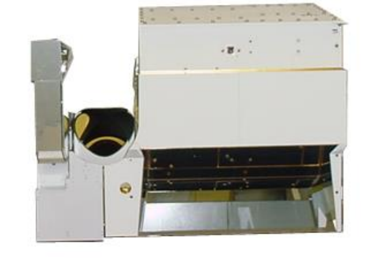
The Cross-track Infrared Sounder (CrIS):



Its high accuracy and special properties for establishing a climate record

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Dave Tobin, Bob knuteson, Joe Taylor, Fred Best
University of Wisconsin - Madison
Space Science and Engineering Center (SSEC)

NASA Sounder Science Team Meeting
Marriott Greenbelt
24-26 October 2017

Abstract

- **The CrIS operational sounder has an accuracy significantly better than 0.2 K 3-sigma over most of its spectral range for most scene types.** The basis for this statement, along with a definition of the rare exceptions, will be presented.

- In addition, we will discuss the special properties that CrIS shares with other carefully designed **Fourier Transform Spectrometer (FTS) sensors** that **provide a high degree of sensor-to-sensor independence** of their radiance properties.

- This characteristic makes these sensors **especially well-suited for operational weather applications and for creating a long term climate record like** that envisioned for the **CLARREO** program.

- **The operational sounders** (CrIS, IASI, and the future FY3 HIRASs) plus AIRS **will be crucial components of such a climate record.**

CrIS: Its high accuracy & special properties for climate

A. CrIS Radiometric Accuracy

B. CrIS Spectral Calibration

C. Advantages of FTS for High Accuracy and Climate Trending

D. Conclusions

Backup: Background on Accuracy Advance from High Spectral Resolution

CrIS: Its high accuracy & special properties for climate

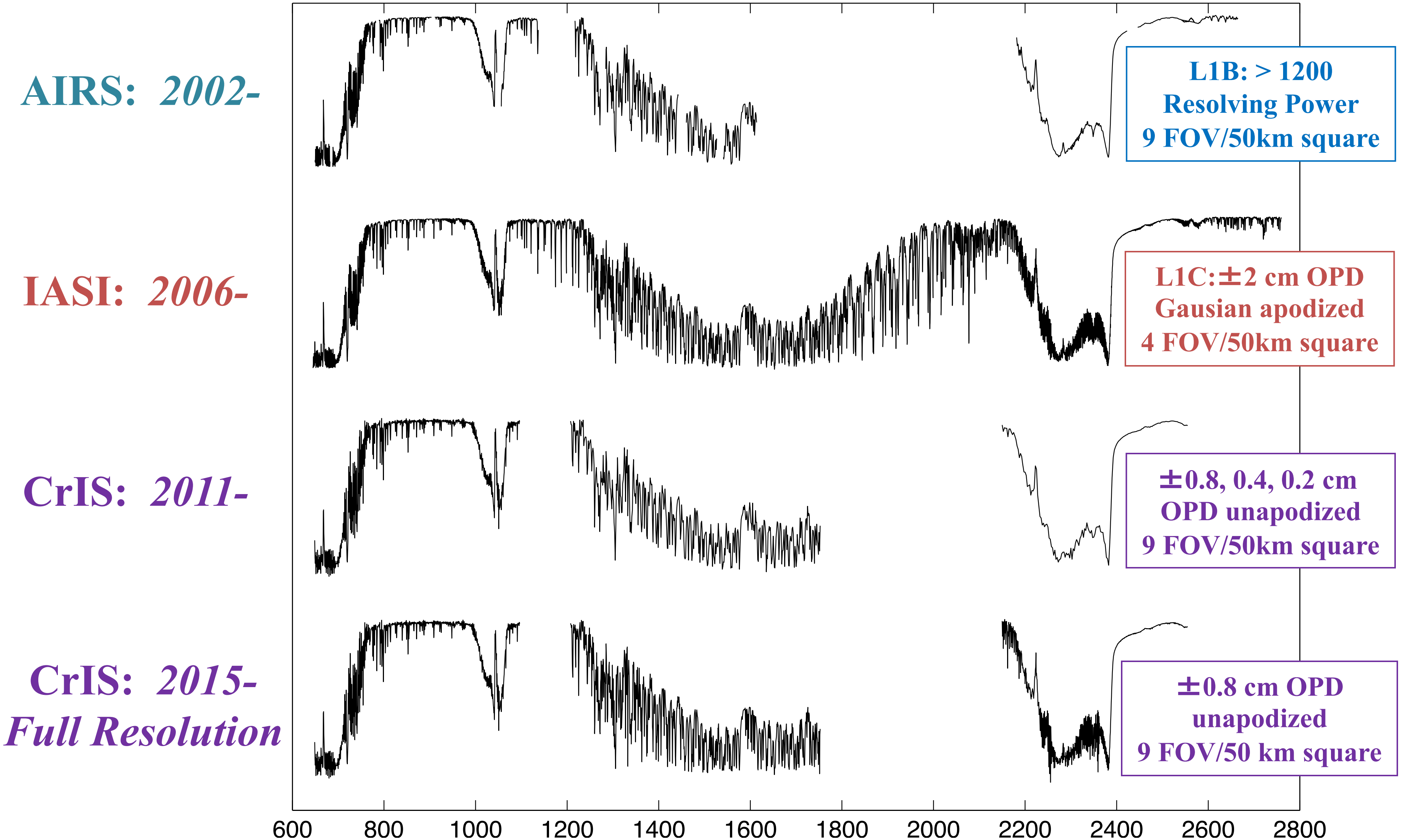
- **A. CrIS Radiometric Accuracy**
- **B. CrIS Spectral Cali**
- **C. Ad**

Accuracy

CrIS Accuracy is generally better than 0.2 K 3-sigma

ckup: Background on Accuracy Advance from High Spectral Resolution

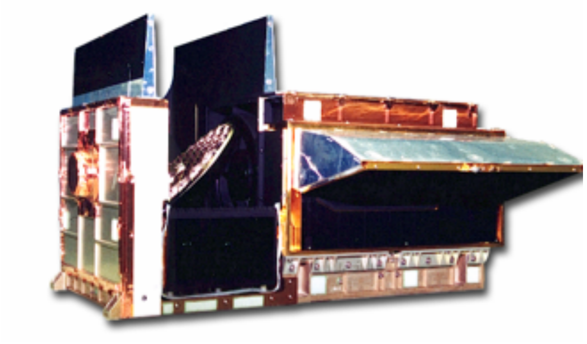
Spectral Coverage and Resolution Comparison



