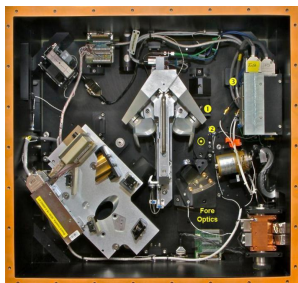




IR Measurements for CLARREO: the Compelling Need for an On-orbit SI Reference Sensor

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F. A. Best, J. K. Taylor, D. C. Tobin,
P. J. Gero, R. O. Knuteson

University of Wisconsin-Madison
Space Science and Engineering Center



ARI IR Prototype



Sun Climate Symposium, Session 5
19 May 2022



IR Climate Benchmarking & Intercalibration

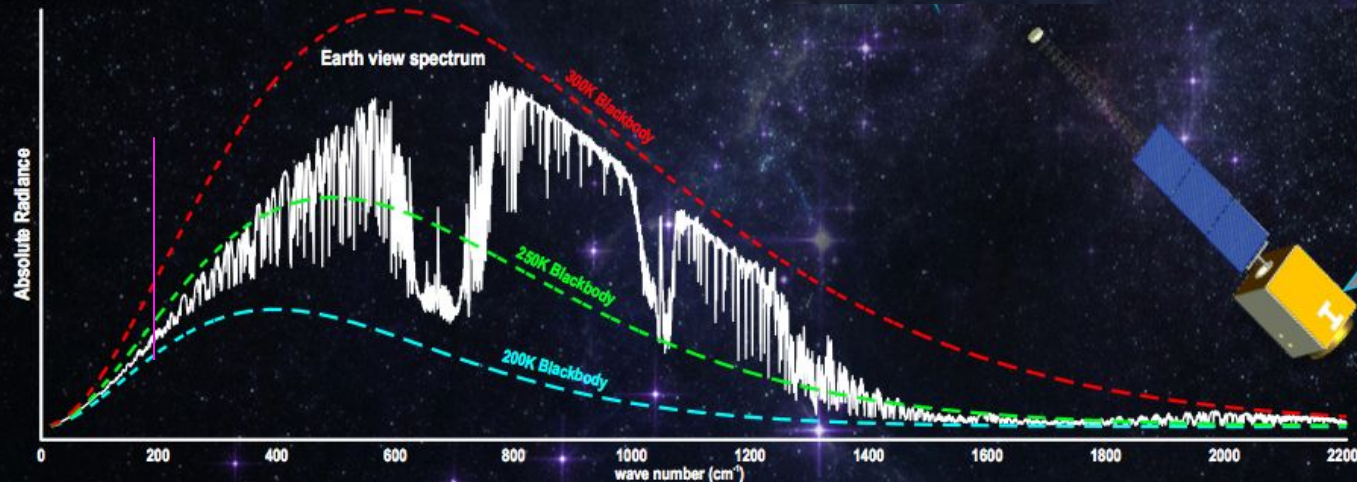
2011 NASA Earth Venture proposal

Benchmarking Radiance for Climate Change:

With the rapid increase in climate forcing through the addition of infrared active molecules to the atmosphere by fossil fuel combustion and the probability of carbon release from expanding melt zones in the Arctic, the need for irrefutable observations to define the current state of the atmosphere is becoming increasingly critical. The first goal of the Zeus mission is to provide a global benchmark climate record for this and future generations that, by virtue of its high accuracy determined against international standards on-orbit, establishes a new foundation for quantitatively defining the rate of climate change. Achieving this goal will provide decision support for a range of societal issues including water resources, human health, natural resources, energy management, insurance infrastructure, and others that are linked to our understanding of how climate is changing. *The first science objective of Zeus is to provide a benchmark of the thermal infrared radiance spectrum against which similar future observations can be compared to establish atmospheric change with credibility.*

Benchmarking Radiance for Climate Forecast Testing:

Significant uncertainties exist in forecasts of our future climate. For example, the differences between the IPCC Fourth Assessment models is significant indeed, ranging from virtually no predicted change to a change of 0.6 K/decade between the Japanese medium resolution model and the GISS-EH model for the North American region. Central to the climate sensitivity discrepancy among different IPCC models, is their different climate feedback strengths. To narrow down the uncertainty of climate projection given by the ensemble of these models, it is imperative to measure and confront these models with the feedback strengths measured from observations. *To address this issue, the second science objective of Zeus is to provide a benchmark of the thermal infrared radiance spectrum to determine longwave forcings and longwave feedbacks for testing climate models.*



Benchmarking Radiance for Reanalysis and Intercalibration:

Weather forecast systems utilize data from a wide range of satellite systems and sensors that are primarily designed for operational weather forecast requirements. Eliminating biases between the various sensors is important for making optimal use of the data, and is a primary goal of the Global Space-based Intercalibration System (GSICS) and data assimilation centers. A spectral radiance dataset with high accuracy and on-orbit traceability is required for both Reanalysis methods employing data assimilation techniques and direct intercalibration techniques such as Simultaneous Nadir Overpass analyses to anchor the calibration of the operational weather sensors. *Addressing this issue, the third science objective of Zeus is to provide a benchmark of the thermal infrared spectrum that can provide reference intercalibration for other sensors and for anchoring reanalysis.*



Infrared SI Reference: ARI

Absolute Radiance Interferometer



- ➔ A. **CLARREO Past & Future**
- B. **Why ARI is Needed Now**
- C. **The ARI Approach**
- D. **A Pathfinder Mission**



