High Accuracy IR Radiances for Weather & Climate

Spectral Calibration, Radiometric validation (IASI / JAIVEx) & the role for future climate benchmark satellites (CLARREO)

David C. Tobin and Hank Revercomb
(representing a full team of colleagues:
Fred A. Best, William L. Smith*, James G. Anderson,**
Robert O. Knuteson, Joe K. Taylor, Daniel D. LaPorte,
Steven Dutcher, Ray K. Garcia, Scott D. Ellington,
Mark W. Werner, Douglas P. Adler,
Nick N. Ciganovich, and Kenneth Vinson)

University of Wisconsin-Madison,
Space Science and Engineering Center
* Hampton University; **Harvard University

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Perspective

- **Era of High Spectral Resolution IR Sounding from space is here & impacting numerical weather forecasts (AIRS, IASI, soon followed by CrIS & hopefully GIFTS)**
- **The High information content allows retrieval of trace gases, cloud and surface properties, in addition to temperature and water vapor profiles– *stems from broad spectral coverage, low noise, and high absolute accuracy***
- **A new standard in absolute accuracy is being demonstrated with aircraft sensors referenced to NIST – a few 0.1 K 3-sigma is possible using the fundamental advantages of high resolution, good blackbodies, & atmospheric spectral calibration**
- **An exciting new Climate Mission, CLARREO, has emerged**

Topics

1. **Spectral Stability and Calibration is Key:** *High resolution greatly reduces calibration errors associated with filter radiometers, as well as increasing information content*

2. **Radiance Validation from high spectral resolution aircraft observations:** *a sound foundation for advancing weather forecasting capability*

   - **Joint Airborne IASI Validation Experiment (JAIVEx), 14 April - 4 May 2007**

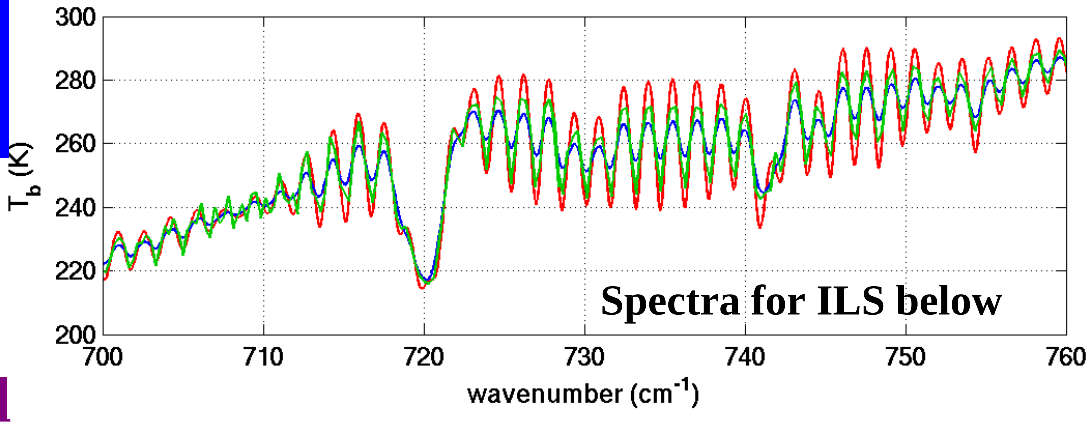
3. **The CLARREO benchmark Climate Mission: A logical extension of demonstrated high accuracy, spectrally resolved radiance measurement capability—**
   A key new tool for detecting and assessing climate change

1. Spectral Stability and Calibration:

High resolution greatly reduces calibration errors associated with filter radiometers, as well as increasing information content

Spectral Resolution: Long-wave Example

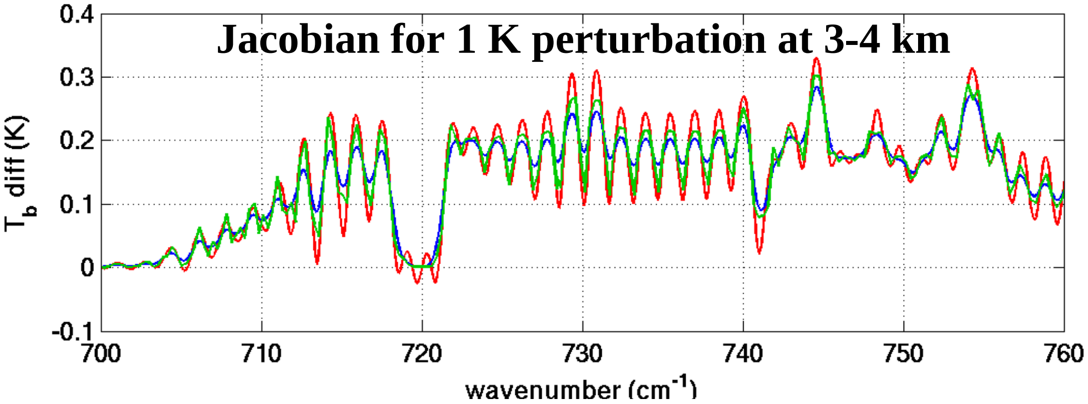
$\Delta\nu = 0.625\ \mathrm{cm}^{-1}$



Spectra for ILS below

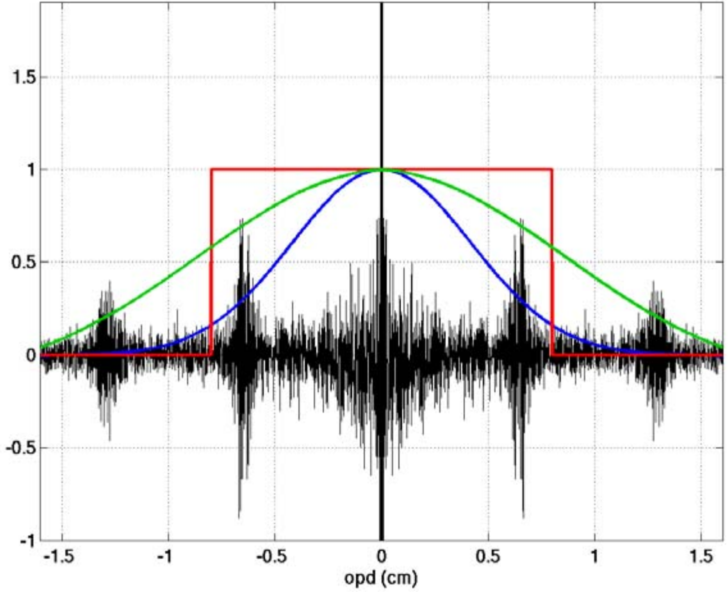
FTS & Grating Compared

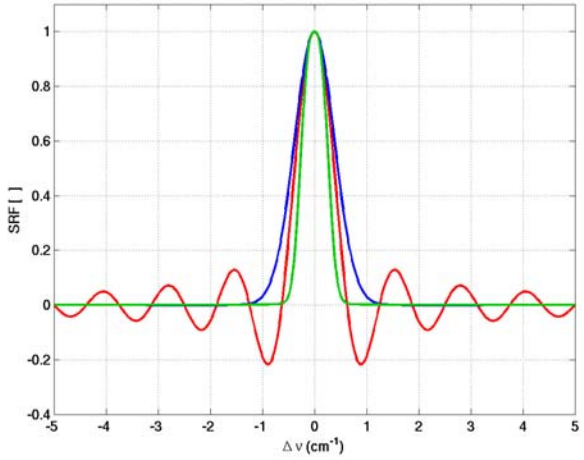
Grating HWHM = $\Delta\nu_{ua}$
= 1/(2*max delay)] &
= 1.43 $\Delta\nu_{ua}$



Jacobian for 1 K perturbation at 3-4 km

ILS Equivalent in
Optical Path Difference Space





ILS

FTS, unapodized

Grating HWHM
= $\Delta\nu_{ua}$
= 1.43 $\Delta\nu_{ua}$

ua= unapodized

Spectral Calibration Knowledge

- Channel Centers need to be known very accurately, with a goal of less than 1 ppm
- This is tighter than originally required of AIRS and CrIS, although both can meet the tighter goal that is being met by IASI too (spec of 1% of $\Delta\nu = \nu/1200$ implies 8 ppm)

Spectral Calibration:

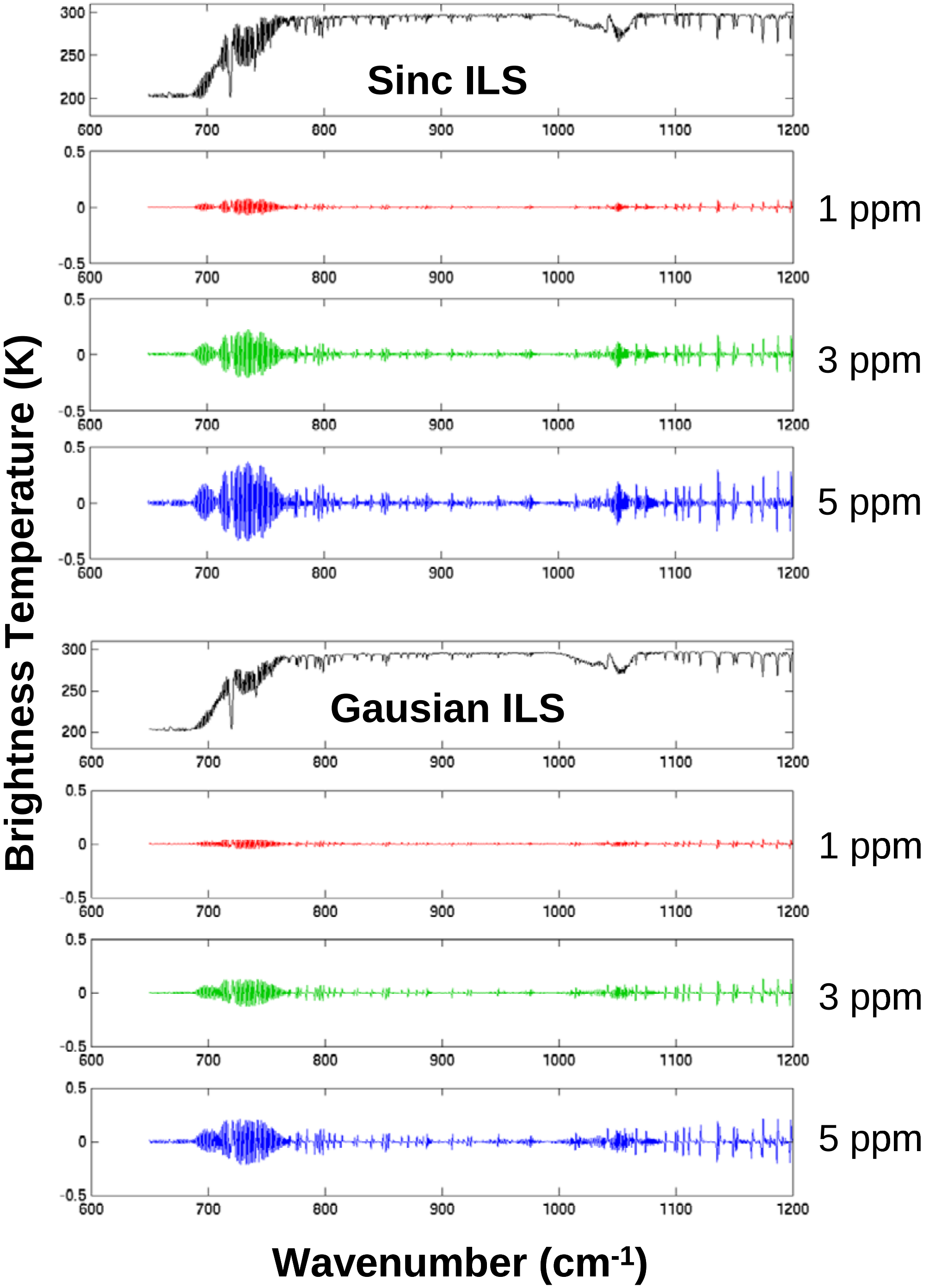
Long-wave, $\Delta\nu=0.625\ \mathrm{cm}^{-1}$

T_b errors for labeled spectral shift error in ppm

Note that 5 ppm is equivalent to 0.6 % of $\Delta\nu$ at 750 cm^{-1}

Also, note that the larger errors for the sinc ILS are consistent with its larger absorption line amplitudes and sounding sensitivity

< 1 ppm is desirable



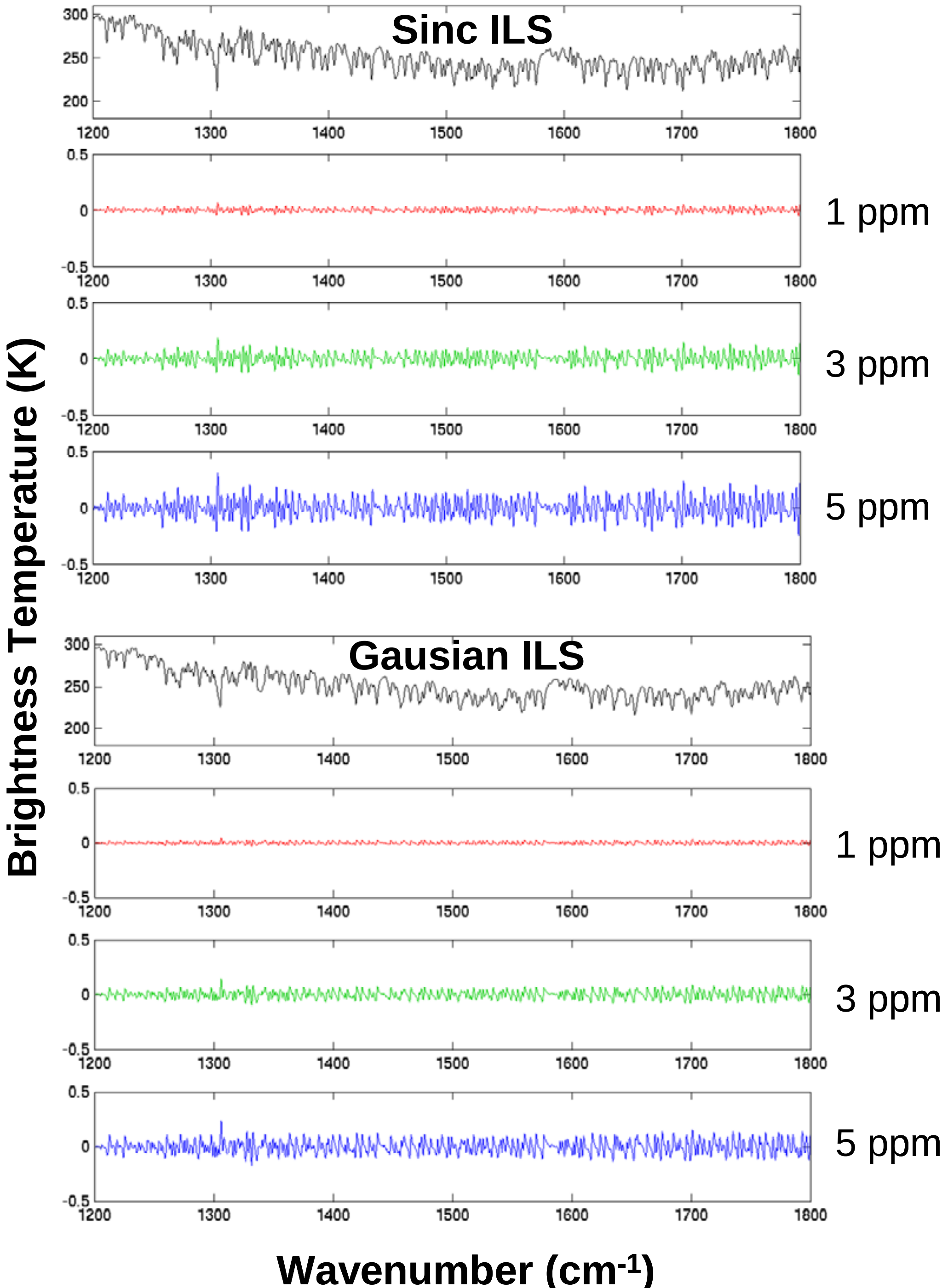
Spectral Calibration:
Mid-wave, $\Delta\nu$=1.25 cm^{-1}

T_b errors for labeled spectral shift error in ppm

Note that 5 ppm is equivalent to 0.6 % of $\Delta\nu$ at 1550 cm^{-1}

Also, note that the larger errors for the sinc ILS are consistent with its larger absorption line amplitudes and sounding sensitivity

< 1-3 ppm is desirable



Spectral Calibration:

