

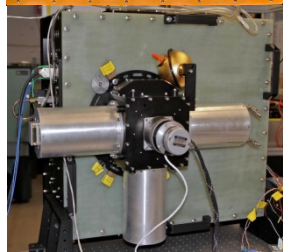
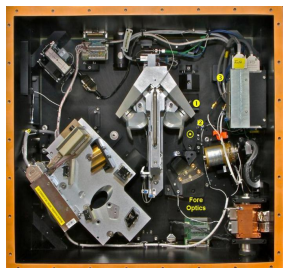


The IR Absolute Radiance Interferometer (ARI) for CLARREO:

Heart of a Pathfinder Mission Concept for
Establishing a Key Climate Benchmark (Part-1)

Hank Revercomb, Fred Best, David Tobin,
Joe Taylor, Jon Gero, Robert Knuteson,
Douglas Adler, Claire Pettersen,
Mark Mulligan, Robert Holz, Fred Nagle

University of Wisconsin-Madison
Space Science and Engineering Center



ARI IR Prototype

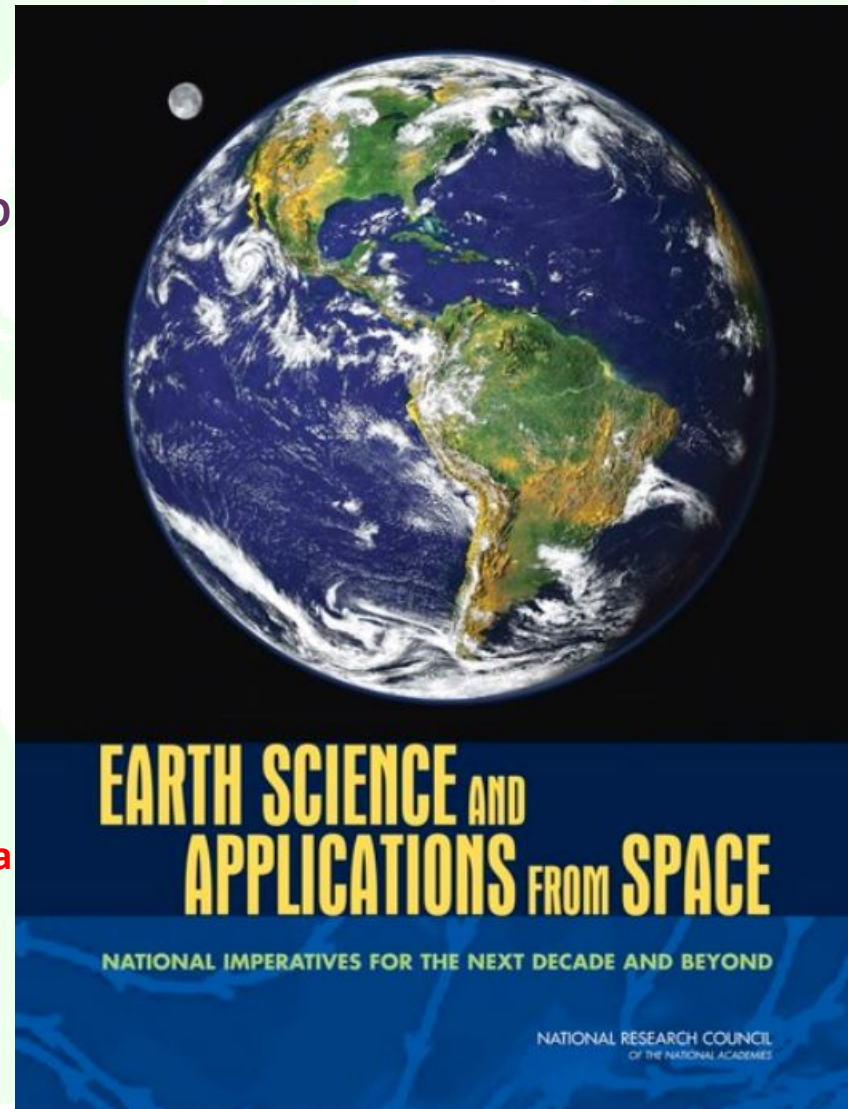


An SI-Traceable Space-based Climate Observing System
London, England, 9-11 September 2019



CLARREO Introduced in 2007 DS

- **CLARREO** (Climate Absolute Radiance & Refractivity Observatory)
a 2007 Decadal Survey Tier 1 mission
 - IR & Reflected Solar spectra coupled with GPS RO
 - (1) unprecedented measurement accuracy,
0.1 K IR brightness T, 0.4 % RS radiance, and 0.1 % GPS RO refractivity 5-20 km
(all 3-sigma, proven on orbit with SI standards),
 - (2) unbiased spatial and temporal sampling, and
 - (3) **much higher climate change sensitivity**
than existing climate records
(from total integrated IR & Solar data)
 - Metrology lab on-orbit serves as “NIST in orbit”
- **CLARREO** to Benchmark Earth’s climate
 - **High accuracy removes need for overlapping data**
- **CLARREO** as an Inter-calibration Standard
 - GSICS (Global Space-based Inter-Cal System)
 - e.g. Greatly enhancing the value of the climate record from high spectral resolution IR sounders starting in 2002 (AIRS, IASI, CrIS, HIRAS) & ERB sensors

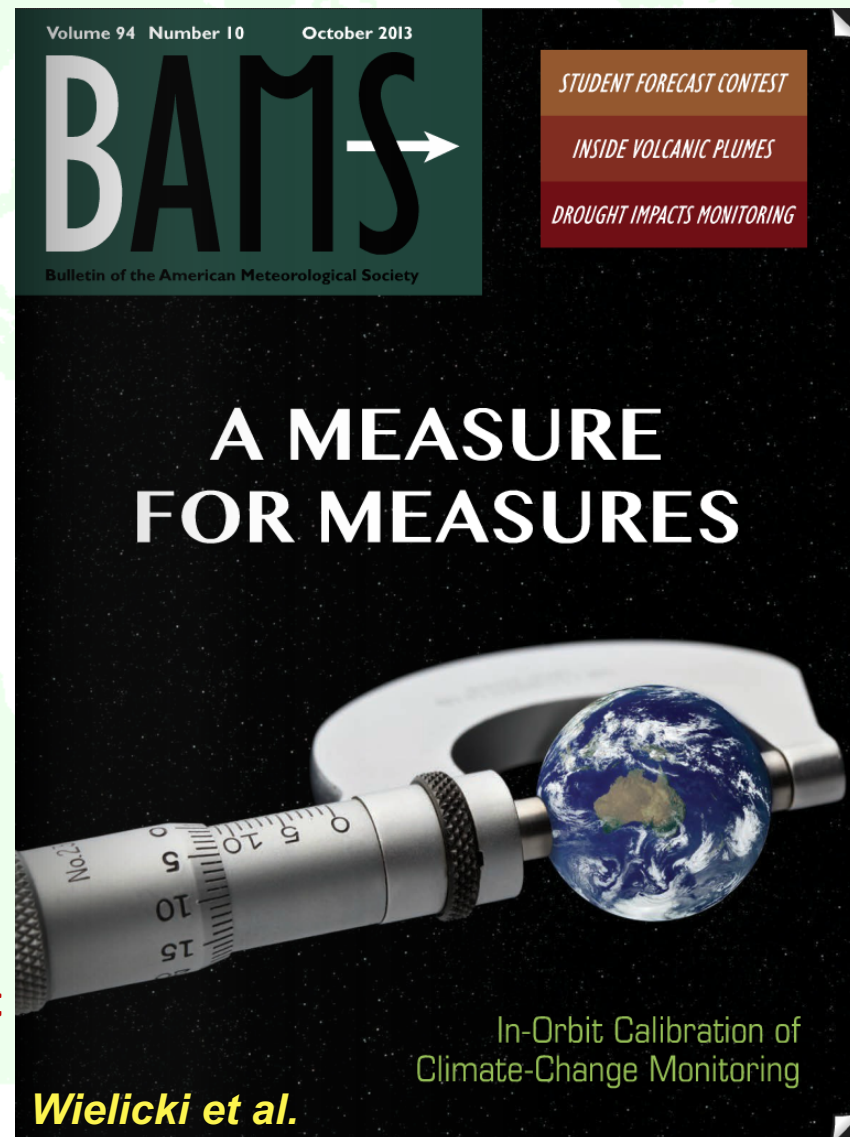


Cover of 2007 Decadal Survey

NASA CLARREO Timelines

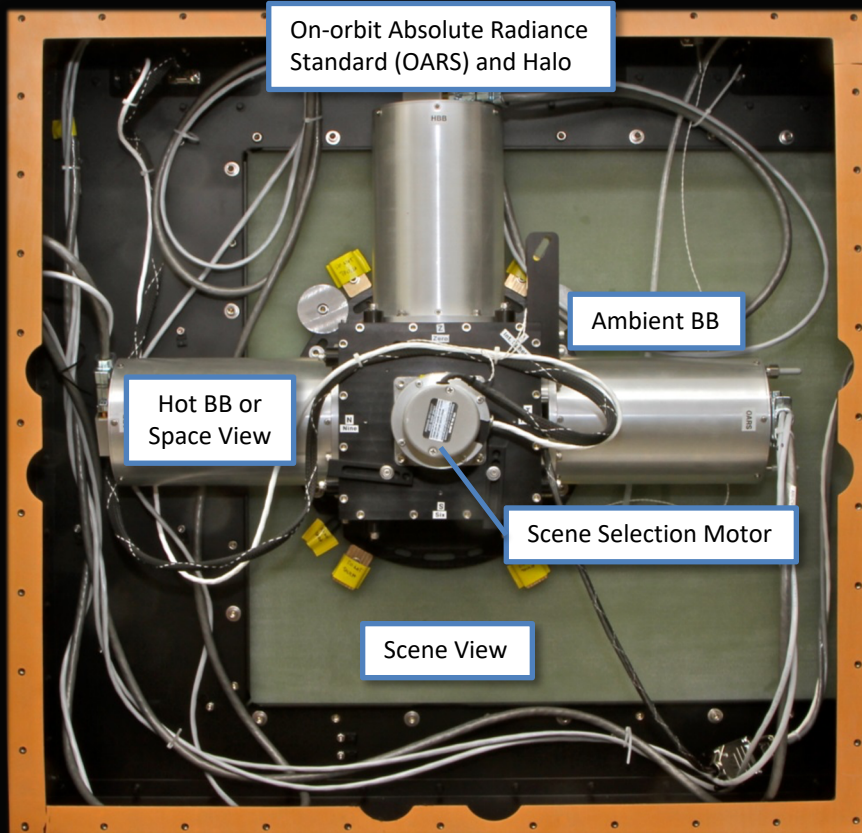
(Climate Absolute Radiance and Refractivity observatory)

- **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 in development IR not yet supported



CLARREO Absolute Radiance Interferometer (ARI) IR Prototype

On-orbit Verification & Test System*



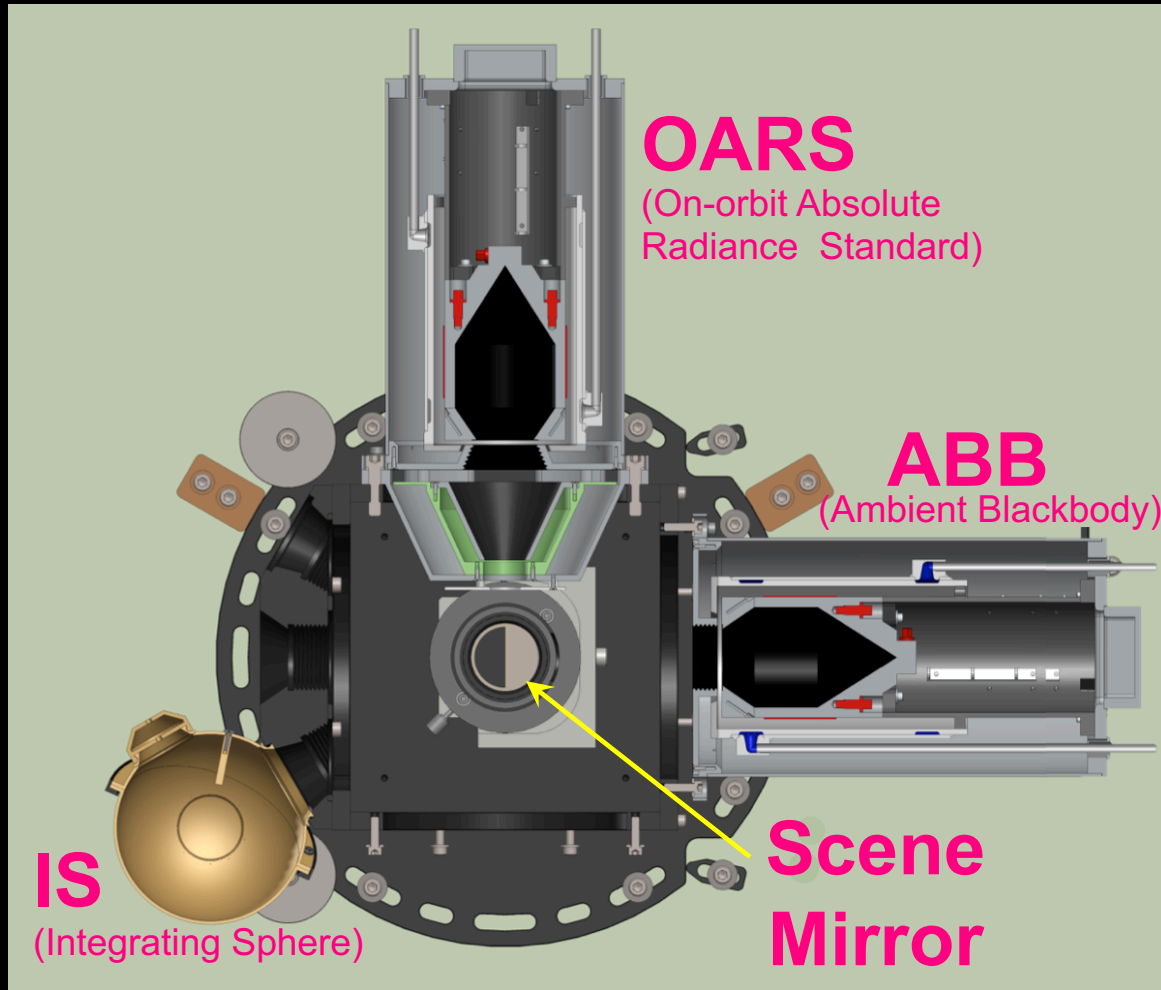
** Shown without integrating sphere*



Dashed line indicates OVTS enclosure envelope.