EOS Aqua

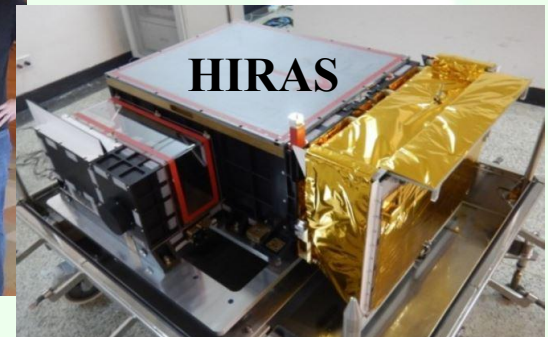
1330 orbits



Suomi NPP & JPSS



0930 MetOp orbit



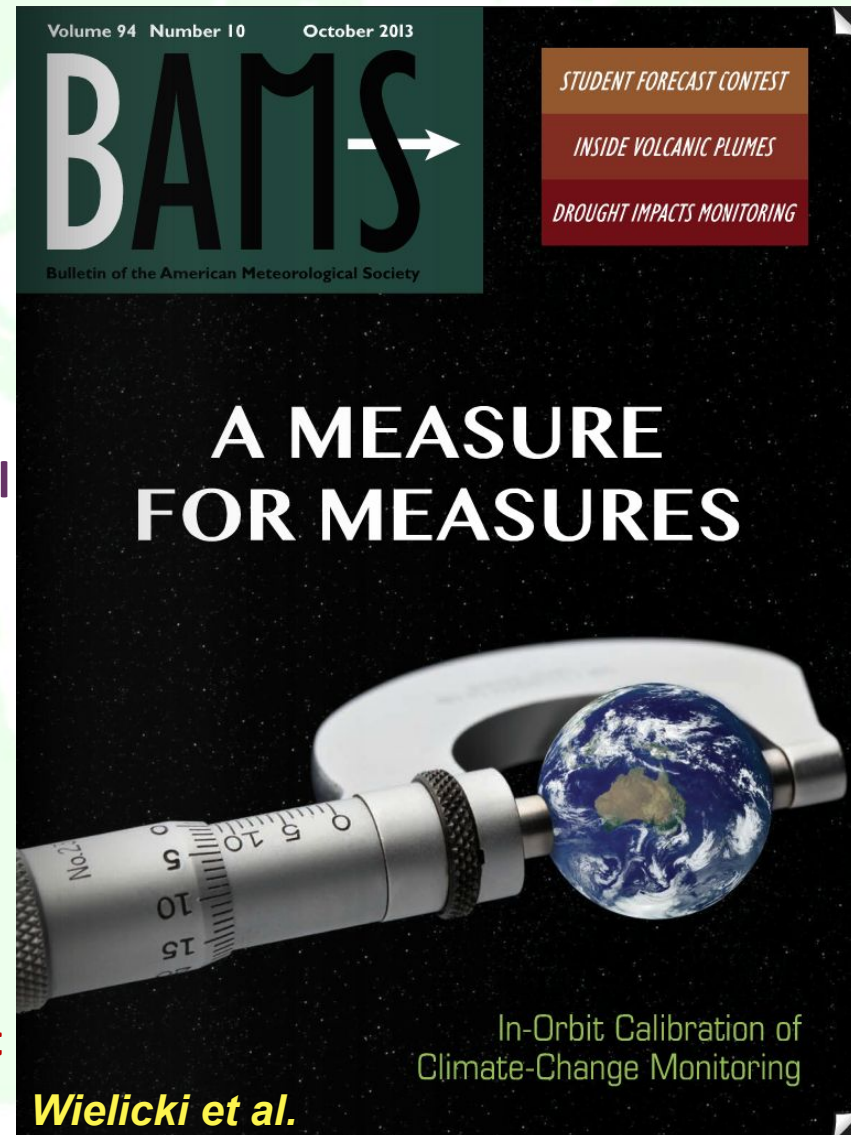
0530 FY3E orbit

+ FORUM

A. NASA CLARREO Background

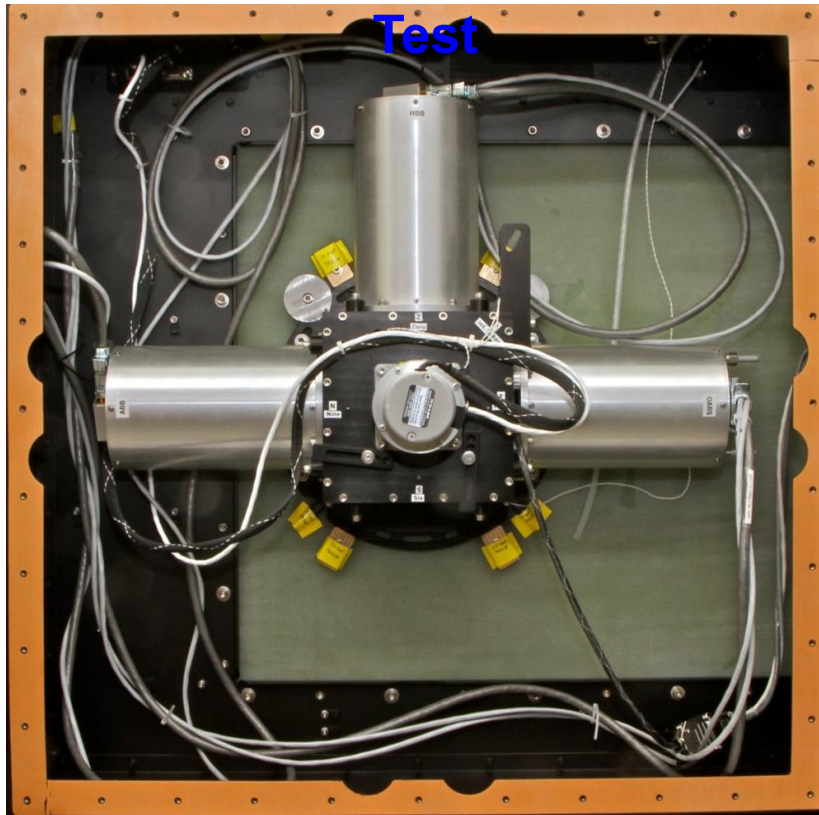
(Climate Absolute Radiance and Refractivity observatory)