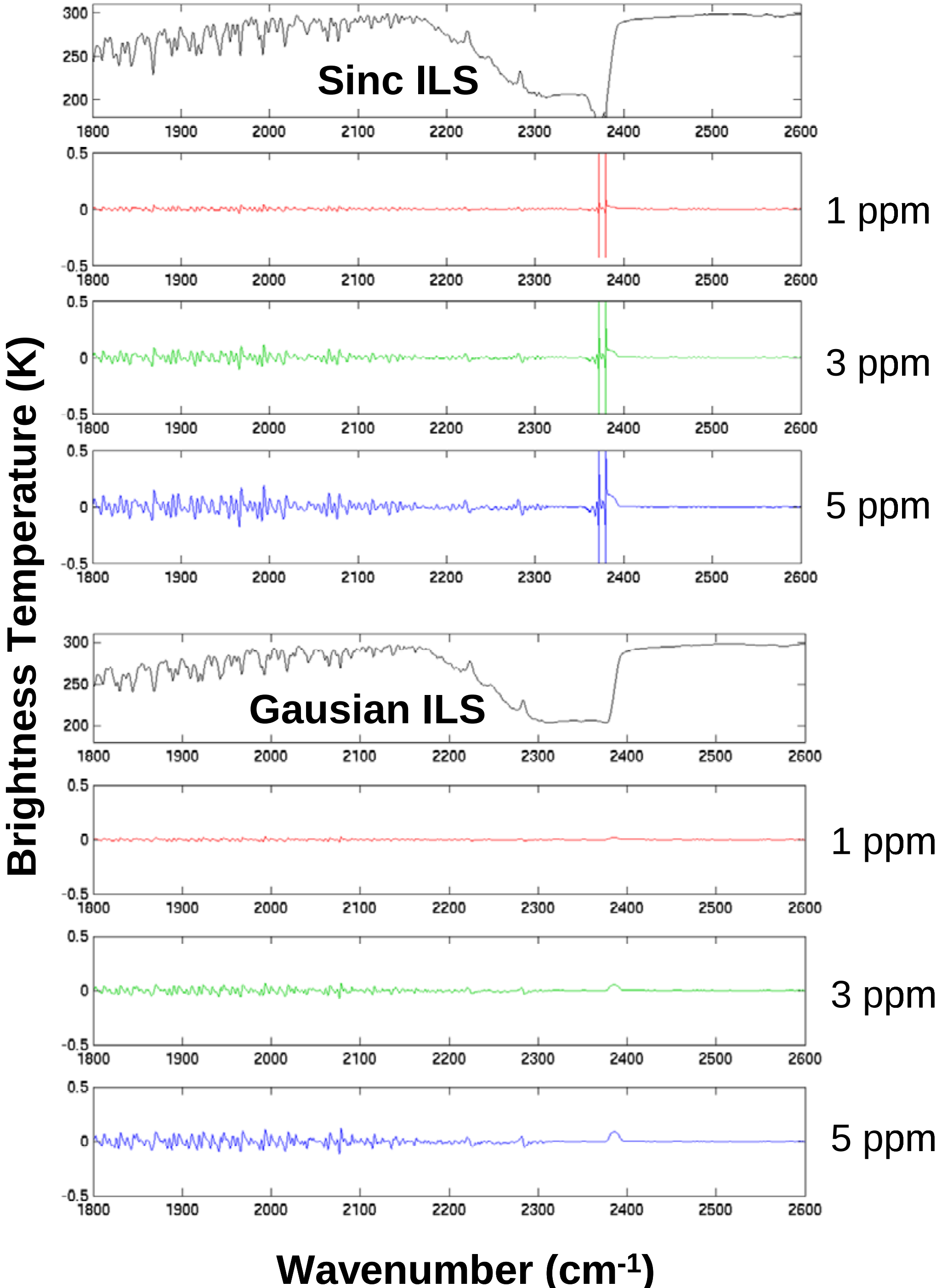
Short-wave, $\Delta\nu=2.5\ \text{cm}^{-1}$

T_b errors for labeled spectral shift error in ppm

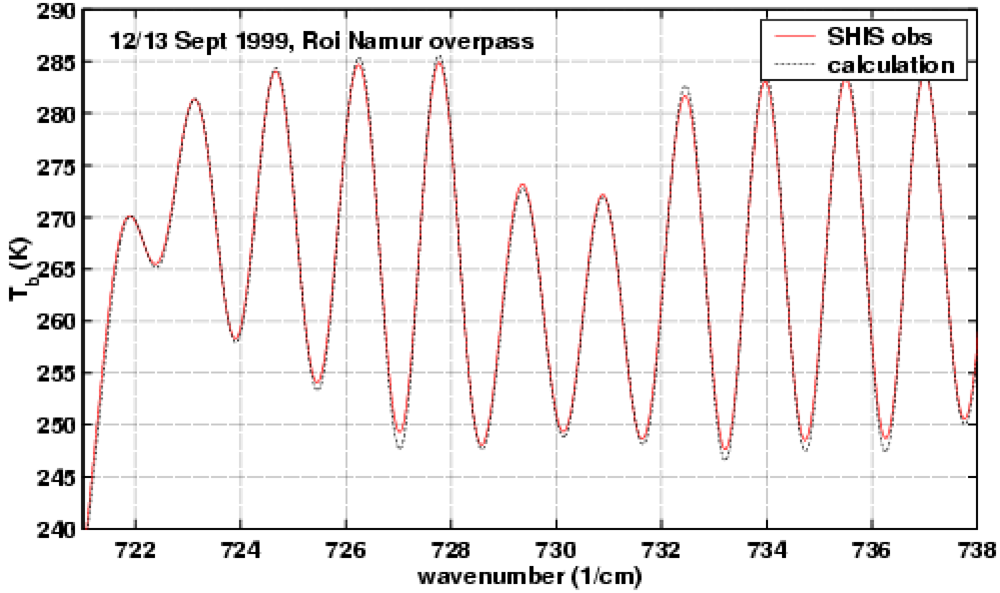
Note that 5 ppm is equivalent to 0.45 % of $\Delta\nu$ at 2250 cm^{-1}

Also, note that the larger errors for the sinc ILS are consistent with its larger absorption line amplitudes and sounding sensitivity

< 3 ppm is desirable



Atmospheric Spectral Calibration: S-HIS example

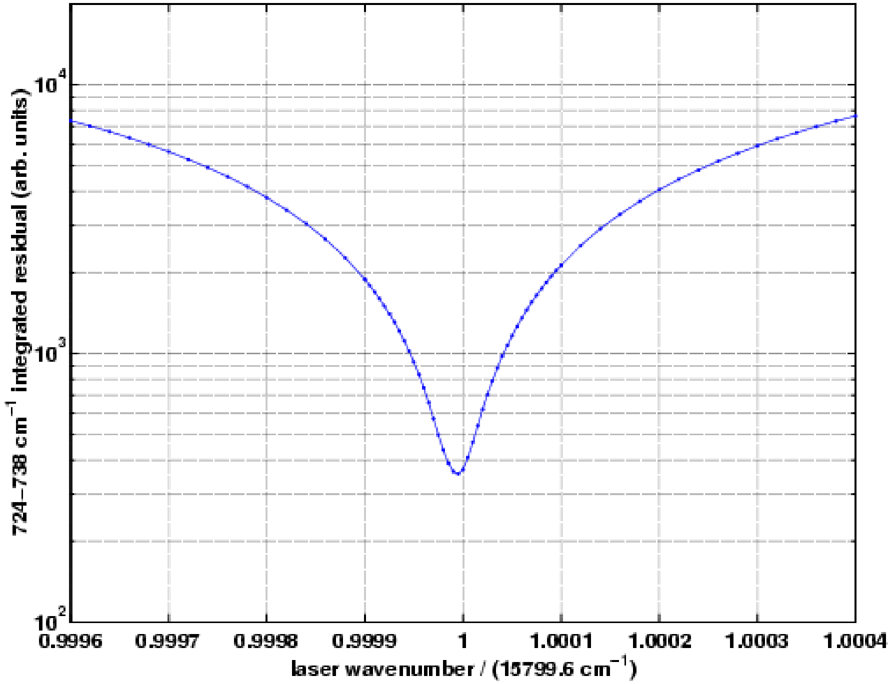


Atmospheric CO_2 lines

wavenumber Scale chosen
to minimize difference

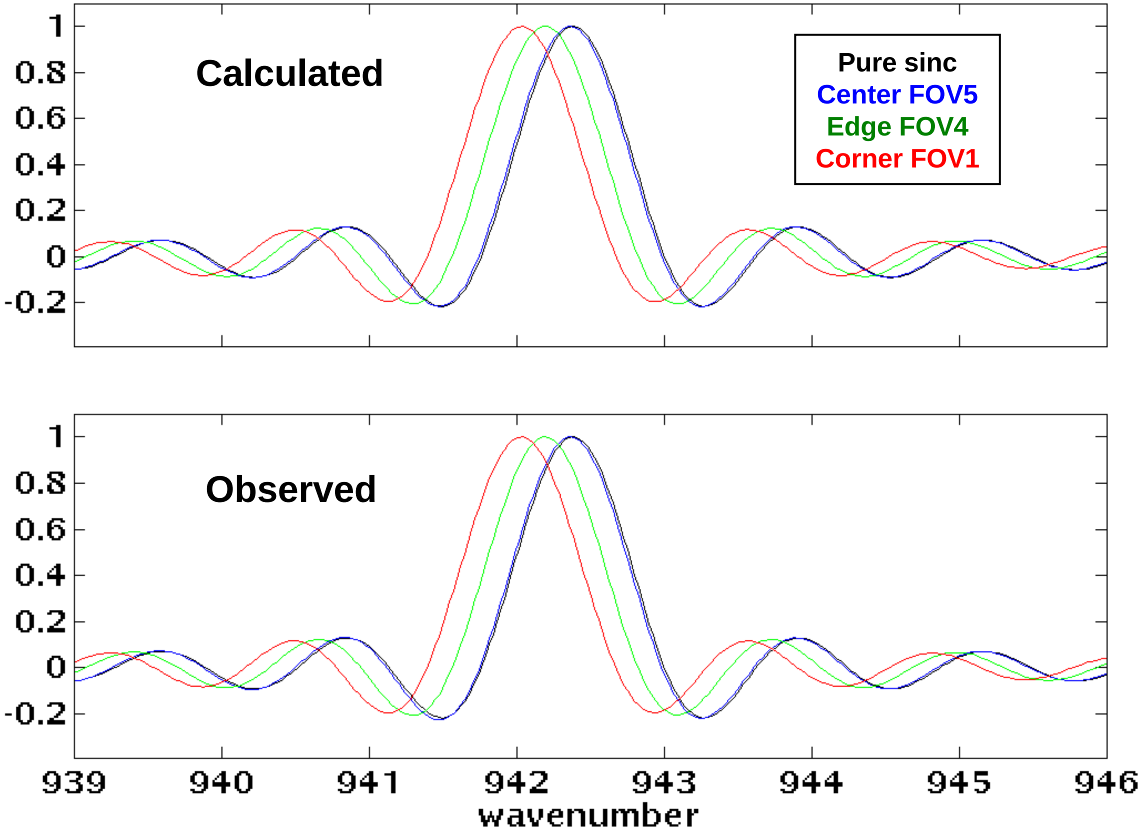
Estimated accuracy =1.2 ppm
(1 sigma)

With many samples,
the 3-sigma accuracy is < 1 ppm



CrIS ILS: Measured compared to Calculated

CrIS Observed and Calculated Instrument Line Shape (ILS) using a 10 micron CO2 laser

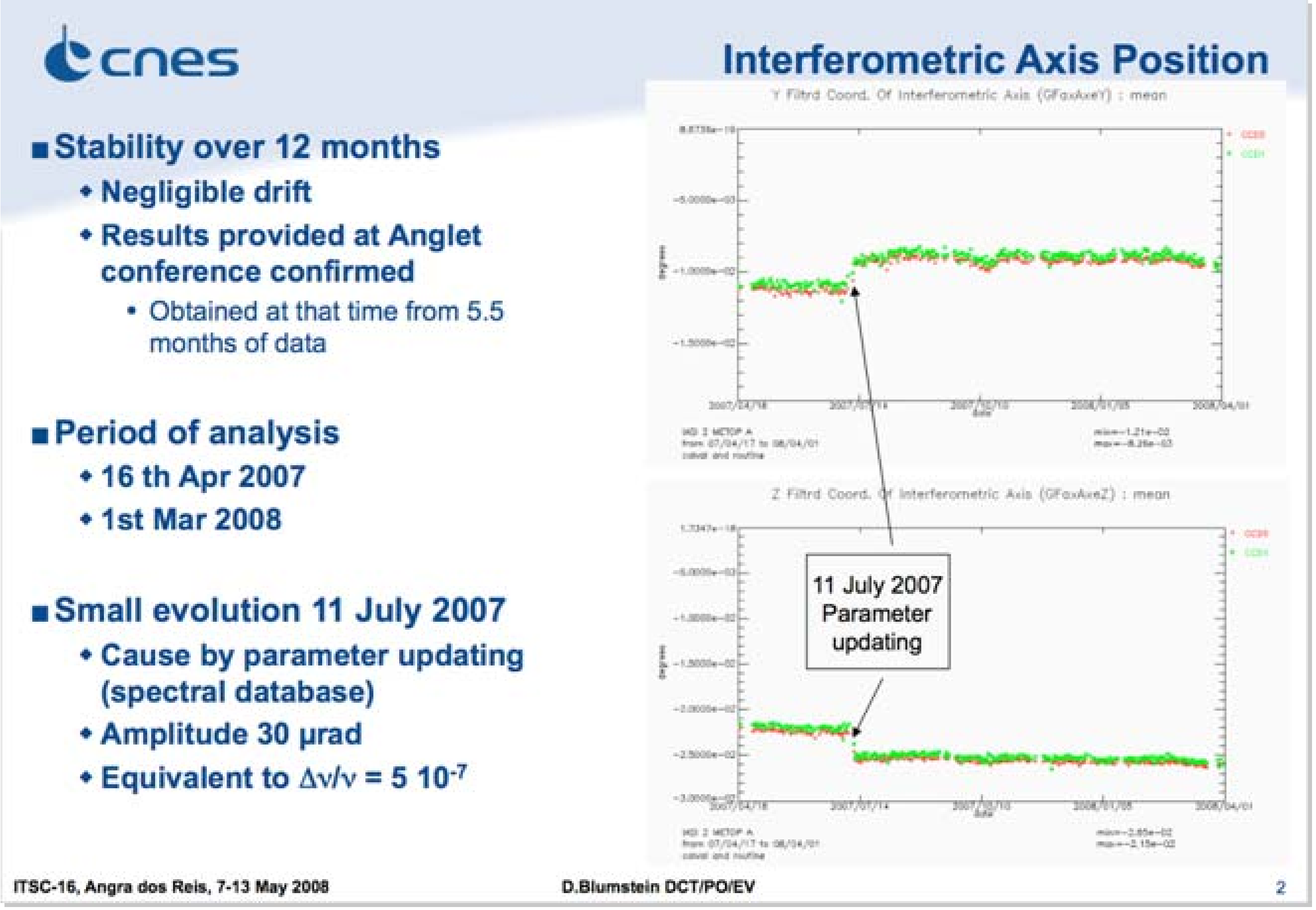


		Center FOV	Edge FOV	Corner FOV
centroid (cm^{-1})	Obs	942.367	942.195	942.034
	Calc	942.366	942.195	942.034
FWHM (cm^{-1})	Obs	0.747	0.757	0.767
	Calc	0.751	0.759	0.767
Lfoot	Obs	0.358	0.329	0.313
	Calc	0.347	0.328	0.313
Rfoot	Obs	0.347	0.326	0.311
	Calc	0.345	0.329	0.313

FTS design expectations, including sub ppm stability, confirmed by test results

IASI Spectral Performance is excellent

- IASI utilizes a gas cell stabilized laser and analysis of line positions in Earth view spectra for spectral calibration
- On-orbit, uncorrected variations are < 0.5 ppm (!)
- Atmospheric Calibration is performed continuously with a 5700 sec filter of 8 sec estimates
- Resulting variations are order 0.1 ppm or less (!)



cnes

Interferometric Axis Position

- Stability over 12 months
  - Negligible drift
  - Results provided at Anglet conference confirmed
    - Obtained at that time from 5.5 months of data
- Period of analysis
  - 16 th Apr 2007
  - 1st Mar 2008
- Small evolution 11 July 2007
  - Cause by parameter updating (spectral database)
  - Amplitude 30 µrad
  - Equivalent to $\Delta\nu/\nu = 5\ 10^{-7}$