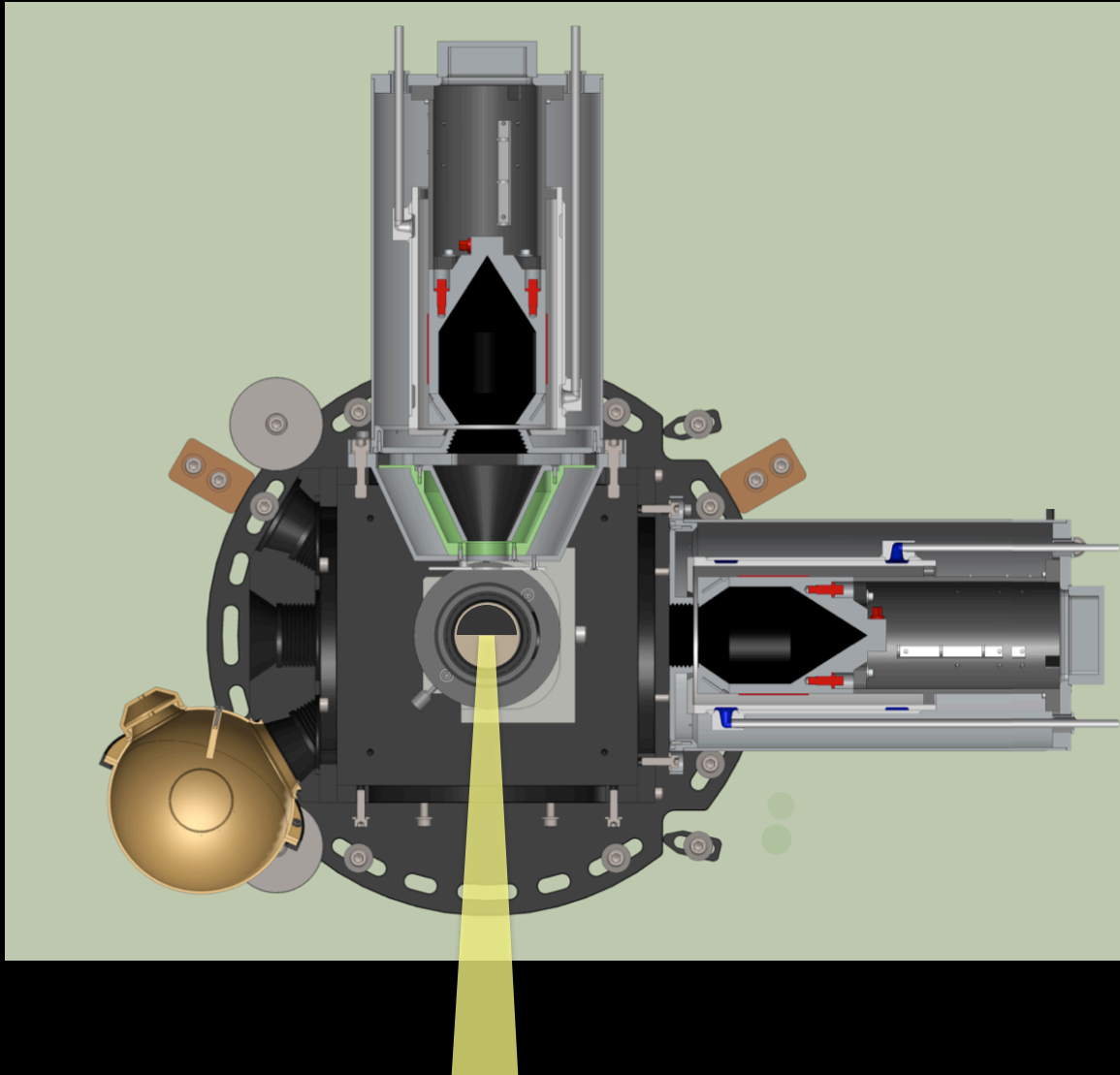
From Taylor, et al., 2016

ARI Front-End Key Elements

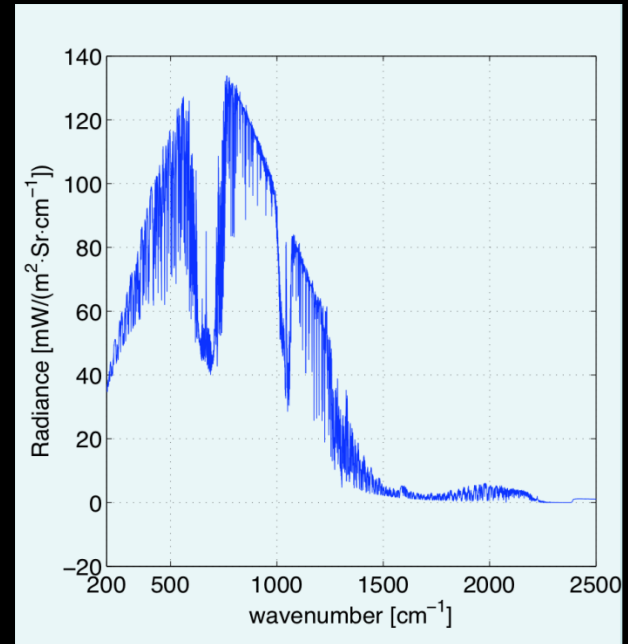


Following views illustrate ARI concepts

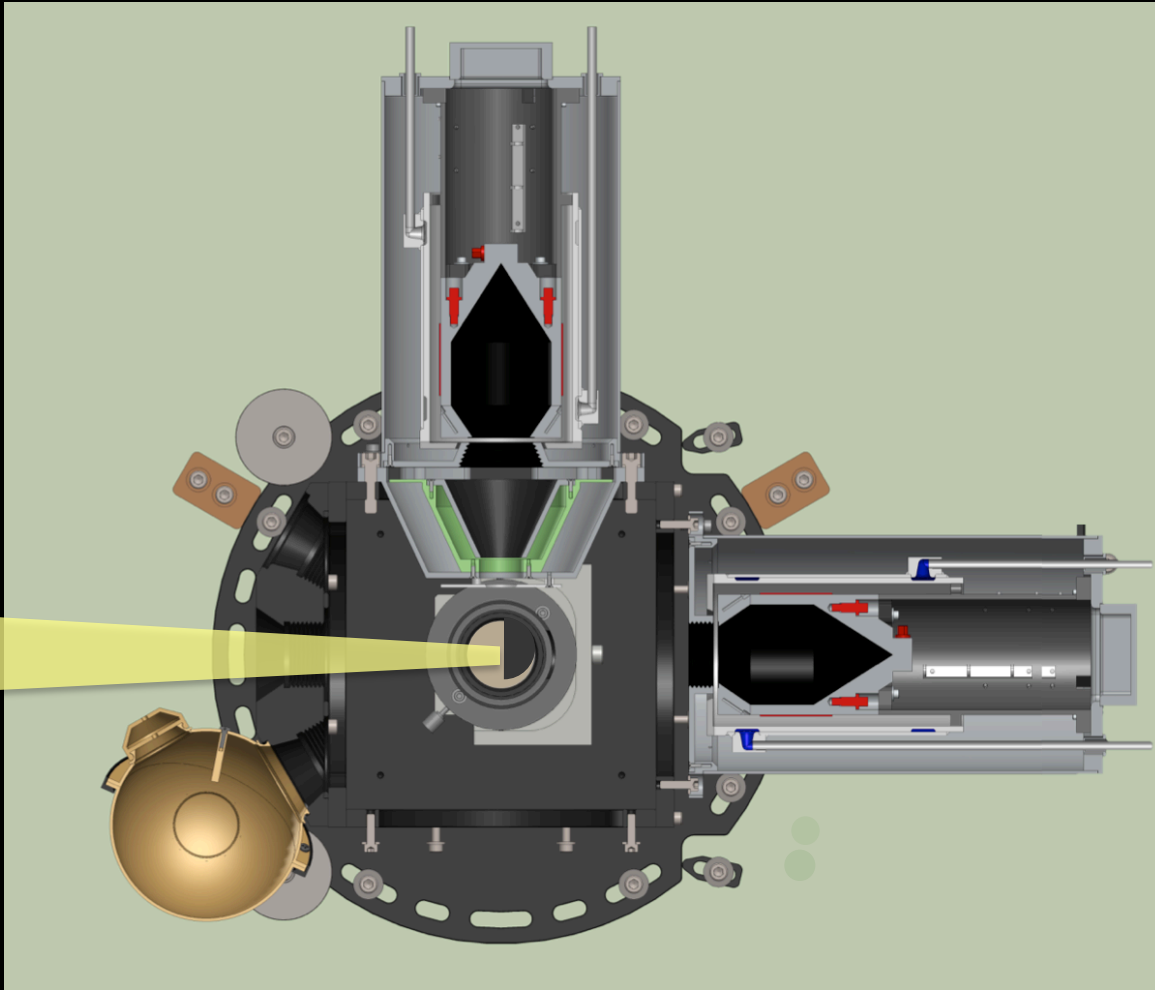
Calibrated FTS: Earth View-Nadir only



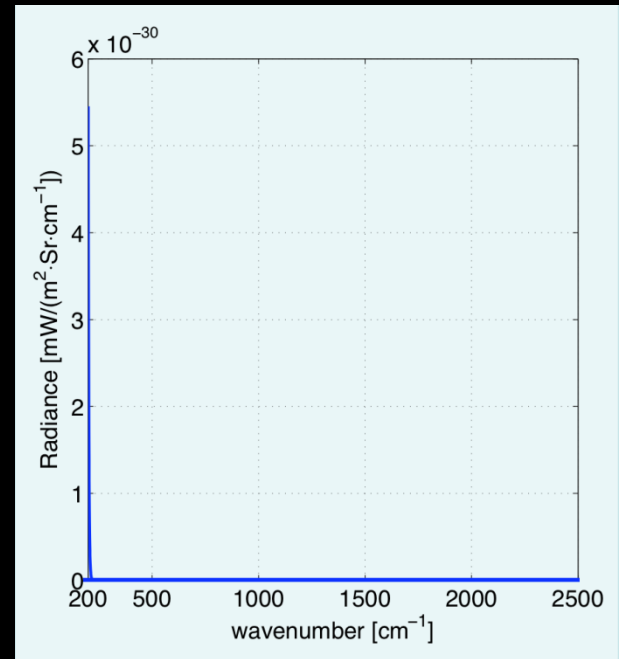
Earth view taken
every 20 seconds



Calibrated FTS: Space Calibration View



Space view taken
every 20 seconds



Calibrated FTS: Ambient Blackbody (ABB)

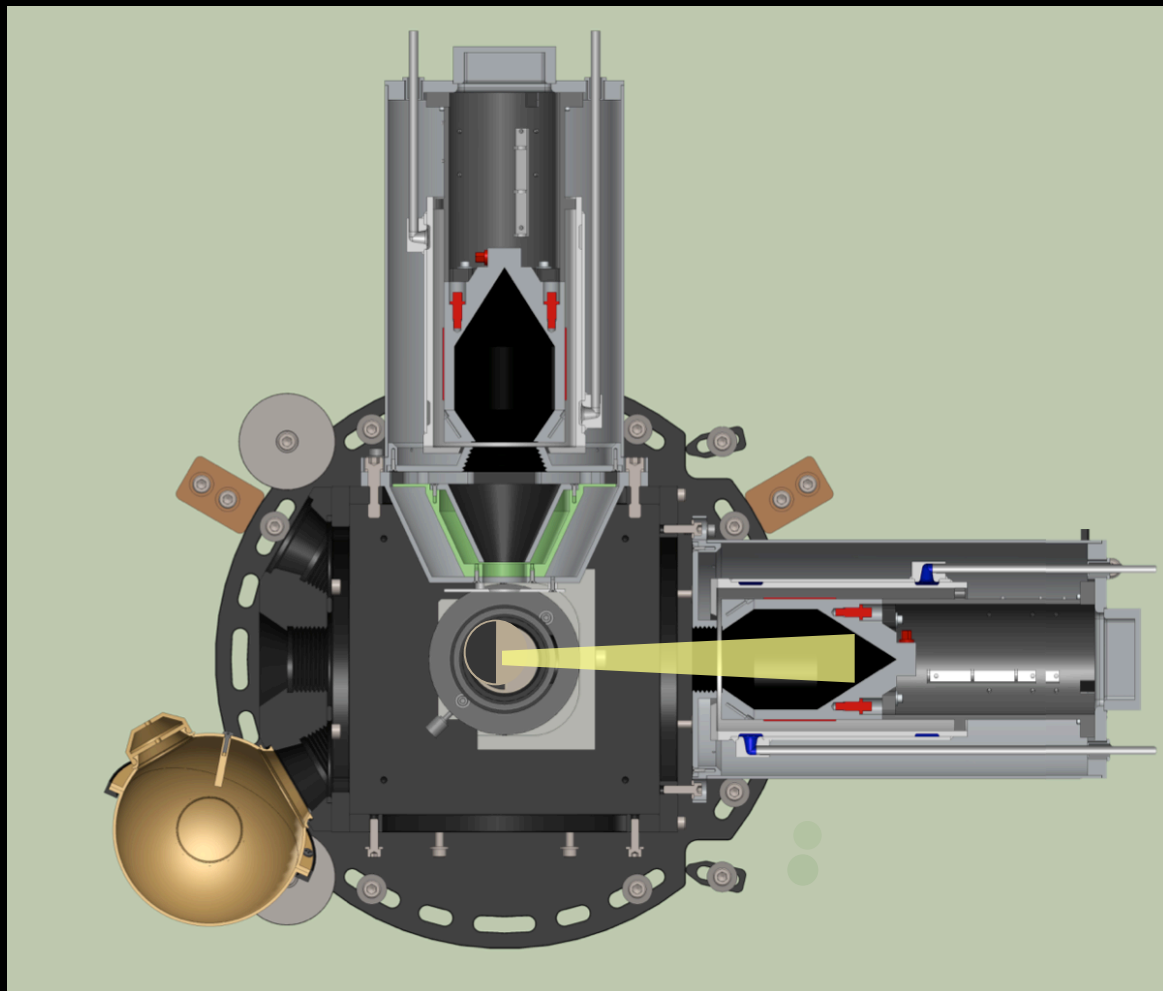
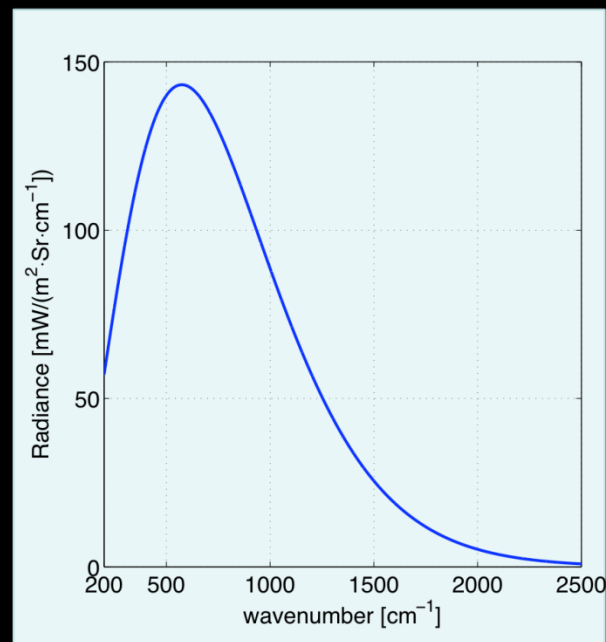