- **2008 CLARREO** –Assigned to NASA LaRC
Defined by 2007 Decadal Survey
 - Concept: To significantly increase information content and accuracy (proven on-orbit) of Climate data
 - Approach: To fly Emitted IR and Reflected Solar(RS) Spectrometers and GPS-Radio Occultation sensors in a global observatory
- **2011 CLARREO** –mission funding removed
- **2011-16 CLARREO** – Science Team studies continued (Wielicki et al., BAMS, Oct 2013)
- **2012-2014 New Instrument Technologies**
Achieved TRL 6 under NASA ESTO IIPs:
LASP for RS and UW-SSEC & Harvard for the IR
- **2016- IR & RS Pathfinders in President's budget**
Reflected Solar Pathfinder launch 2023
IR not yet supported

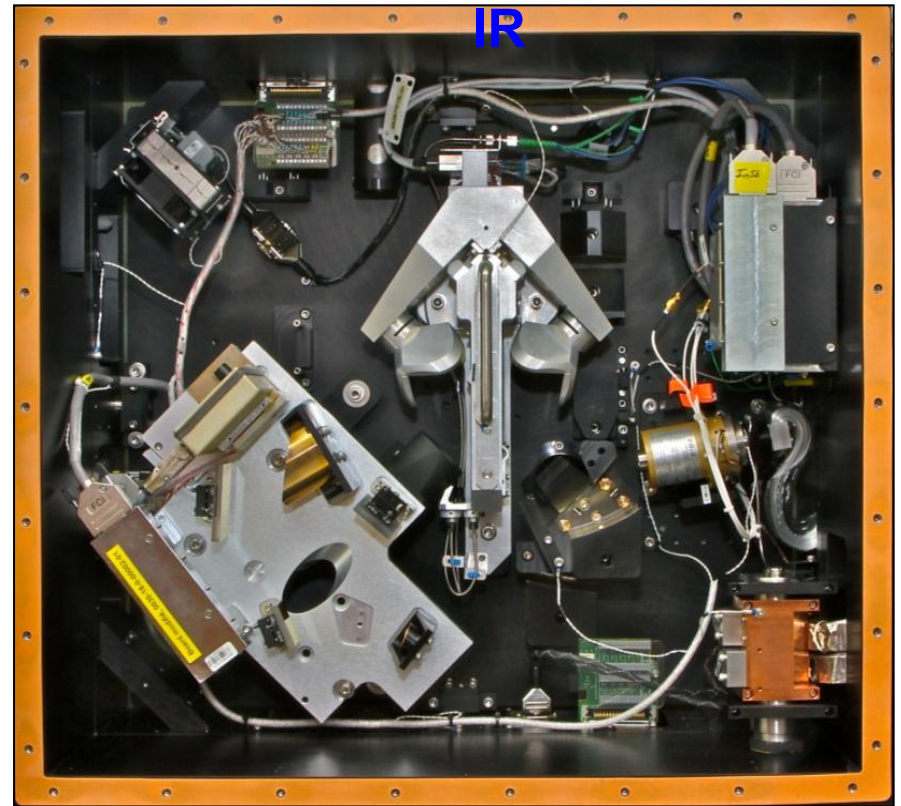


ARI: The CLARREO IR Prototype

On-orbit Verification &
Test



Calibrated FTS with Far
IR



 *remote sensing*

Published June

2020

The Infrared Absolute Radiance Interferometer (ARI) for CLARREO
Taylor, Revercomb, Best, Tobin, Gero



IR Sounding & establishing a CLARREO Style Benchmark

- **Sounding:** Globally, the fleet of high spectral resolution IR sounders for NWP and weather forecasting now give global coverage with 4 hour dt, suitable for climate sampling (0530 HIRAS, 0930 IASI, 1330 CrIS/AIRS)
- **Climate:** This international sounder fleet has proven to be widely useful for climate studies (e.g. NASA supports L1B climate quality CrIS/AIRS processing)
- **Opportunity:** Greatly enhanced value for climate possible by flying one CLARREO-type benchmark sensor, SI-traceable on-orbit, to inter-calibrate the fleet to better than 0.1 K 3-sigma, an order of magnitude improvement