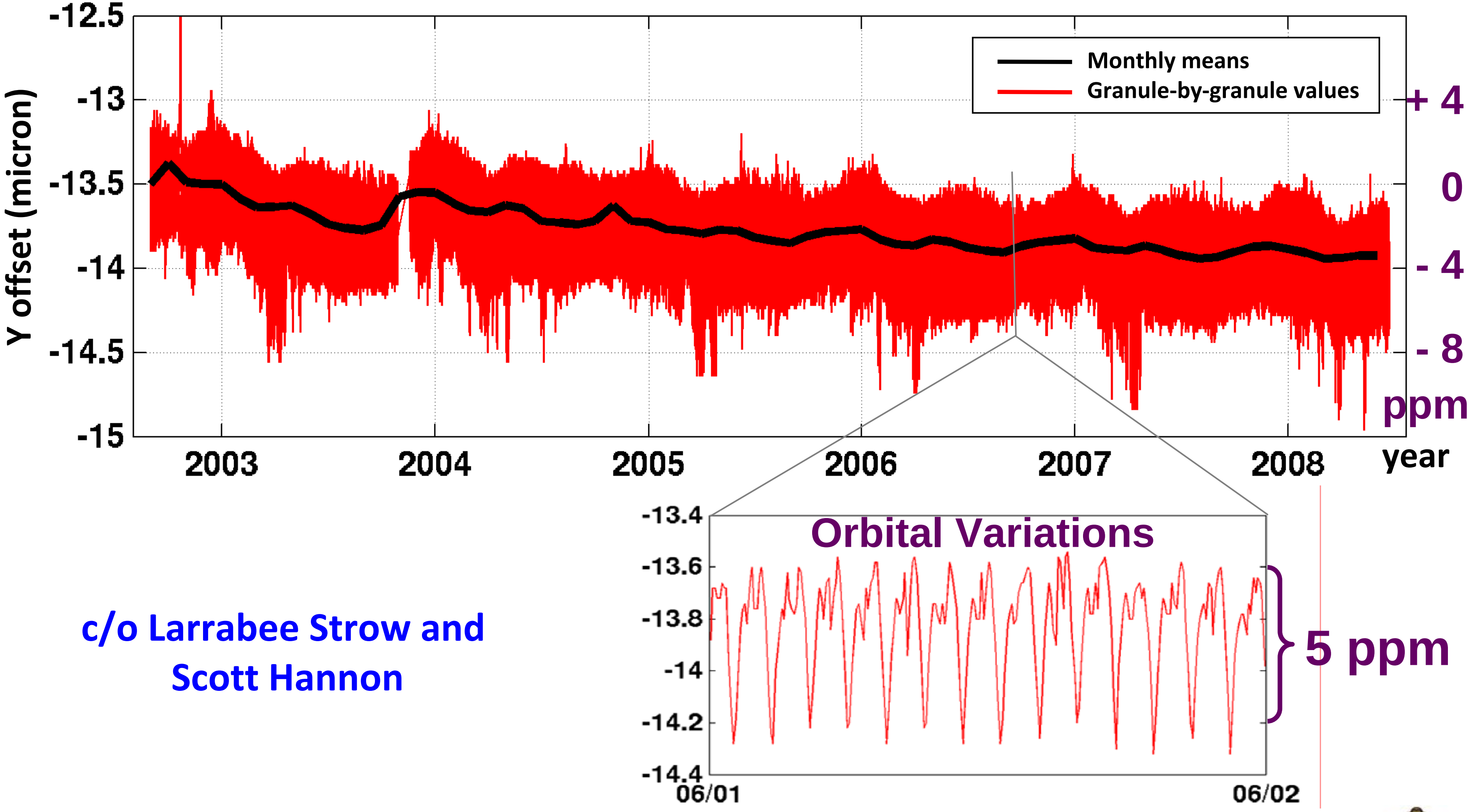
11 July 2007
Parameter
updating

ITSC-16, Angra dos Reis, 7-13 May 2008 D.Blumstein DCT/PO/EV 2

c/o Denis Blumstein

AIRS Spectral Shifts

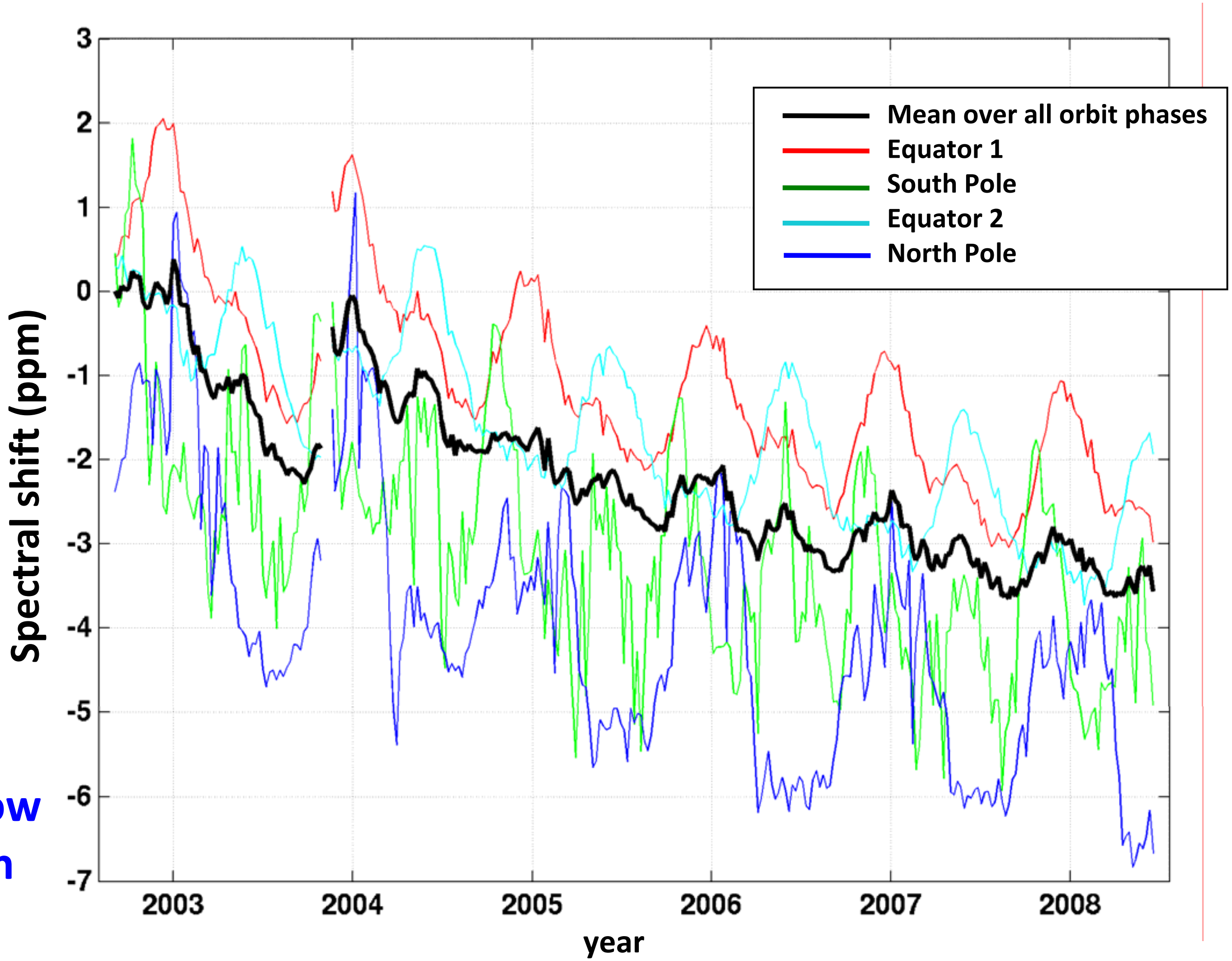
from high peaking channels of Earth view spectra



c/o Larrabee Strow and Scott Hannon

AIRS Spectral Shifts

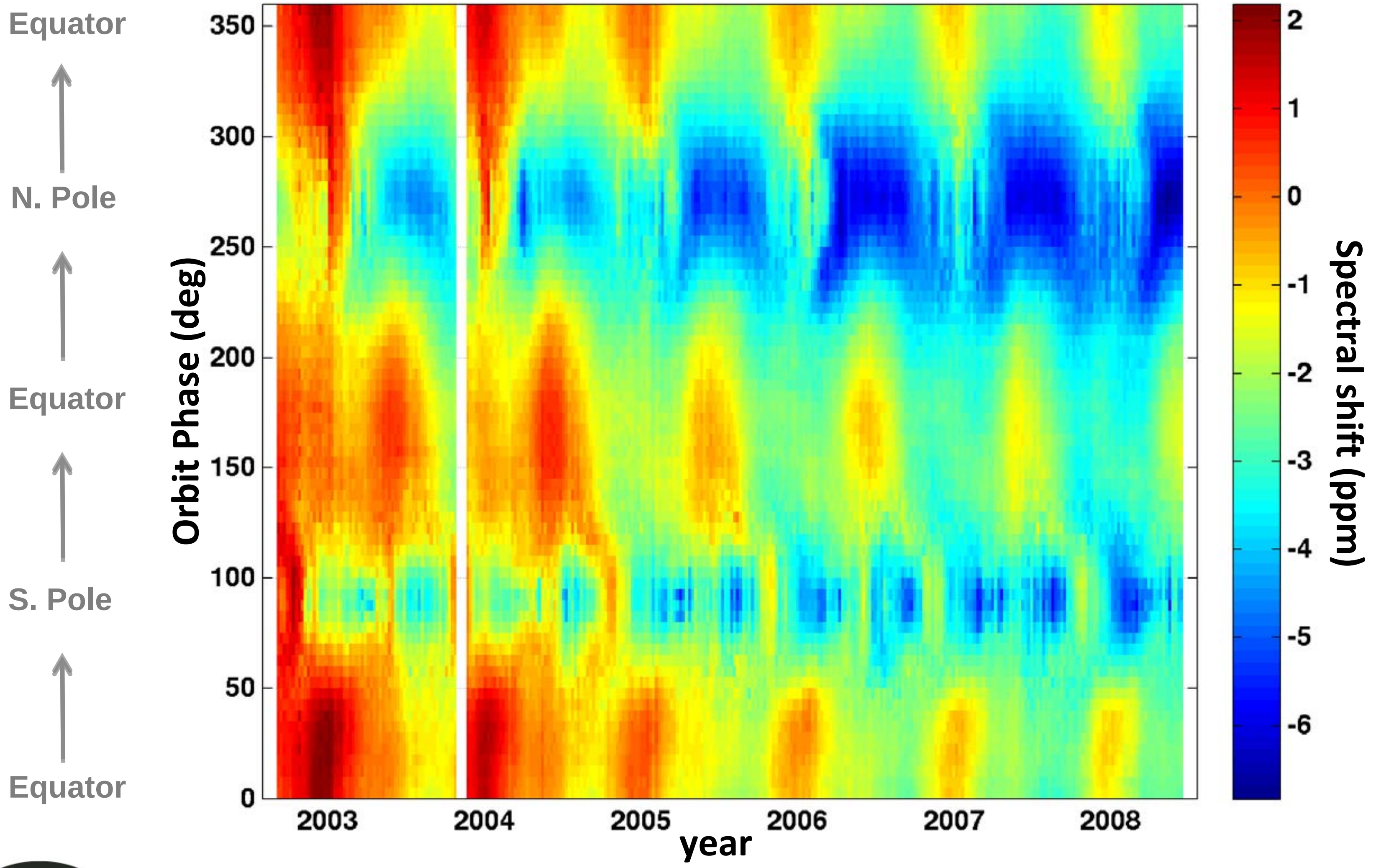
from high peaking channels of Earth view spectra



c/o Larrabee Strow and Scott Hannon

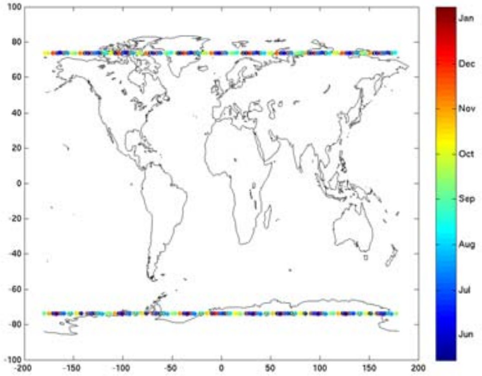
AIRS Spectral Shifts

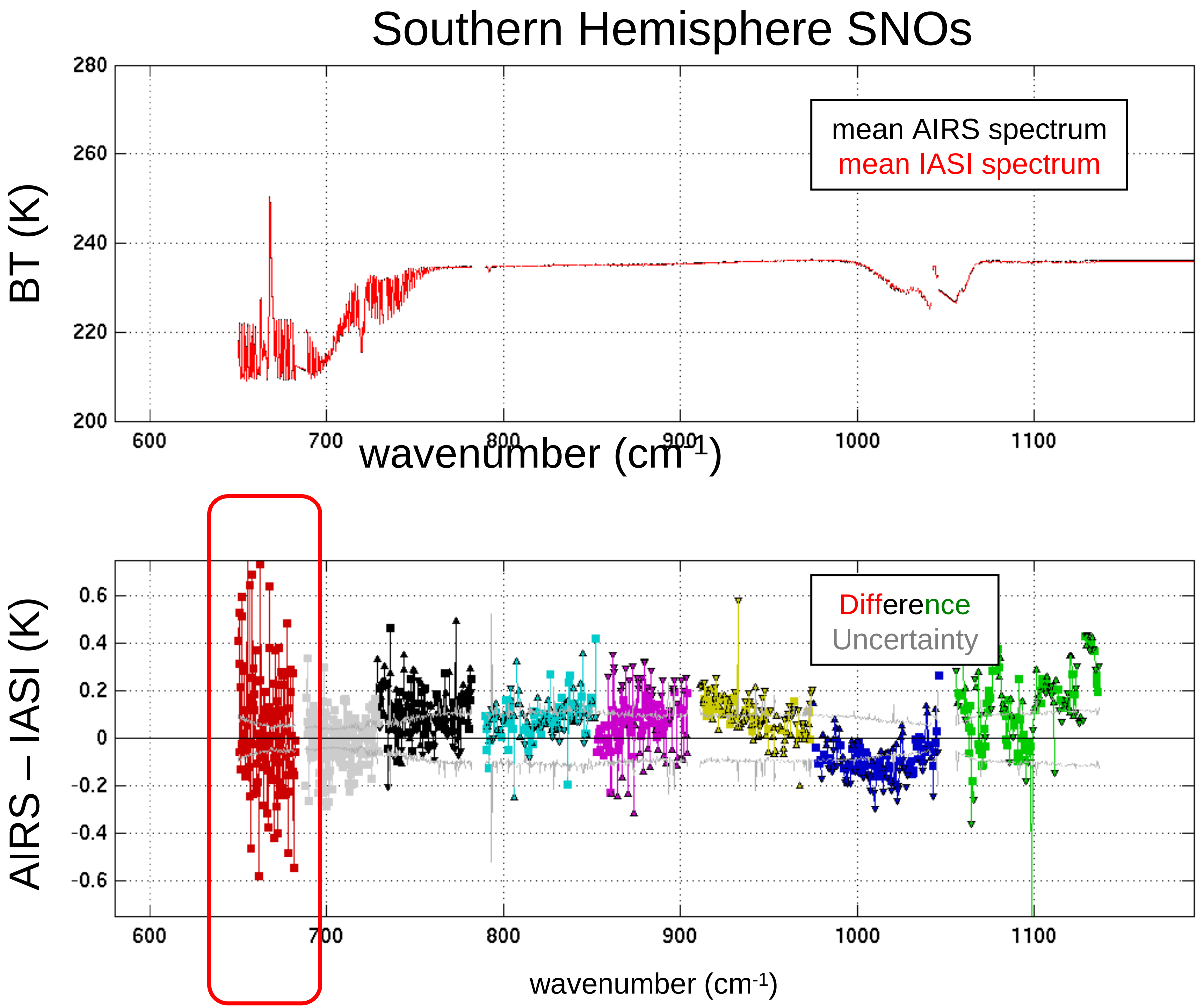
from high peaking channels of Earth view spectra



c/o Larrabee Strow and Scott Hannon

AIRS/IASI Simultaneous Nadir Overpass Comparisons show differences consistent with spectral shift analysis




Southern Hemisphere SNOs

AIRS Spectral Shifts
from high peaking channels of Earth view spectra

- Variations are accurately tracked using high peaking channels of Earth view spectra (1 estimate per granule)

- Spectral shifts for entire FPA derived from existing L1B data display trends on several time scales:
  - **3.5 ppm long term since launch**,
  - **2.5 ppm peak-to-peak seasonally**, and
  - **6.0 ppm peak-to-peak for each orbit**

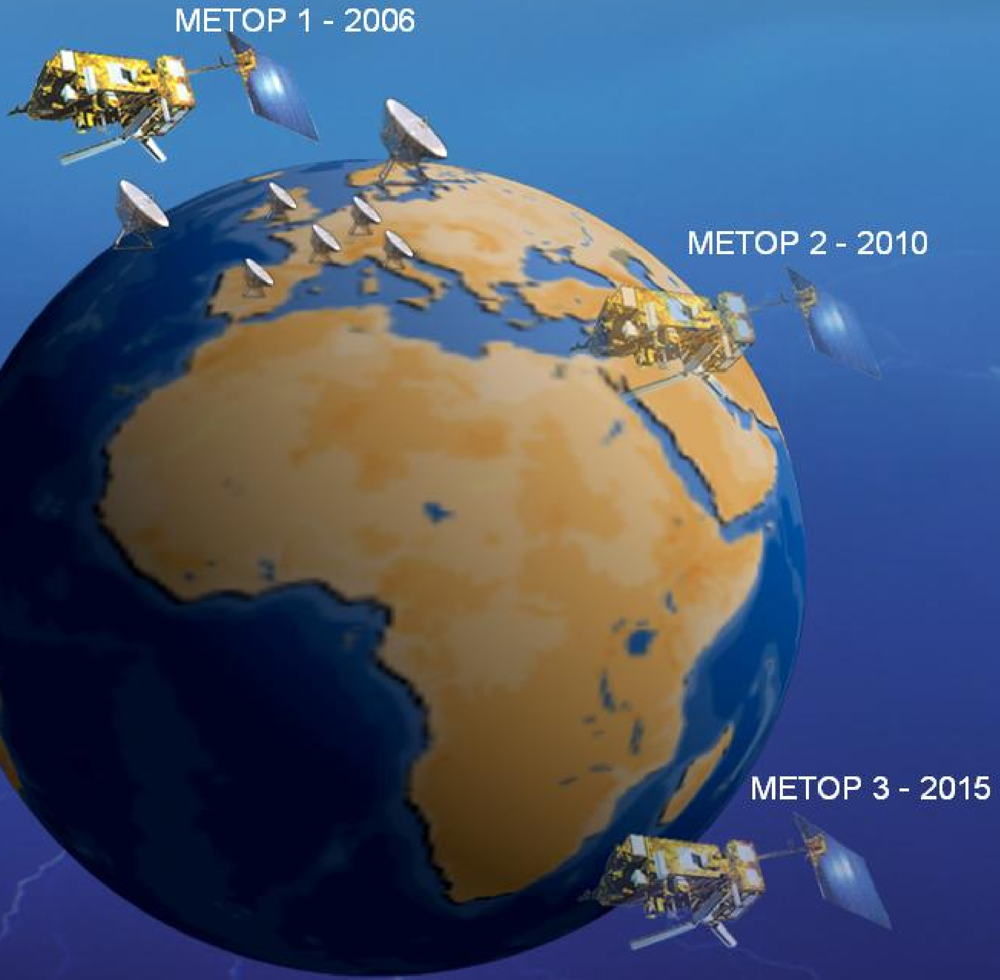
- Refined L1B (or L1C) products incorporating this knowledge are anticipated

2. Radiance Validation from high spectral resolution aircraft observations:

Aircraft sensors can tie on-orbit sensors to International Standard (NIST in US)

METOP

- Eumetsat Polar System Elements
- 14 years of operation
- >95% reliability on 5 years