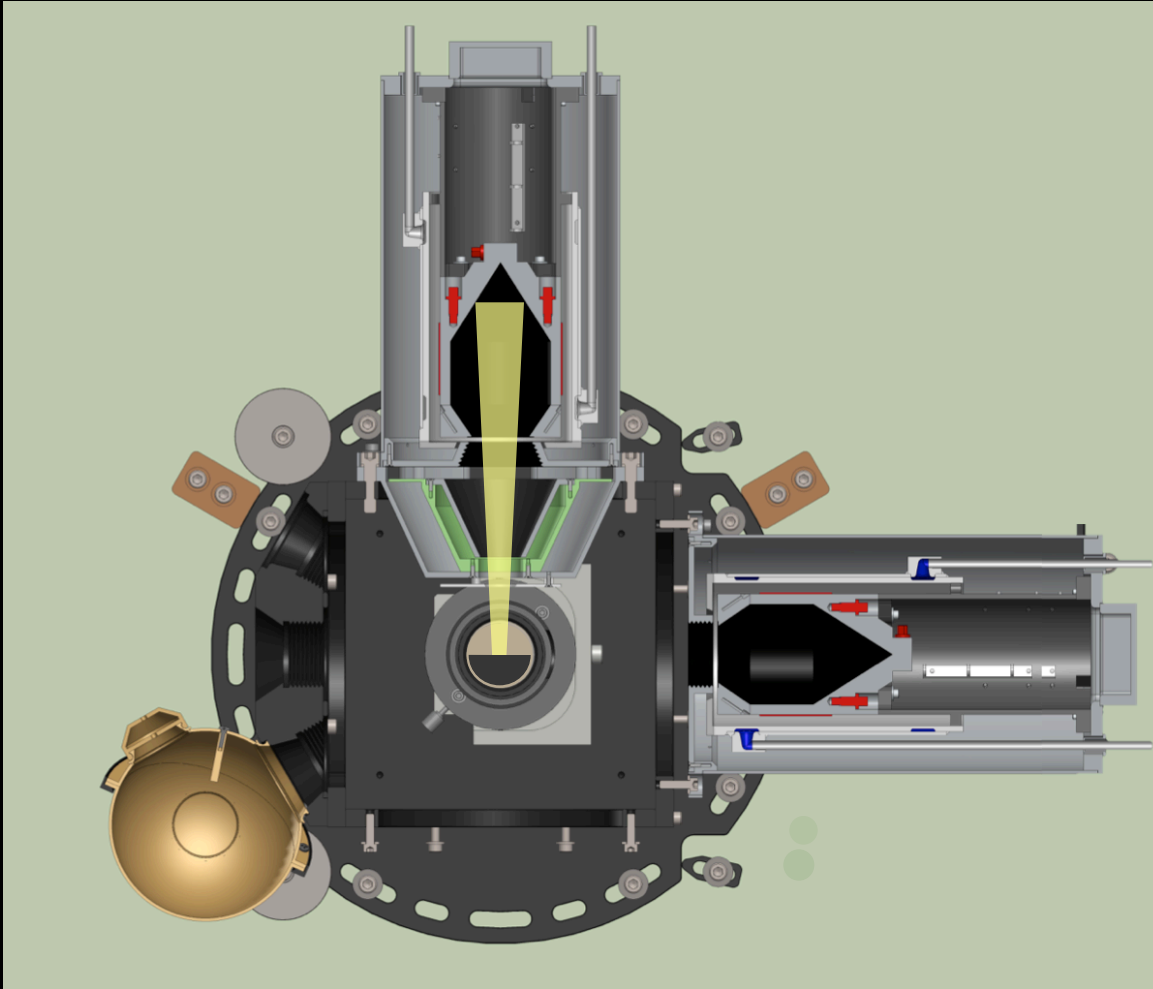
ABB view taken
every 20 seconds



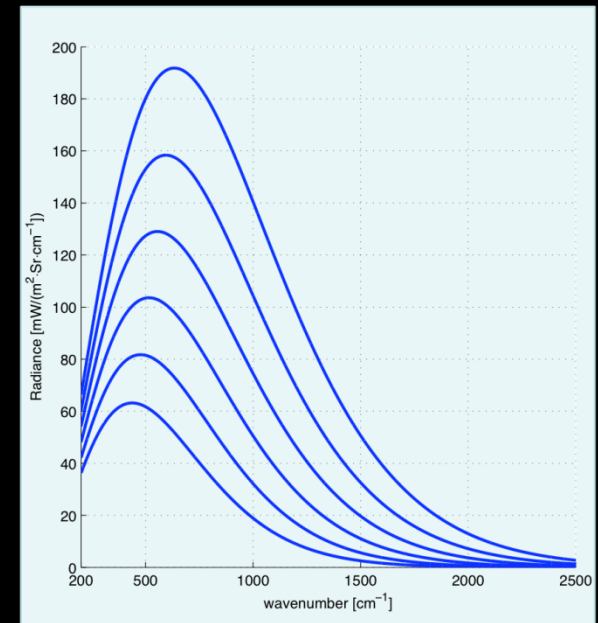
Emissivity > 0.997

OVTs: Variable Temperature OARS View

(On-orbit Verification and Test System)

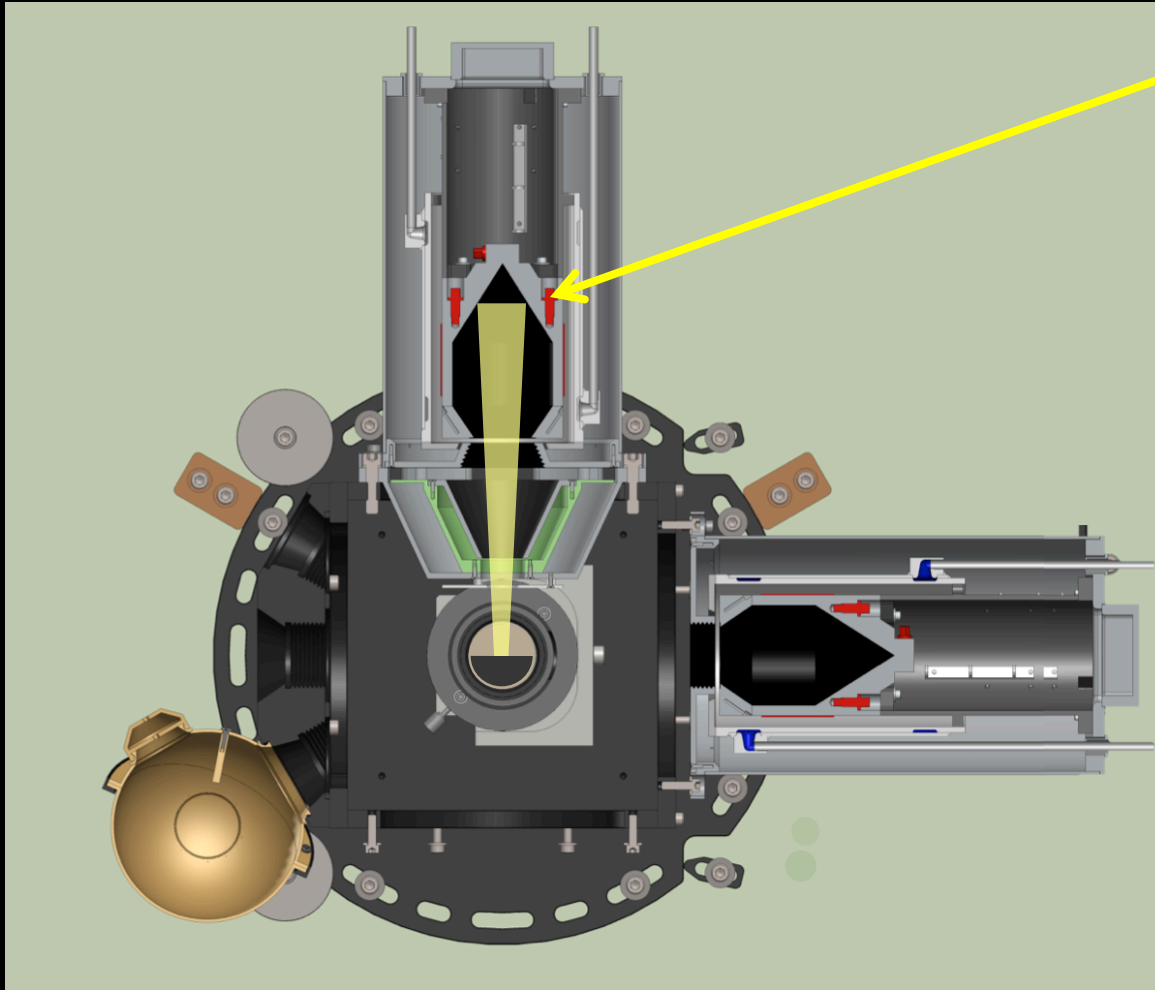


Controllable to a wide range of temperatures to verify absolute radiance and instrument linearity
Si-traceable without long-term stability assumptions



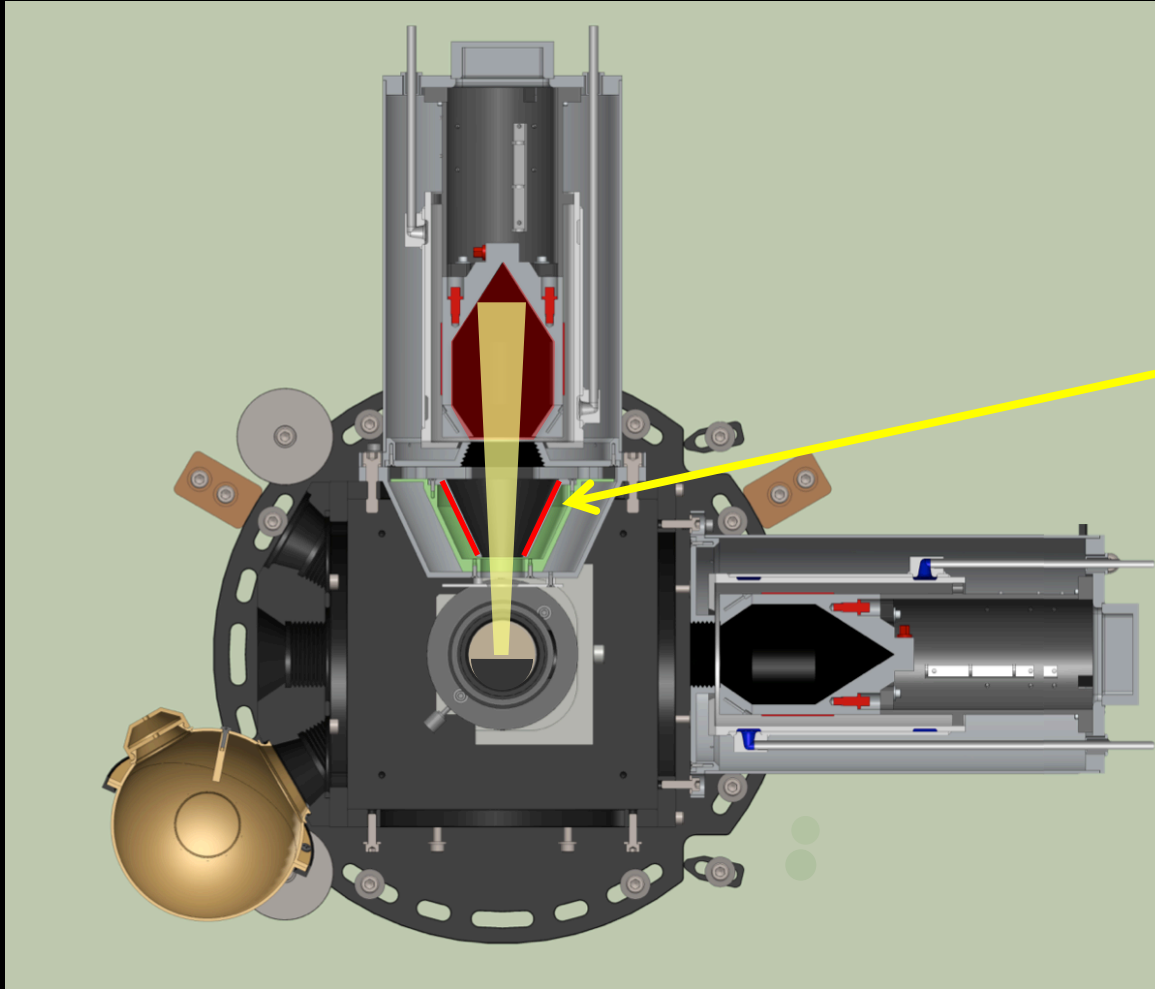
Emissivity > 0.997

OVTs: Thermistor Temperature Calibration



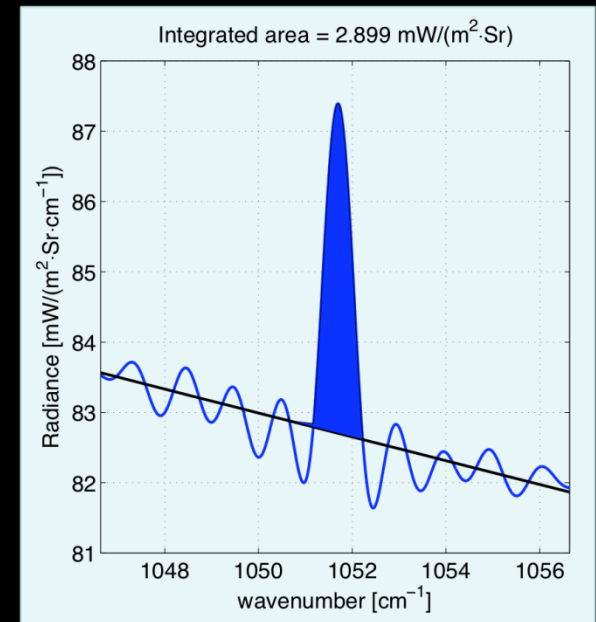
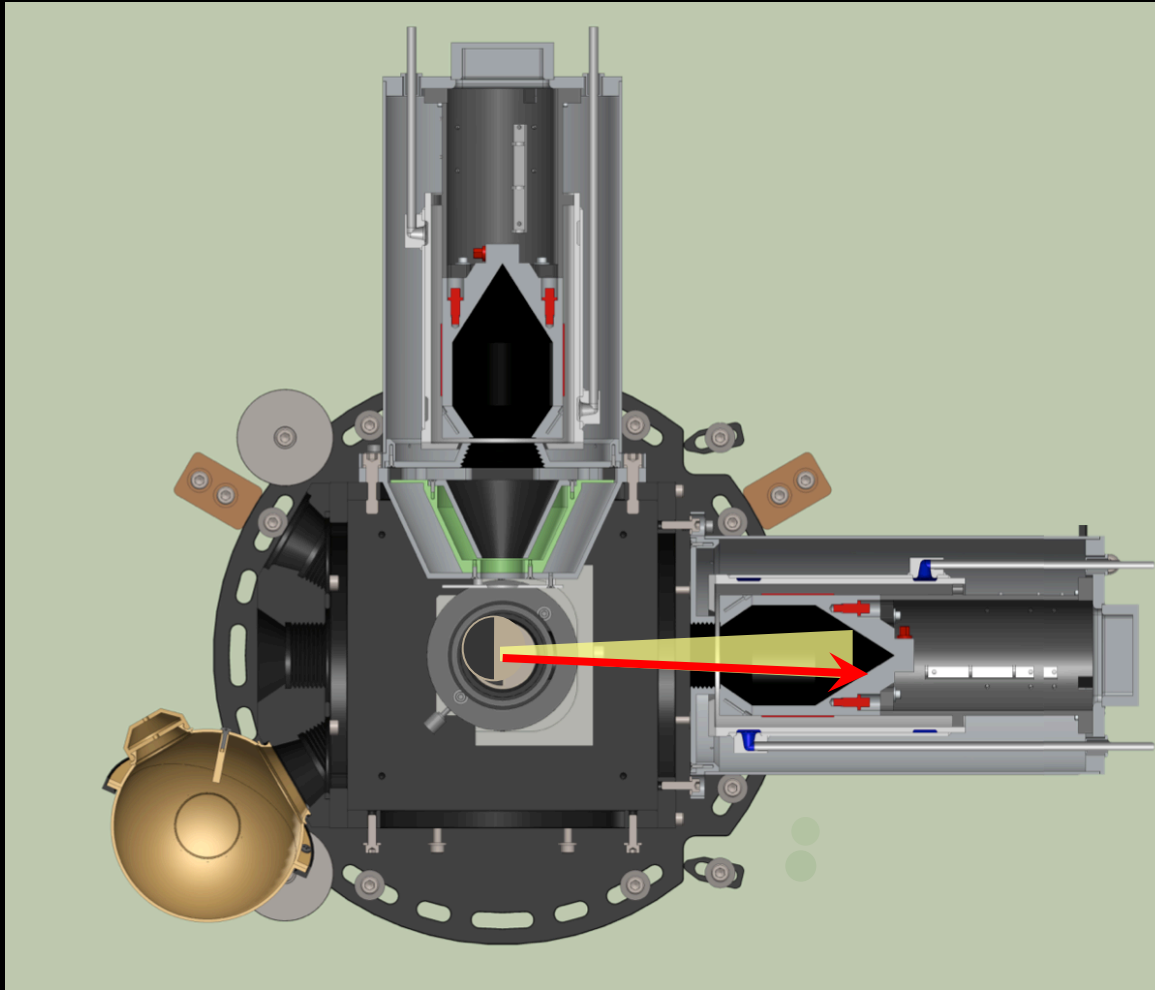
The OARS has miniature phase change cells containing Ga, H₂O, and Hg, used for periodic temperature calibration at 30, 0, and -38 °C. Establishing a fundamental T scale on-orbit.