Infrared SI Reference: ARI

Absolute Radiance Interferometer



A. CLARREO Past & Future

Single ARI Reference could
achieve CLARREO IR goal
by Sounder Inter-Calibration



EOS Aqua

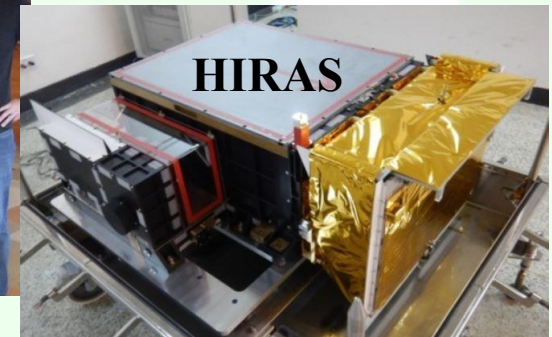
1330 orbits



Suomi NPP & JPSS



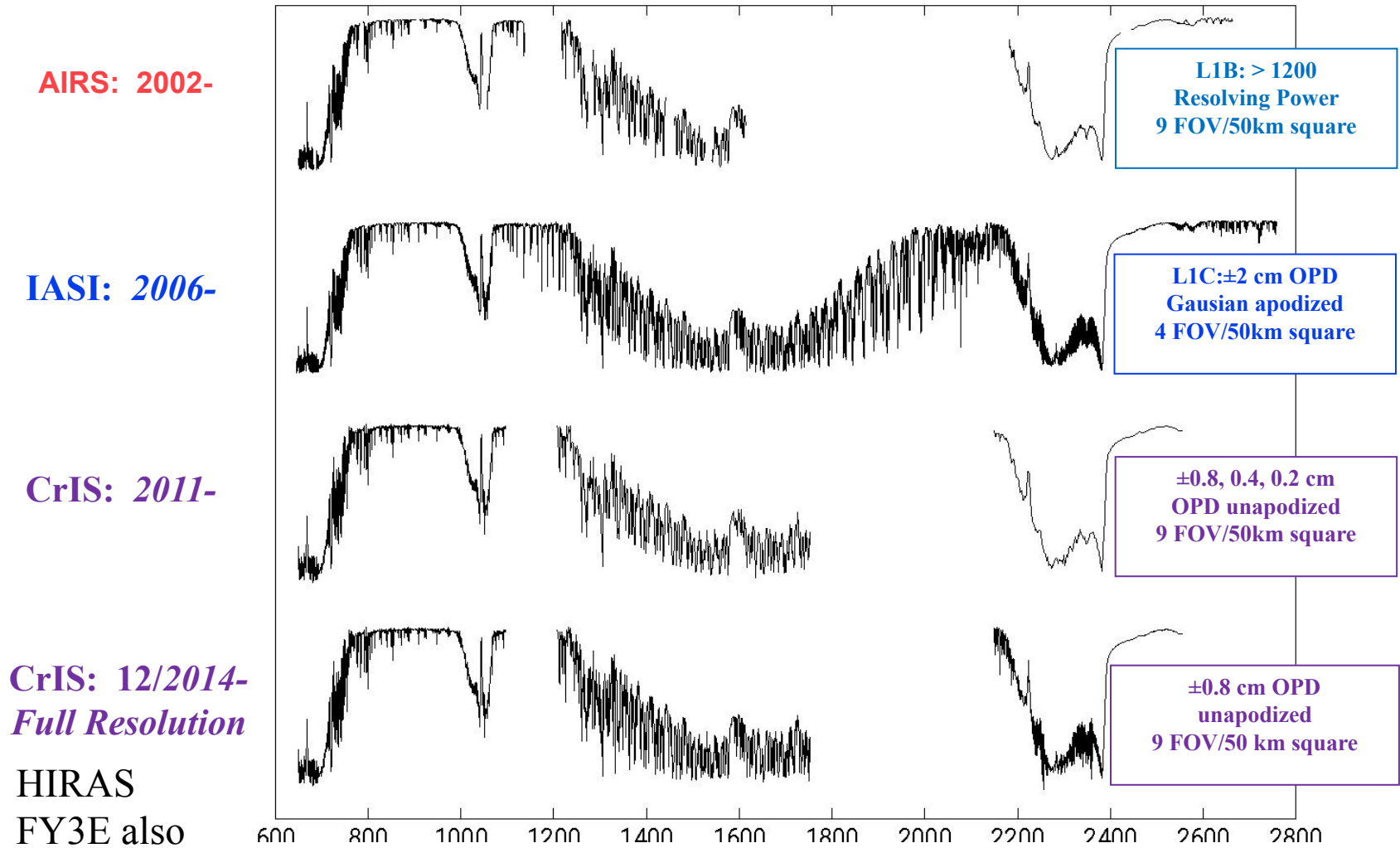
0930 MetOp orbit



0530 FY3E orbit

+ **FORUM**

Spectral Coverage and Resolution Comparison



Infrared SI Reference: ARI

Absolute Radiance Interferometer



A. CLARREO Background

➔ B. Why ARI is Needed Now

C. The ARI

**Climate Requires
Higher, Proven, Accuracy
and Information Content**



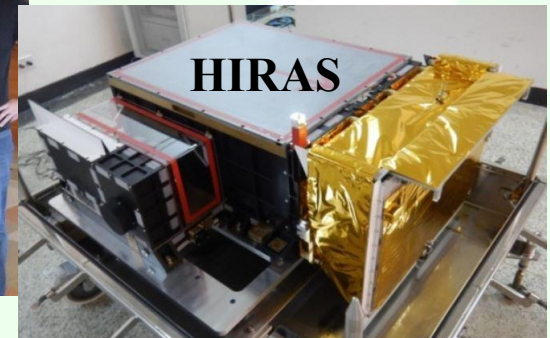