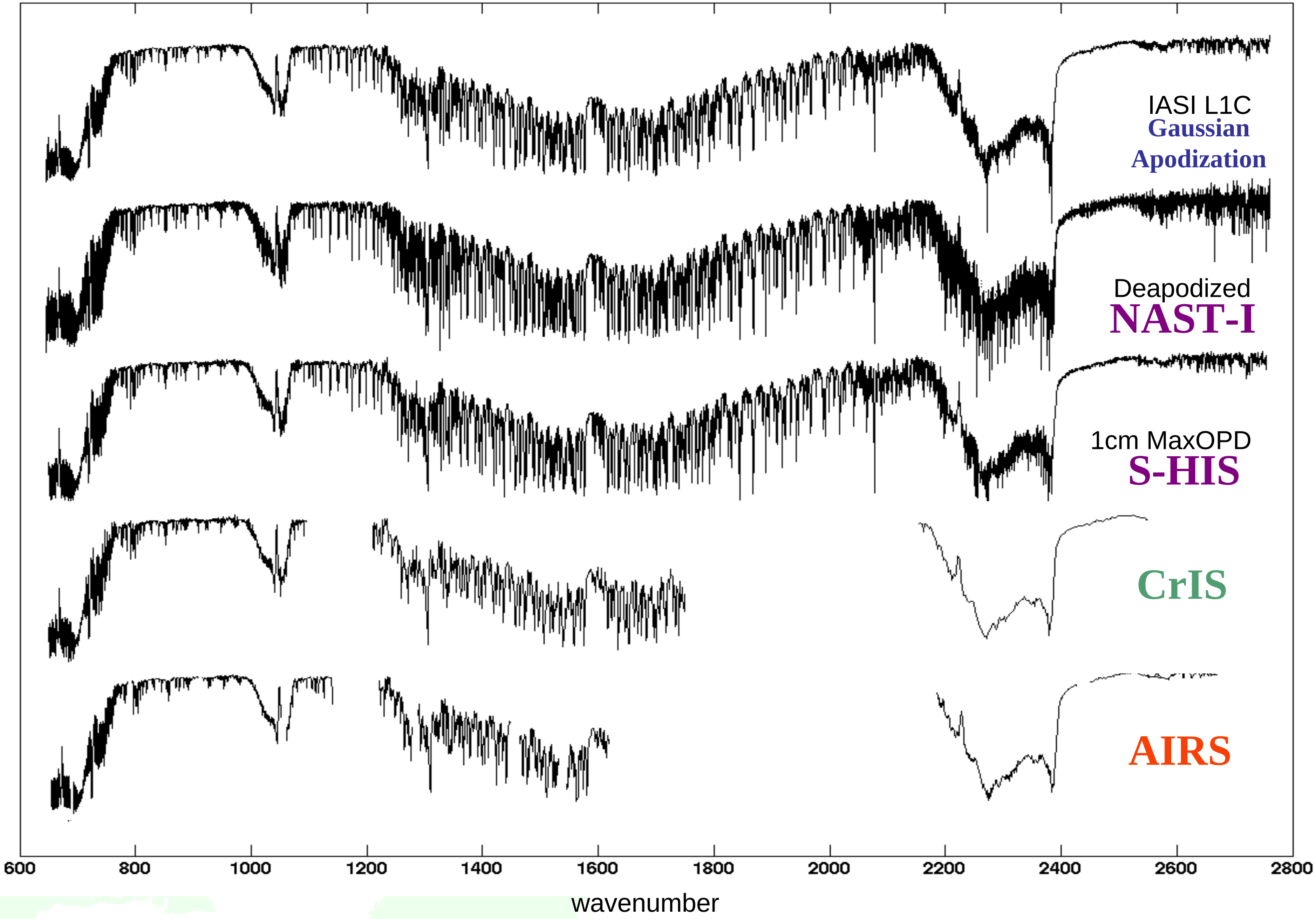
IASI on Metop

19 October 2006 launch

- full cross-track scan
- 2x2 12 km pixels
sample 50x50 km

IASI T_b Spectrum:

Processed to represent S-HIS & NAST-I, AIRS & CrIS

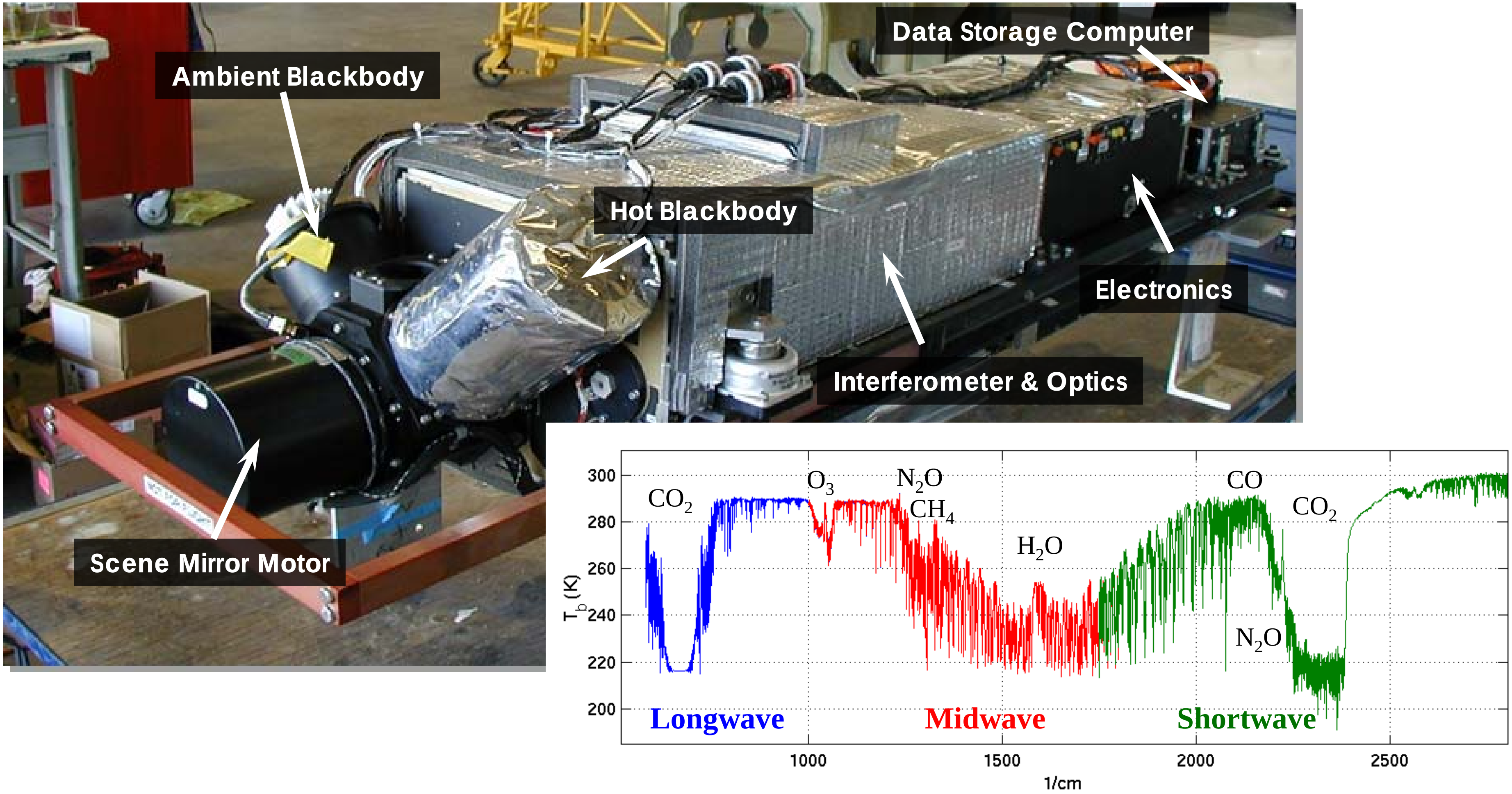


Joint Airborne IASI Validation Experiment (JAIVEx)

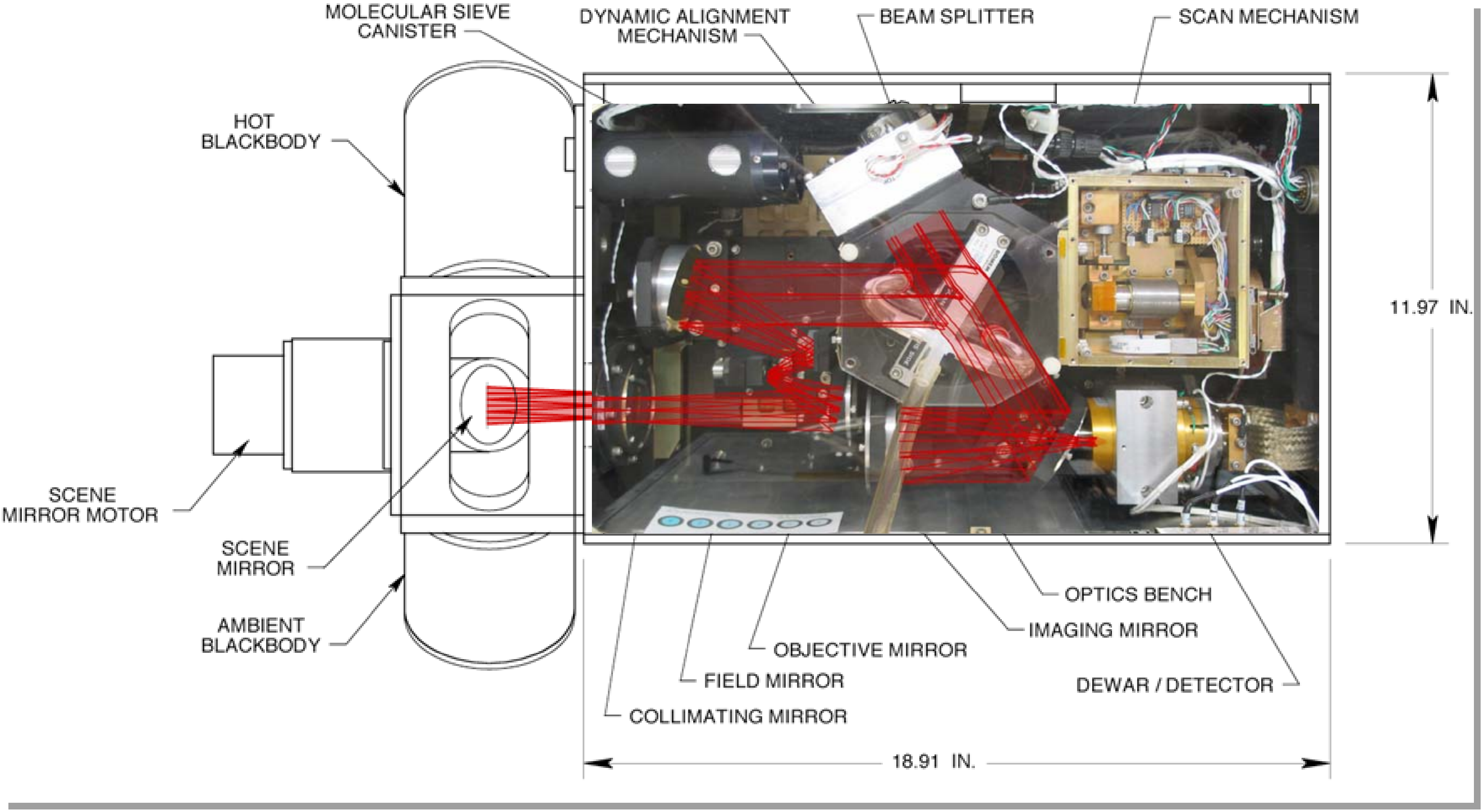
- **What:** Metop and Aqua satellite under-flights for radiance and retrieval validation
- **Who:** NPOESS Airborne Sounder Testbed team (NAST-I/M & S-HIS on NASA WB57) & UK team (ARIES on Facility for Airborne Atmospheric Measurements BAe146-301)
- **When:** 14 April to 4 May 2007
- **Where:** Comparisons over the Gulf of Mexico and Oklahoma ARM site reached from Houston airbase

Scanning HIS Aircraft Instrument:

Inter-comparisons connect high res. sensor calibrations



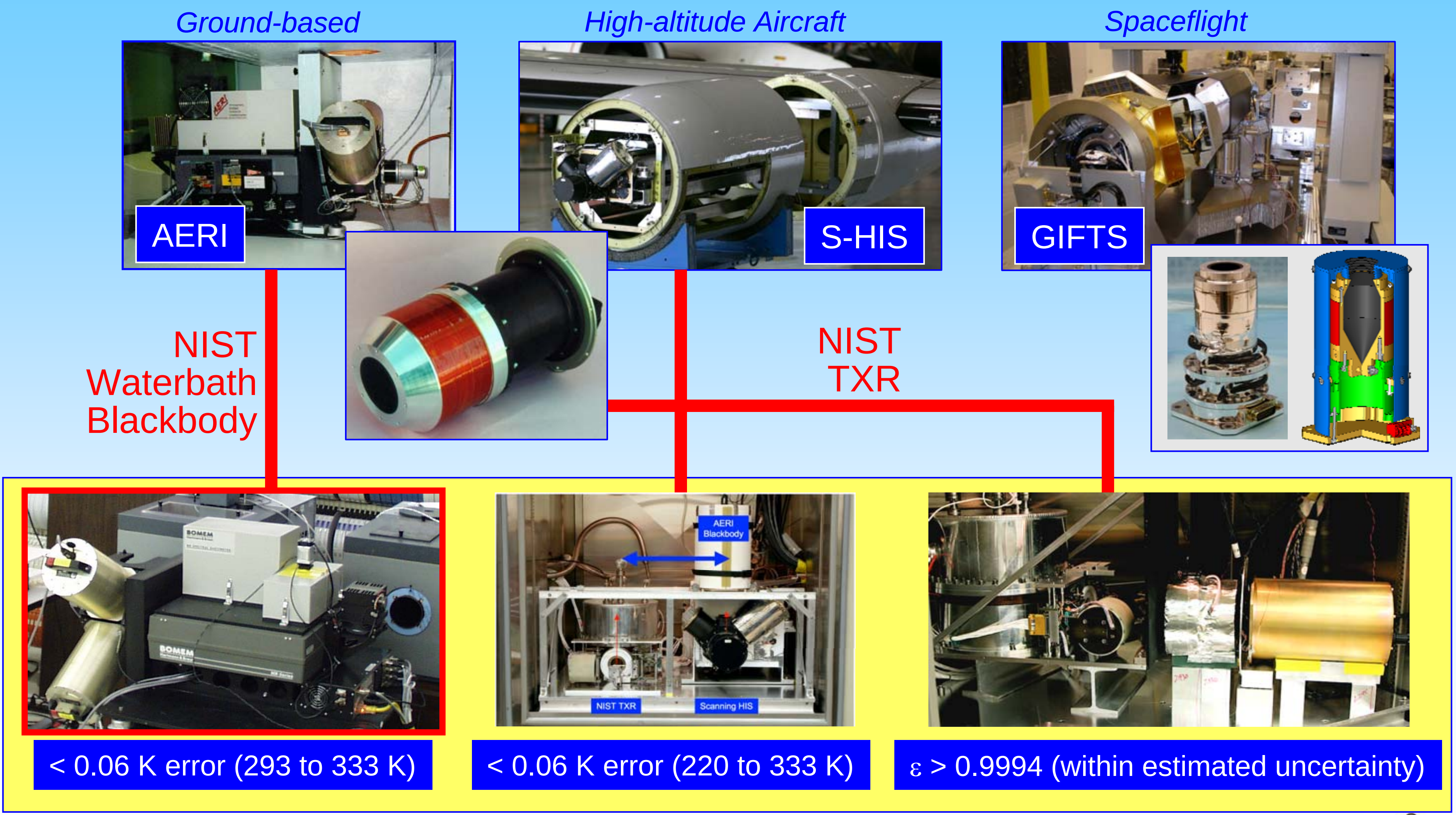
Interferometer Module



S-HIS Aircraft Platforms

[illegible]

SSEC Spectrometer Ties to NIST



< 0.06 K error (293 to 333 K)

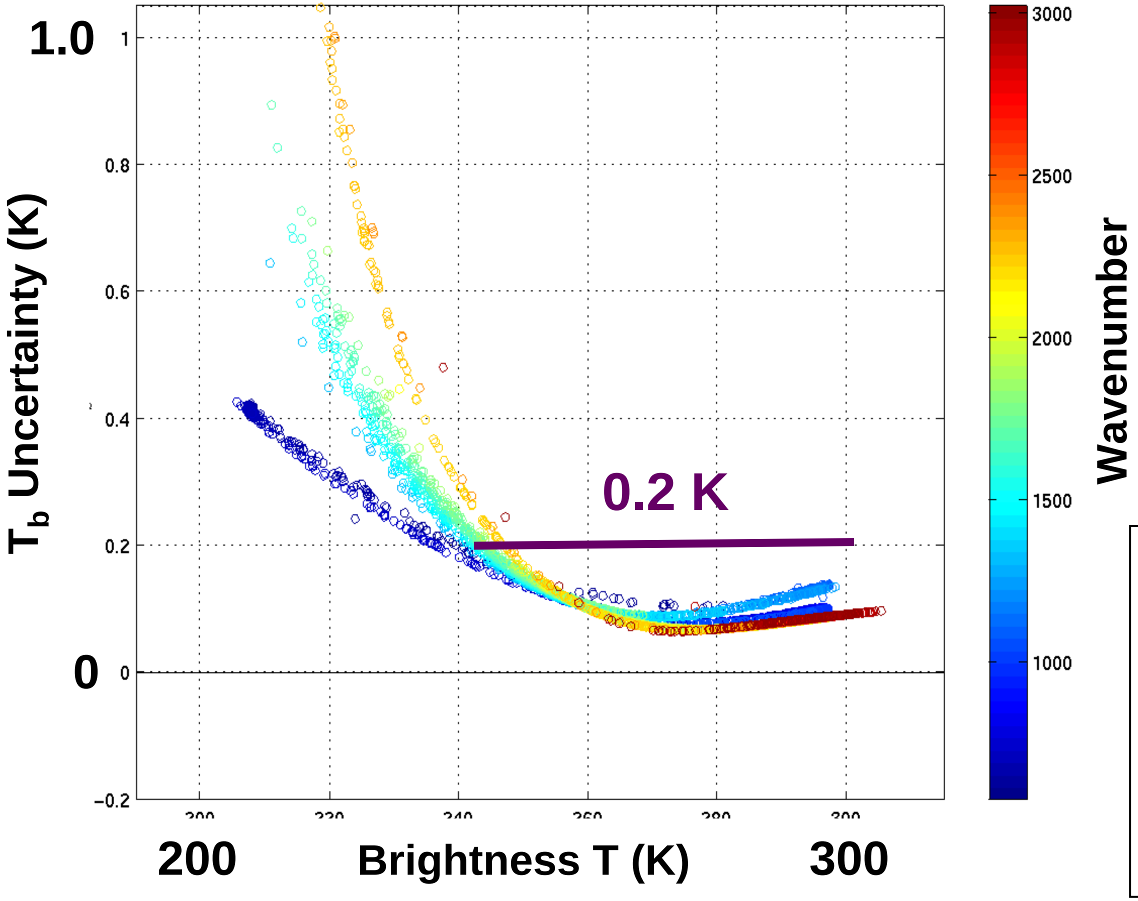
< 0.06 K error (220 to 333 K)

ε > 0.9994 (within estimated uncertainty)