OVTs: OARS Spectral Emissivity – Heated Halo



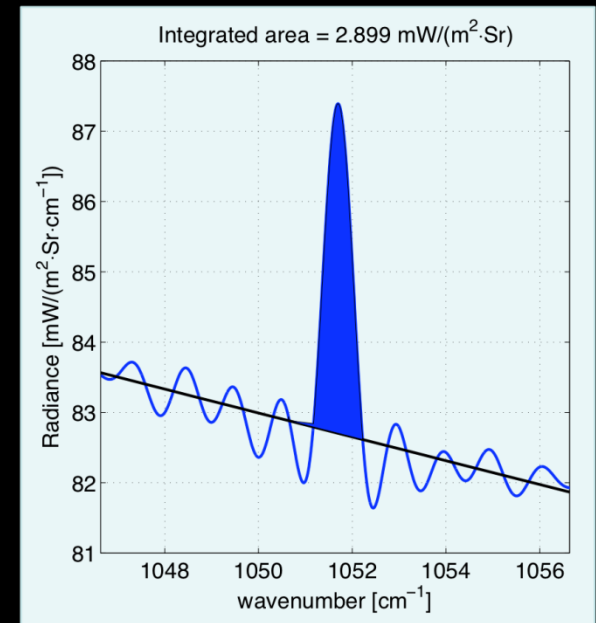
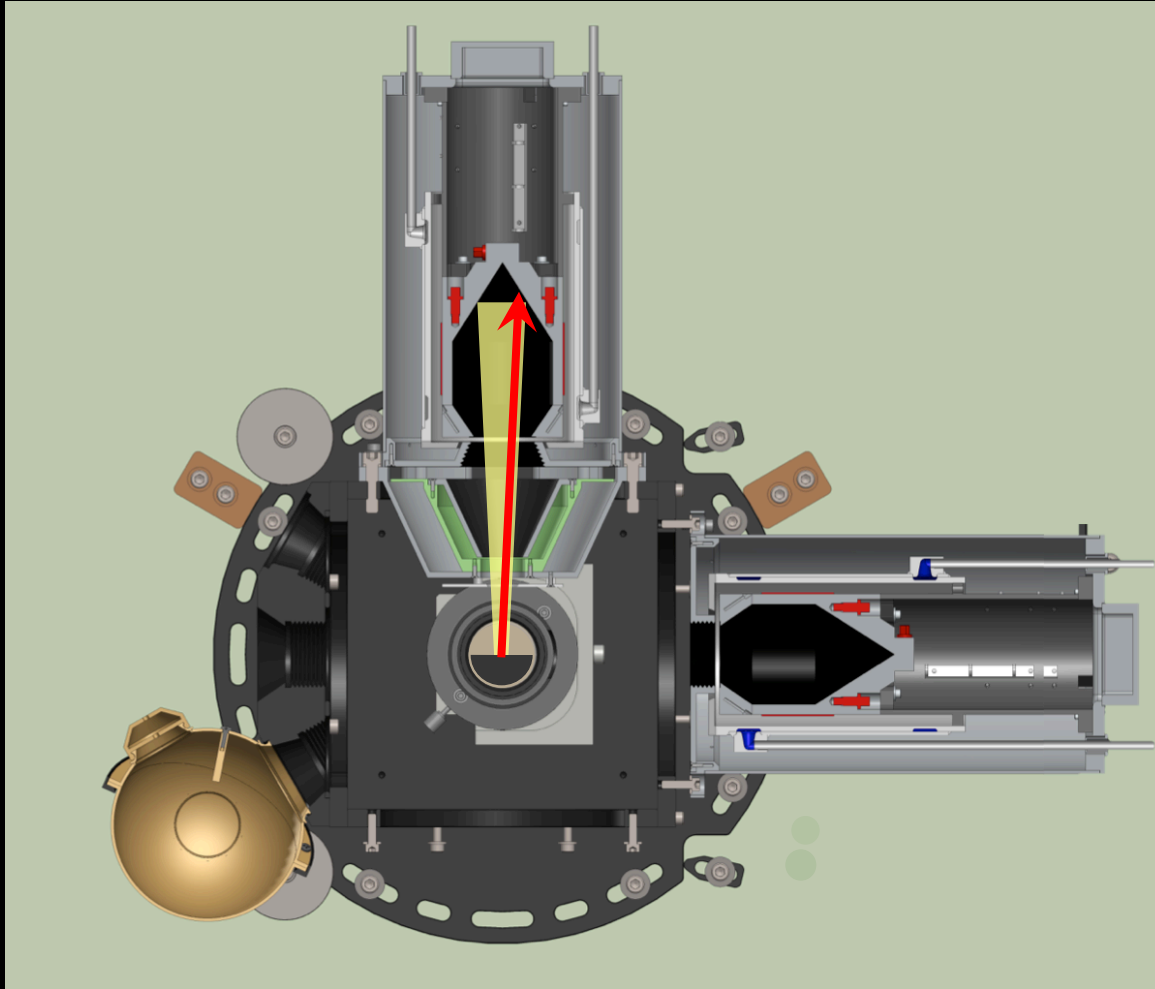
The Heated Halo is used periodically for measuring the blackbody cavity spectral emissivity. Quantifying any unexpected degradation to better than 0.1 %

OVTs: ABB Emissivity – QCL 9.5 μm Source



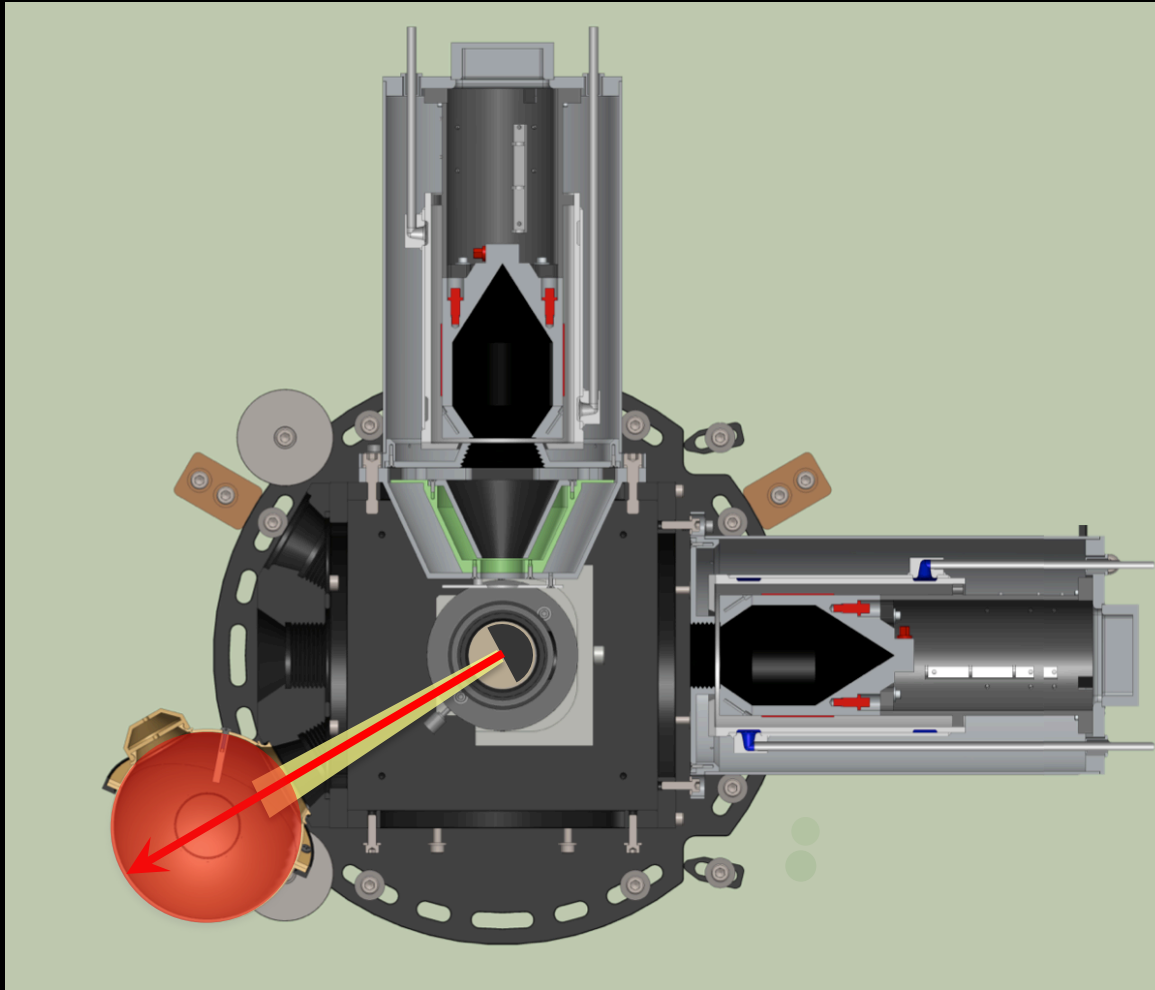
Compares ABB to OARS emissivity

OVTs: OARS Emissivity – QCL 9.5 μm Source

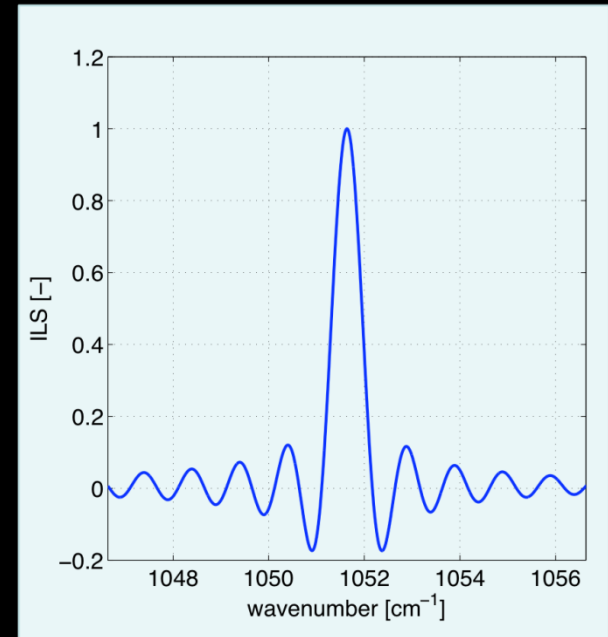


Compares ABB to OARS emissivity

OVTS: Instrument Line Shape – QCL Source

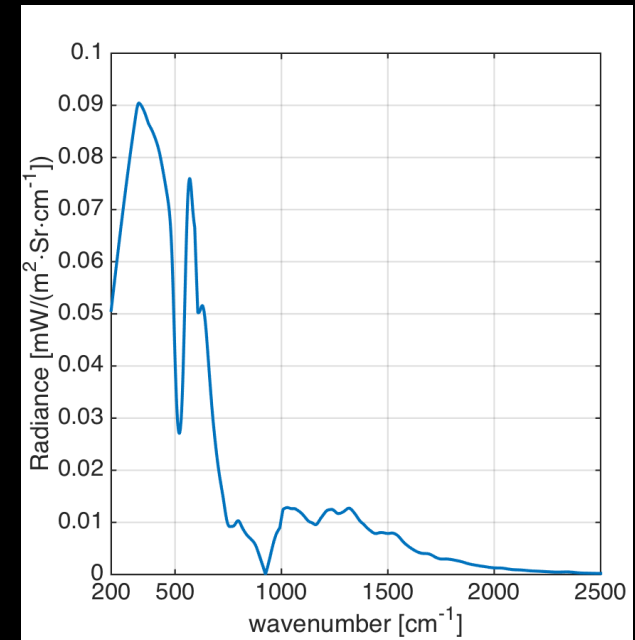
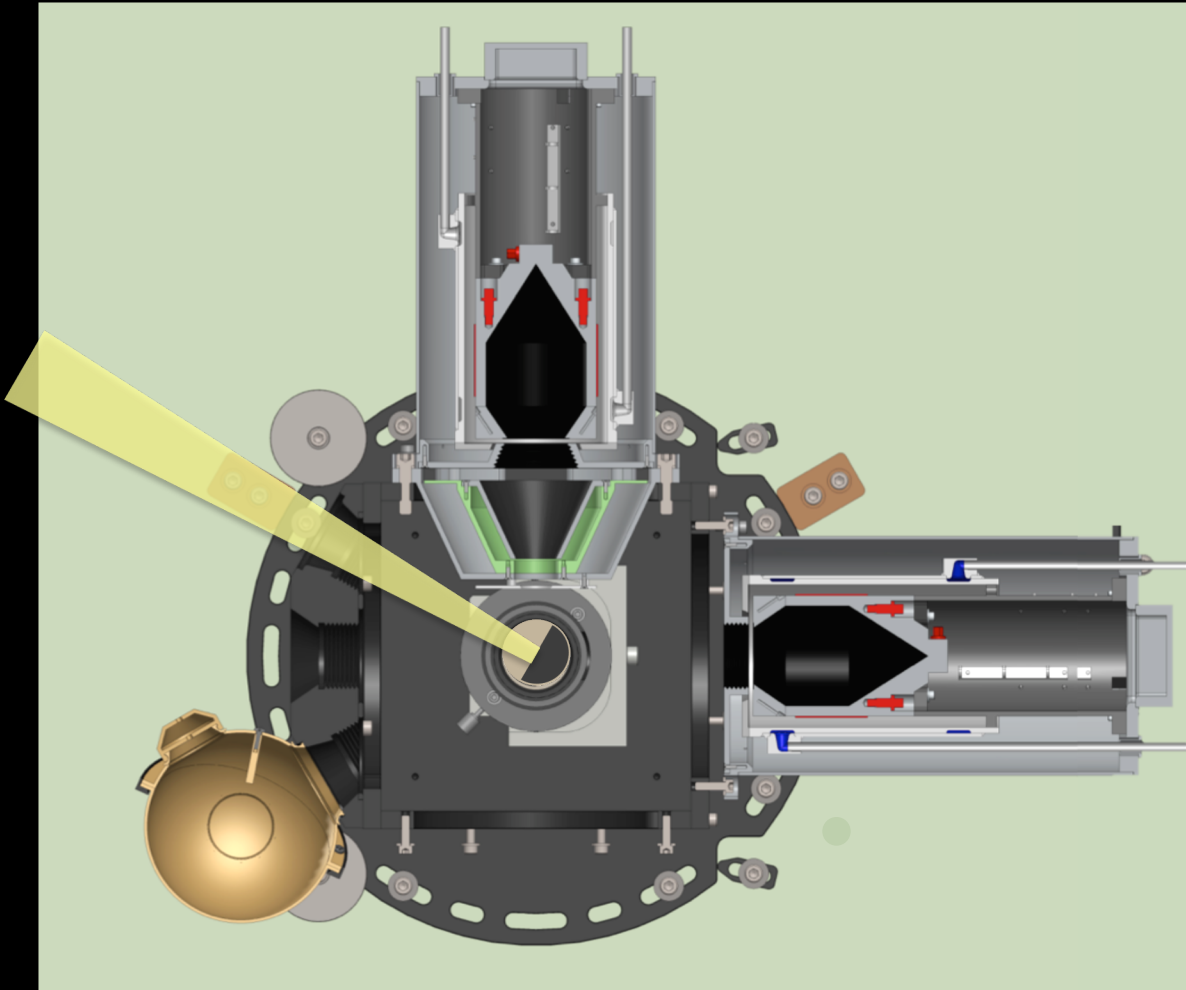