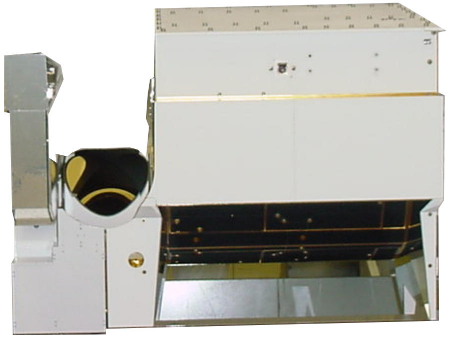
from LBLRTM for US Standard Atmosphere

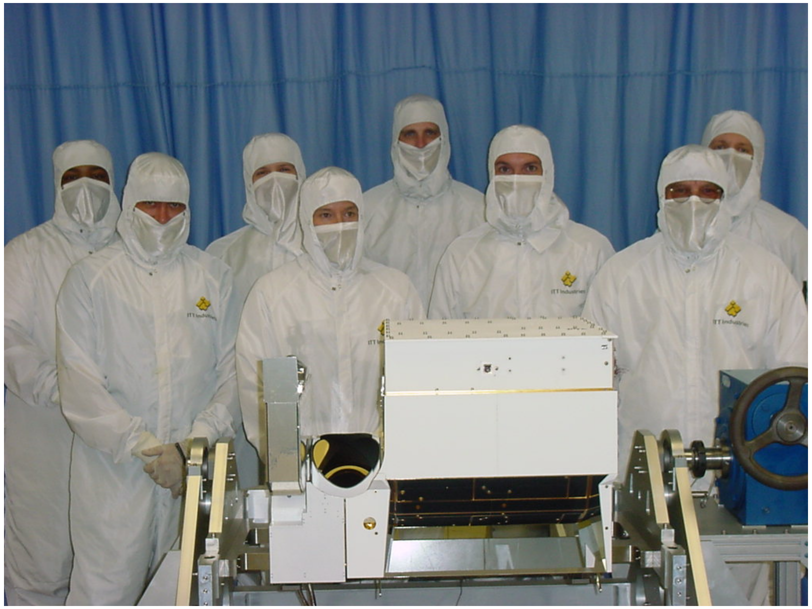
CrIS—about the size of HIRS

HIRS
(20 ch):
30+ year
history



CrIS
(1307 ch):
NPP/JPSS

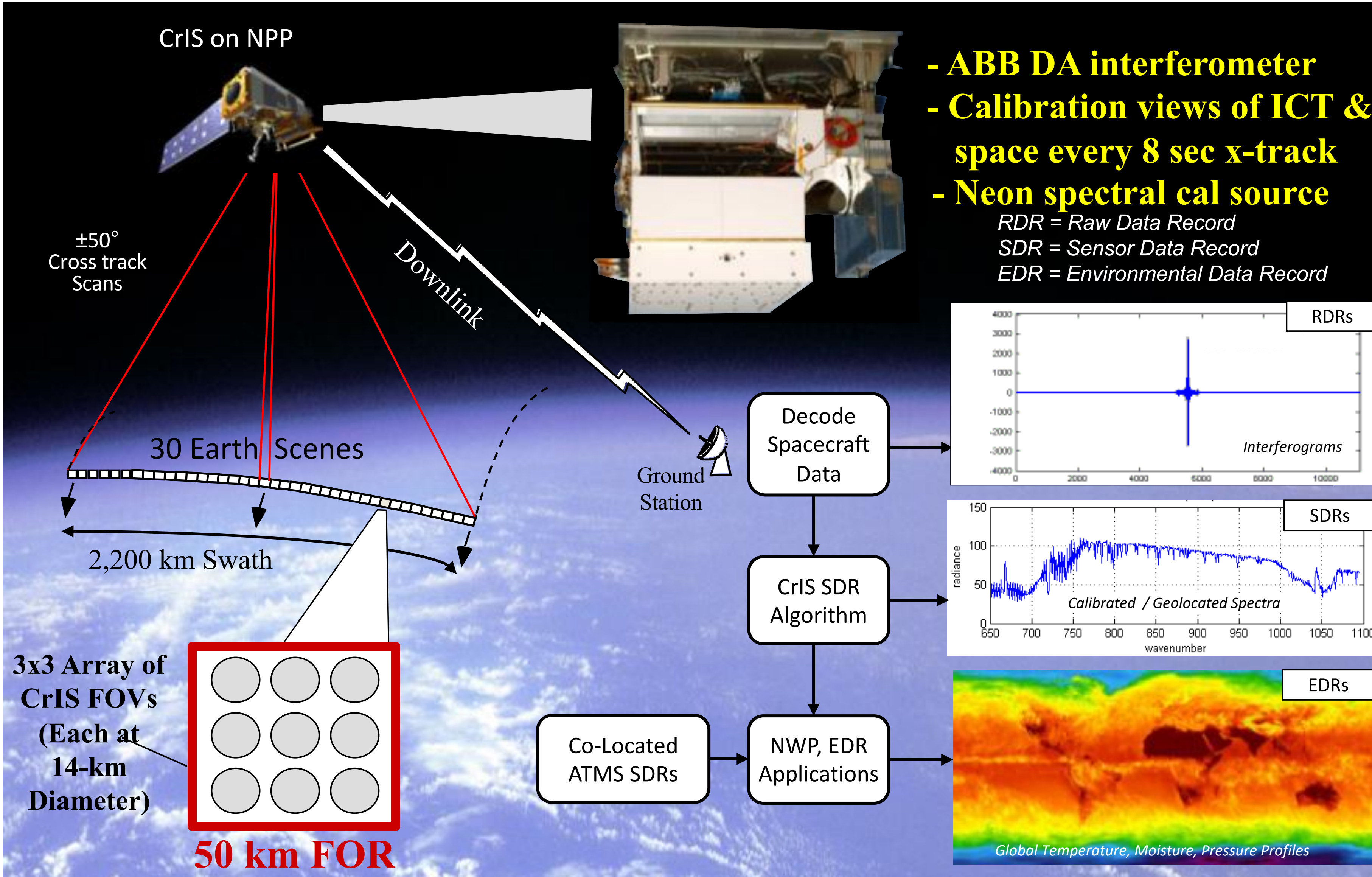




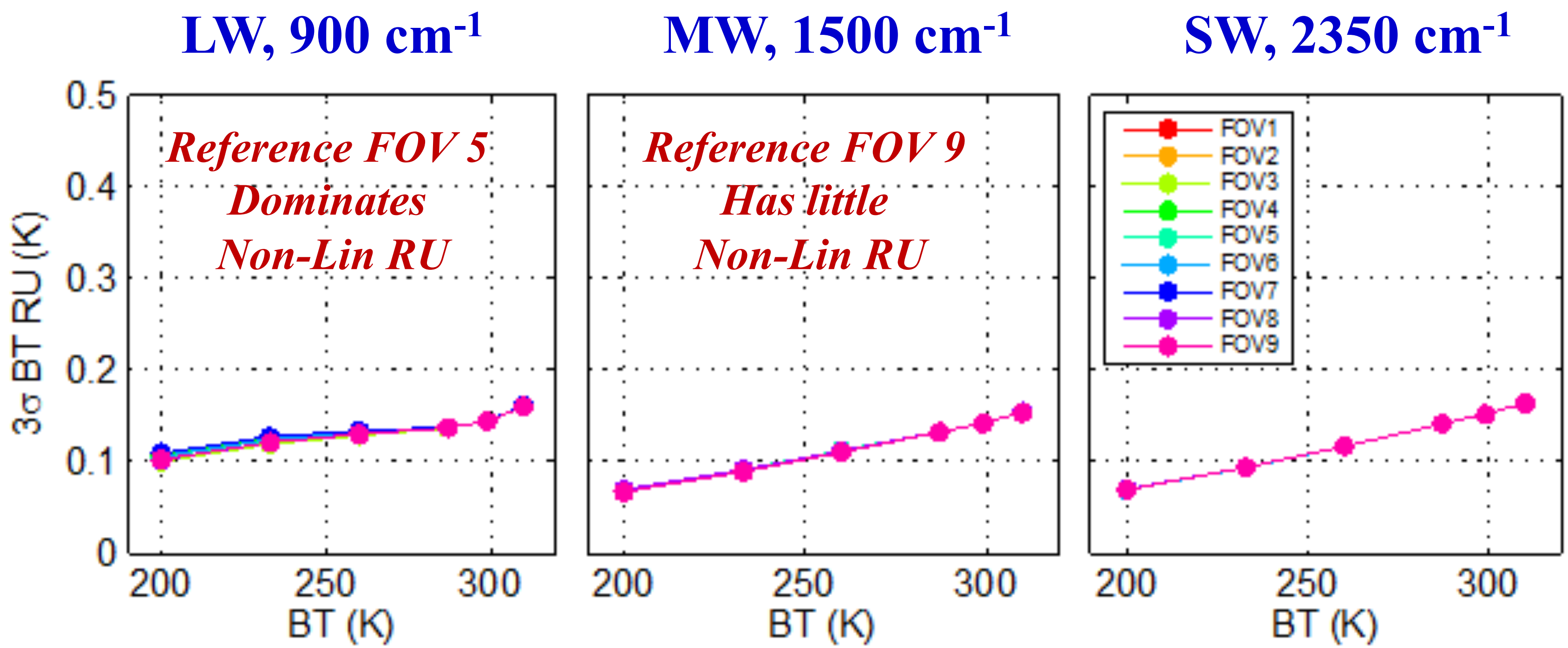
Volume: < 71 x 80 x 95 cm
Mass: 146 kg
Power: 110 W

from Williams, Glumb and Predina, ITT, August 2005 SPIE

CrIS Operational Concept



On-orbit FOV-to-FOV comparisons used to eliminate non-linearity uncertainty differences



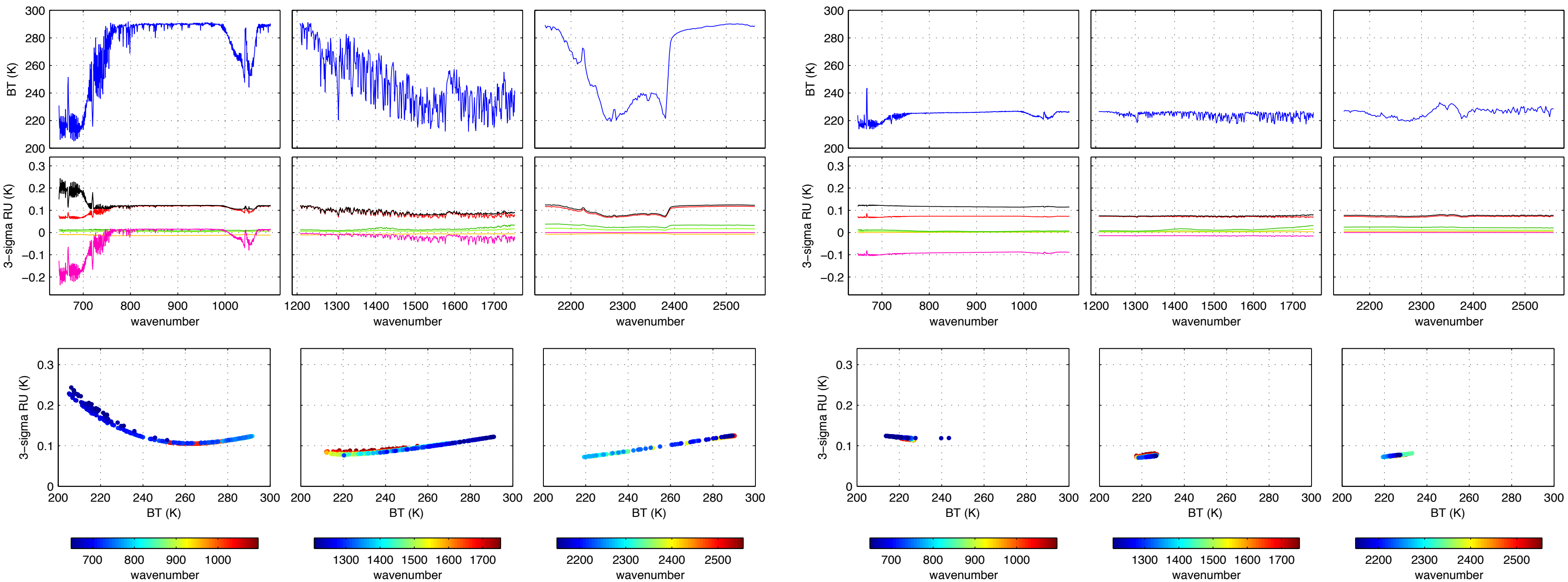
- *SW is linear with uncertainty dominated by ICT temperature uncertainty*
- *LW/MW FOV-to-FOV uncertainty spread from non-linearity differences after Thermal/Vacuum testing is largely eliminated*

Final on-orbit uncertainty

for blackbody spectra < 0.2 K 3-sigma!

On-Orbit RU Estimates (3-sigma)

typical warm, ~clear sky spectrum | high, thick cloud



	3-σ uncertainties
T_{ICT}	*112.5 mK*
ε_{ICT}	*0.03*
$T_{ICT,Refl,Meas}$	*1.5 K*
$T_{ICT,Refl,Model}$	*3 K*
T_{ST}	*0 K*
ε_{ST}	*0*
$T_{ST,Refl}$	*0 K*
a_2	*
Total RU	