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**

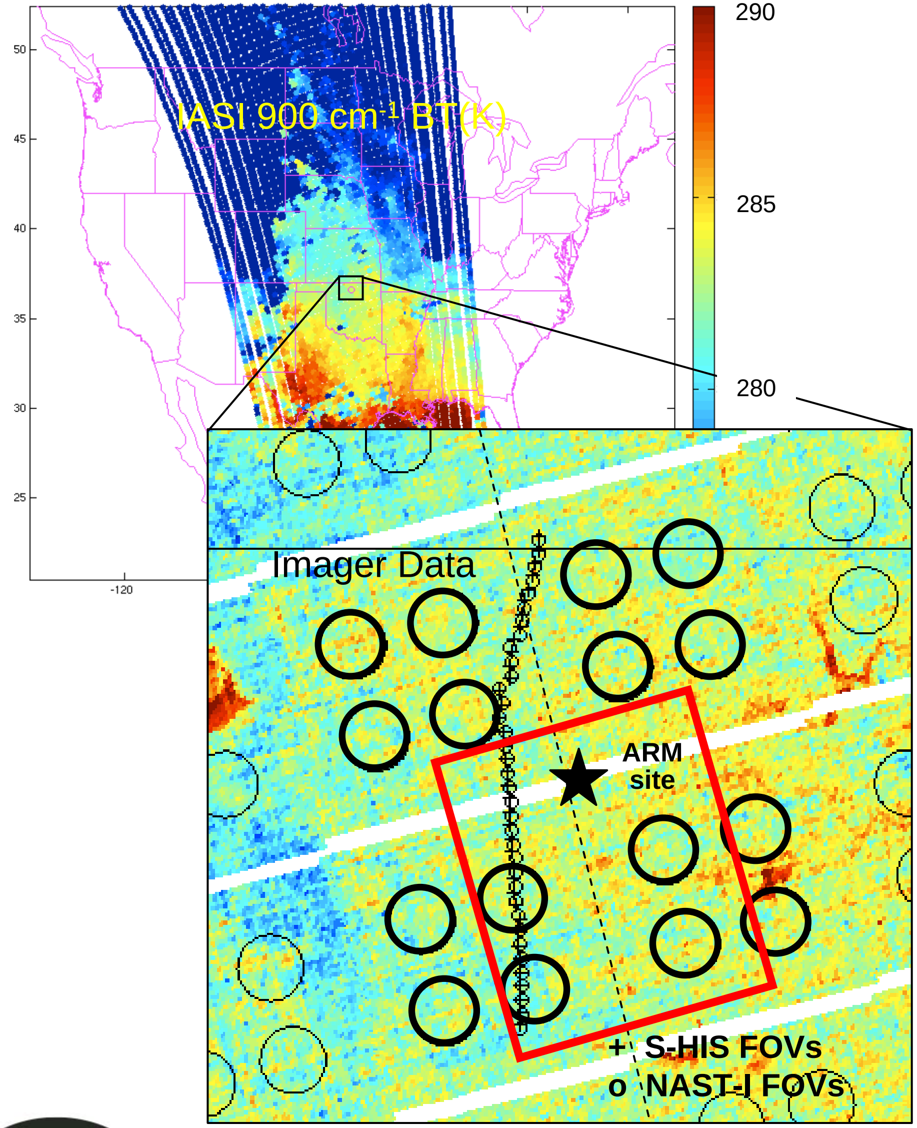


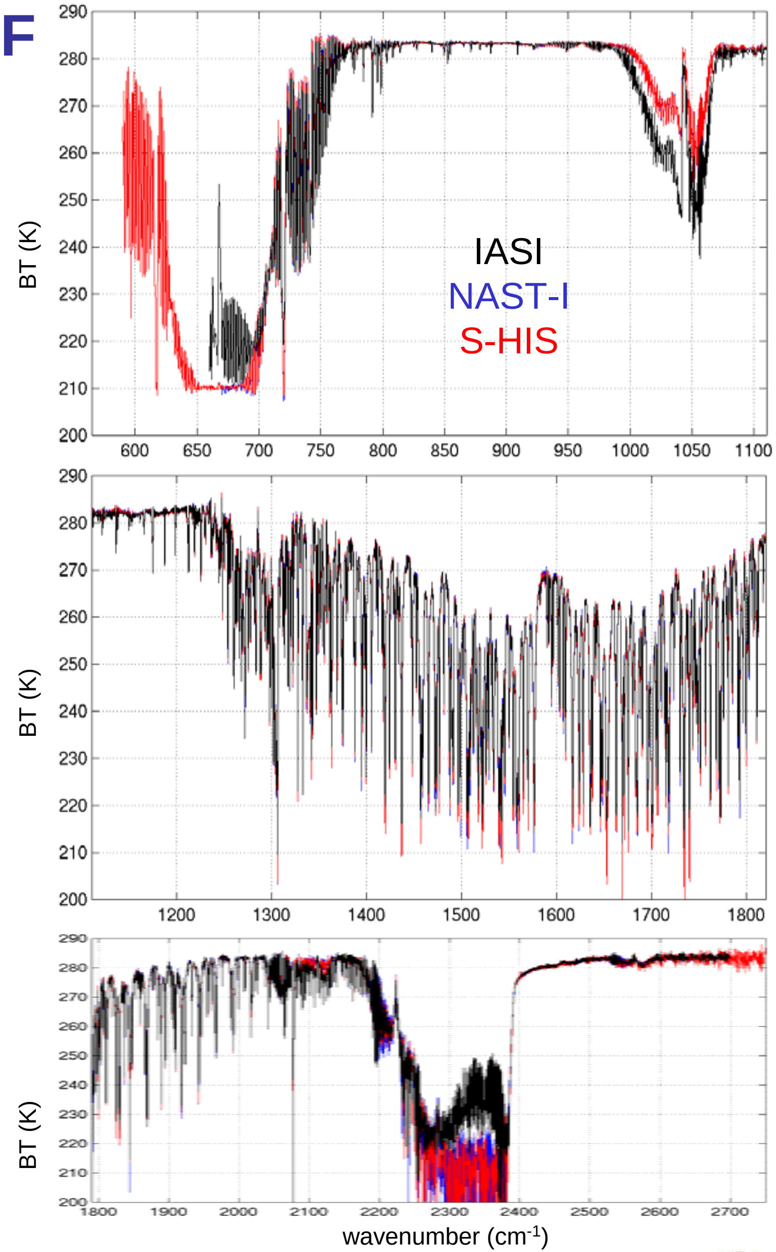
T_{ABB} = 260 K
T_{HBB} = 310 K

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

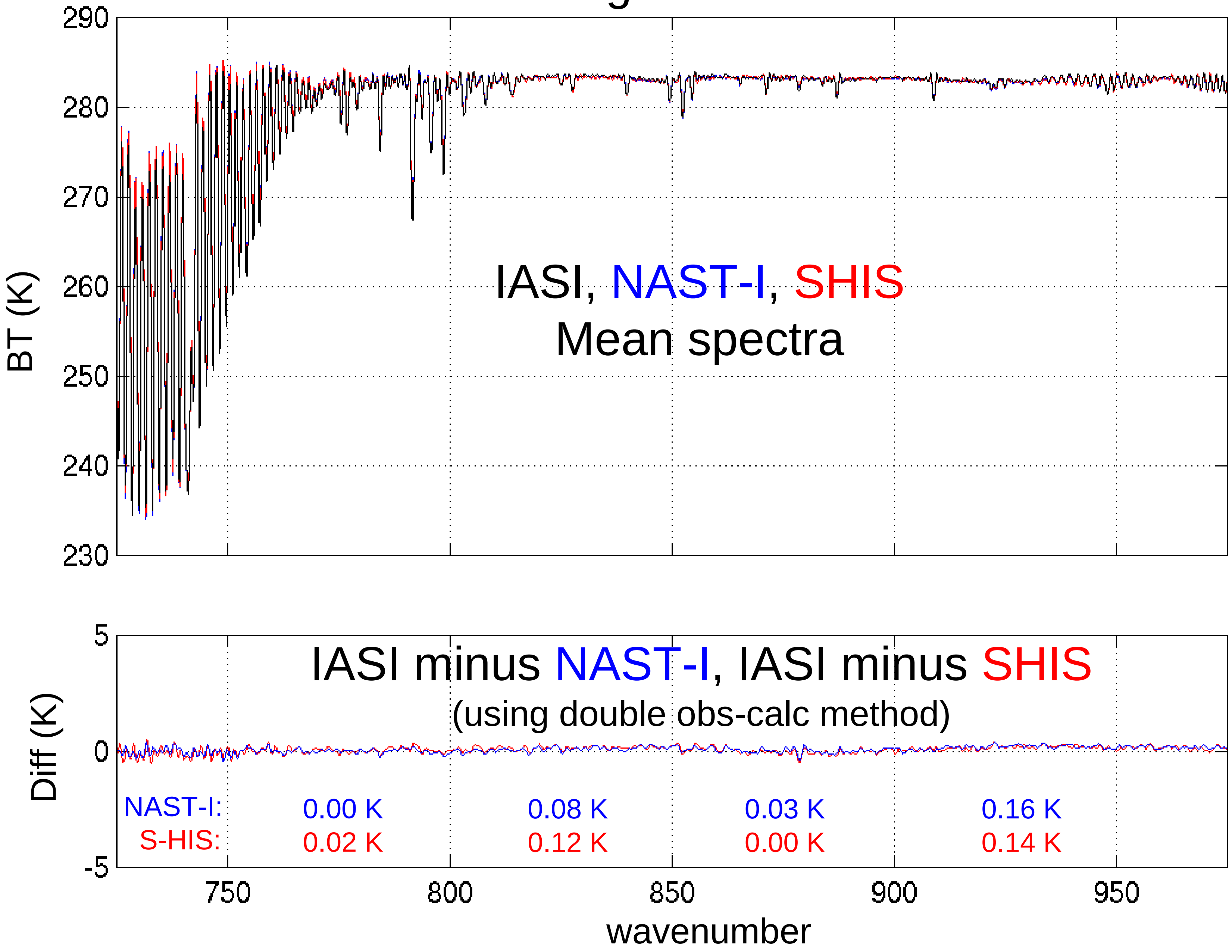
MetOp overpass of Oklahoma ARM CF

19 April 2007

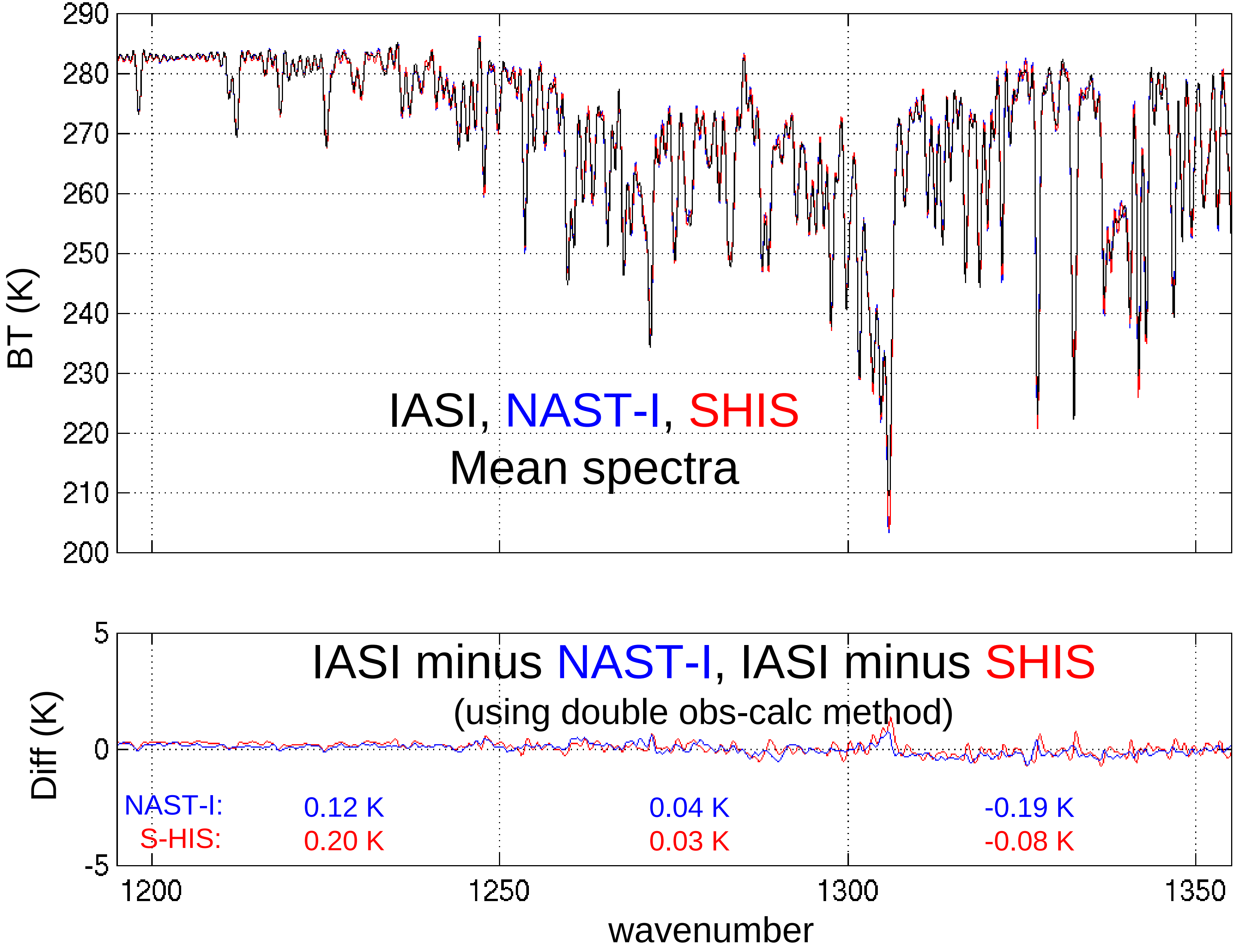




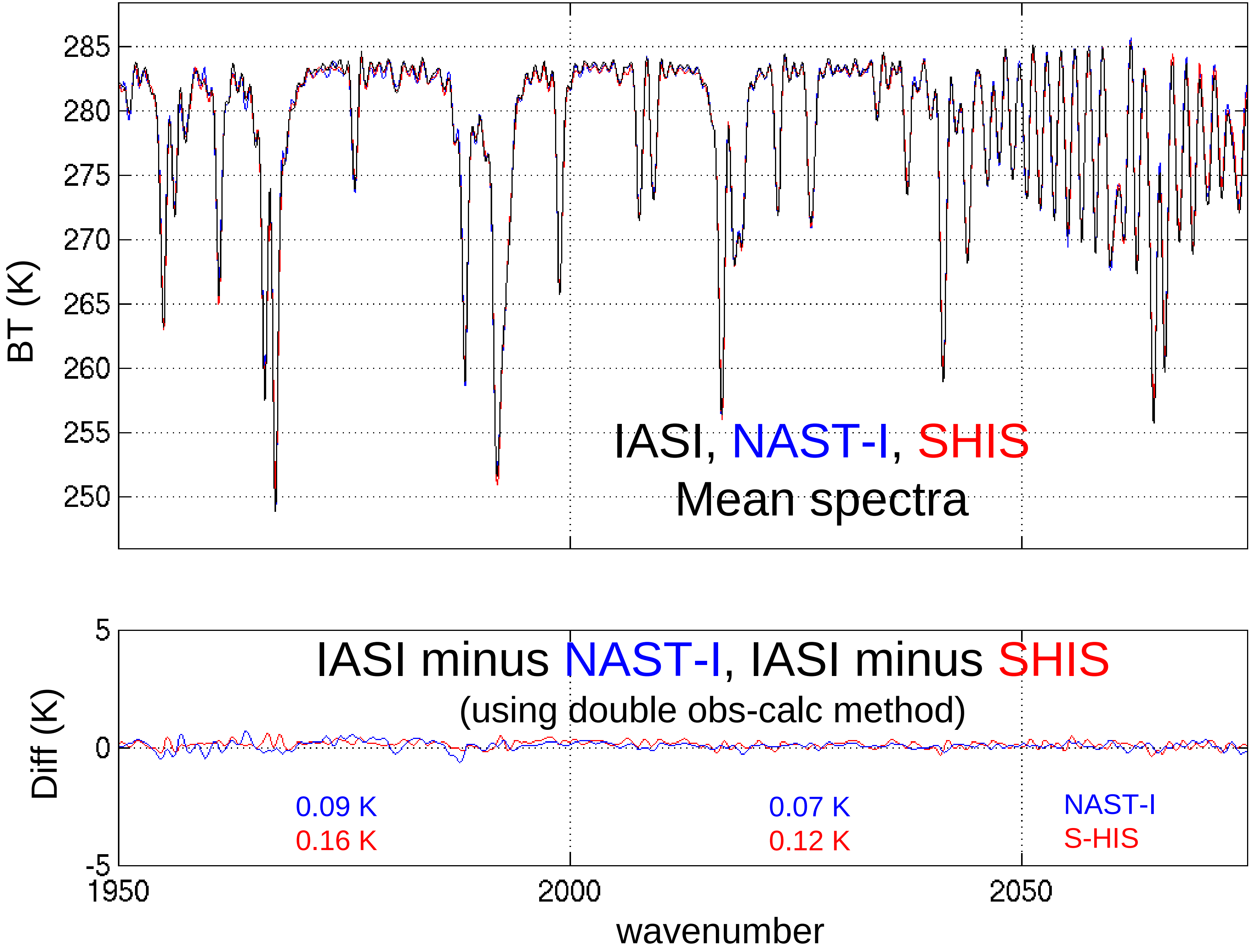
IASI Longwave Validation



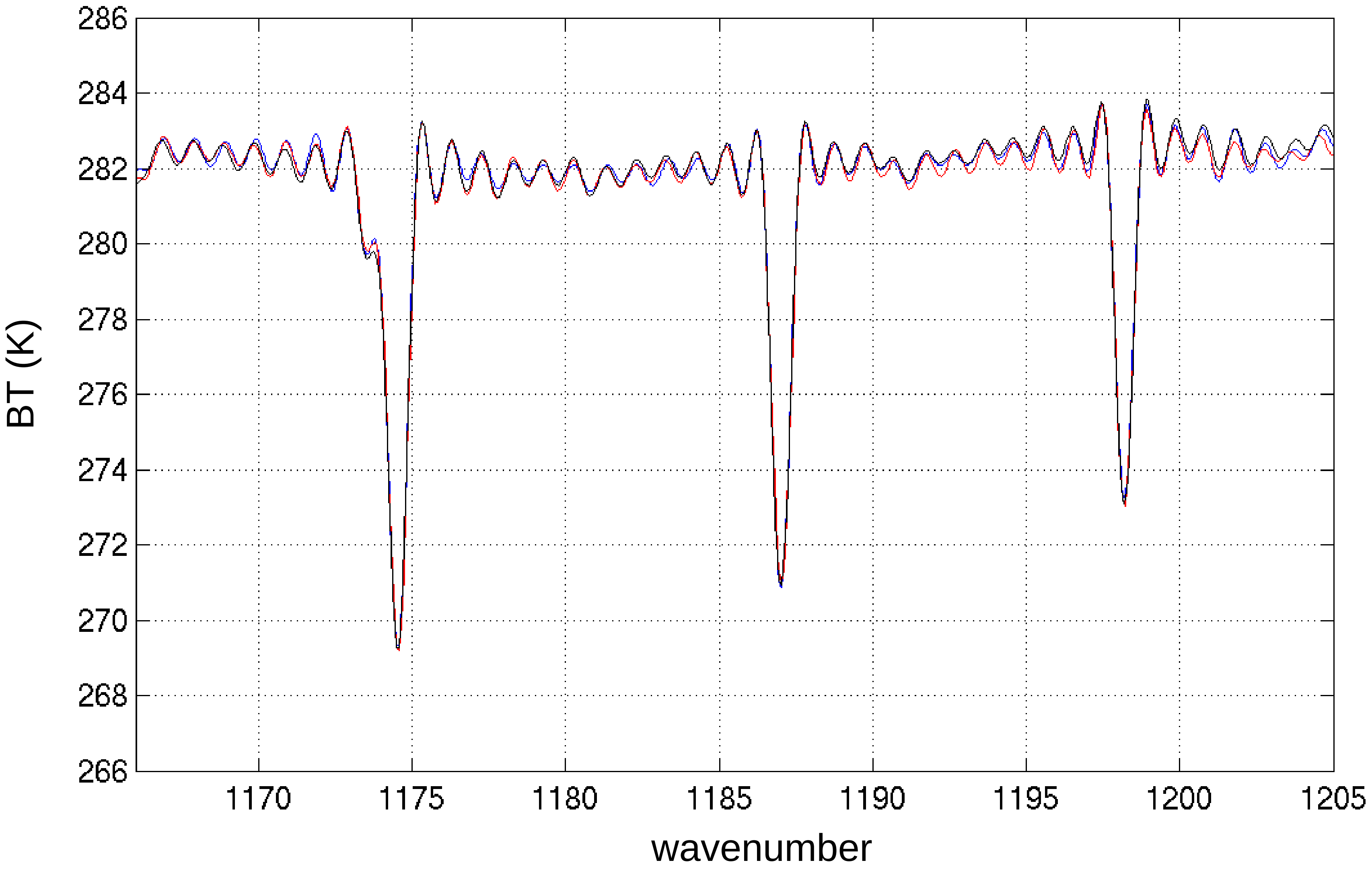
IASI Midwave Validation



IASI Shortwave Validation



IASI, NASTI, and SHIS

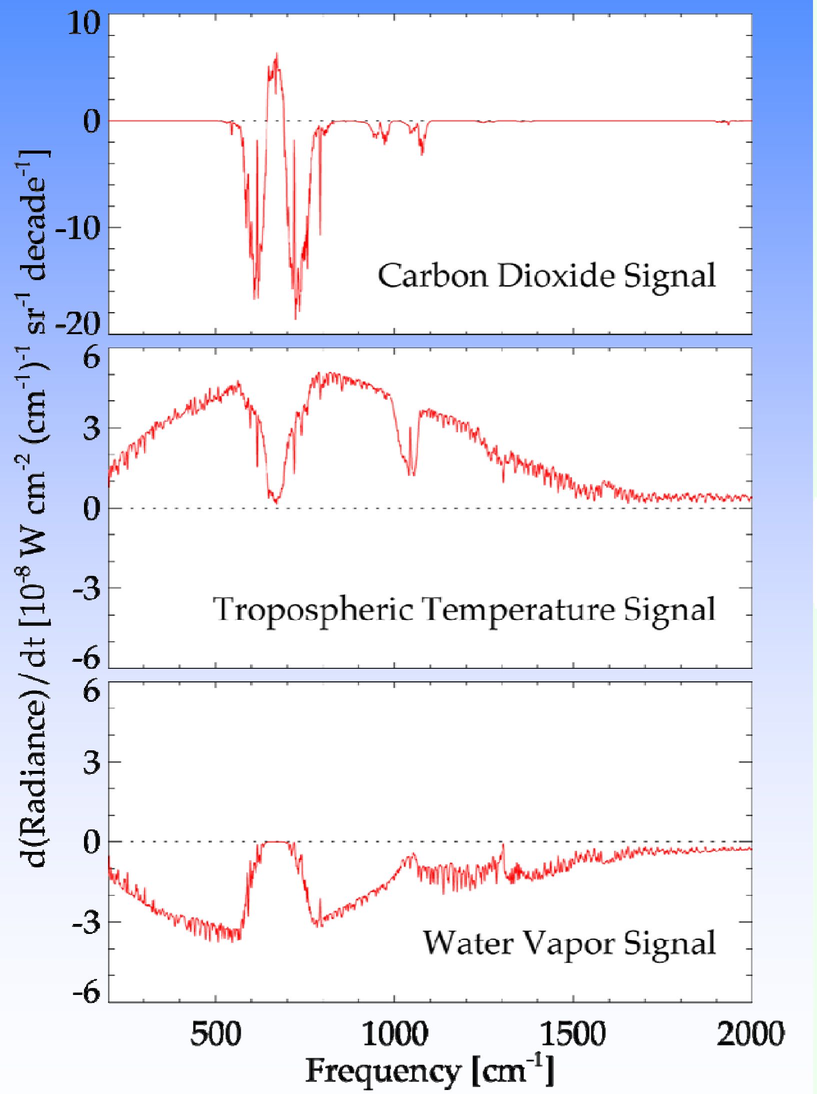


Aircraft Radiance Validation Results Summary

- **Aircraft Validation** (of high resolution spectra): New, highly accurate capability proven 2002-2007
- **AIRS**: Differences from Scanning HIS generally <0.2 K [Tobin et al., JGR, 2006]
- **TES**: Better than 0.5 K agreement in most regions (also characterized small, spectrally correlated noise from variable sample-position-errors) [Shephard et al., JGR, submitted April 2007]
- **IASI**: These preliminary results are comparable to AIRS validation results with higher spectral resolution & contiguous spectral coverage

Perspective for Essential Climate Benchmarking from Space

- Modern spaceborne, aircraft and ground-based spectrometers demonstrate great strides in calibration accuracy for weather & climate sensors
- The technical heritage provides a strong foundation for a new climate mission aimed at establishing a climate benchmark record
- **But, for climate benchmarking, currently planned measurements need augmentation to**
  (1) remove the far IR blind spot,
  (2) provide higher accuracy, proven in orbit; &
  (3) couple these advances with unbiased spatial and temporal sampling



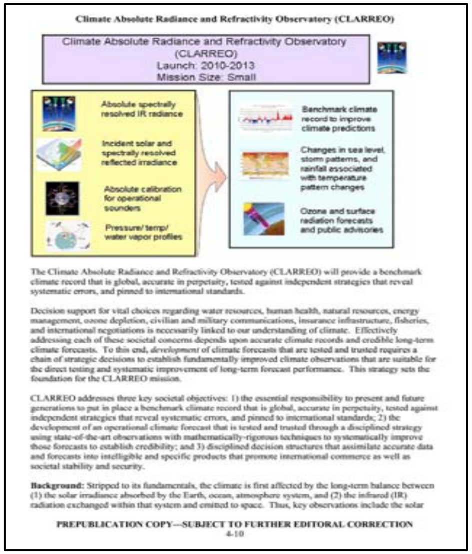
3. The CLARREO Mission

IR spectral signature identifies change and conveys information about what has changed

Climate Absolute Radiance and Refractivity Observatory (CLARREO):

features Spectrally Resolved Radiance and GPS measurements

NASA is pursuing CLARREO as a promising new start, based on the NRC "Decadal Survey" Report—Also strongly recommended by ASIC3, edited by George Ohring



Climate Absolute Radiance and Refractivity Observatory (CLARREO)

Climate Absolute Radiance and Refractivity Observatory
(CLARREO)
Launch: 2010-2013
Mission Size: Small

Absolute spectrally resolved IR radiance

Incident solar and spectrally resolved reflected irradiance

Absolute calibration for operational sounders

Pressure/ temp/ water vapor profiles

Benchmark climate record to improve climate predictions

Changes in sea level, storm patterns, and rainfall associated with temperature pattern changes

Ozone and surface radiation forecasts and public advisories

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) will provide a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards.

Decision support for vital choices regarding water resources, human health, natural resources, energy management, ozone depletion, civilian and military communications, insurance infrastructure, fisheries, and international negotiations is necessarily linked to our understanding of climate. Effectively addressing each of these societal concerns depends upon accurate climate records and credible long-term climate forecasts. To this end, *development* of climate forecasts that are tested and trusted requires a chain of strategic decisions to establish fundamentally improved climate observations that are suitable for the direct testing and systematic improvement of long-term forecast performance. This strategy sets the foundation for the CLARREO mission.

CLARREO addresses three key societal objectives: 1) the essential responsibility to present and future generations to put in place a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards; 2) the development of an operational climate forecast that is tested and trusted through a disciplined strategy using state-of-the-art observations with mathematically-rigorous techniques to systematically improve those forecasts to establish credibility; and 3) disciplined decision structures that assimilate accurate data and forecasts into intelligible and specific products that promote international commerce as well as societal stability and security.