Spectral ILS monitor
Supports SI-traceability



OVTS: Space-2 View

Used to characterize polarization*



*Instrument design provides Earth viewing immunity to polarization

Infrared ARI for CLARREO: 3 Talks

- **Part 1: Heart of a Pathfinder Mission Concept for Establishing a Key Climate Benchmark**
i.e. What this new type of sensor offers
- **Part 2: New Technologies For On-Orbit Verification and Test, Fred Best**
i.e. How ARI works
- **Part 3: Assessing the Ability to Serve as a Satellite Intercalibration Reference, Dave Tobin**
i.e. How will ARI be used to unify key IR obs

Infrared ARI for CLARREO



- A. Historical Background**
- B. Accuracy / Uncertainty**
- C. The ARI Approach**
- D. Pathfinder Mission & Applications**



EOS Aqua

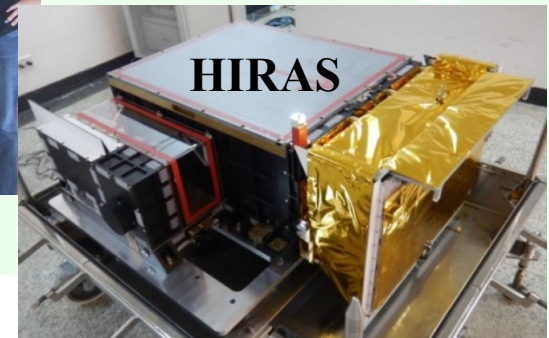
1330 orbits



Suomi NPP & JPSS



0930 MetOp orbit



0530 FY3E orbit

Infrared ARI for CLARREO



➔ A. Historical Background

B. Accuracy / Uncertainty

C. Evolution of US Climate
Observing Systems

D. Future Mission
& Applications



EOS Aqua

1330 orbits



Suomi NPP & JPSS



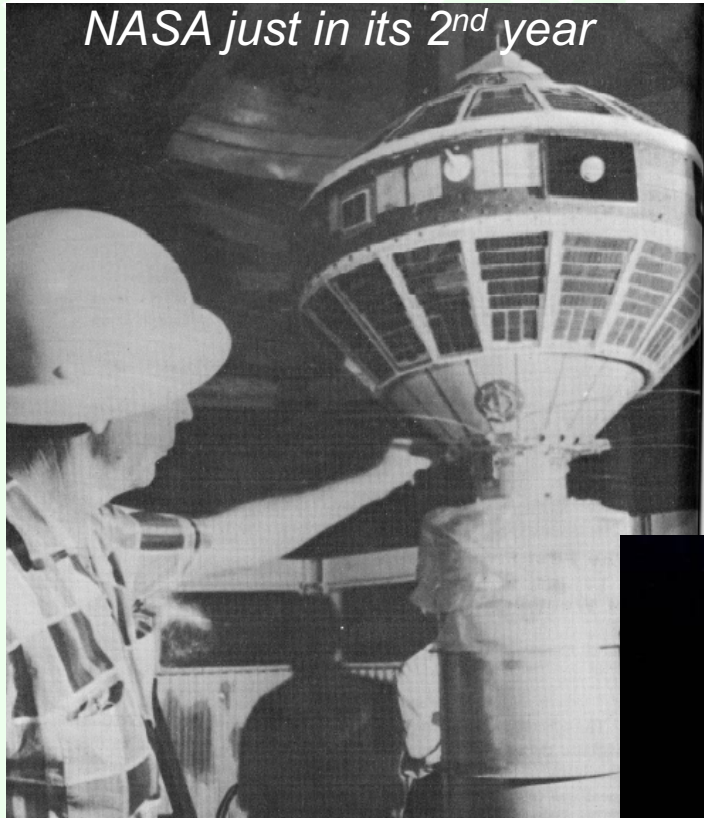
0930 MetOp orbit



0530 FY3E orbit

Earth Radiation Budget, how it started

13 Oct 1959-Feb 1960 Explorer 7



Spheres also on
TIROS 1961-63
**Earth Albedo
Determined**

**The 1st meteorological satellite
instrument to observe the Earth**

- Radiometer designed by
Verner Suomi & Robert Parent
- Omni-directional spheres
- 3-color (black, white, gold)

Broad spectral response set by “color”



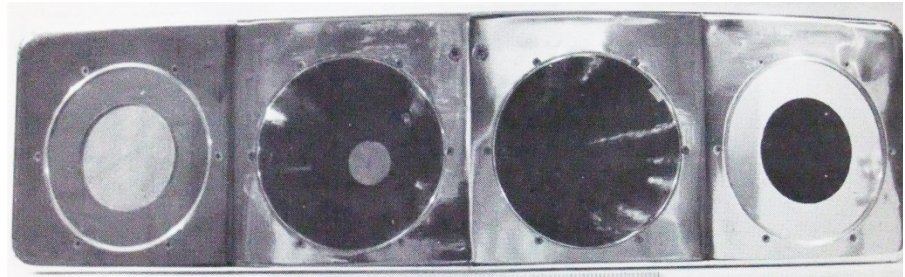
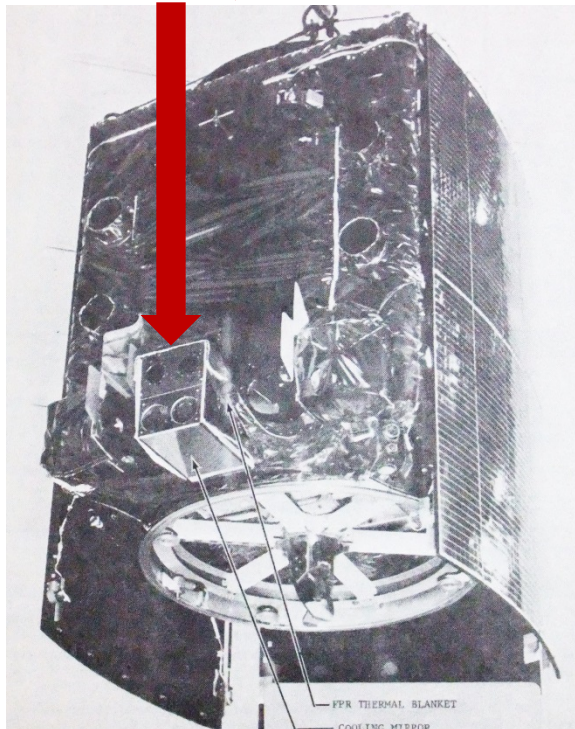
An outgrowth of measuring
the energy budget of a corn field



1966-1972 Black and White Flat Plate Radiometers followed for flux measurements of the Earth Radiation Balance

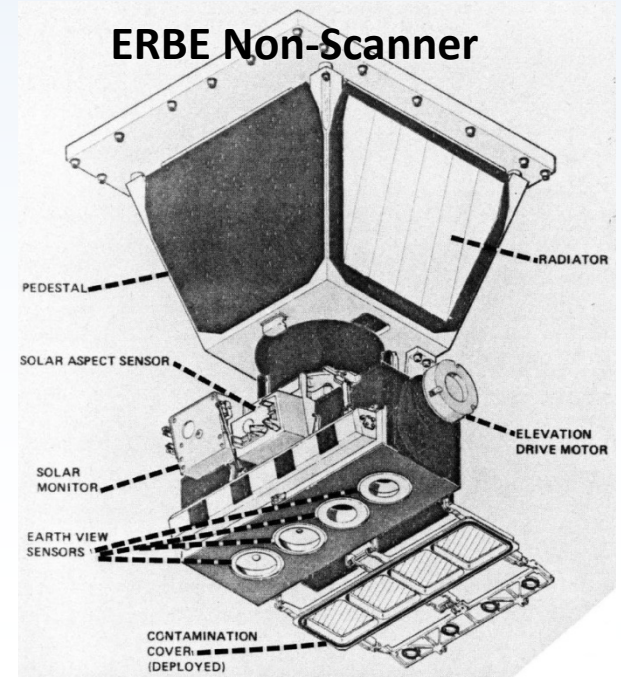
Many flights carried Suomi/Parent Radiometers

- ESSA 3, 5, 7, 9 spinners, 1966-69
- ITOS 1, 1970
- NOAA 1, 1970



Active Cavity Radiometer, 1975-late 1990s

- Developed fast ACR for UW ERBOS* mission
- Electrical Substitution Cavity Radiometer to improve flux accuracy from Nimbus ERB
- Used high emissivity for total spectral band & a quartz filter for the Shortwave band
- On ERBE Non-Scanner 1984-late 90's
- Dropped from future missions in favor of higher spatial resolution radiance data for cloud forcing investigations



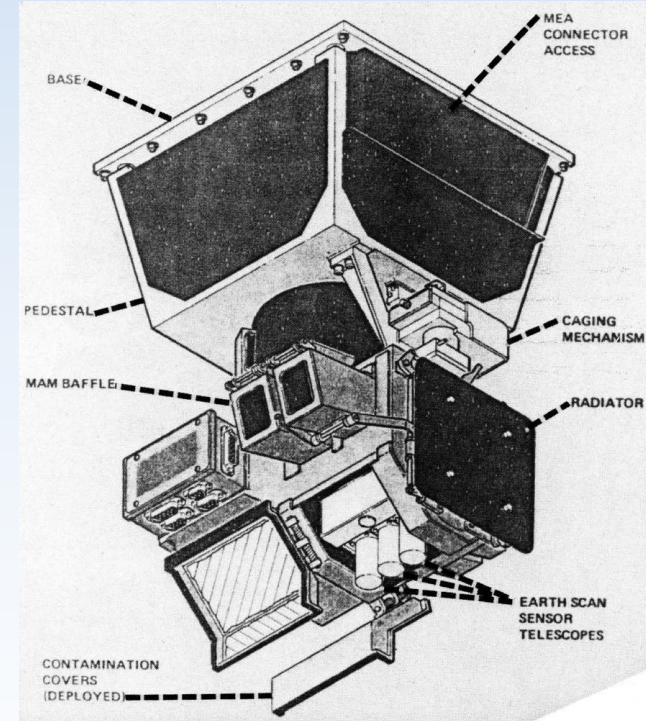
* *Earth Radiation Budget Observing System, not selected for ERBE*

Scanning Radiometers, 1984-future

- Measure radiance and convert to fluxes with Angular Distribution Models: 1st proposed by Tom Vonder Haar
- Spectral bands are total :Solar or Shortwave (SW), Earth Emitted or Longwave (LW), and total (TOT)

➤ *Current US Earth Radiation Budget measurements from CERES (1998-), the follow-on from ERB and ERBE*

➤ *New NASA Earth Venture Continuity sensor in the selection process*



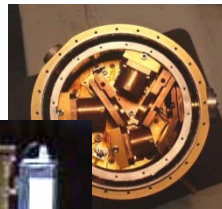
**ERBE 3-band Scanner
similar to CERES**

**ERBE showed that, on the average,
clouds cool (Ramanathan)**

**For better accuracy, these traditional observations should be
supplemented with high spectral resolution observations!**

Fourier Transform Spectro-radiometer

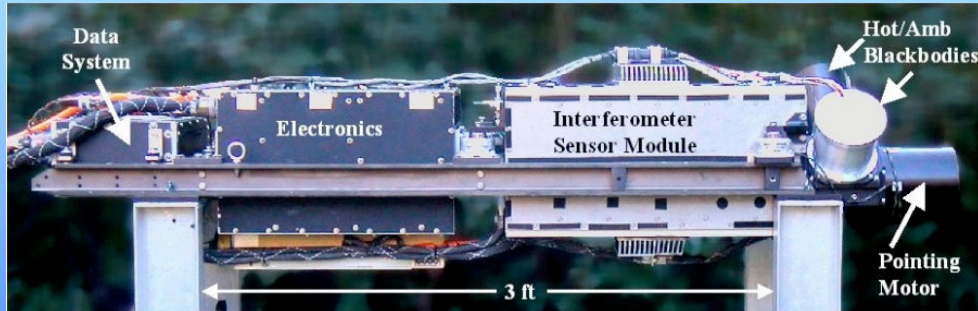
- 1978-1985: Designed high spectral resolution instrument for “Sounding” [T(p), WV(p)] from GEO leading to **High-resolution Interferometer Sounder (HIS)** aircraft sensor
- Flew on high altitude NASA U2/ER2 aircraft 1985-1998
- 3-17 μm at 0.34 cm^{-1} resolution (Resolving power > 1700)
- First demonstration of high vertical resolution sounding (2.5-3 times improvement) from high spectral resolution IR
- Significant contribution to improved spectroscopy from accurately calibrated, long path atmospheric spectra



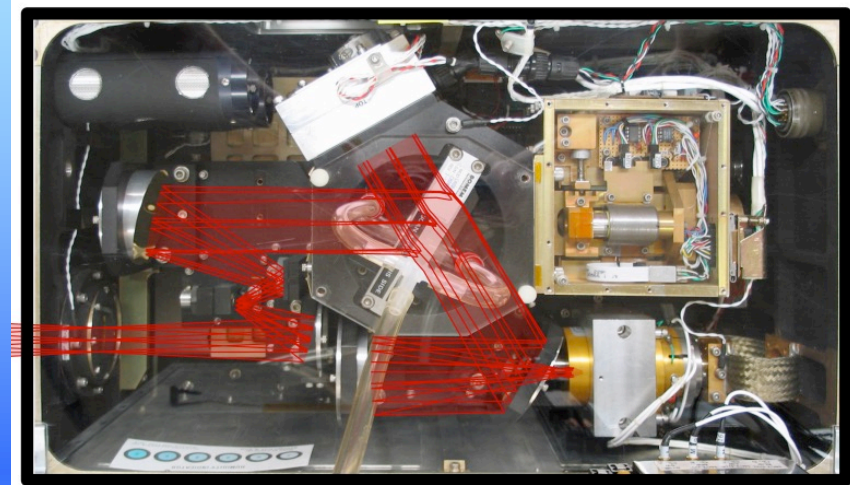
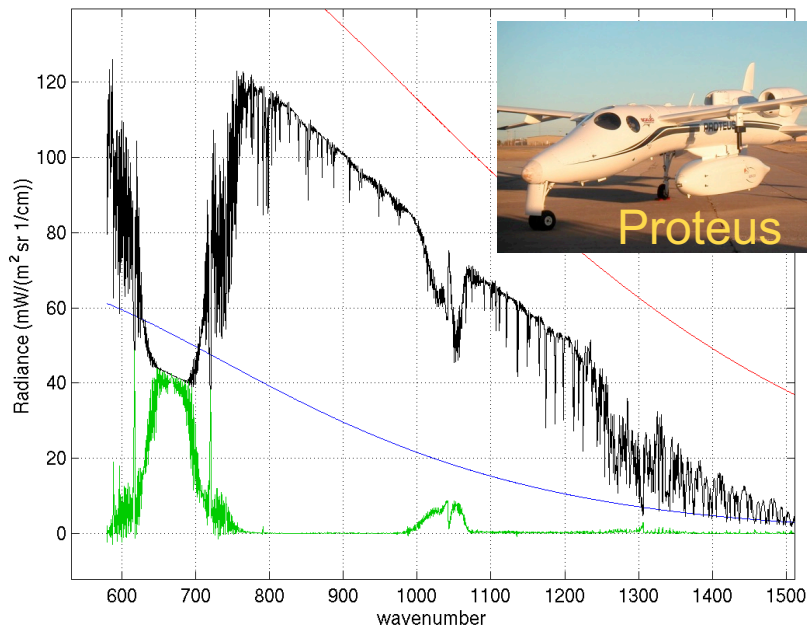
*high spectral resolution
reduced uncertainties from
degrees to tenths of
degrees!*
(See Goody & Haskins, 1998)