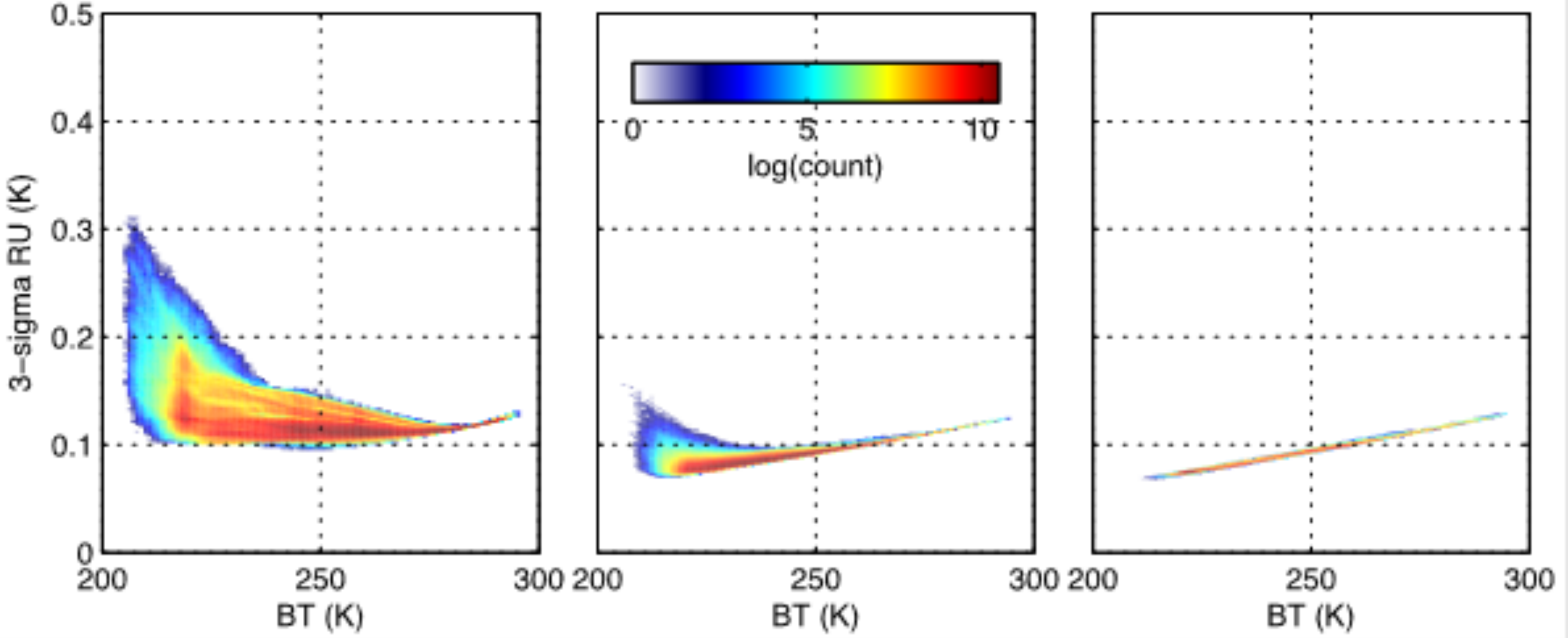
Non-linearity Parameter a_2

*	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

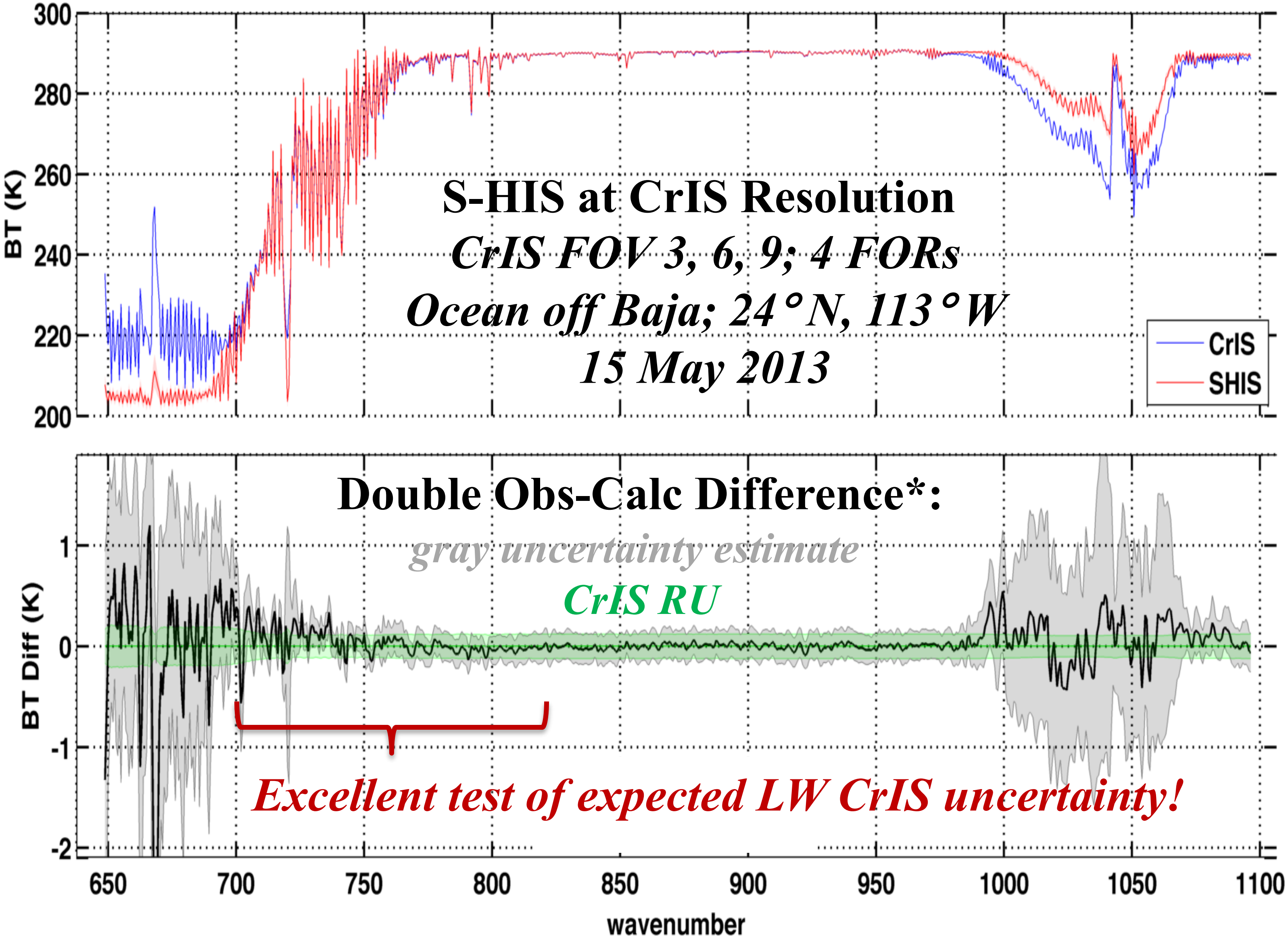
On-Orbit RU Estimates (3-sigma)

Density plot for one orbit includes all spectral channels and FOVs



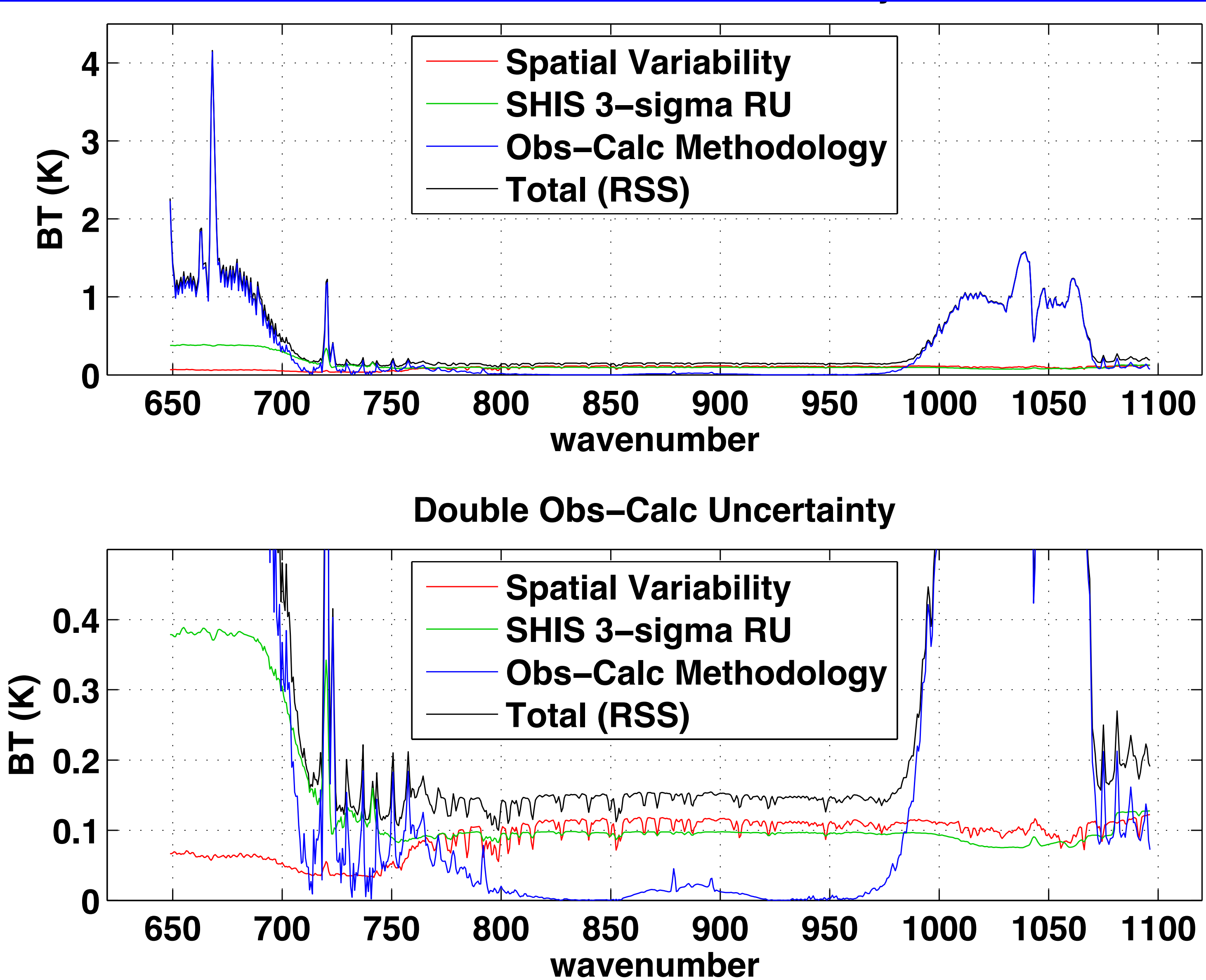
For typical atmospheric spectra
RU values can exceed 0.2 K 3-sigma
for a few cold LW spectra