Background: Stripped to its fundamentals, the climate is first affected by the long-term balance between (1) the solar irradiance absorbed by the Earth, ocean, atmosphere system, and (2) the infrared (IR) radiation exchanged within that system and emitted to space. Thus, key observations include the solar

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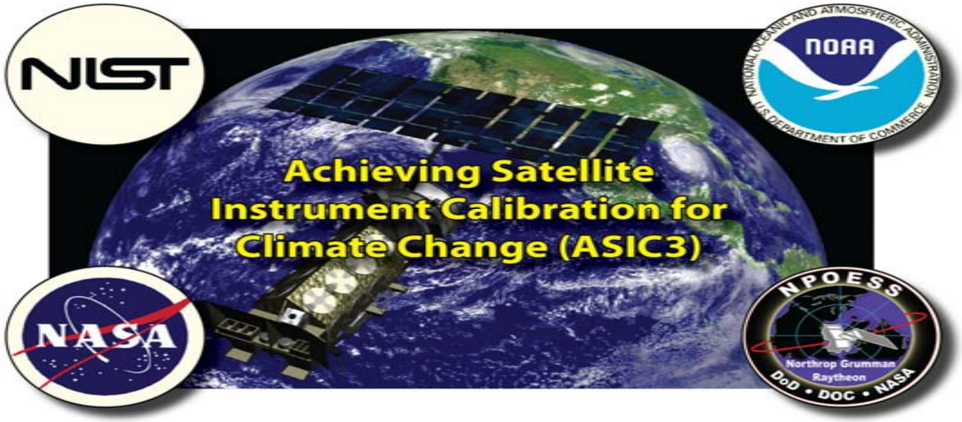
4-10



CLARREO Goal

- **Establish highly accurate global benchmark measurements from satellite that detect and characterize climate change over decadal time scales**
  - – Determine annual regional changes on scales of order 15ºx30º latitude/longitude
  - – Determine seasonal changes (bi-monthly) on larger scales of order 50ºx50º

CLARREO: New Paradigms for Benchmark Climate Measurements

1) **High information content**, rather than just monitoring total radiative energy budget
(i.e. spectrally resolved radiances covering large parts of the spectrum as a product, rather than total IR or Solar fluxes—can separate IR & Solar obs.)

2) **Very high absolute accuracy, with measurement accuracy proven on orbit** (stability not sufficient)
   a) minimizes climate change detection time and
   b) relieves the need for mission overlap
(Must consider Total Accuracy = RSS of Spatial/ Temporal biases and measurement accuracy)

3) **Commitment to ongoing Benchmark Missions** planned with 5-8 year lifetime every 8-10 years
(Data for Model trend evaluation is needed for the foreseeable future, certainly the next century—therefore, affordability is a key ingredient)

CLARREO: Flow-down Corollaries

1) **Primary products are direct observables, not derived fluxes or retrieved properties (par. 1, 2)** [e.g. spectrally resolved, IR, nadir radiances (broadband, including far IR), averaged over regions and time of day to control spatial and temporal biases]

2) **Interferometer instrument type (par. 1-3)**

3) **Minimize complexity (par. 2-3)** (do one thing very well—e.g. no cross-track scanning, design for low biases, noise can be relatively high, keep non-linearity and polarization artifacts small)

Deploy an orbital configuration optimized for global coverage and to minimize sampling bias (par. 2) [e.g. equally spaced, truly polar orbits (90º inclination) giving global coverage and equal time of day sampling every 2 months—explicit diurnal cycle measurement]

CLARREO General IR Science Drivers

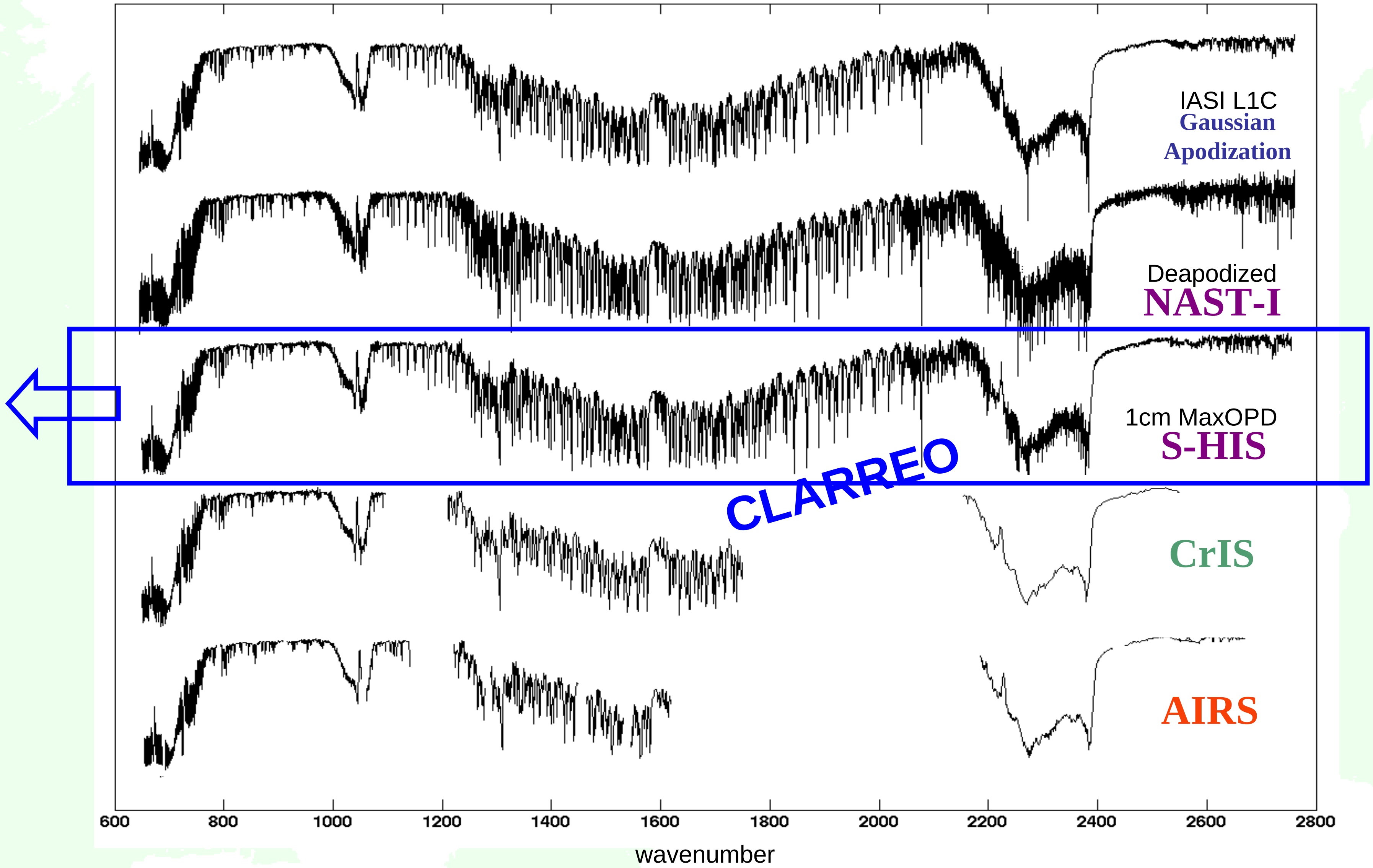
- **Information Content:** Capture the spectral signatures of regional and seasonal climate change that can be associated with physical climate forcing and response mechanisms (to unequivocally detect change and refine climate models)
- **Absolute Accuracy:** <0.1 K 2-sigma brightness T for combined measurement and sampling uncertainty (each <0.1 K 3-sigma) for annual averages of 15ºx30º lat/long regions (to approach goal of resolving a climate change signal in the decadal time frame)
- **Calibration transfer to other spaceborne IR sensors:** Accuracy approaching the measurement accuracy of CLARREO using Simultaneous Nadir Overpasses (to enhance value of sounders for climate process studies-actually drives few requirements)

Flow-Down IR Requirements (1)

- **Spectral Coverage:** 3-50 μm or 200-3000 cm^{-1} (includes Far IR to capture most of the information content and emitted energy)
- **Spectral Resolution:** ~0.5 cm^{-1} (1 cm max OPD) (to capture atmospheric stability, aid in achieving high radiometric accuracy, and allow accurate spectral calibration from atmospheric lines)
- **Spectral Sampling:** Nyquist sampled (to achieve standard spectral scale for multiple instruments)

IASI T_b Spectrum:

Processed to represent S-HIS & NAST-I, AIRS & CrIS



Flow-Down IR Requirements (2)