Scanning HIS Aircraft Instrument

(Scanning High-resolution Interferometer Sounder, HIS; 1998-present)

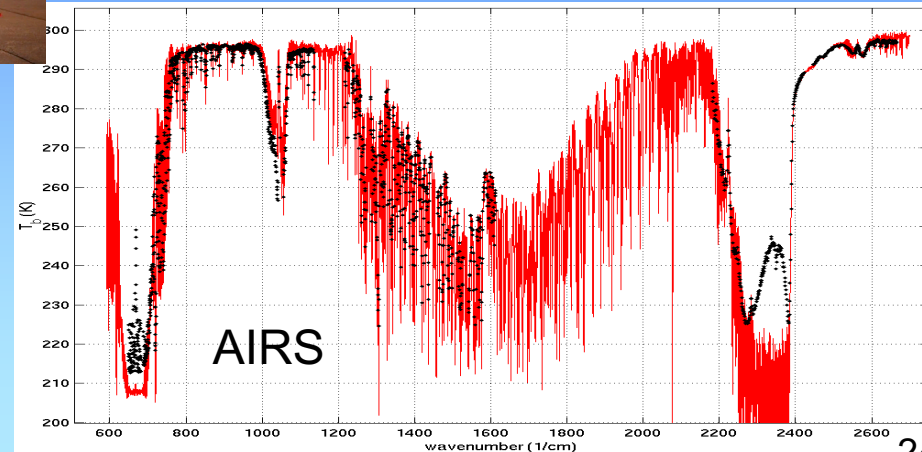


Uplooking and Downlooking Spectra for Remote Sensing



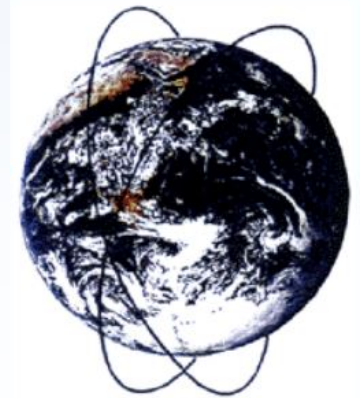
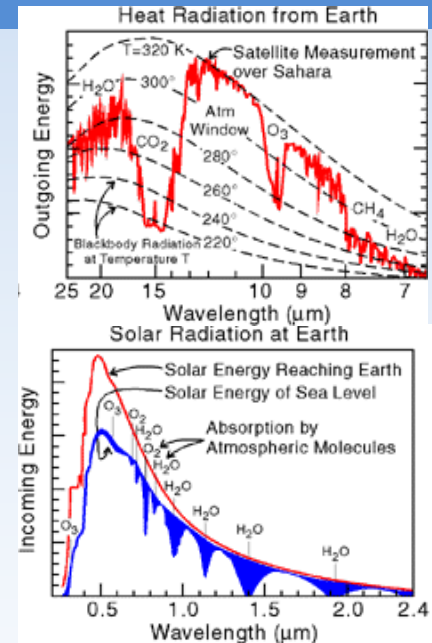
Michelson Interferometer

Satellite Sensor Validation



1993-CLIMSAT: Jim Hansen, NASA GISS

- **Spectrally resolved IR and solar proposed to measure forcings & feedbacks - 3 instruments:**
 - **MINT:** 6-40 μm Michelson Interferometer
 - **EOSP:** 0.4-2.25 μm Earth Observing Scanning Polarimeter
 - **SAGE III:** 0.29-1.02 μm Stratospheric Aerosol and Gas Experiment
- **Two Spacecraft for adequate sampling**
- Emphasized precision/self calibration
- But **expected to rely on observations from subsequent S/C having temporal overlap** to achieve 2-decade observing goal

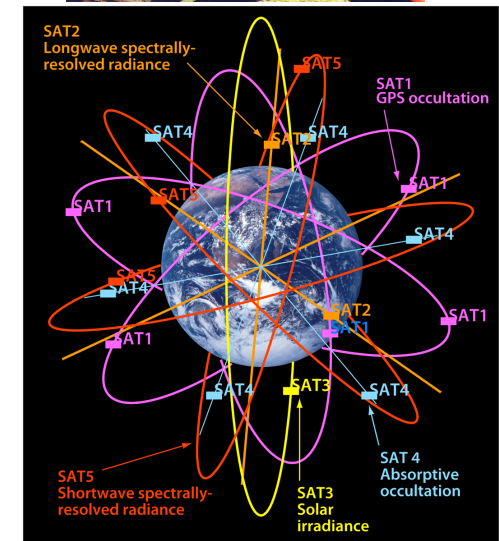
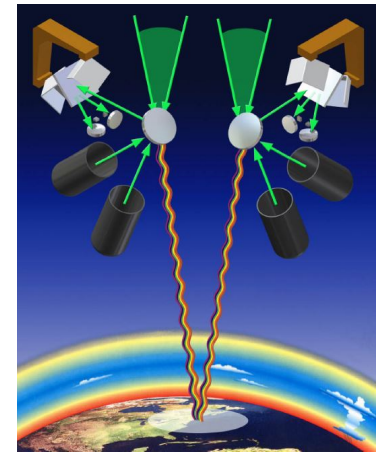


National Aeronautics and Space Administration
Goddard Institute for Space Studies

Goddard Space Flight Center
Sciences and Exploration Directorate
Earth Sciences Division

1996-Arrhenius: Jim Anderson, Harvard

- **Proposed observing system** based on IR Spectrally resolved Radiances ($6\text{-}44\text{ }\mu\text{m}$) with 0.1 K 3-sigma accuracy, ***verified on-orbit***
- Sampling studies showed importance of **multiple, carefully chosen orbits**
- **Evolved to add reflected solar and GPS Radio Occultation for Decadal Survey White Paper in 2005**
(Harvard teamed with UW-SSEC, NIST, U of Colorado, SwRI, U of Graz)



Jim
Anderson
2006

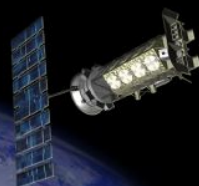


What would a Climate Program “Board of Inquiry” place at the top of the priority list?

- We have a fundamental responsibility to future generations to put in place a climate record that is accurate in perpetuity, testable by scientists from any nation at any time in the future, and is global in coverage.
- Long-term climate forecasts that are tested, trusted and systematically improved.
- **Eloquently supporting the argument that on-orbit accuracy verification & testing is a crucial requirement**

2006 ASIC³

Achieving Satellite Instrument Calibration for Climate Change (ASIC³)



Center for Satellite Applications and Research
National Environmental Satellite, Data, and Information Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce



NIST



Achieving Satellite Instrument Calibration for Climate Change (ASIC³)

Report of a Workshop Organized by

National Oceanic and Atmospheric Administration
National Institute of Standards and Technology
National Aeronautics and Space Administration
National Polar-orbiting Operational Environmental Satellite System-Integrated Program Office
Space Dynamics Laboratory of Utah State University

At the National Conference Center, Lansdowne, VA, May 16-18, 2006

Edited by George Ohring

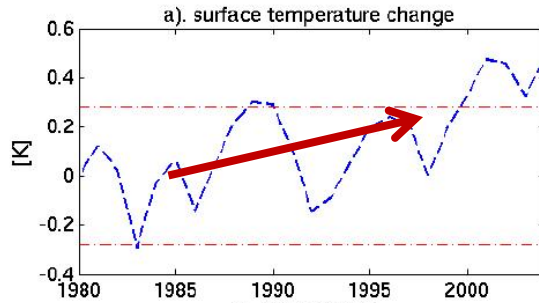
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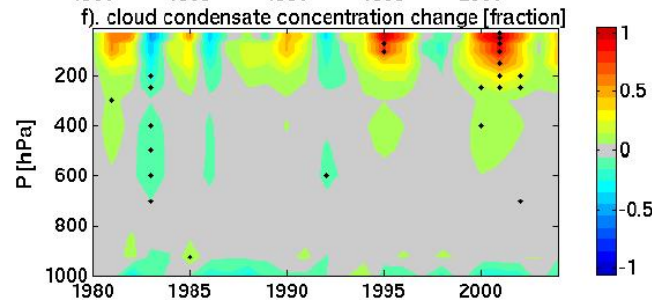
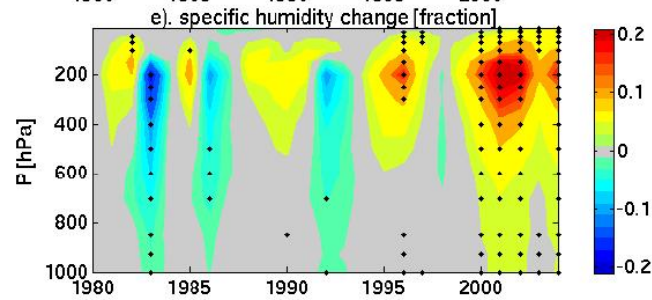
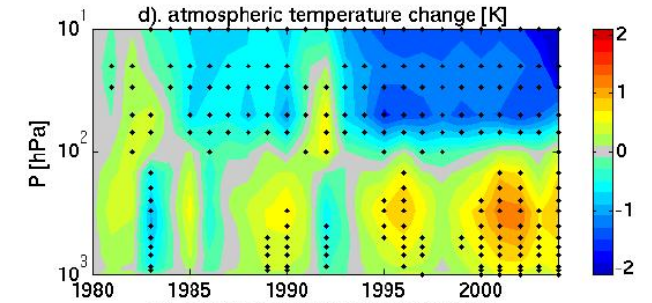
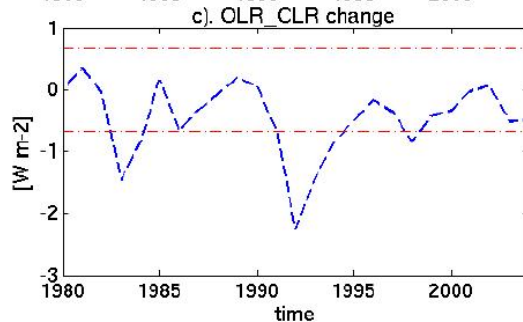
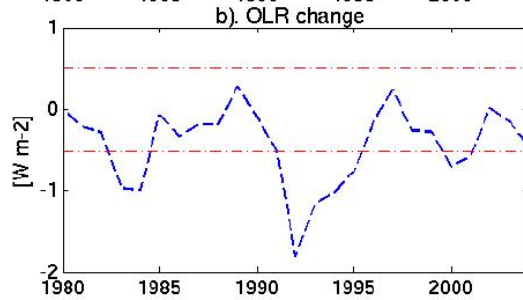
CM2 25-yr Annual Mean Trends

Yi Huang thesis (Ramaswamy, advisor), 2008

Surface T
trend



All sky &
Clear
Flux trends



Temperature,
Humidity,
& Cloud
trends
from
Spectral
Radiance

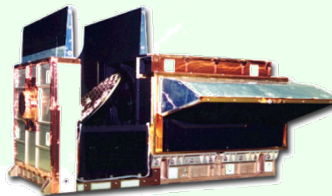
Black dots indicate changes > 3 x standard deviation of unforced means

Note OLR Insensitivity to the trends in
Ts, Atmospheric T, WV, and Clouds

High Spectral Resolution Infrared Sounding from Polar Orbit for operational weather

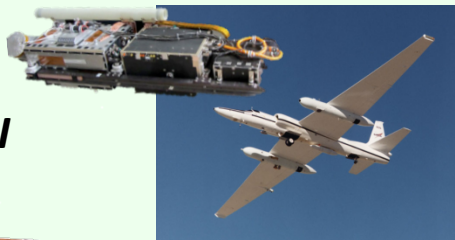
1978-

HIRS
(20 ch)



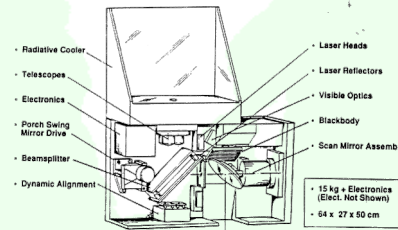
1986-

**HIS,
S-HIS,
NAST-I**



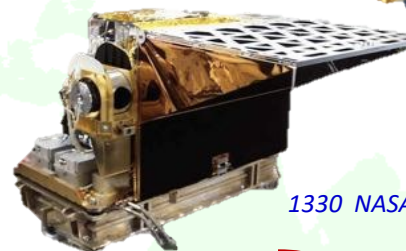
1990/91

**ITS
(~CrIS)**
UW-SSEC led Design



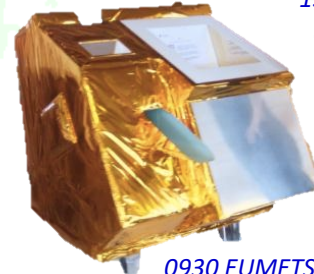
2002-

AIRS
(2378 ch)



2006-

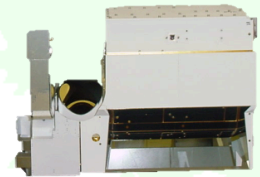
IASI
(8461 ch)



0930 EUMETSAT METOP

2011-

CrIS
(2211 ch)



1330 Suomi-NPP
(NOAA/NASA)

2016 **HIRAS**

Stepping stones

Advantages of FTS for High Accuracy in IR

- **First order knowledge of ILS:** (or Spectral Response Function)
The ILS is established by the FTS approach, mainly depending on a small set of wavelength independent parameters
Note- AIRS SRFs were determined in ground testing using an FTS
- **Single detector can cover broad spectral bands:** This simplifies optical and detector configurations and avoids calibration issues related to FOV dependence of spectra (e.g. AIRS c_{ij} properties)
- **Spectral stability:** Insensitivity to instrument T changes
- **On-orbit spectral calibration source practical** (CrIS neon source)
- **Any non-linearity can easily be monitored on orbit**
using its out-of-band signature

Key Advantage of FTS for Consistency in IR

➤ **Standardization of spectra from different instruments:**

A rigorous mathematical formalism allows straight forward transformation of ARI spectra to CrIS Spectral properties for comparison or trending (or clearly IASI or CrIS to CrIS).

- **Spectral Scale standardization is straight forward for FTS** that is naturally Nyquist sampled
- **First order ILS standardization is routine**, and techniques for removal of subtle responsivity influences (ringing) are being developed in Europe and at UW-SSEC

Infrared ARI for CLARREO



A. Historical Background

➔ B. Accuracy / Uncertainty

C. The ARI Approach

D.