Intercalibration with S-HIS on ER2

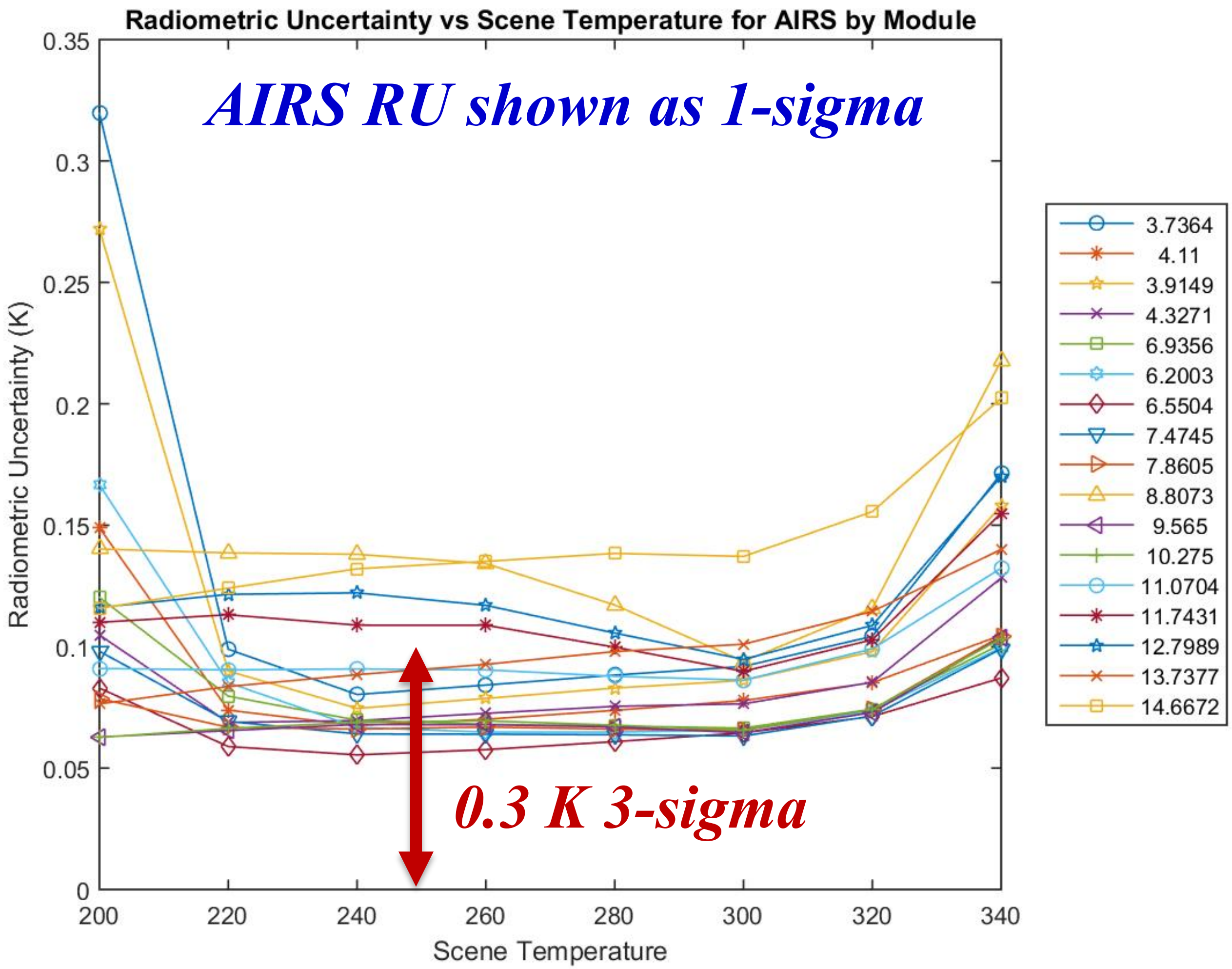


*kCARTA with ECMWF reanalysis

Double Obs-Calc Uncertainty



AIRS Radiometric Uncertainty

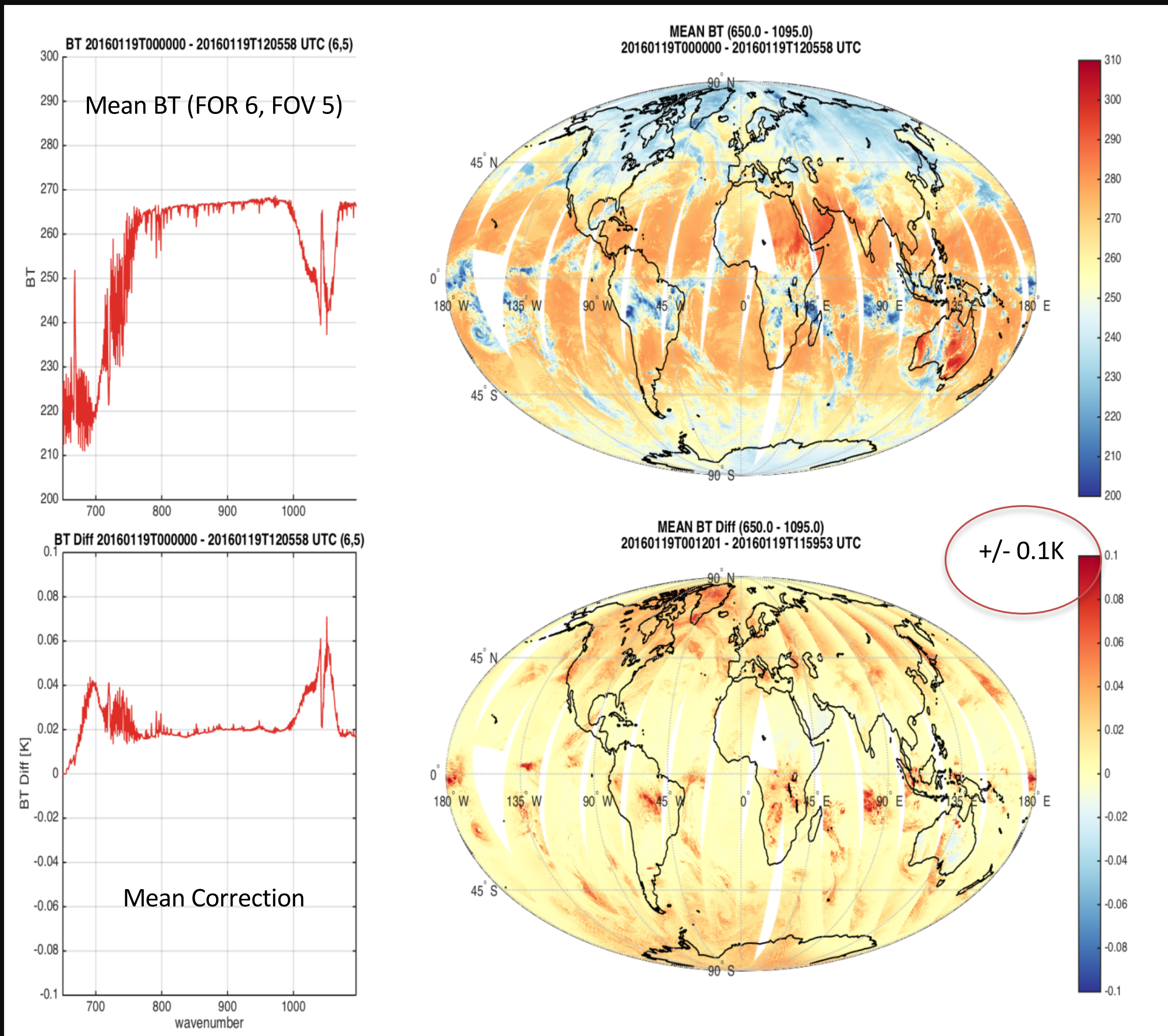


Tom Pagano, 2017

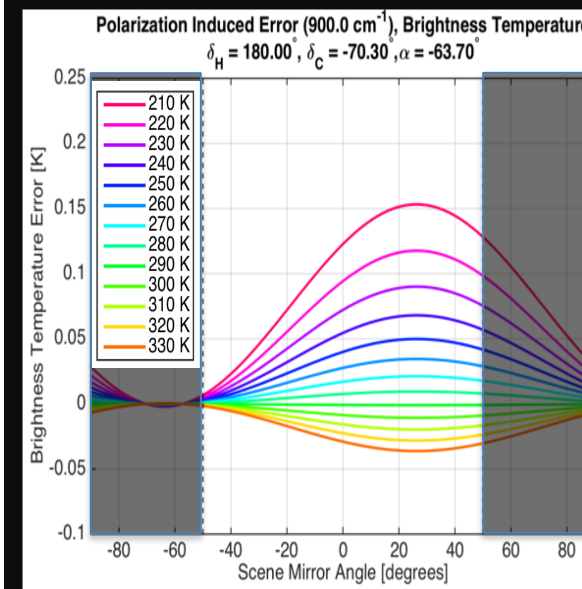
Exceptions that can exceed 0.2 K under limited and rare conditions

- **Polarization:** (gold scene mirror induced)
  Correction developed, but not yet implemented
  (error examples follow)
- **Ringing:** (every other point oscillation - spectrally local)
  - Numerical filter induced source identified and rigorous correction developed
  - Responsivity related source identified as "true ringing" handled in calculations and correction also discovered recently
- **FOV5 anomaly:** (unexplained error in FOV5)
  Large at 668 cm^{-1} Q-branch for some cold scenes
  (only major anomaly without identified root cause)

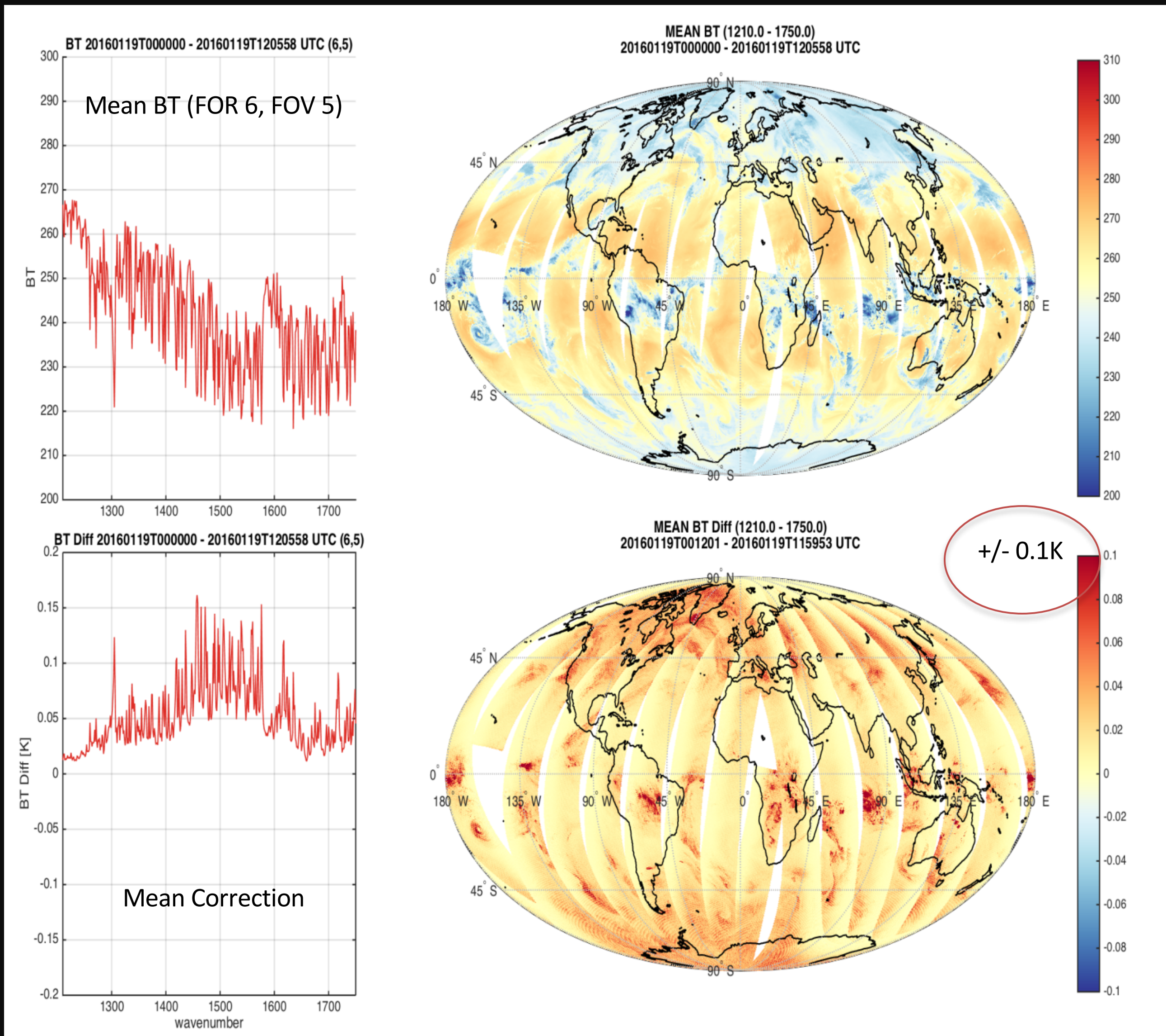
Mean BT and Mean BT Diff (Uncorrected – Corrected), LW
2016J019: 00:12– 12:00



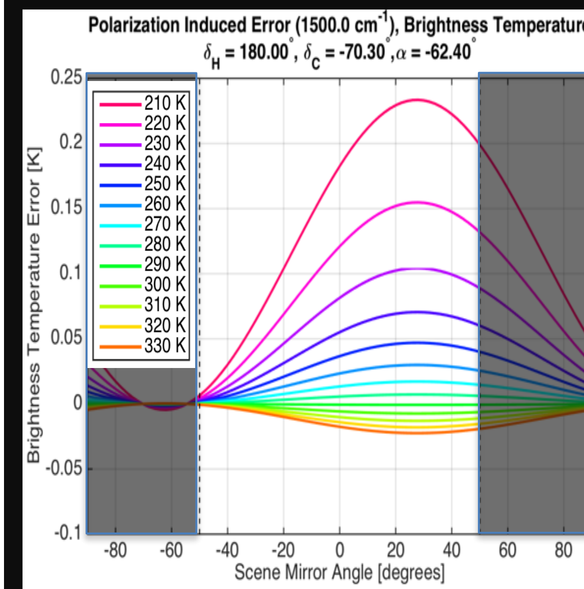
- LW: α = -63.7°
- LW correction maximum near FOR 6 – 7 (FOR 6, FOV 5 shown at far left)



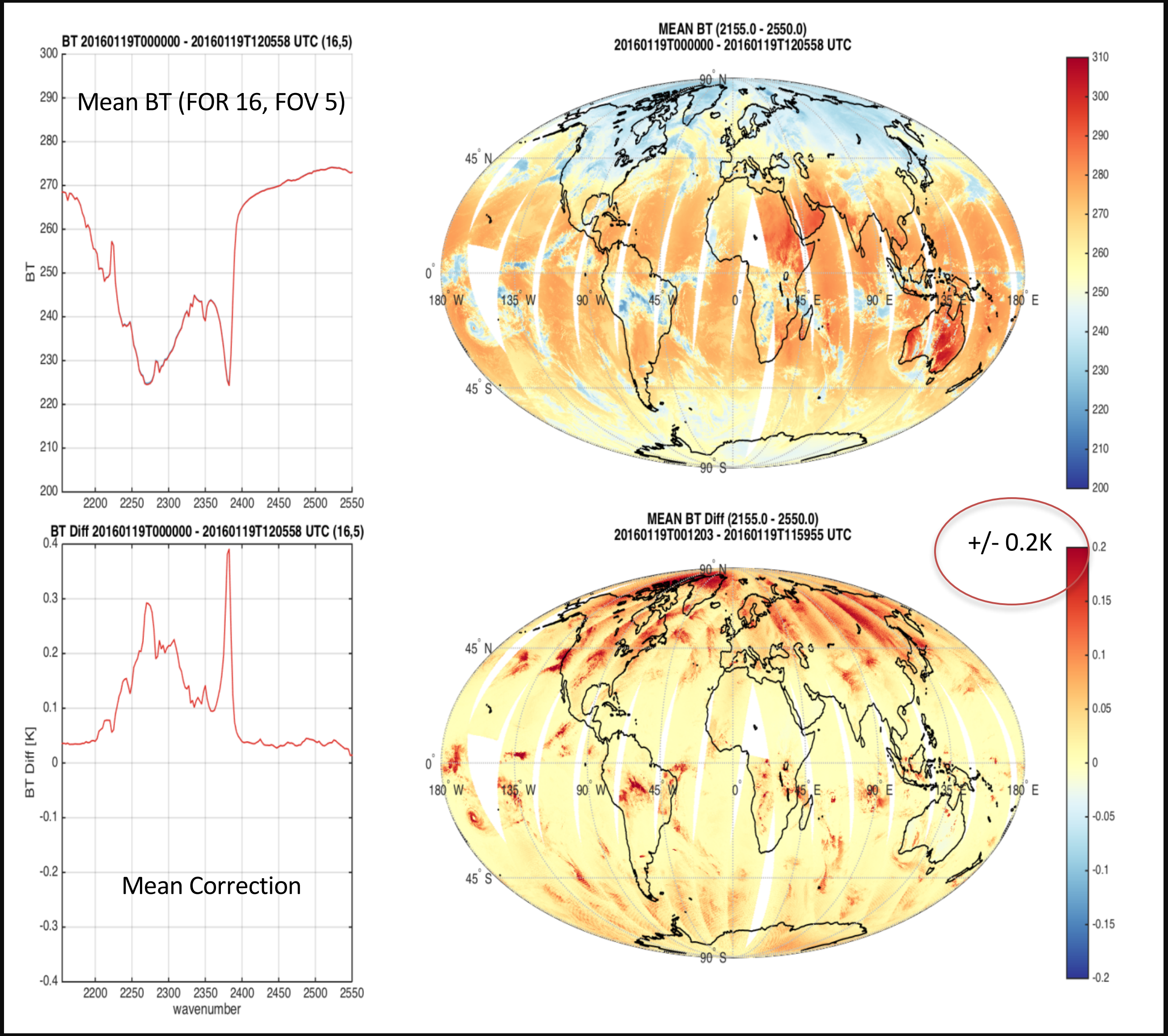
Mean BT and Mean BT Diff (Uncorrected – Corrected), MW
2016J019: 00:12– 12:00