EOS Aqua



Suomi NPP & JPSS



0930 MetOp orbit



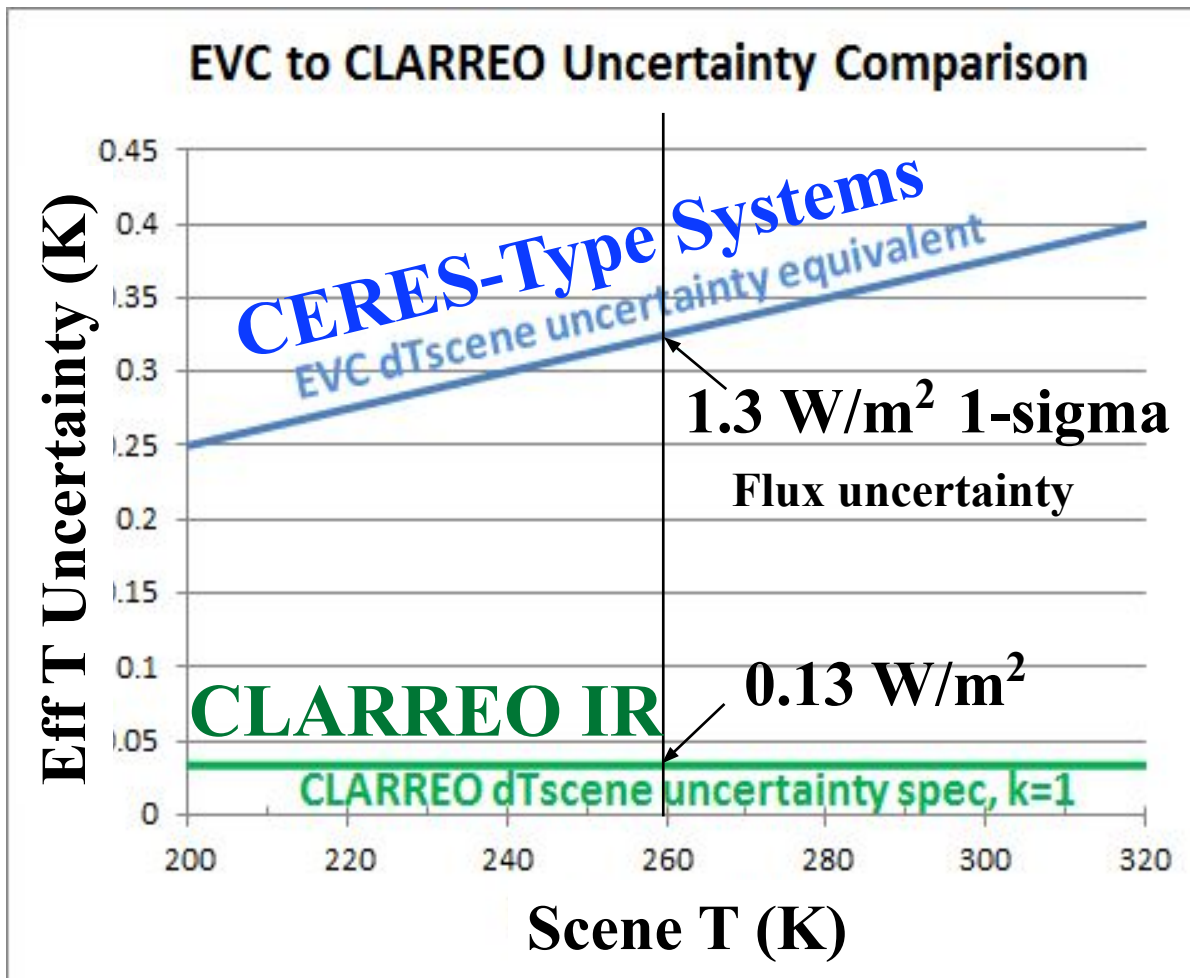
0530 FY3E orbit

+ FORUM

CLARREO Spectrally Resolved Uncertainties

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

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



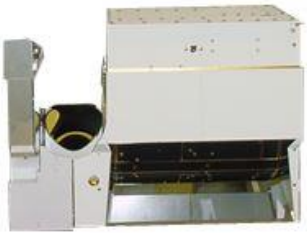
Earth imbalance
~ 1 W/m²

Greenhouse forcing
~ 3.5 W/m²

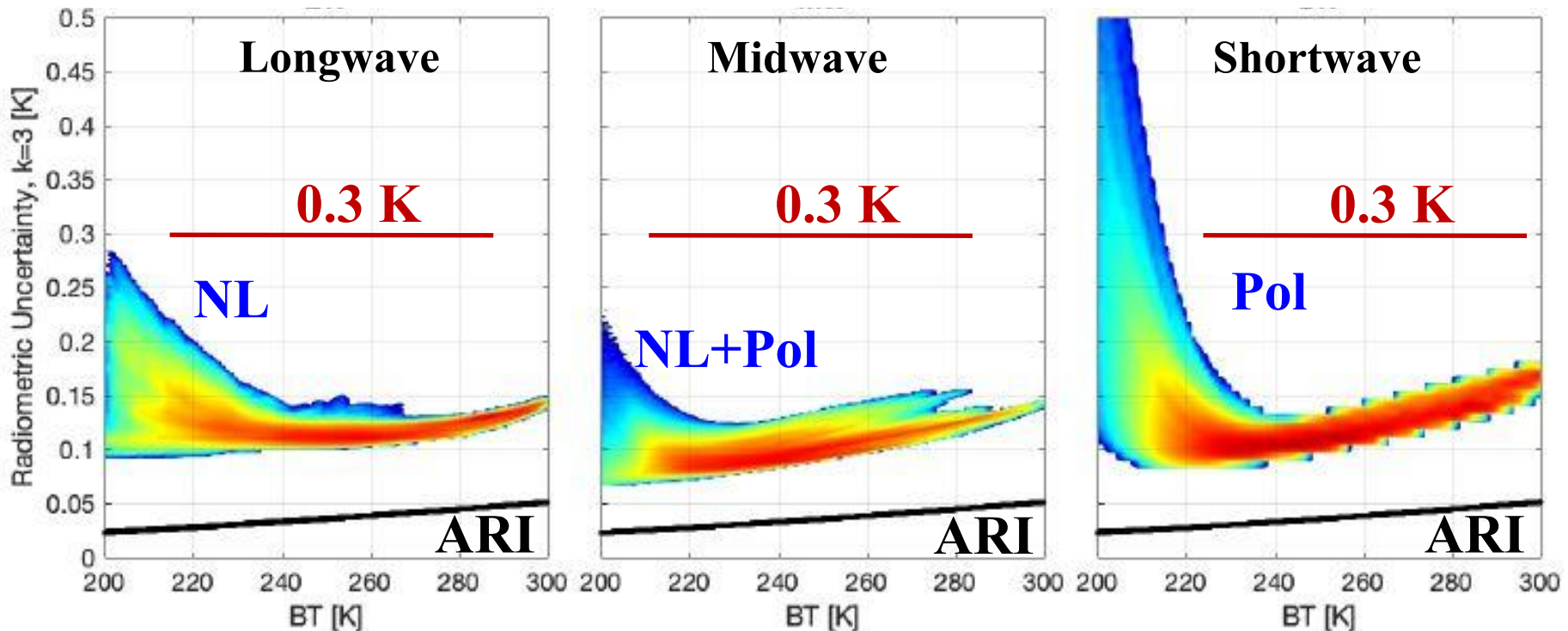
And ARI will beat Spec
by ~ a factor of 2

CrIS RU Estimates Compared to ARI

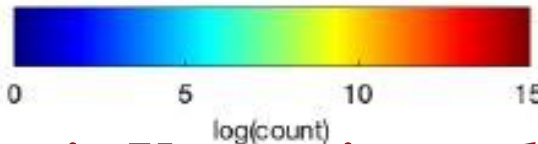
(3-sigma)



Cold T dominated by correction residuals for
(1) Non-linearity (NL)
(2) Polarization (Pol)