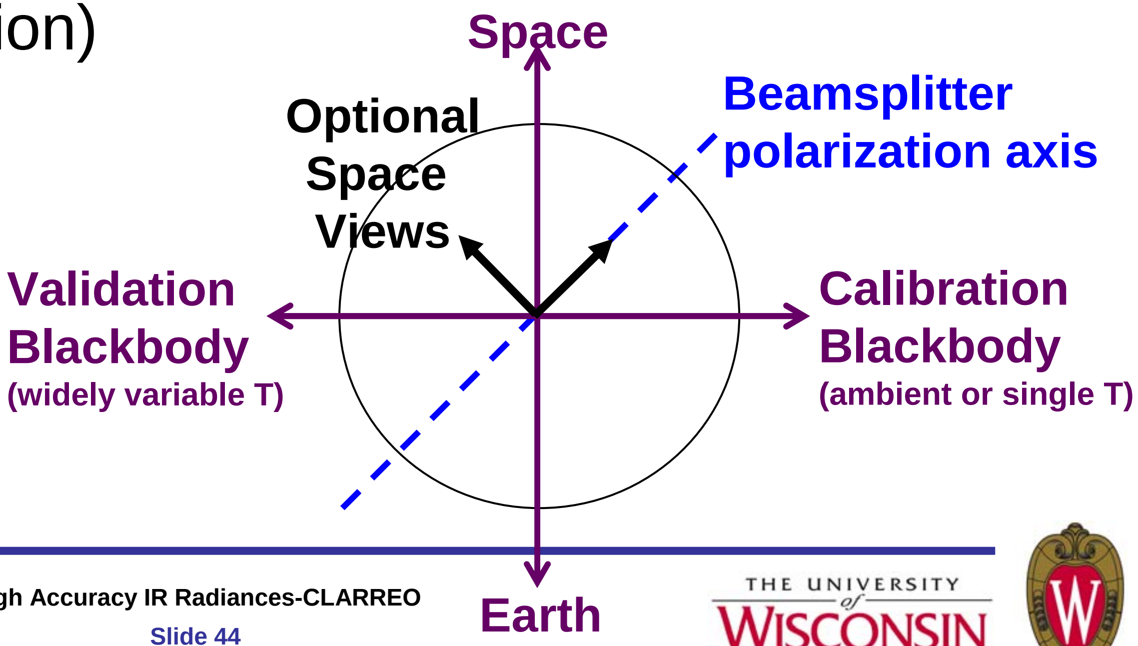
- **Spatial Footprint & Angular Sampling:**
  Order 100 km or less, nadir only
  (no strong sensitivity to footprint size, nadir only captures information content)
- **Spatial Coverage:** Complete global sampling
  (to not miss critical high latitude regions)
- **Orbits:** 3 90º inclination orbits spaced 60º apart
  (to minimize sampling biases that RSS with measurement uncertainty)
- **Temporal Resolution and Sampling:**
  < 15 sec resolution and < 15 sec intervals
  (adequate to reduce sampling errors and noise)

Flow-Down IR Requirements (3)

- **Spectrometer Approach:** 2 Fourier Transform Spectrometers
  (dual FTS sensors to detect unexpected drifts and give full spectral coverage with noise performance needed for calibration transfer and on-orbit characterization testing)
- **Noise:** NEdT(10 sec) < 1.5 K for climate record,
  < 1.3 K for cal transfer
  (not very demanding)
- **Detectors:** Pyroelectric for one FTS and cryogenic PV MCT and/or InSb for the other

Flow-Down IR Requirements (4)

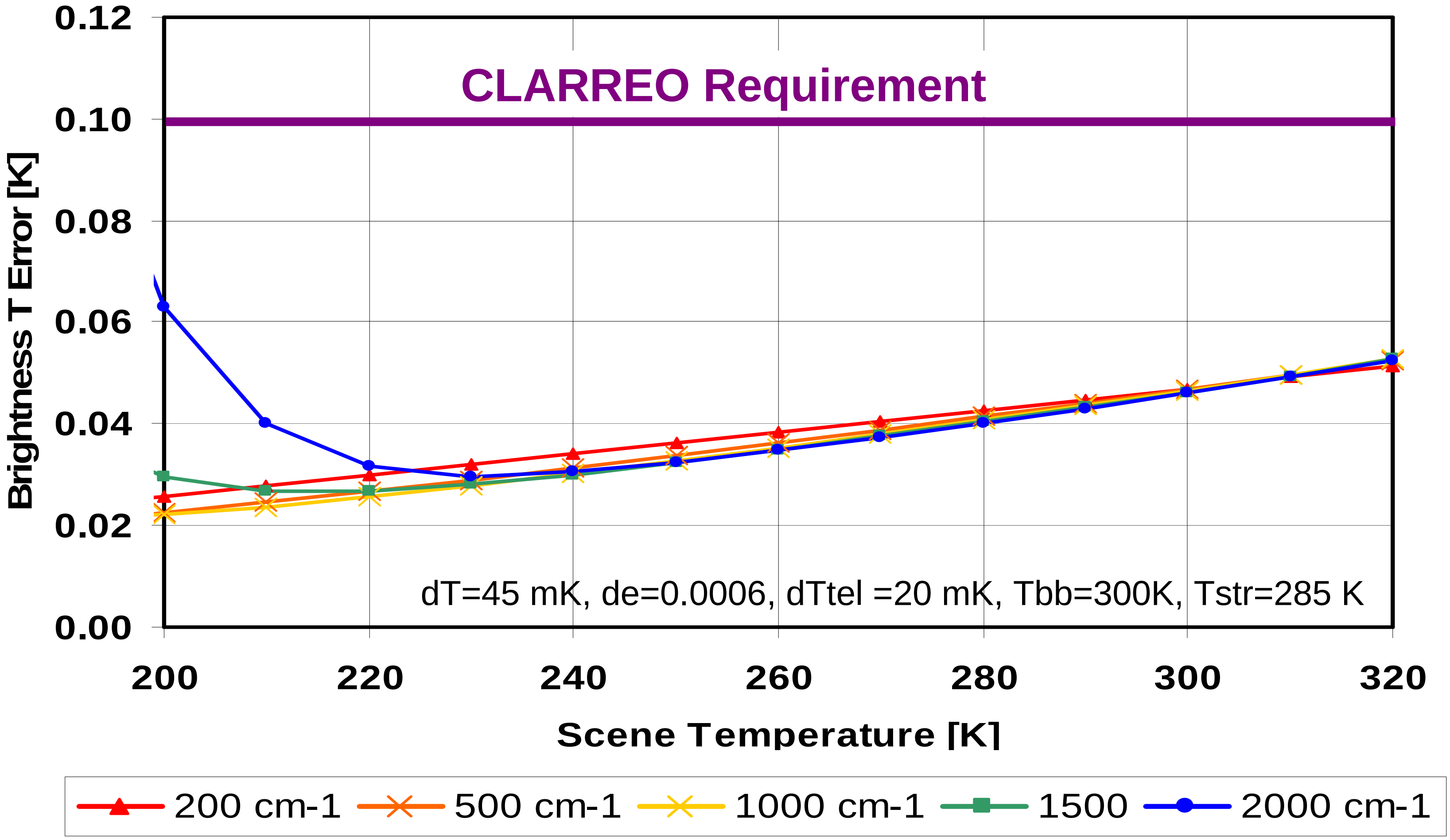
- **On-orbit characterization:** provide non-linearity and polarization test capability
  - Non-linearity from Out-of-band Harmonics and variable temperature blackbody
  - Polarization from multiple space view directions (design also minimizes effects of gold scene mirror induced polarization)



Flow-Down IR Requirements (5)

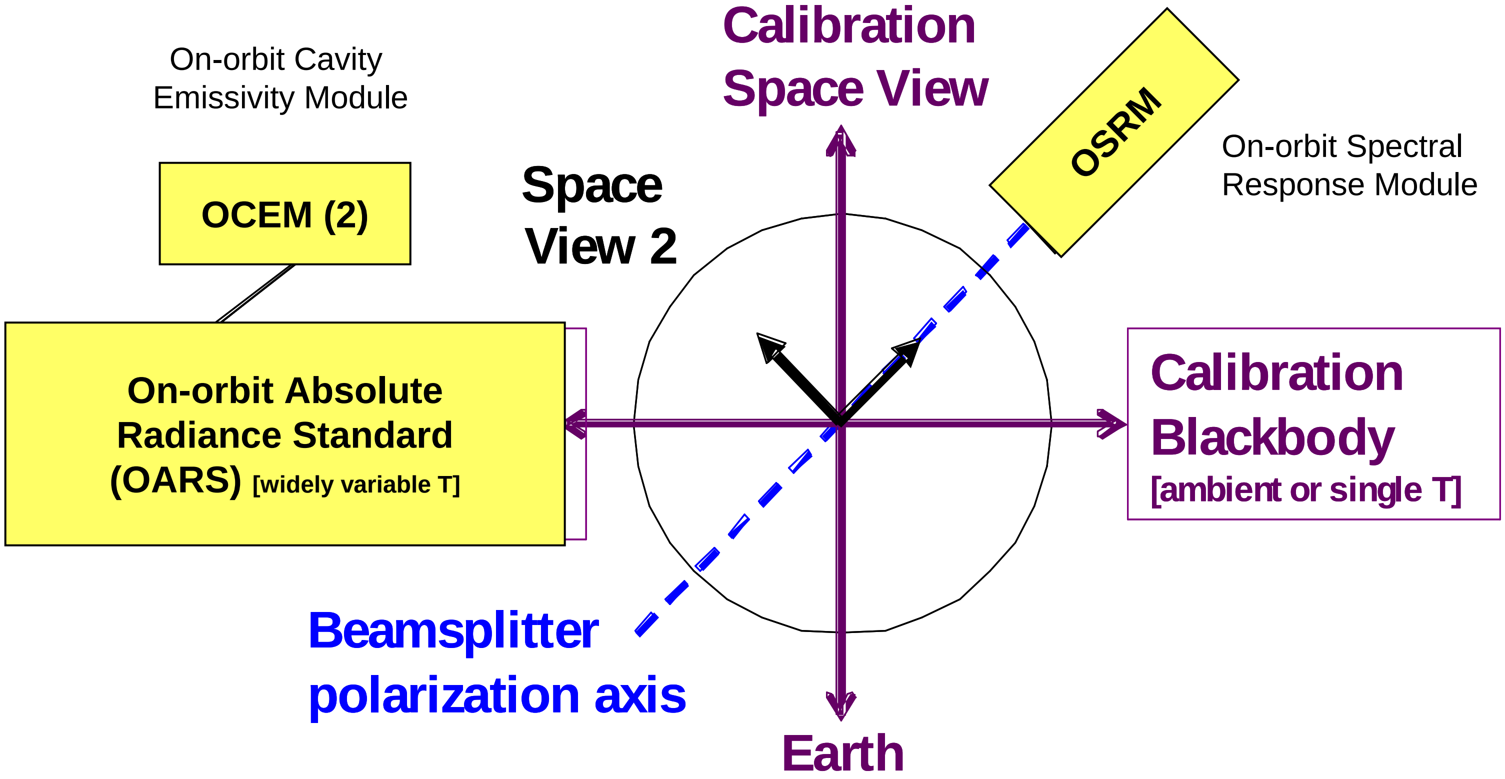
- **Pre-launch Calibration/Validation:** Characterization against NIST primary infrared standards and evaluation of flight blackbodies with NIST facilities
  (recent “best practice”)
- **On-orbit Calibration:**
  Onboard warm blackbody reference (~300K), with phase change temperature calibration, plus space view, supplemented with characterization testing
  (to detect any slow changes)
- **Validation, On-orbit:**
  Variable-temperature Standard Blackbody, with on-orbit absolute T calibration and reflectivity measurement
  (to maintain SI measurements on orbit)

CLARREO Radiometric Performance



Estimated 3-sigma calibrated brightness temperature uncertainty

A New Class of Advanced Accuracy Satellite Instrumentation for CLARREO



On-orbit Cavity
Emissivity Module

OCEM (2)

**On-orbit Absolute
Radiance Standard
(OARS)** **[widely variable T]**

**Space
View 2**

**Calibration
Space View**

OSRM

On-orbit Spectral
Response Module

**Calibration
Blackbody
[ambient or single T]**

**Beamsplitter
polarization axis**

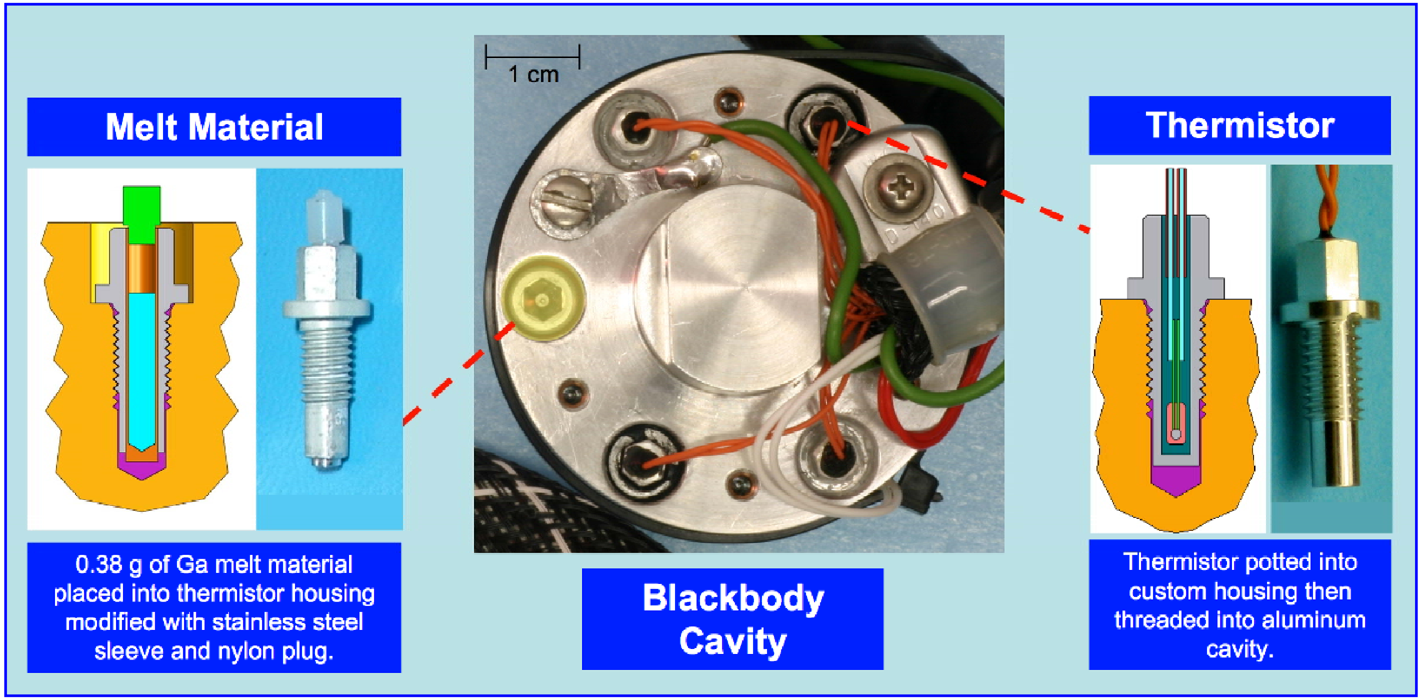
Earth

Viewing configuration providing immunity to polarization effects.

New Developments

On-orbit Absolute Radiance Standard (OARS)

- **The OARS is a source that will be used to maintain SI traceability of the radiance spectra measured by separately calibrated dual interferometer sensors**
- **Multiple phase change material signatures establish absolute temperature knowledge to 10 mK throughout the mission lifetime**



Melt Material

0.38 g of Ga melt material placed into thermistor housing modified with stainless steel sleeve and nylon plug.

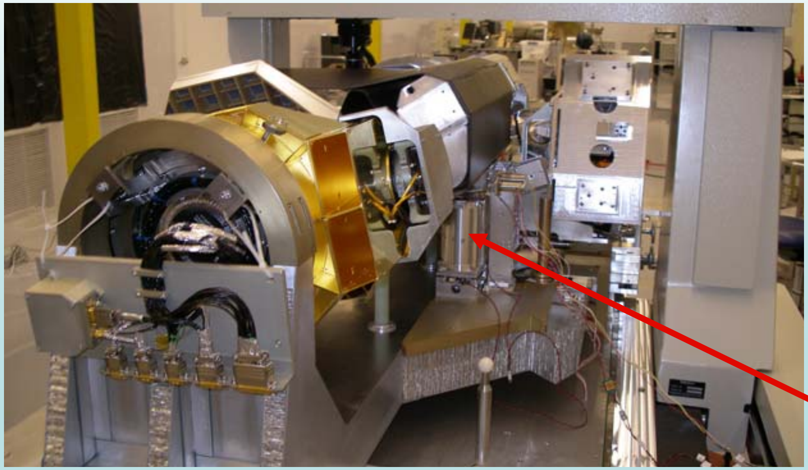
Blackbody Cavity

Thermistor

Thermistor potted into custom housing then threaded into aluminum cavity.