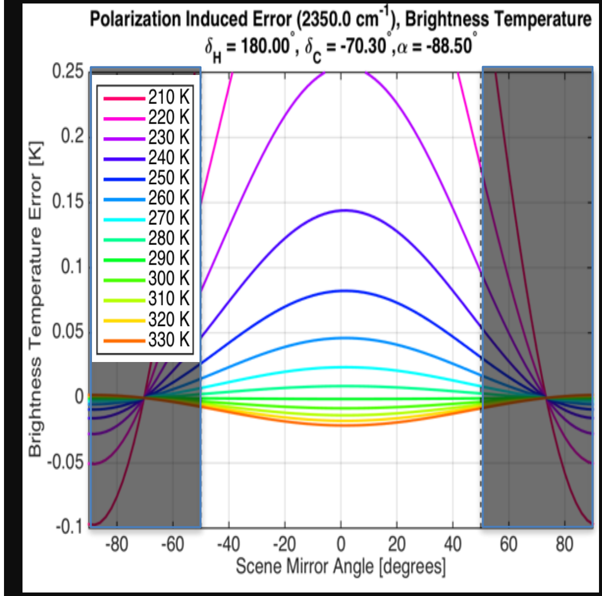
- MW: α = -62.4°
- MW correction maximum near FOR 6 – 7 (FOR 6, FOV 5 shown at far left)



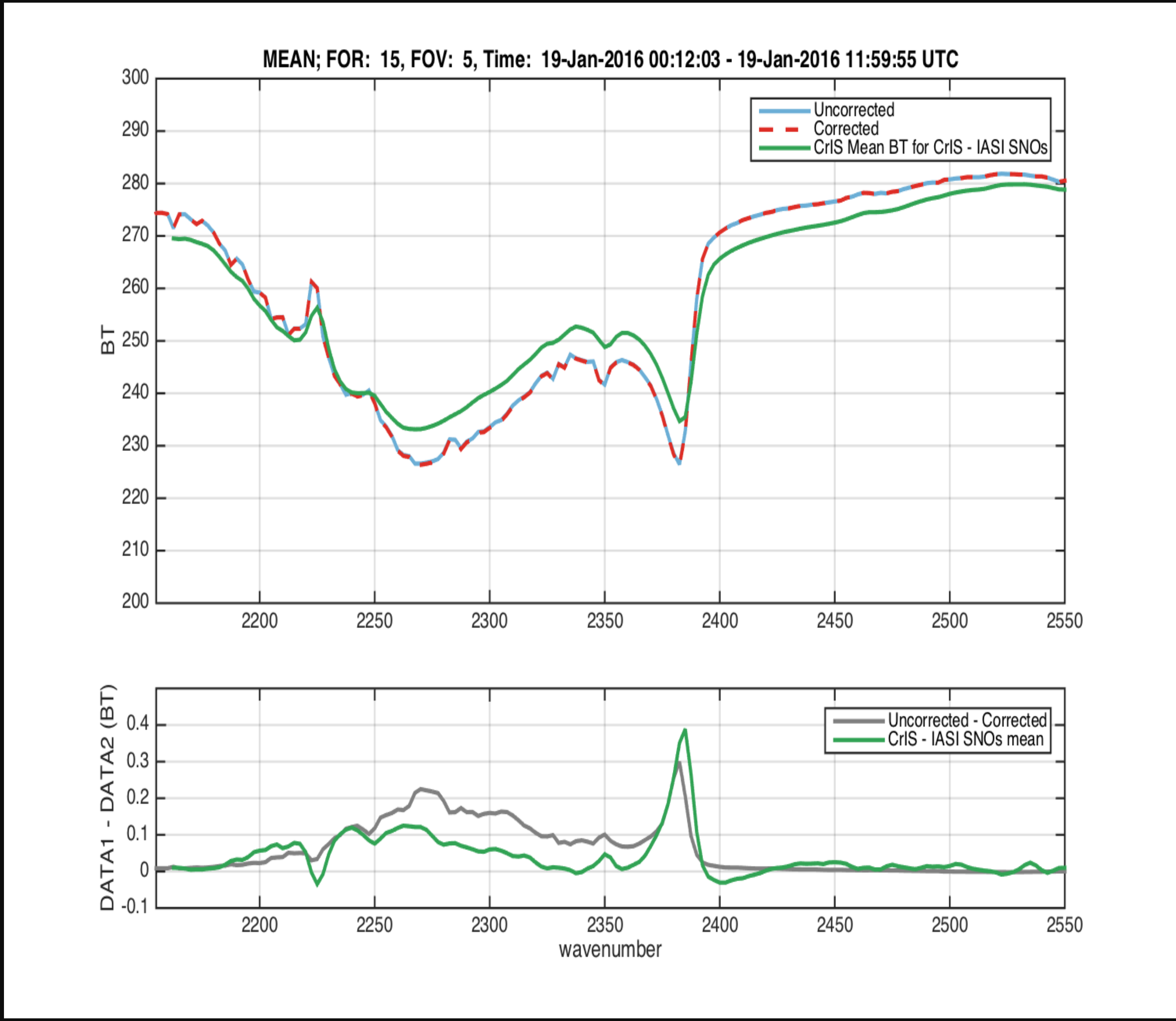
Mean BT and Mean BT Diff (Uncorrected – Corrected), SW
2016J019: 00:12– 12:00



- SW: α = -88.5°
- SW correction maximum near FOR 15 – 16 (FOR 16, FOV 5 shown at far left)



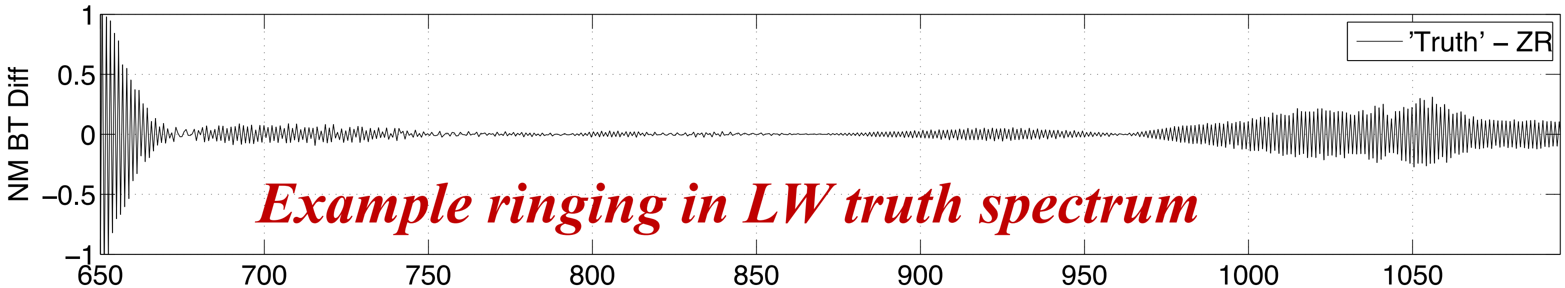
Mean BT and Mean BT Diff (Uncorrected – Corrected), SW Compared to CrIS – IASI SNOs Residual Example



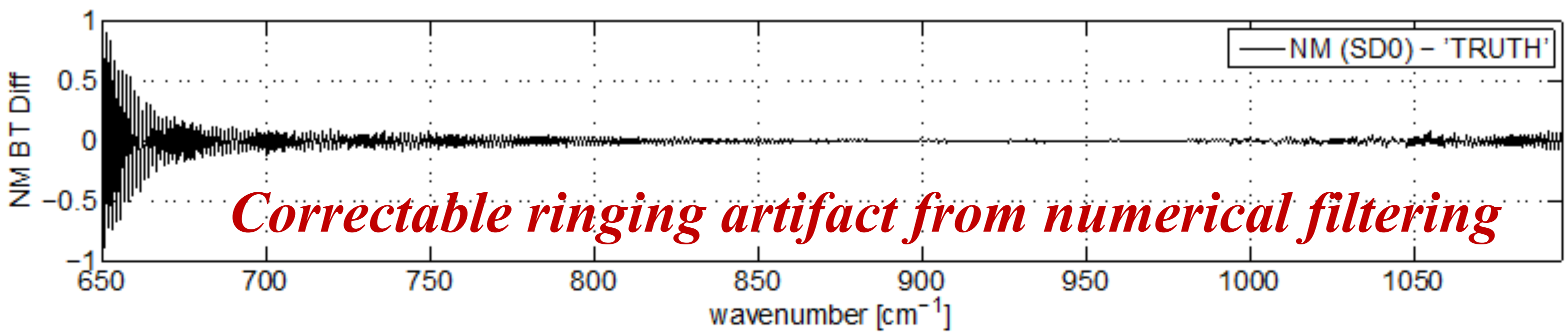
- Tried to use a SNO ensemble with a mean BT similar in spectral shape and temperature to mean of ½ day example data presented herein
- Polarization correction and CrIS – IASI SNO mean residual BT have similar spectral shape and magnitude

Gibbs Ringing: Truth and Artifact

- **Responsivity band limits cause "truth" spectra to ring:** Calculation of "truth" spectra with CrIS Responsivity removes obs-calc artifacts (correction also in progress)



- **Numerical Filter Ringing Artifacts:** Correctable ringing artifacts result at LW end of LW band



- **Net Ringing Artifacts:** Significant in limited spectral regions and can be reduced to order 0.1 K there

Performance Notes:
(what did **not** happen)

- Spectrally correlated interferometric noise is exceptionally small– therefore, the vibration isolation stage was not deployed
- Almost no interferometer fringe count errors
- Radiation/particle induced Spikes are very rare and have proven to be correctable!
- No signs of transmittance reduction from Ice

