbit RU



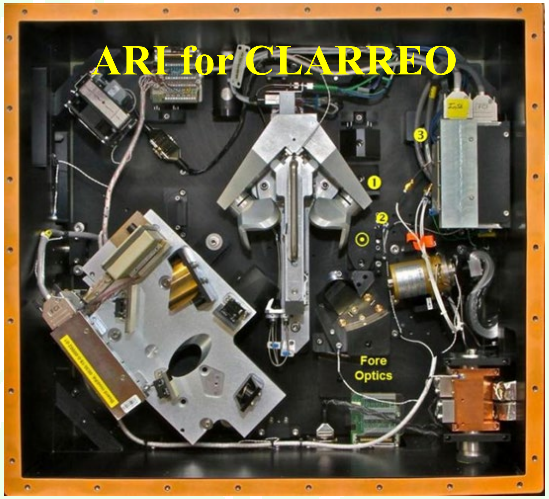
CLARREO Absolute Radiance Interferometer (ARI) detectors chosen for high degree of linearity & non-scanning design is immune to polarization error

- ***ARI represents a huge Radiometric Uncertainty improvement over the sounding fleet - expect total uncertainty of fleet of AIRS, IASI, HIRAS, CrIS to be at least 2 times CrIS alone***
- ***Then with ARI, the operational sounders can be inter-calibrated, (thereby, proven on-orbit) and can provide the unbiased sampling needed for high quality climate products***

Infrared SI Reference: ARI

Absolut … eter

1 ARI Leverages other spectometers for spatial coverage needed for Benchmark



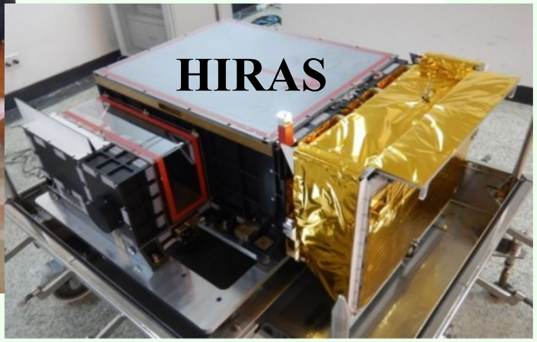
D. A Pathfinder Mission

1330 orbits

EOS Aqua

Suomi NPP & JPSS

0930 MetOp orbit



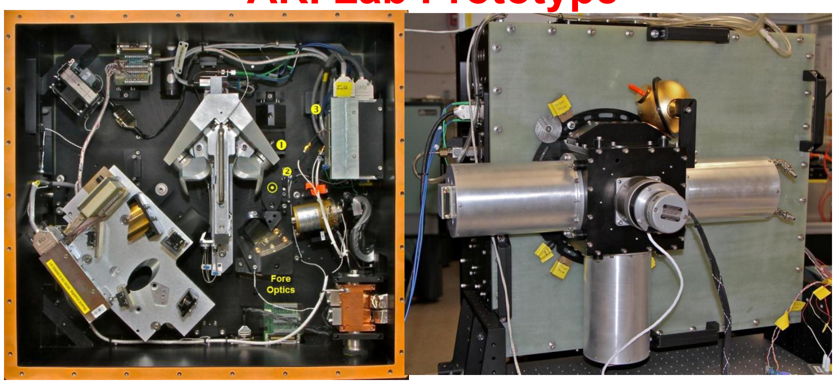
0530 FY3E orbit

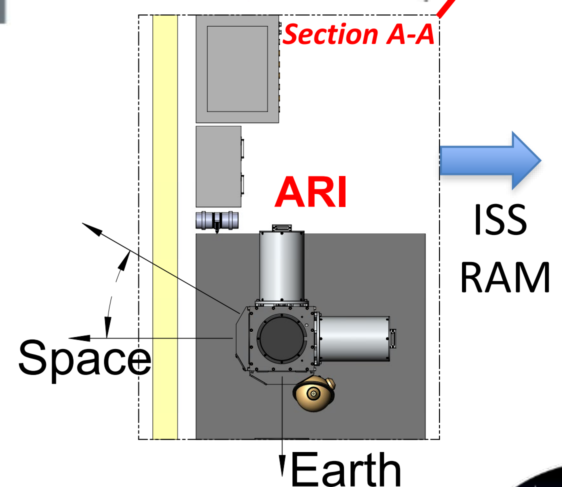
+ FORUM

CLARREO IR Pathfinder Mission:
International Space Station example

International Space Station

ARI Lab Prototype

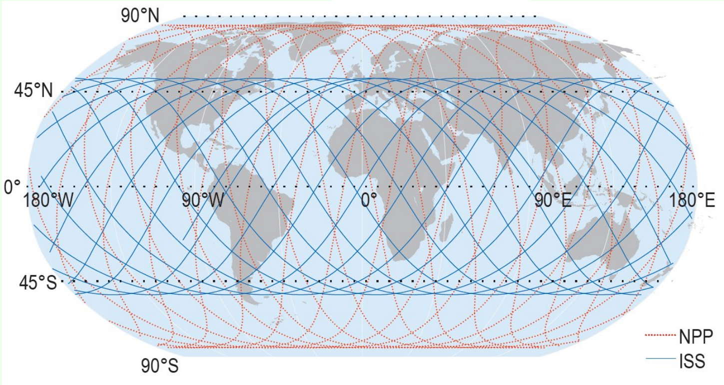




CLARREO IR Reference Ready

- **Accuracy better than 0.1 K 3-sigma brightness temperature at scene T_b that will be connected to SI T scale established on-orbit has been demonstrated & understood**

- **It is expected that the fleet of operational sounders will soon provide the sampling needed for achieving an 0.1 K 2- sigma climate record (next year, FY3-E HIRAS will provide the Early morning orbit, thereby completing the configuration that now has 2 FTS instruments in both the 0930 and 1330 orbits),**



ESA FORUM would also be inter-calibrated to extend high, proven accuracy in the Far IR to polar regions

- **Therefore, with inter-calibration, even an inexpensive IR pathfinder-type mission can provide a credible benchmark**

SI-Traceable Space-based Climate Observing System Workshop (SITSCOM) Conclusion

(in press and not yet released)

- *Improvements need to be made in the thermal infrared to reach the required SI-traceability goals from independent sensors through at least 200 to 2000 cm^{-1}.*

  FORUM will not meet this accuracy through the entire infrared spectrum, and its accuracy goals are still in development. The Chinese LIBRA mission is meant to achieve those goals through improvement over multiple missions. The developed infrared SITSat spectrometer intended for the full CLARREO mission is intended to meet these goals but has not yet been manifested for flight.

  An infrared CLARREO Pathfinder mission should be developed and launched as soon as practical.

- **The world's space agencies should initiate plans to strategically sustain on an operational basis an SITSCOS into the long-term**

Summary

- Higher accuracy will establish a benchmark that begins to resolve the Earth radiative imbalance from space and allows better and quicker interpretation of model predictions
- ARI Radiance observations use on-orbit standards and testing to assure accuracy expectations e.g. fundamental on-orbit temperature scale and emissivity measurements
- For an ARI pathfinder on ISS, intercalibration with operational sounders will allow a climate radiance benchmark to be started at all latitudes
(with Far IR extended to the poles via the FORUM Mission)
- Ongoing CLARREO-like Missions will also provide a higher accuracy, better proven reference for the WMO Global Space-based Inter-Calibration System (GSICS)