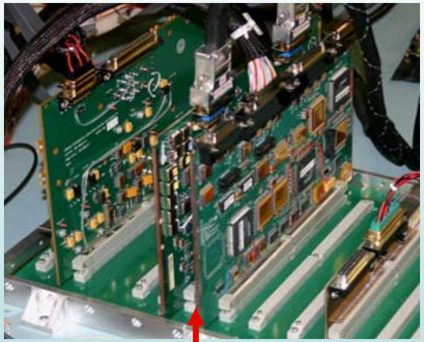
OARS Implementable in UW-SSEC Developed GIFTS EDU Blackbody

GIFTS Engineering Development Unit

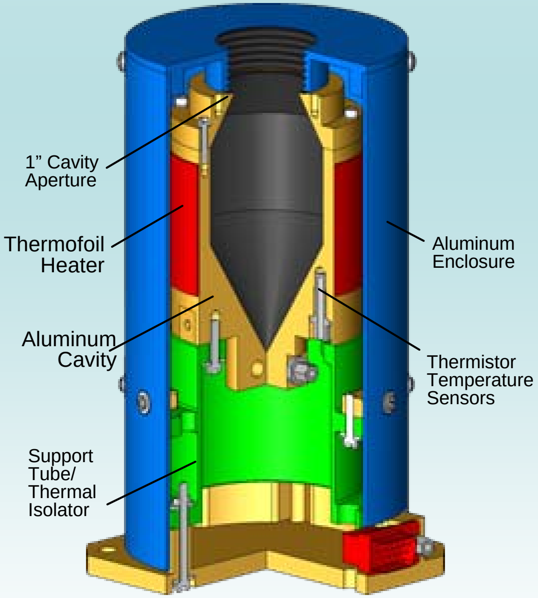


Key Parameter	Specification	As Delivered
Measurement Range	233 to 313 K	233 to 313 K
Temperature Uncertainty	< 0.1 K (3 σ)	< 0.056 K
Blackbody Emissivity	> 0.996	> 0.999
Emissivity Uncertainty	< 0.002 (3 σ)	< 0.00072
Entrance Aperture	1.0 inch	1.0 inch
Mass (2 BBs + controller)	< 2.4 kg	2.1 kg
Power (average/max)	< 2.2/5.2 W	2.2/5.2 W

Blackbody Controller Card

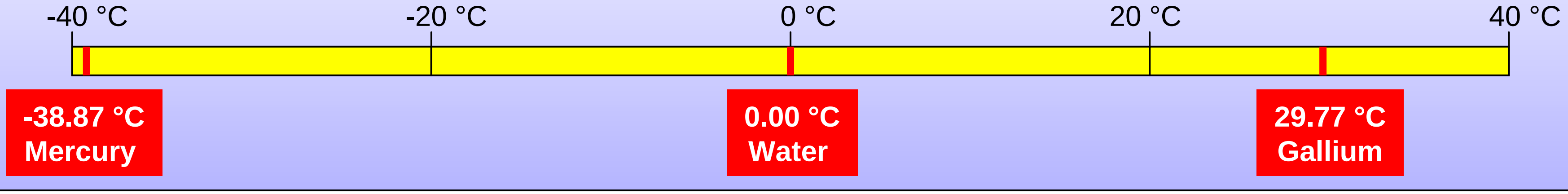


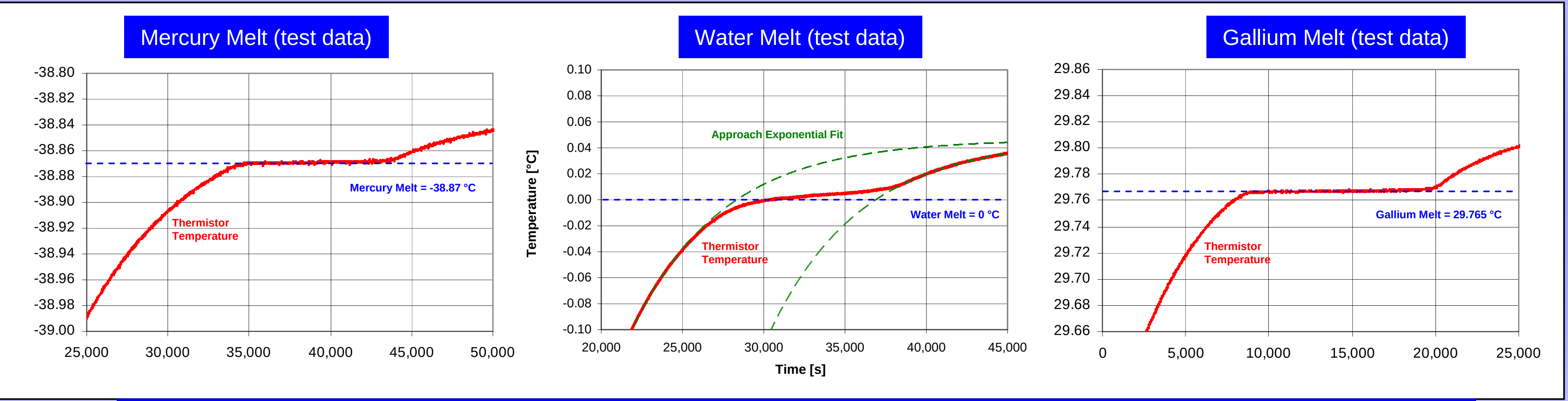
Blackbody (2)



3 Melt Points Calibrate Wide Dynamic Range

(using GIFTS BB Configuration)





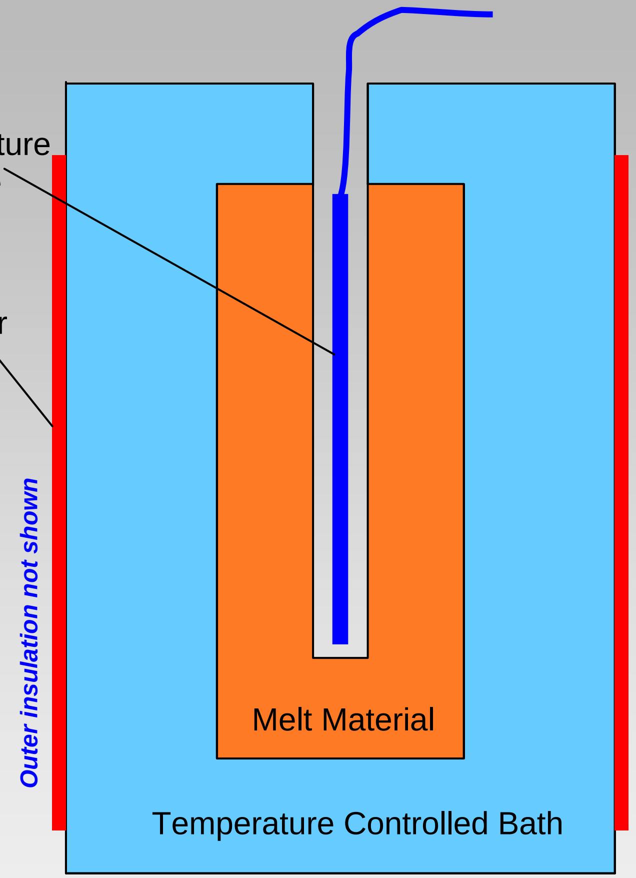
Mercury Melt (test data)

Water Melt (test data)

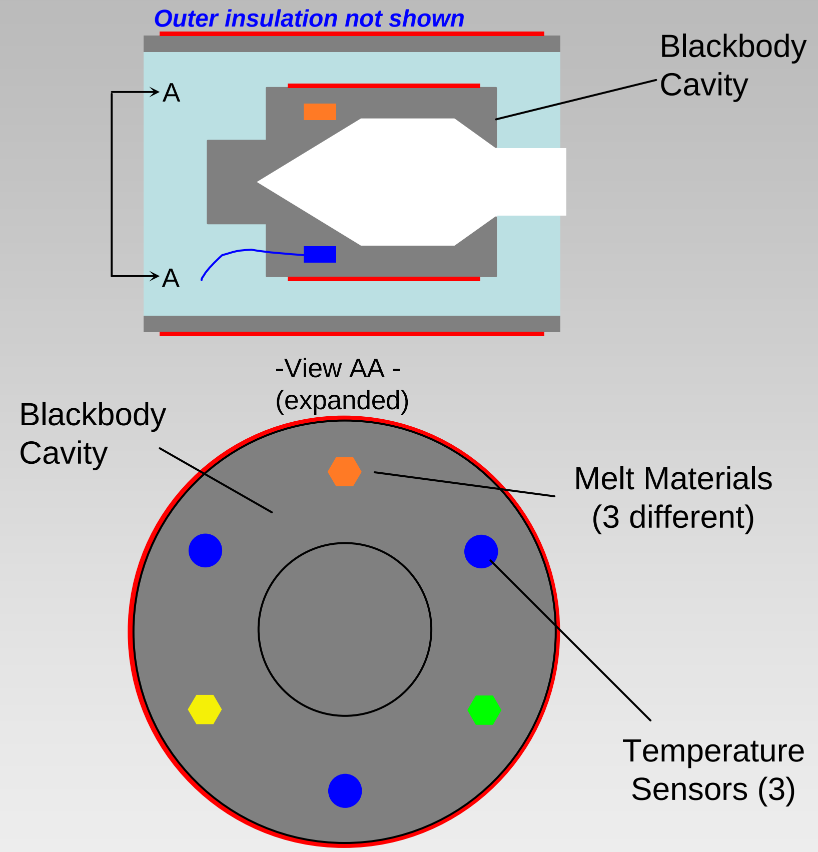
Gallium Melt (test data)

Melt Signatures Provide Absolute Temperature Calibration Accuracies better than 10 mK for full atmospheric Temperature Range

Comparison to Traditional Approach

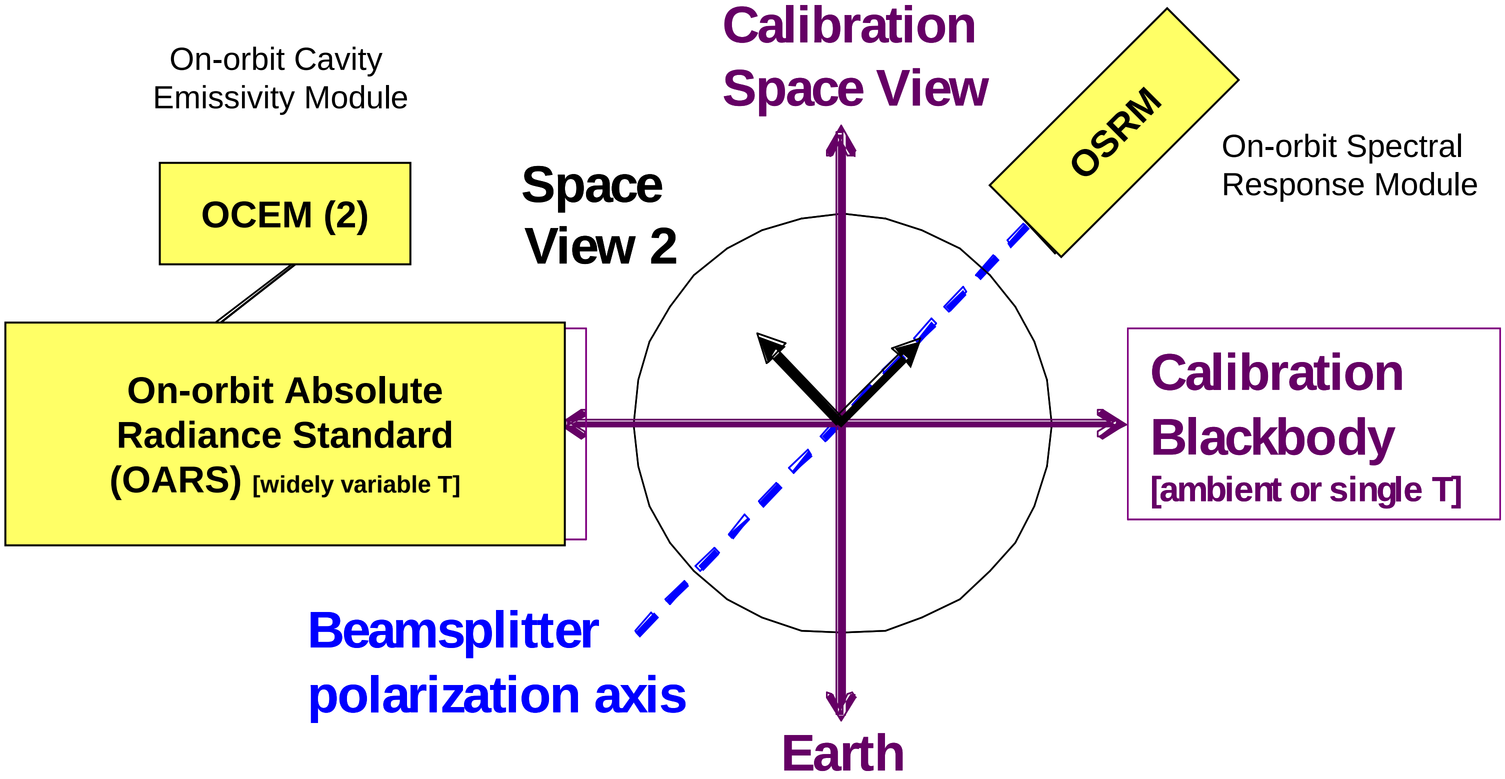


Traditional Laboratory Calibration Scheme



New Blackbody Calibration Scheme

A New Class of Advanced Accuracy Satellite Instrumentation for CLARREO



On-orbit Cavity
Emissivity Module

OCEM (2)

On-orbit Absolute Radiance Standard (OARS) **[widely variable T]**

Space View 2

Calibration Space View

OSRM

On-orbit Spectral
Response Module

Calibration Blackbody
[ambient or single T]

Beamsplitter polarization axis

Earth

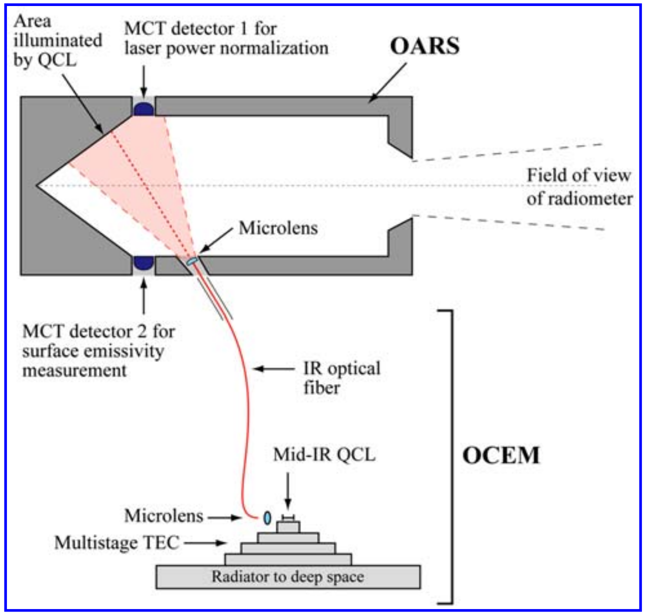
Viewing configuration providing immunity to polarization effects.

New Developments

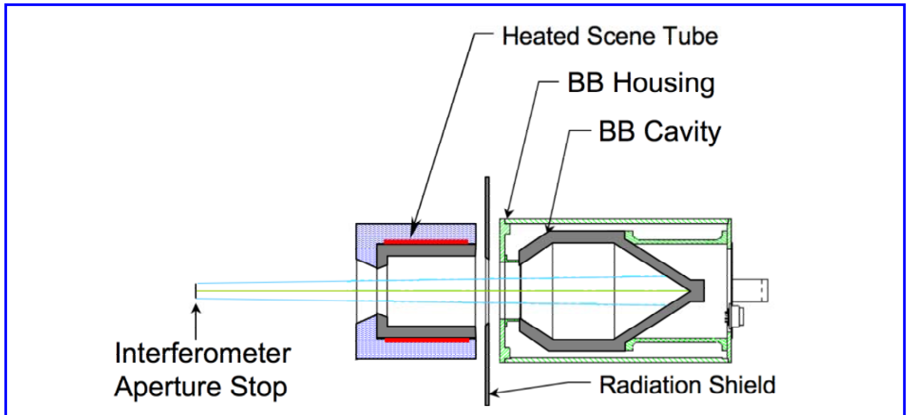
On-orbit Cavity Emissivity Module (OCEM)

Directly determines the on-axis emissivity of the OARS throughout the instrument lifetime on-orbit. Two versions will be developed:

- one using a quantum cascade laser source (Harvard), and
- one based on a heated halo source (Wisconsin).



Harvard QCL Approach

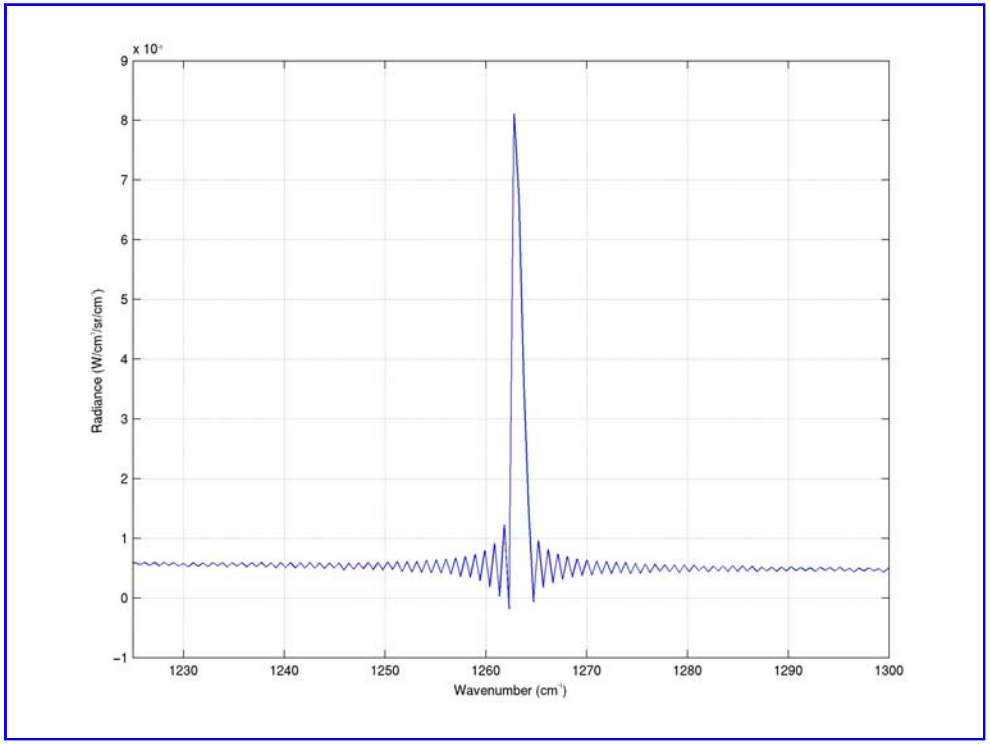


$$M_{instrument} = \underbrace{\varepsilon \bullet B(T_{bb})}_{\text{direct radiance from BB}} + \underbrace{(1-\varepsilon)\bullet[F \bullet B(T_{tube}) + (1-F)\bullet B(T_{bg})]}_{\text{reflected radiance from BB}}$$

UW Heated Halo Approach

On-orbit Spectral Response Module (OSRM)

Uniquely determines the spectral instrument line shape of the interferometers over the lifetime of the instrument on-orbit.



Signature of the instrument lineshape superimposed on a blackbody spectrum. The baseline spectrum is that of a room temperature blackbody. The monochromatic radiation from a QCL at 1263 cm^{-1} is directed into the cavity and the resulting spectrum resolved at 0.5 cm^{-1} reveals the spectrometer lineshape.

CLARREO Summary

- An excellent, low cost, climate benchmark mission has been defined and has good technical readiness
- The mission is based on several new observing paradigms
- One key is an on-orbit calibration validation reference source, and an exciting new approach for on-orbit temperature calibration is now available for assuring the accuracy of that reference
- Corresponding new retrieval methods are under development to interpret the signatures of climate change (regional means of nadir radiances) in terms of climate forcing and response mechanisms. For climate, mean errors or biases must be minimized rather than standard deviations.