CrIS: Its high accuracy & special properties for climate

SSEC

A. **CrIS Radiometric Accuracy**

B. **CrIS Spectral Calibration**

C. **Advantages of F… Accuracy and …**

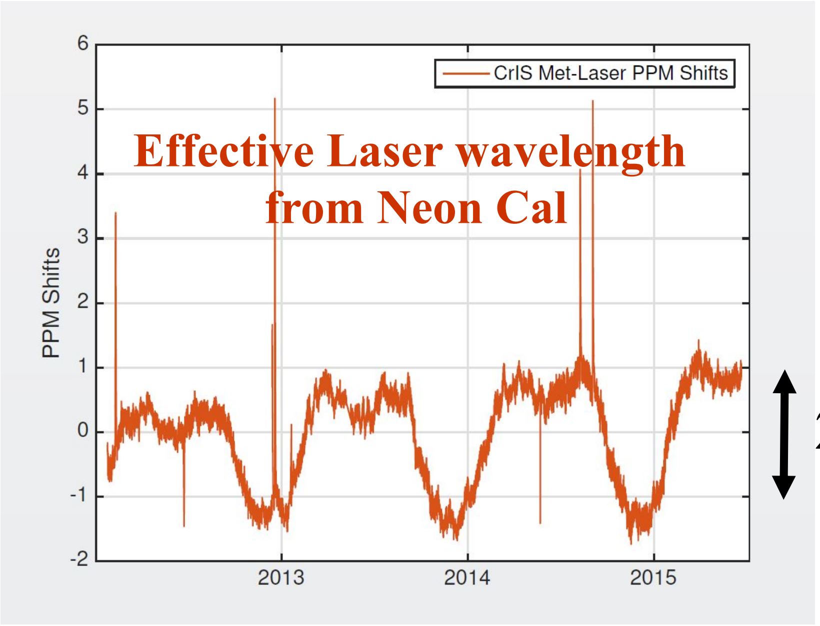
D…

B… und on A…acy Advance from High Spectral Resolution

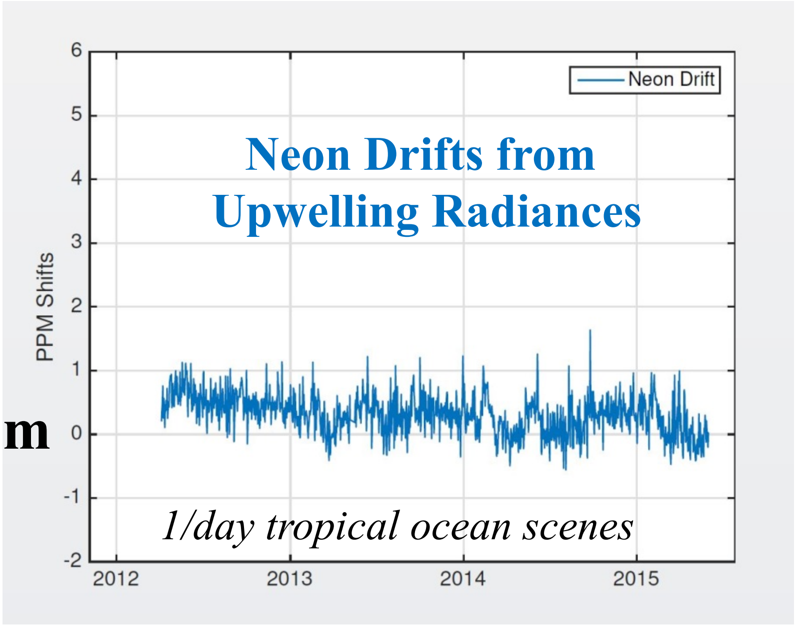
CrIS Spectral Calibration is consistently better than 1 ppm

Spectral Calibration is very Stable

from Larrabee Strow, Aug 2015



2 ppm



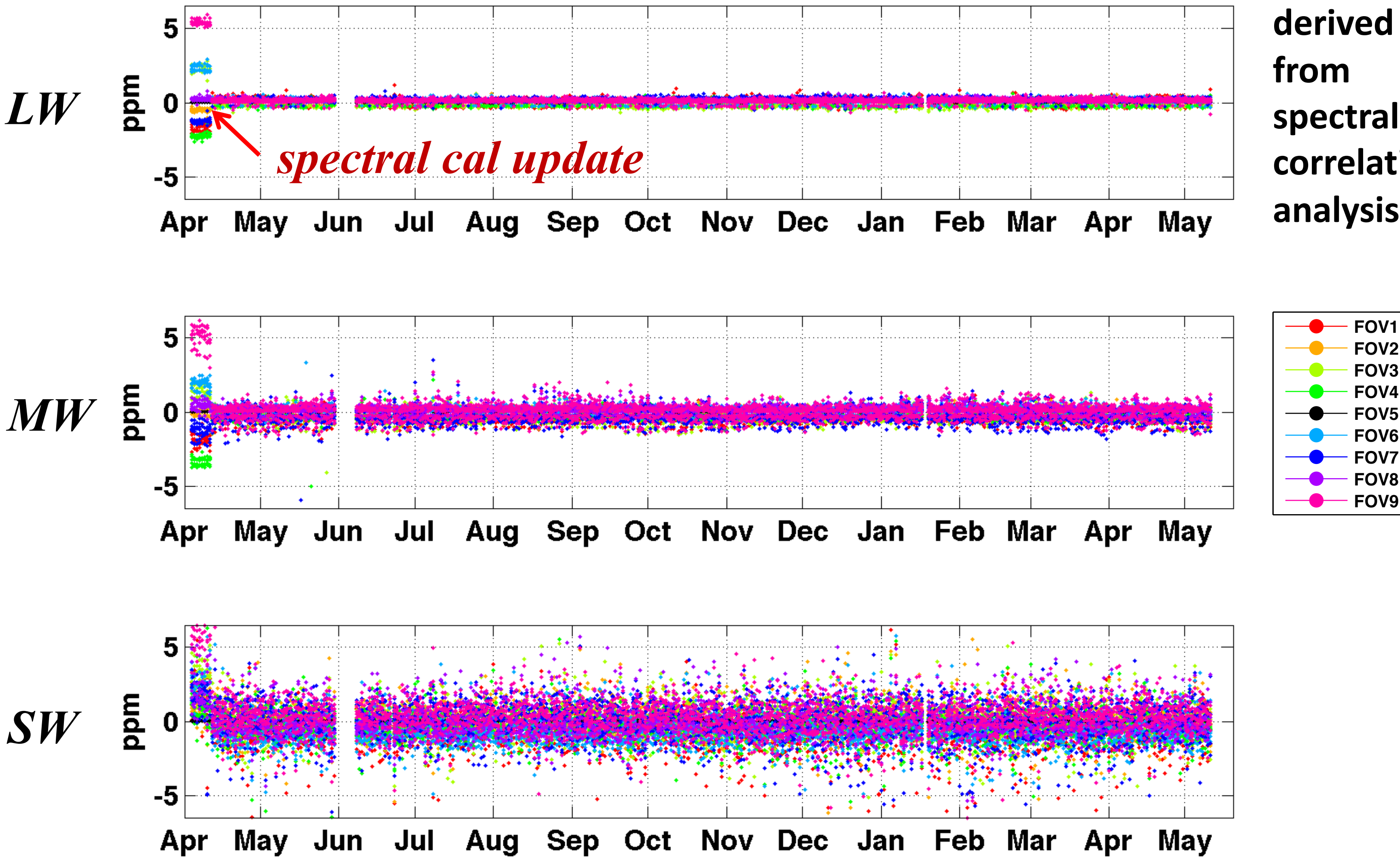
Variation of FTS effective metrology laser wavelength calibrated with stable onboard Neon source <u>reduces final error to </u>< 1 ppm!

Note: (1) Daily variation is generally < 0.5 ppm
(2) Annual variation is < 3 ppm uncorrected
(3) Neon cal results in < 1 ppm spectral cal error

see also Chen, Han, and Weng, 2017

Spectral Calibration Shifts w/r/t FOV5

IDPS SCRIS files, |lat|<= 60 deg.



derived from spectral correlation analysis

All FOVs agree to significantly better than 1 ppm!

On-Orbit Spectral Calibration Summary

- **Absolute calibration uncertainty is < 1 ppm**
  (from atmospheric calibration with calculated spectra)

- Both Neon lamp views and Earth view analyses show **uncorrected spectral calibration variations are < 3 ppm p-p** with a largely annual periodicity

- **Neon lamp is used to remove this annual variation**
  (agreement with Earth view analyses proves value)

- **Inter-FOV agreement is a few tenths ppm** and very stable with time

CrIS Interferometer provides excellent spectral knowledge and stability

CrIS: Its high accuracy & special properties for climate

SSEC

A. CrIS Radiometric Accuracy

B. CrIS Spectral Calibration

C. Advantages of FTS for High Accuracy and Climate Trending

D. Conclusion

olution

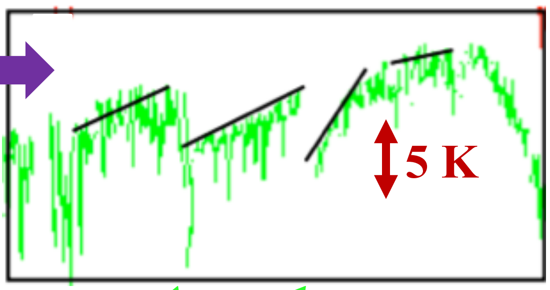
The FTS approach is especially well-suited to climate benchmarking

Advantages of FTS for High Accuracy

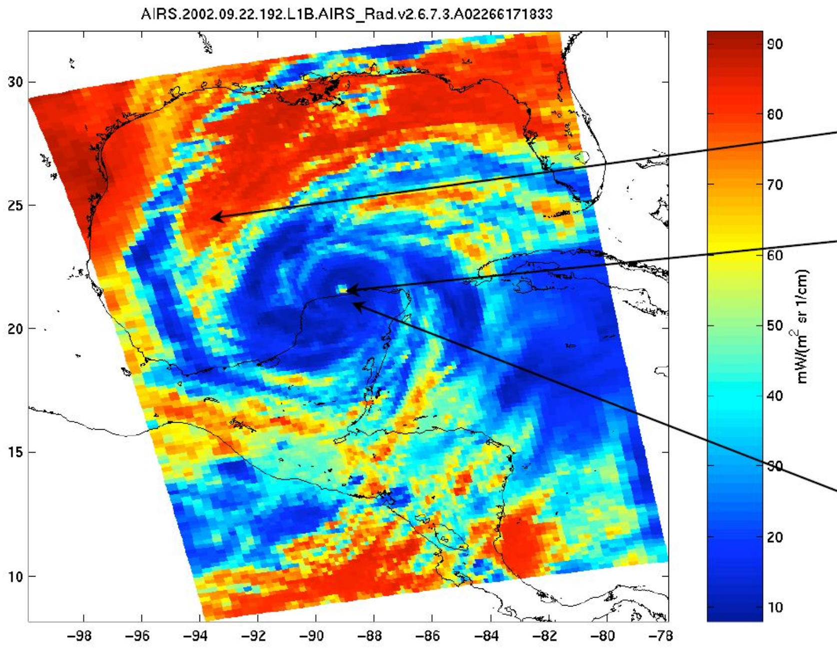
- **First order knowledge of ILS:** (or Spectral Response Function) The ILS is established by the FTS approach, mainly depending on a small set of wavelength independent parameters
  Note- AIRS SRFs were determined in ground testing using an FTS
- **Single detector can cover broad spectral bands:** This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

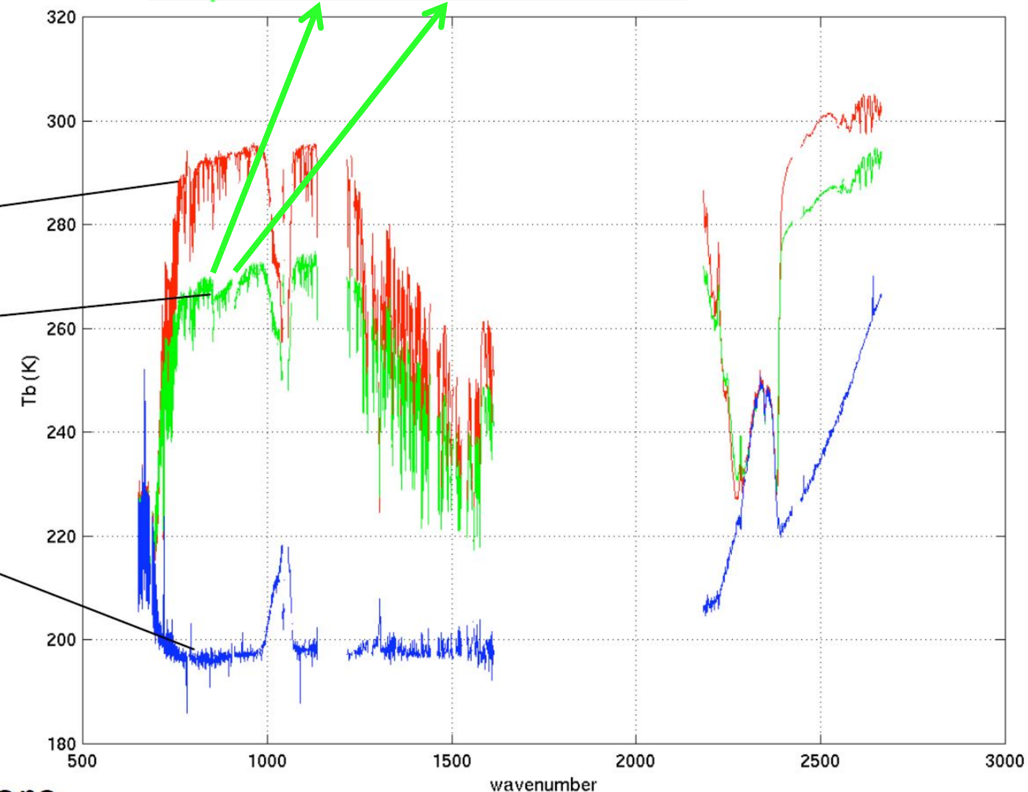
Hurricane Isadore Illustrates AIRS C_{ij} Issue