CrIS RU Density plots



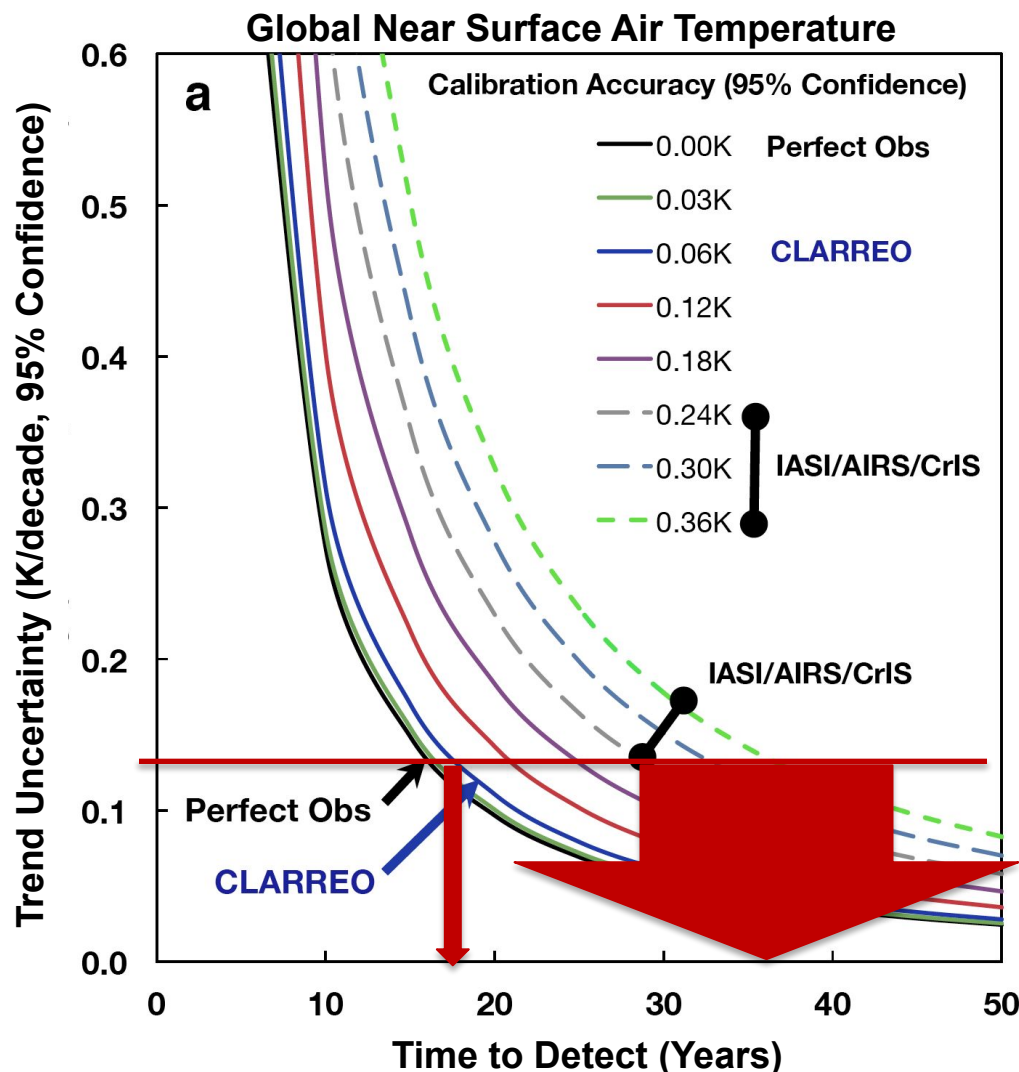
ARI RU

Sounder Fleet Radiometric Uncertainty at least 2 times worse

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

Wielicki et al.,
BAMS, 2013

Example with
~ factor of 2
shorter
Time to Detect



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

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



**How ARI Achieves
Higher, Proven, Accuracy**



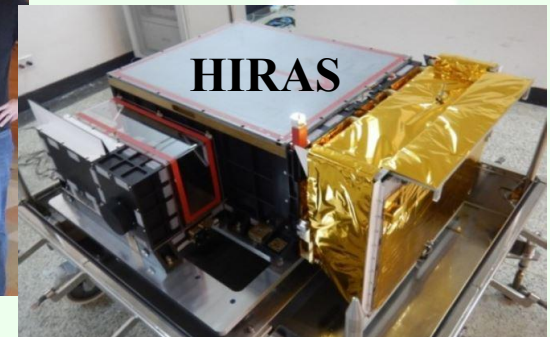
EOS Aqua



Suomi NPP & JPSS



0930 MetOp orbit

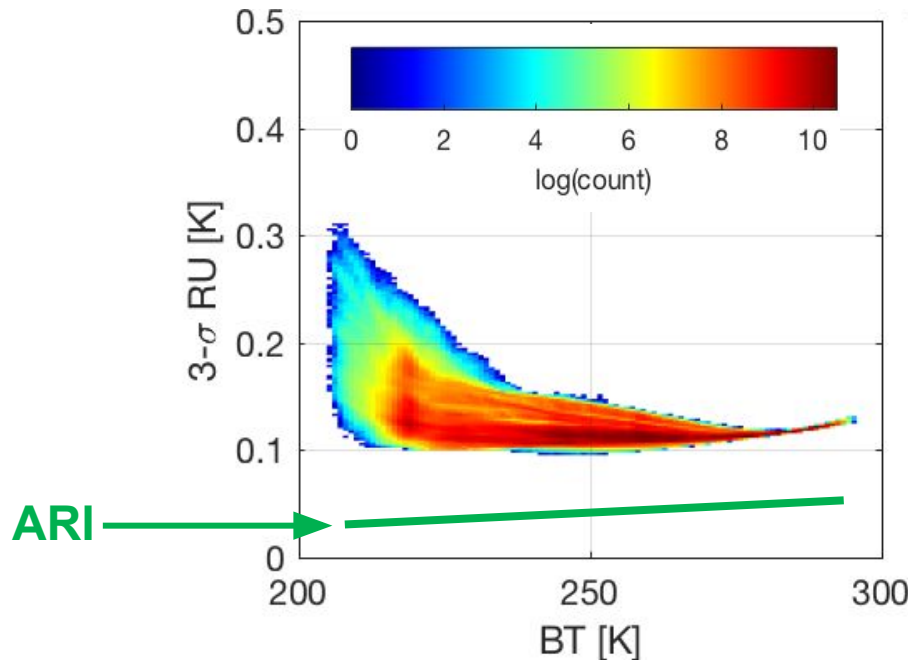


0530 FY3E orbit

+ FORUM

ARI promises Order of Magnitude higher proven Accuracy