**Modern sounder accuracy
sets the stage for ARI**



EOS Aqua

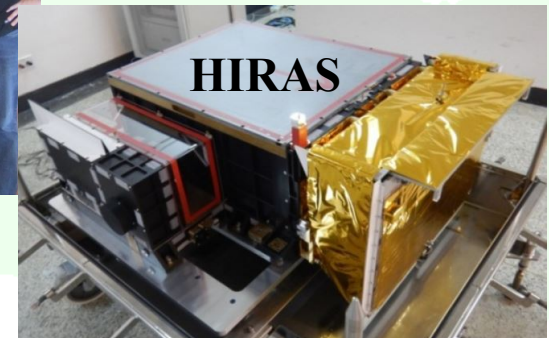
1330 orbits



Suomi NPP & JPSS



0930 MetOp orbit



0530 FY3E orbit

Radiometric Uncertainty (RU)

For Earth emitted spectral measurements, we advocate for**
defining RU to be 3-sigma Brightness Temperature (T_b)
uncertainty at scene T_b , because:

1. RU is then expressed as a physical property that is easy to think about and conceive of how it can arise
2. RU is quite independent of wavelength
3. RU is only weakly dependent on scene temperature

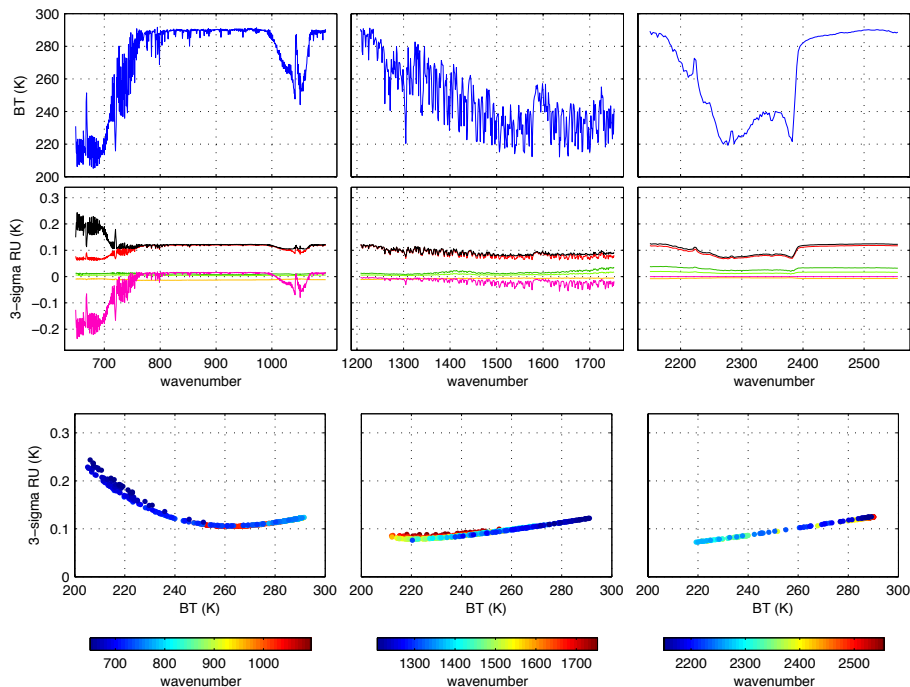
RU is calculated by RSSing the derivative of the T_b calibration equation for each independent parameter x times the parameter uncertainty δx

****Beware of other ways of stating Radiometric Uncertainty performance
e.g. Brightness temperature uncertainty at a fixed temperature like 280 K is
much looser than Brightness temperature uncertainty at scene temperature**

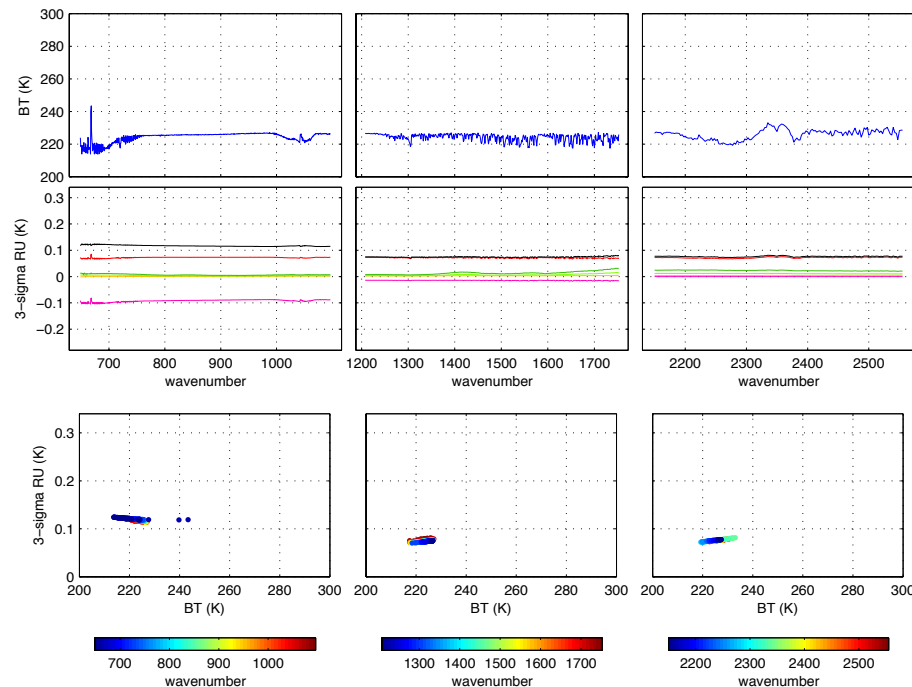
CrIS RU Estimate Example

perturb independent parameters of calibration equation

typical warm, ~clear sky spectrum



high, thick cloud



3- σ uncertainties

112.5 mK

0.03

1.5 K

3 K

0 K

0

0 K

*

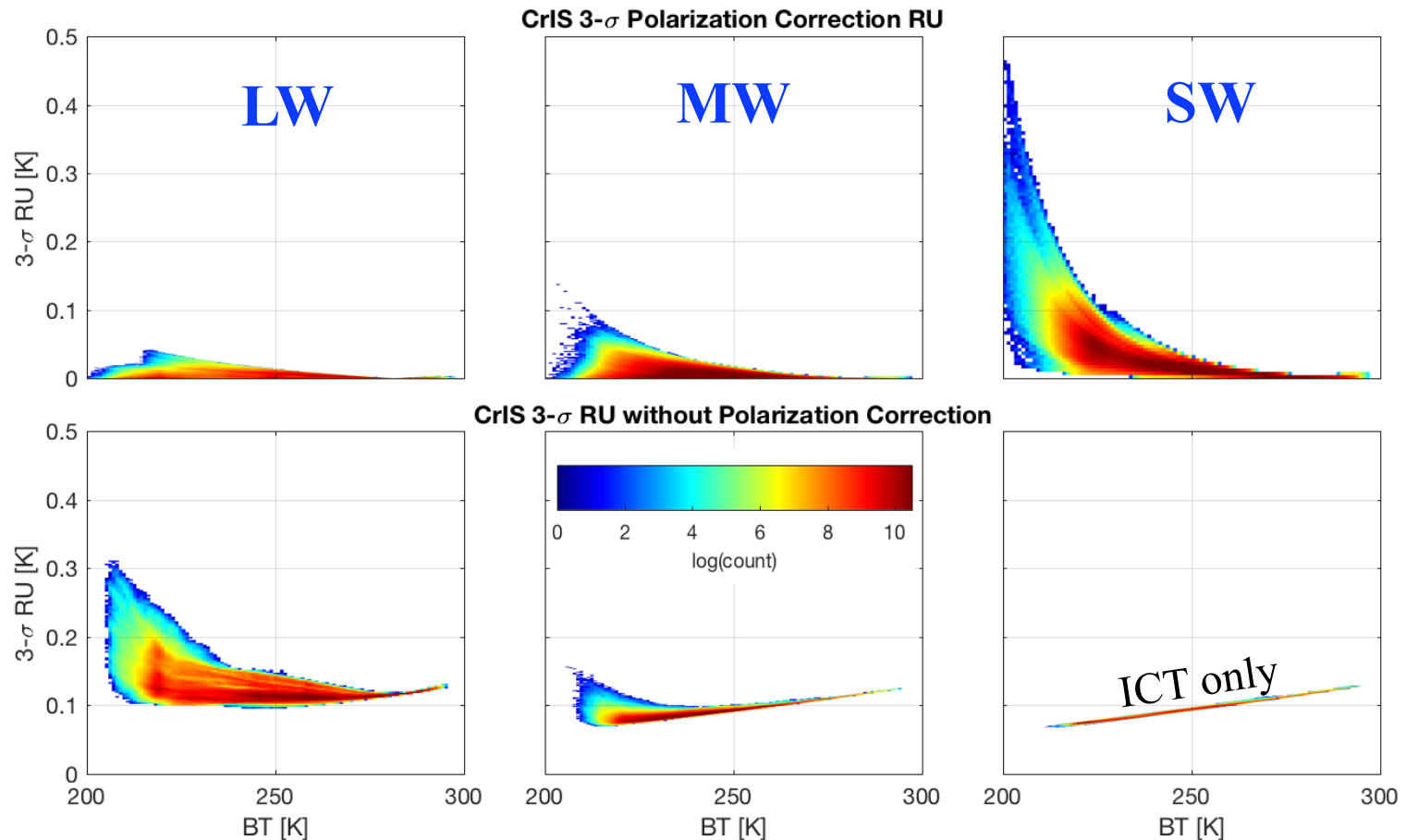
Non-linearity Parameter a_2

*	FOV1	FOV2	FOV3	FOV4	FOV5	FOV6	FOV7	FOV8	FOV9
LW (V ⁻¹)	0.00403	0.00403	0.00403	0.00403	0.00403	0.00403	0.00403	0.00403	0.00403
LW (%)	23	30	26	20	32	24	29	32	18
MW (V ⁻¹)	0.00154	0.00160	0.00157	0.00162	0.00162	0.00168	0.00162	0.00161	0.00128
MW (%)	26	11	6	15	13	54	4	6	49

*For Atmospheric
LW Spectra,
Non-linearity
causes significant
scene dependence
of RU estimate*

CrIS On-Orbit RU Estimates (3-sigma)

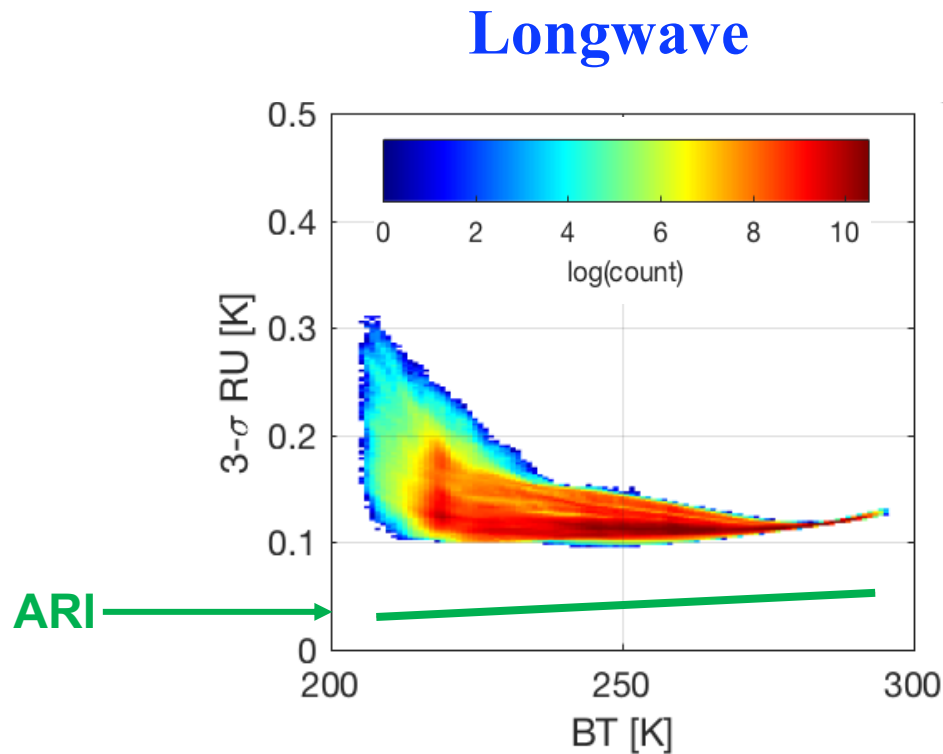
**Polarization
Contribution
to RU
(25% $p_r p_t$
polarizability)**



**RU from ICT
& nonlinearity
Contributions**

- *RSSing the top and bottom row contributions will make all bands look much like the bottom left LW band RU*
- *CrIS is certainly as accurate as any operational sounder*

ARI compared to CrIS On-Orbit RU



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 instruments, especially at cold temperatures*
- *Then, with Inter-Calibration from ARI the operational sounders can be improved and can provide the unbiased sampling needed for high quality climate products*

Infrared ARI for CLARREO



A. Historical Background

B. Accuracy / Uncertainty

➔ C. The ARI Approach

D. Pathfinder

**ARI will provide
higher accuracy
proven on-orbit**



EOS Aqua



Suomi NPP & JPSS



0930 MetOp orbit



0530 FY3E orbit

Absolute Radiance Interferometer (ARI) Prototype

with a short upgrade path to flight

ABB Bomem Interferometer
Modulator "Wishbone"

Input Port 2
Stablé Source

Fore
Optics

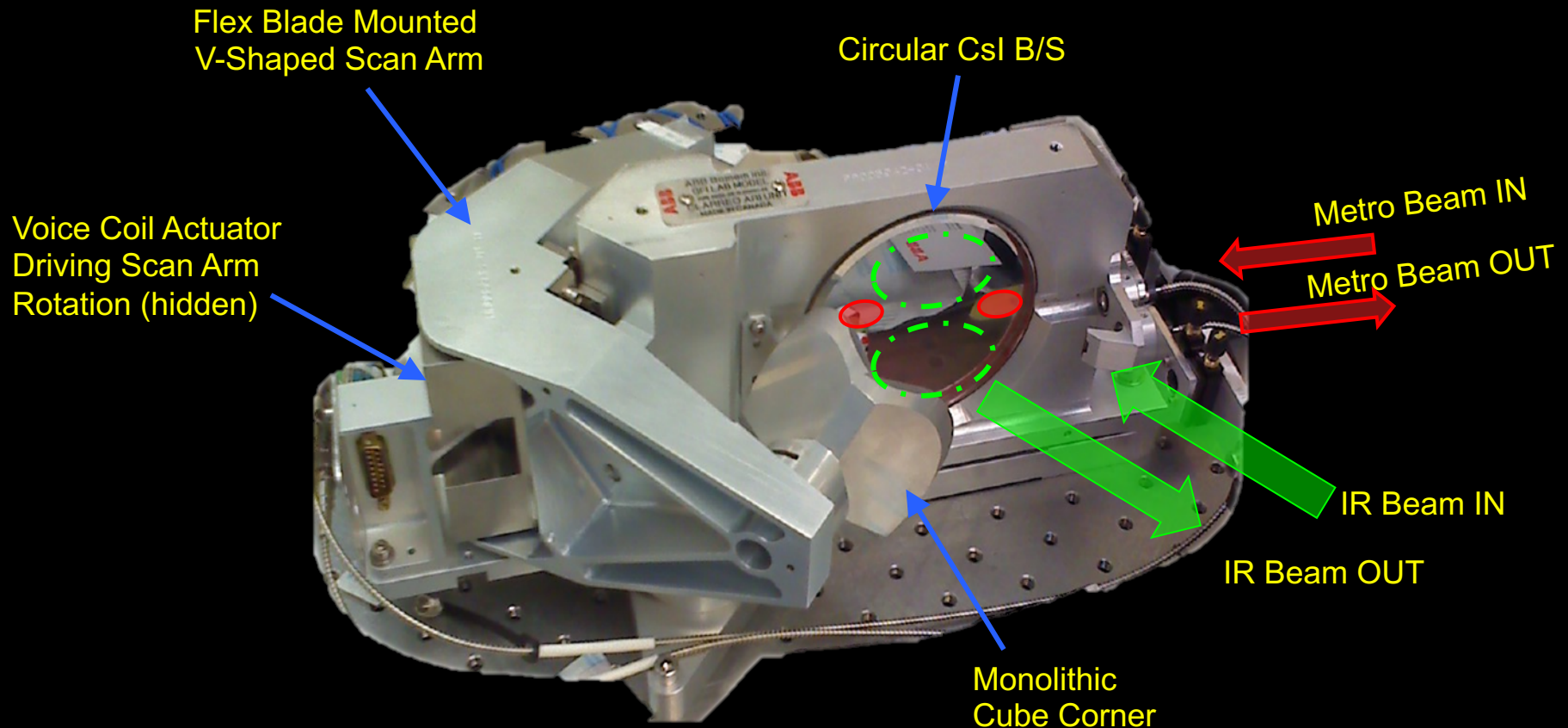
Aft Optics 1/
Pyro-detector

Aft optics 2 (MCT/InSb)
Sterling Cooler Compressor

Calibrated FTS

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

ABB Interferometer Modulator TRL 9



Very Similar to ACE and GoSat FTS

Measurement Standard for Traceability to the SI

SI=International System of Units

- 1) Infrared Radiance: Variable T Blackbody provides a *Measurement Standard* source based on Planck function quantum mechanical theory
- 2) Planck spectrum for a perfect blackbody ($\varepsilon=1$) only depends on Temperature and Wavenumber
- 3) On-orbit Absolute Radiance Standard (OARS) accuracy verification relies on:
 - Temperature Scale established on orbit
 - Spectral Emissivity of cavity blackbody near 1, measured on-orbit from reflected “halo” source
 - Wavenumber referenced to atmospheric lines & ILS monitored with QCL/integrating sphere source