Different parts of the spectrum see different parts of the hurricane



~999 1/cm radiances

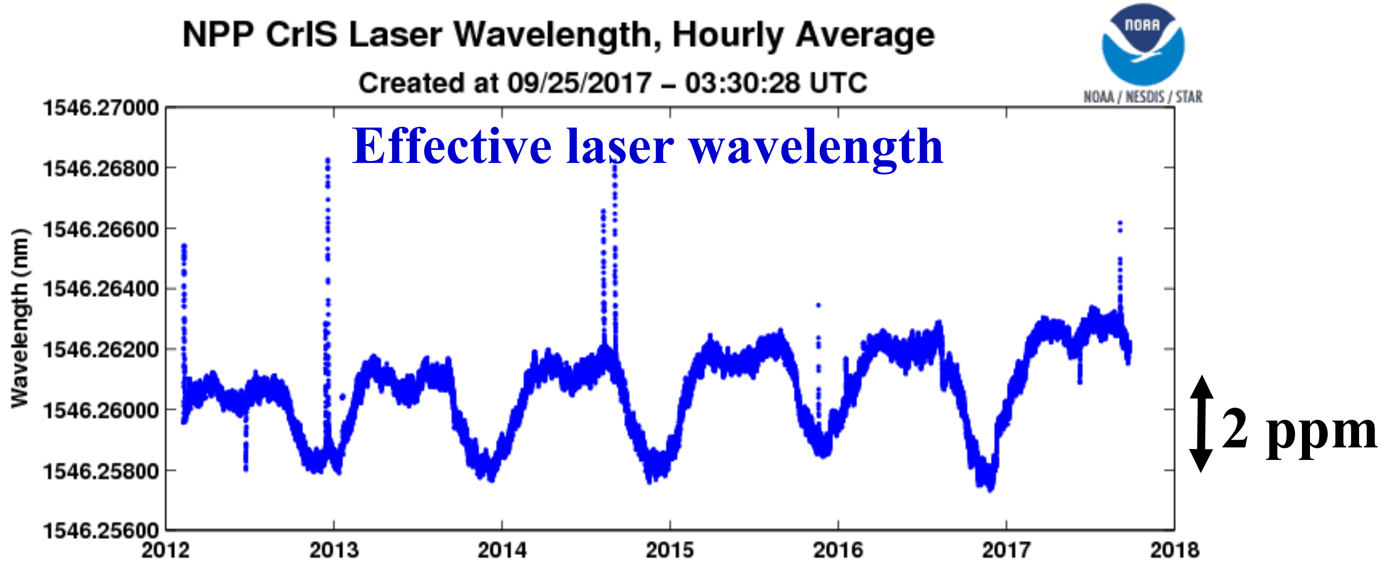




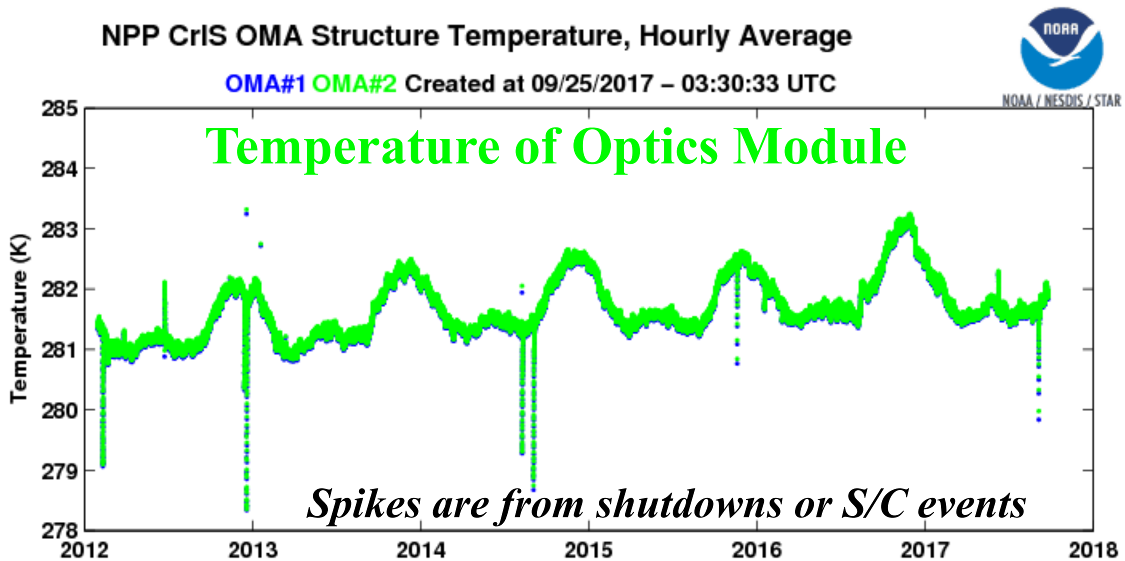
AIRS observations of tropical storm Isadore on 22 Sept 2002 @ ~19:12-19:18 UTC

CrIS FTS Robust to Sensor Thermal Changes

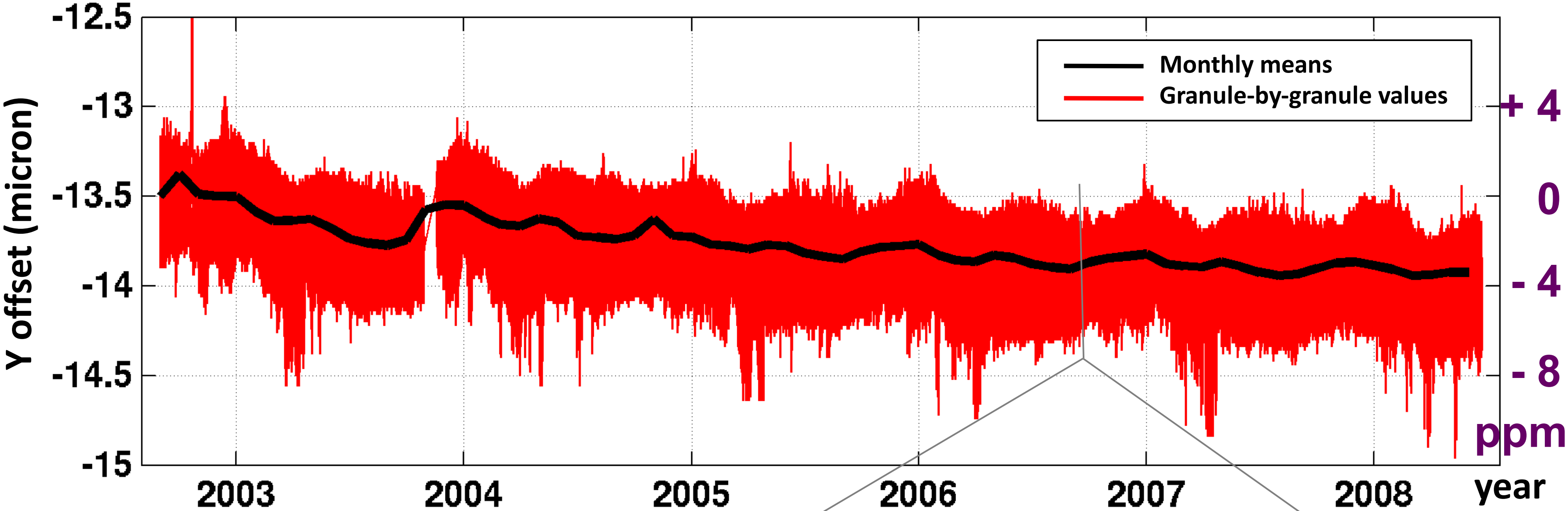
CrIS FTS sensitivity is < 3 ppm / ΔK of optics (eliminated by Neon Cal)



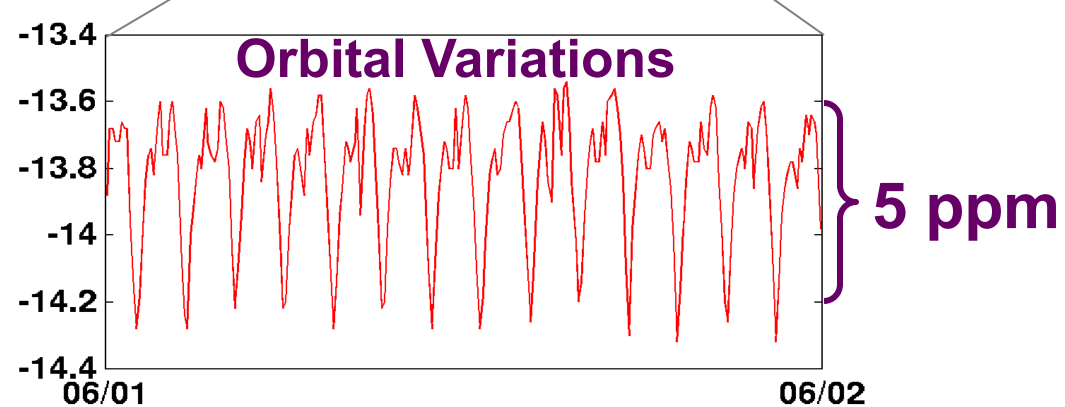
Note: AIRS spectral sensitivity is >150 ppm / ΔK of optics (6 ppm for orbital 0.04 ΔK)



AIRS Spectral Shifts (from tiny T changes)
derived using high peaking channels of Earth spectra