Longwave



□ *ARI detectors chosen for linearity (not low noise) & nadir only viewing design is immune to polarization errors*

□ *ARI represents a huge Radiometric Uncertainty improvement over the sounding fleet of AIRS, IASI, HIRAS, CrIS – expect total uncertainty of fleet to be at least 2 times CrIS alone*

□ *Proven with on-orbit SI References (normally only in T-Vac)*



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

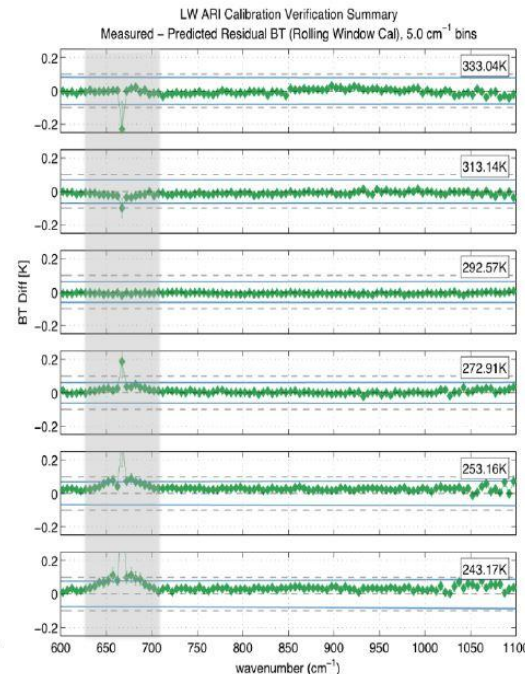
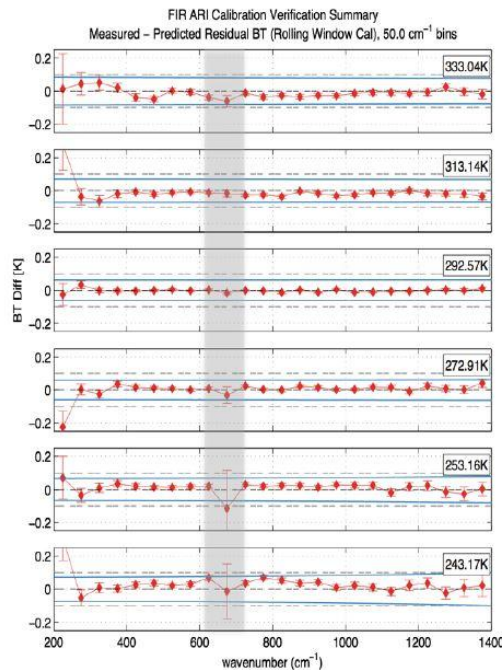
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* Correspondence: joe.taylor@ssec.wisc.edu