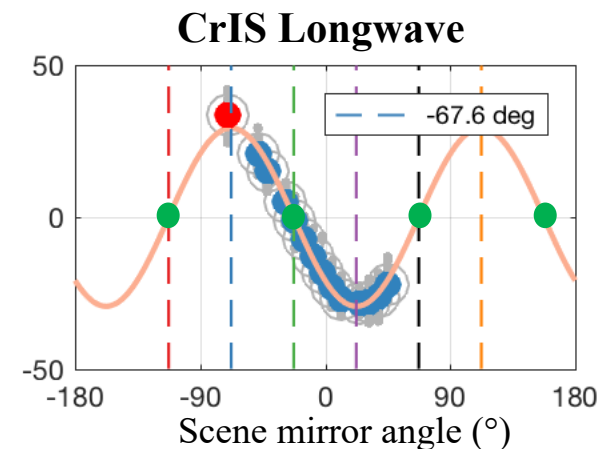
**On-orbit standards replace
unprovable stability assumptions!**



ARI Accuracy Improvements

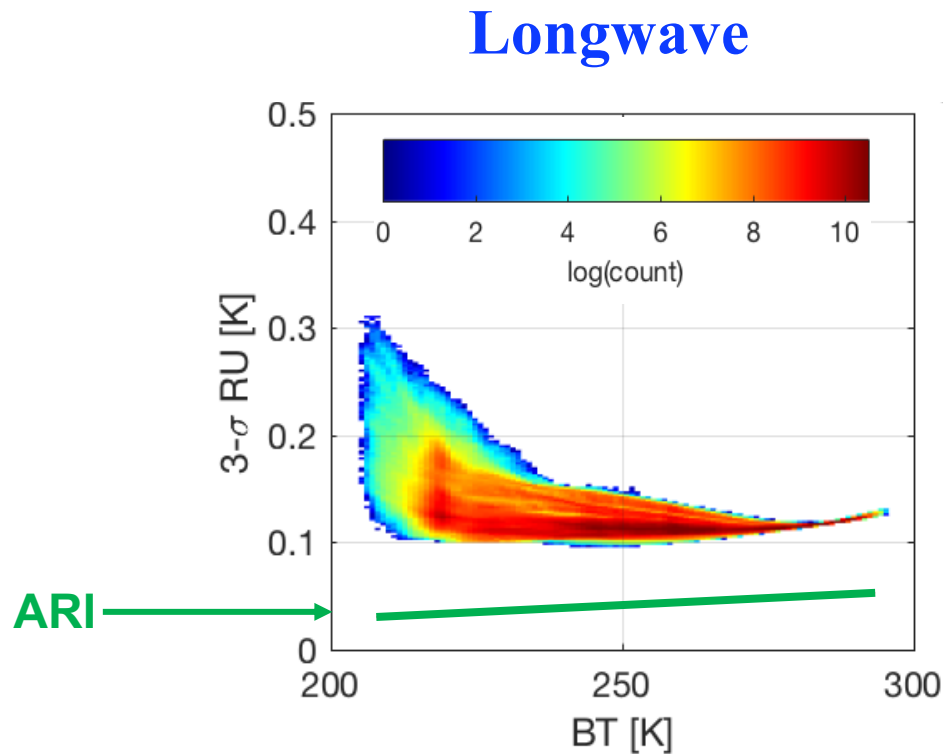
- **Accuracy proven on-orbit using standard (OARS) with T scale established by three miniature phase change cells**
- **Internal Calibration Target T uncertainty is less than half as large (conservatively 45 mK 3-sigma)**
- **Internal Calibration Target emissivity is measured to 0.06 % accuracy on-orbit to account for any drift**
- **Non-linearity Extremely Small**
 - Prioritize Linearity over noise ($NE\Delta T$)
 - Pyroelectric FarIR detector is inherently linear
- **Polarization Sensitivity Extremely Small**

All measurements are made at the **zeros** of the sinusoidal polarization dependence (90° apart)



Also, ARI enjoys the FTS advantages listed earlier

ARI compared to CrIS On-Orbit RU



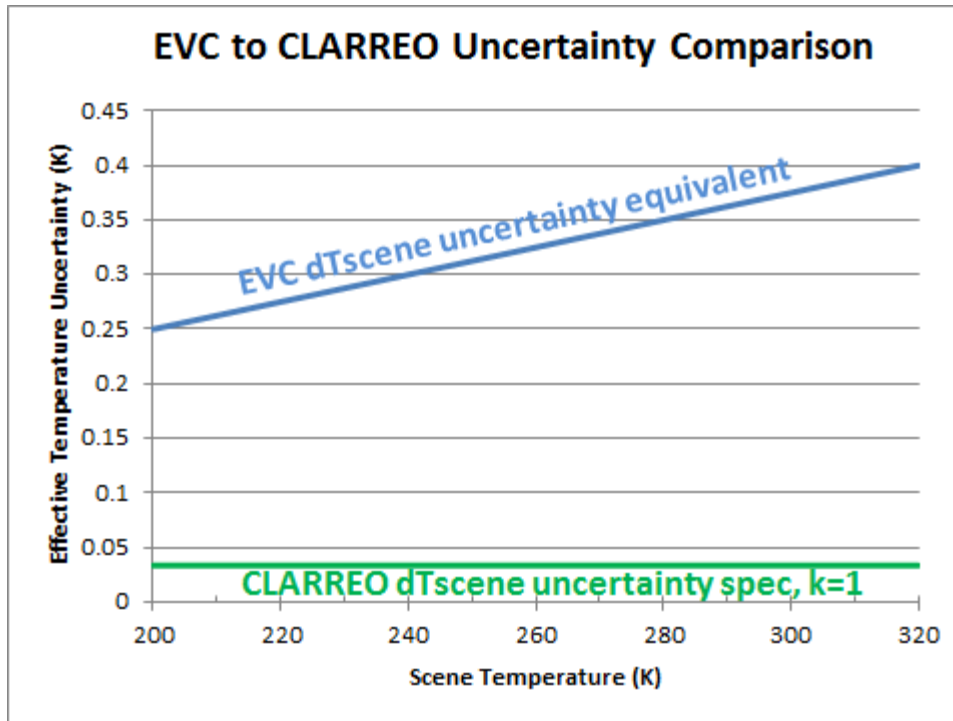
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CLARREO Spectrally Resolved Uncertainties

~ an order of magnitude better than LW total measurements

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



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

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

Key immediate benefits from flying CLARREO ARI asap:

- 1. Make excellent operational sensors even better*
- 2. Leverage the complete data record to establish a more accurate climate benchmark*

➔ **D. Pathfinder Mission & Applications**

CLARREO



EOS Aqua

1330 orbits



Suomi NPP & JPSS



0930 MetOp orbit

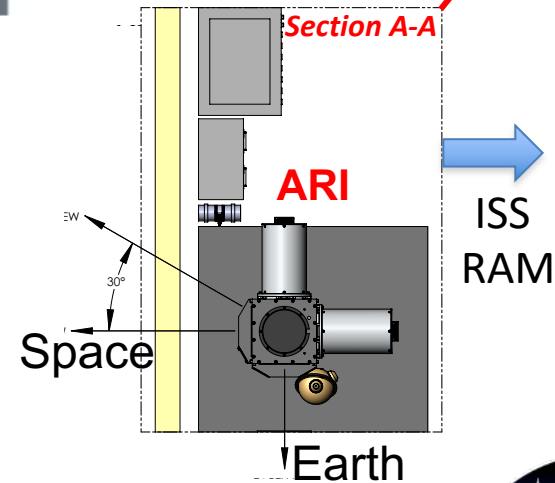
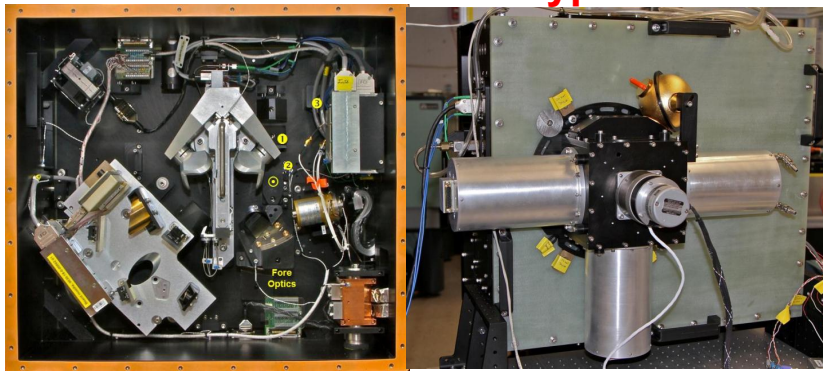


0530 FY3E orbit

CLARREO IR Pathfinder Mission: International Space Station example

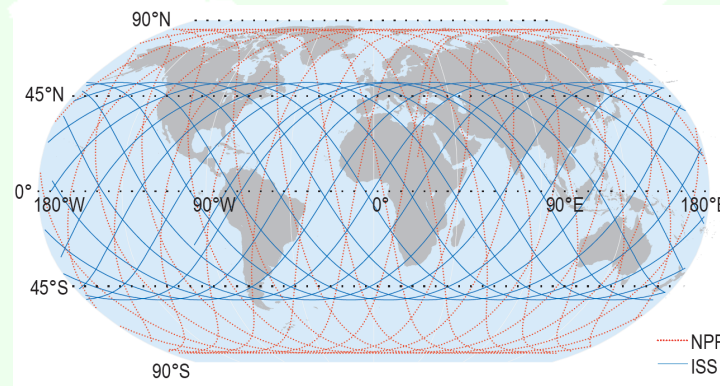


ARI Lab Prototype



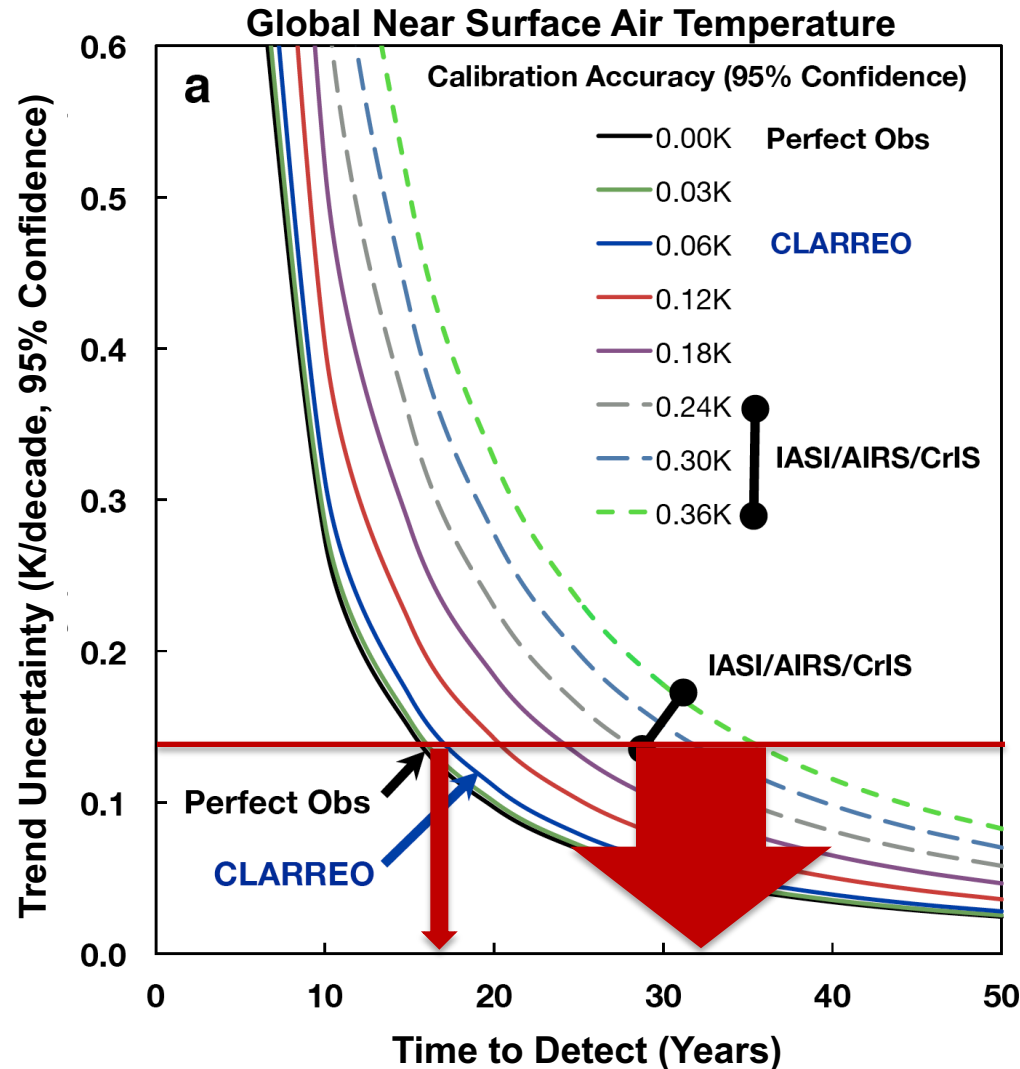
CLARREO IR Reference Ready

- Accuracy better than 0.1 K 3-sigma brightness temperature at scene T_b 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),



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

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

Huge Financial benefit shown by Cooke and Wielicki

Summary

- CLARREO missions emphasize incorporation of rigorous Metrological principles for all observations and climate products
- IR Radiance observations use on-orbit standards and testing to assure accuracy expectations e.g. fundamental on-orbit temperature scale and emissivity measurements
- For a CLARREO pathfinder on ISS, intercalibration with operational sounders will allow a climate radiance benchmark to be started at all latitudes (with Far IR restricted to latitudes < 52 degrees)
- Ongoing CLARREO Missions will also provide a higher accuracy, better proven reference for the WMO Global Space-based Inter-Calibration System (GSICS)