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



Infrared SI Reference: ARI Absolute Radiance Meter



**Single ARI Leverages
other spectrometers
for spatial coverage
needed for Benchmark**



A Pathfinder Mission



EOS Aqua

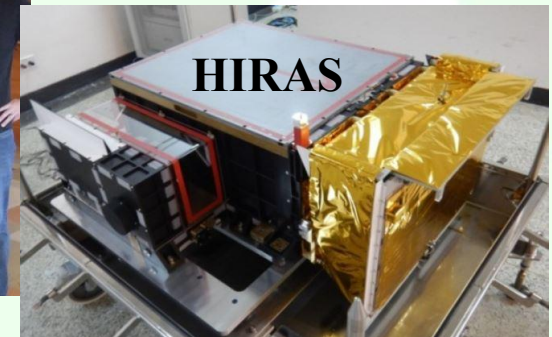
1330 orbits



Suomi NPP & JPSS



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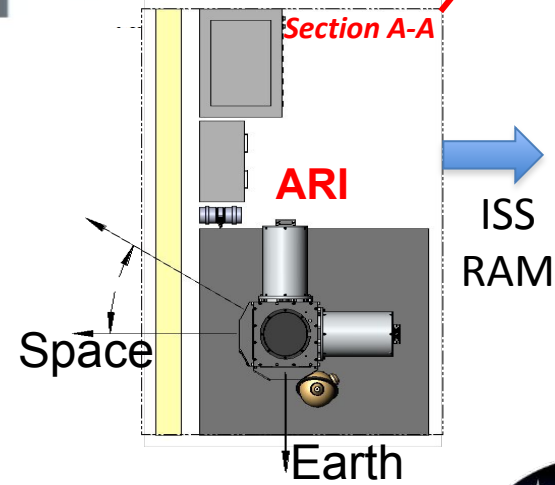
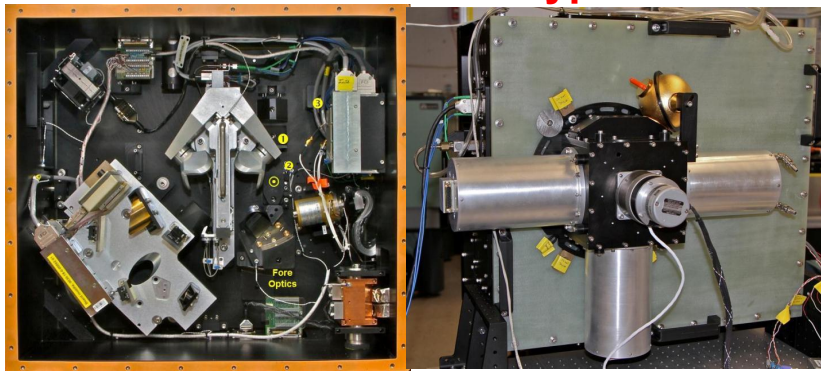
0530 FY3E orbit

+ FORUM

CLARREO IR Pathfinder Mission: International Space Station example

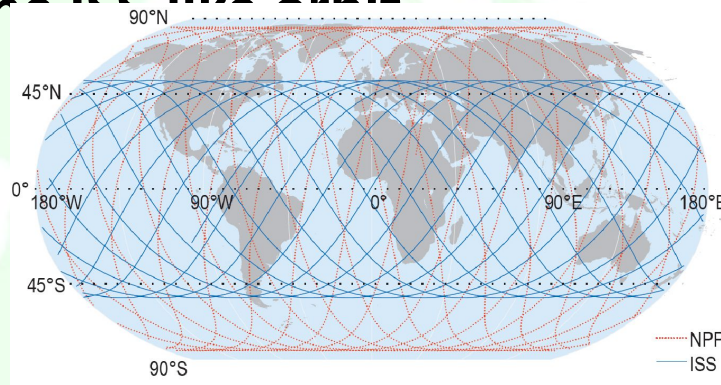


ARI Lab Prototype



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
- The fleet of operational sounders provides the sampling needed for achieving an 0.1 K 2- sigma climate record via intercalibration from the ISS like orbit



- FORUM from ESA 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

- 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**



An SI-Traceable Space-based Climate Observing System

A CEOS, GSICS Workshop

hosted by the UK Space Agency at National Physical Laboratory, London, UK,



September 9-11, 2019

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 $< 0.1 \text{ K } T_B$ $k=3$ for SI benchmarking exceeds other proven capabilities & multiple missions would enhance credibility for decision making

Summary

- Higher accuracy will establish a spaceborne benchmark to resolve information on the scale of the Earth radiative imbalance and allow 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)**