Larrabee Strow and Scott Hannon



AIRS has 6 ppm orbital variations

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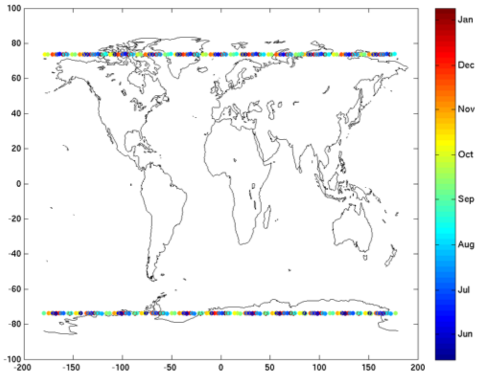
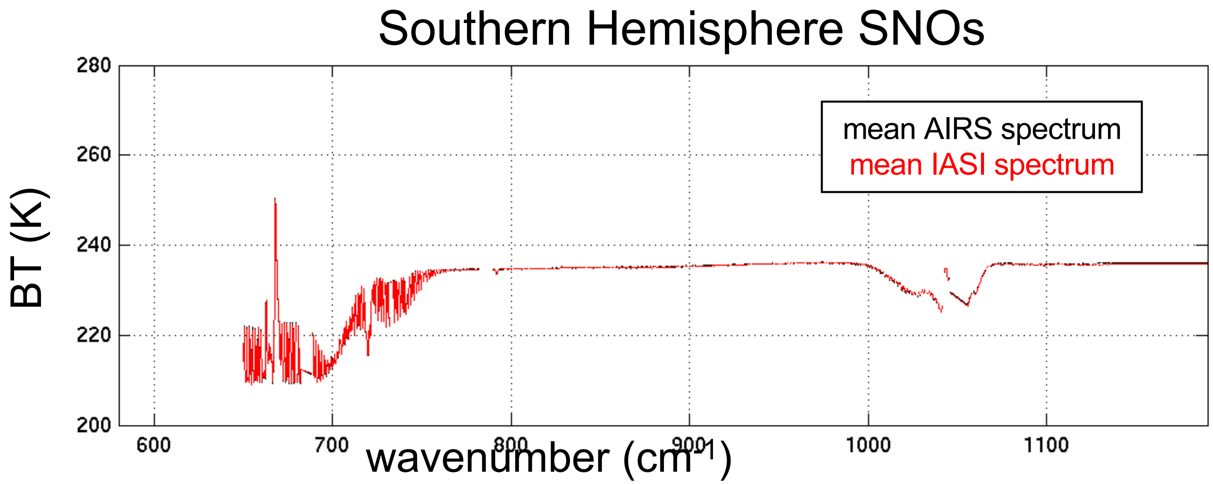
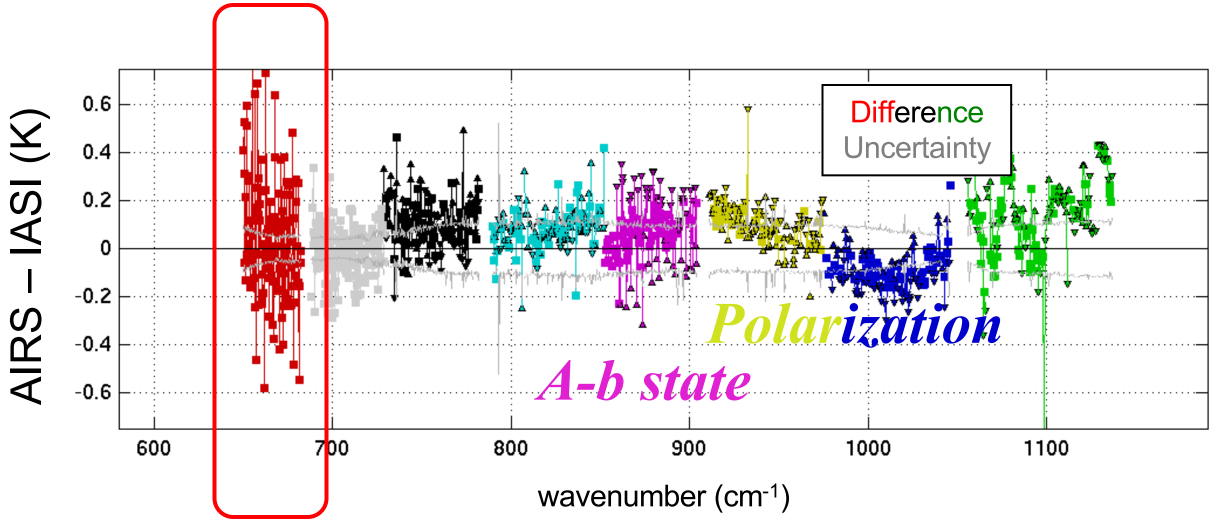
AIRS/IASI Simultaneous Nadir Overpass Comparisons
show differences consistent with spectral shift analysis







Correction for the shifts is possible.
What is the status of this reprocessing??

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Key Advantage of FTS for Climate Trending

- **Standardization of spectra from different instruments:** A rigorous mathematical formalism allows straight forward transformation of IASI spectra to CrIS Spectral properties for comparison or trending (or clearly CrIS to CrIS for JPSS). **Note-** lack of a simple reproducible ILS makes AIRS hard to compare to other instruments-we often resort to double-differences with calculations-it would not even be easy to rigorously compare AIRS to a second AIRS

  - **Spectral Scale standardization is straight forward for FTS** that is naturally Nyquist sampled

  - **First order ILS standardization is routine,** and techniques of removal of subtle responsivity influences have also been recently developed in Europe and at UW-SSEC

CrIS: Its high accura... & special pro... mate

CrIS and other FTS sensors are certainly capable of continuing (and improving on) the AIRS record

A

B.

C. ... High Accuracy

a... Trending

D. Conclusions

Backup: Background on Accuracy Advance from High Spectral Resolution

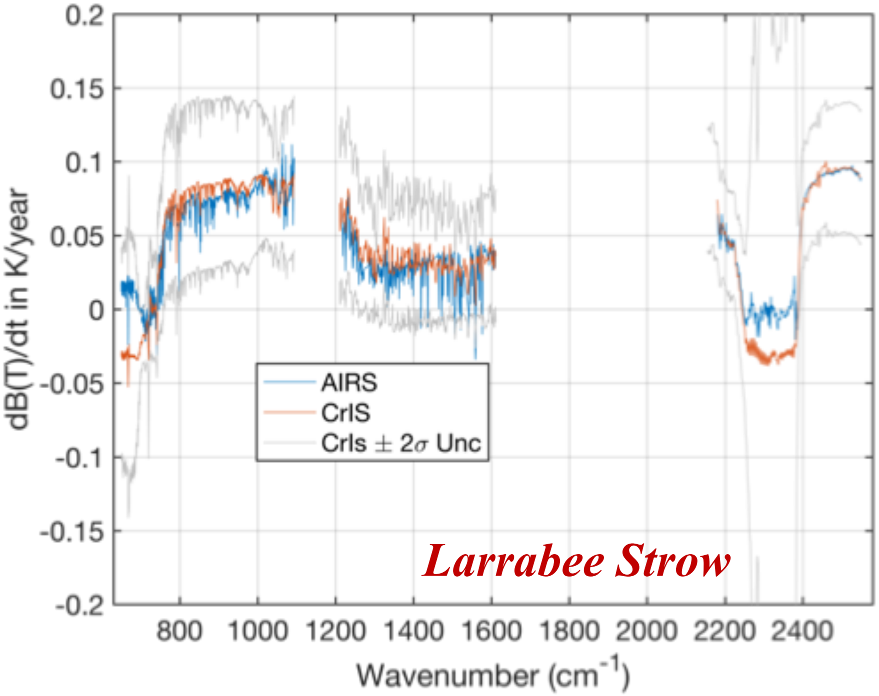
Conclusions (1)

JPSS scientists have been asked whether the CrISs on Suomi NPP and JPSS can continue the AIRS observing record from the NASA EOS program

- **YES is the brief emphatic answer from this material**
- In fact, **CrIS offers significant improvements** that stem from several fundamental advantages that FTS offers over a grating approach (as defined above)
- **And, CrIS data can easily be combined with data from other quality FTS instruments** (e.g. IASI and hopefully those from China & Russia) to create a much more complete climate record (from international cooperation)

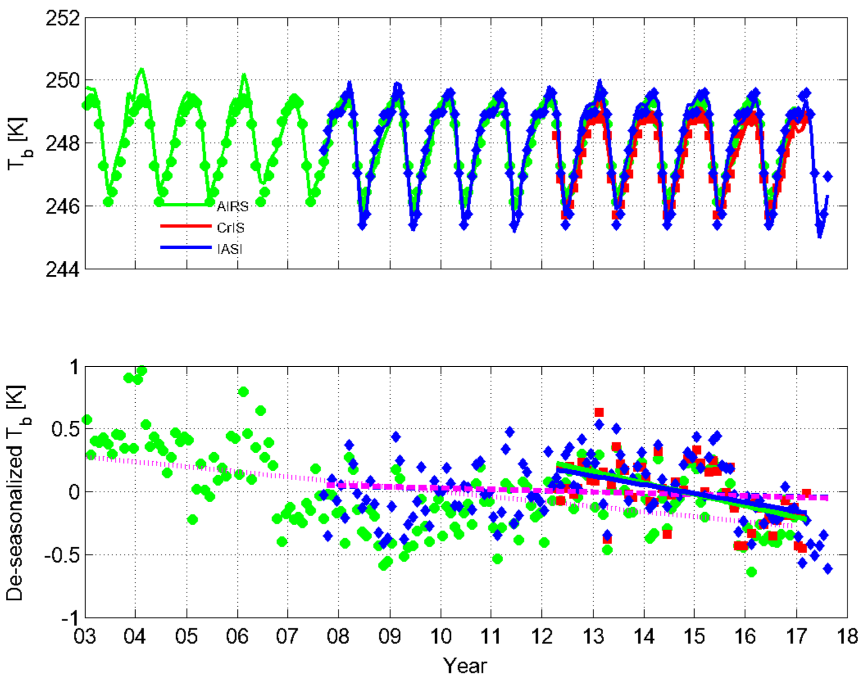
CrIS, AIRS and IASI see highly similar global trends

5 year linear BT trends for Global (random nadir) nighttime data



- **Differences as low as 0.01K/year in the window region**

Monthly mean Global nadir nighttime LW Stratospheric BT (667 cm^{-1}) time series



- **For the overlapping time period (2012 to present) the trends are remarkably similar (-0.09, -0.07,-0.08±0.02 K/year 1-sigma)**

- **Some significant trends observed in the last 5 years!**

Conclusions (2)

JPSS scientists have been asked whether the CrISs on Suomi NPP and JPSS can continue the AIRS observing record from the NASA EOS program

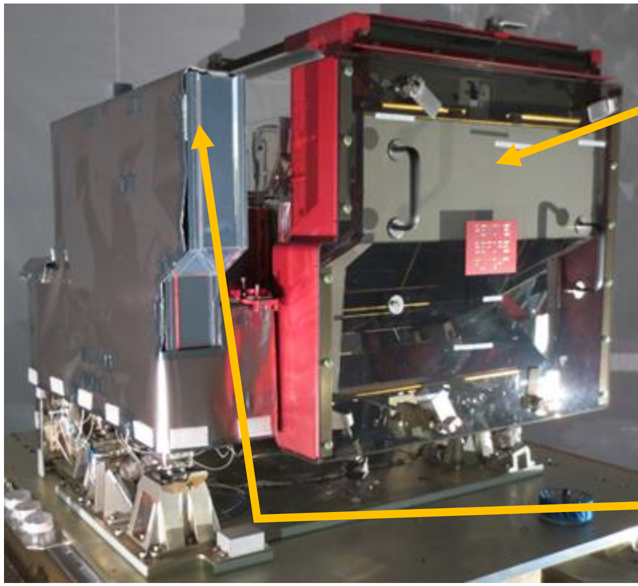
- **Further, CrIS is an excellent platform for Modular capability upgrades** that should be implemented as soon as possible to further enhance its benefits for weather and climate
- **Finally, when the CLARREO FTIR instrument is flown** (based on the UW-SSEC Absolute Radiance interferometer) it will be possible to combine data from all advanced sounders into an even more consistent record with absolute accuracy proven on-orbit by the ARI verification and test system

Advanced CrIS Goals for JPSS 3, 4…
(feasible with modular changes)

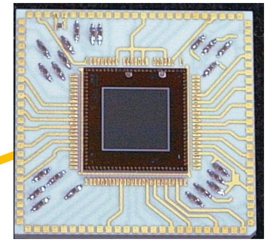
- Contiguous spectral coverage
  - **Trace gas information added**
  - **Intercalibration capability enhanced**
  - **Fused imager-sounder channels better supported**
- Higher spatial resolution and near-contiguous footprints
  - **Improved T & WV fields from better cloud avoidance**
  - **Better surface & near-surface T, WV by resolving unique surface properties**
  - **Two satellites per orbit give global water vapor fluxes and cloud motion winds from tracking the change of retrieved water vapor and cloud distributions, yielding improved heights over currents AMVs**

CrIS With Improved Spatial Resolution

HARRIS
TECHNOLOGY TO CONNECT, INFORM AND PROTECT™



Current CrIS Instrument



Replace 3x3 FPAs with 25x25 FPAs (Harris IRAD)

Replace Signal Processing Circuit Card Assemblies (CCAs) With Fixed-Rate Sampling CCAs Optimized for 25x25 FPAs (Harris IRAD)

Key Features

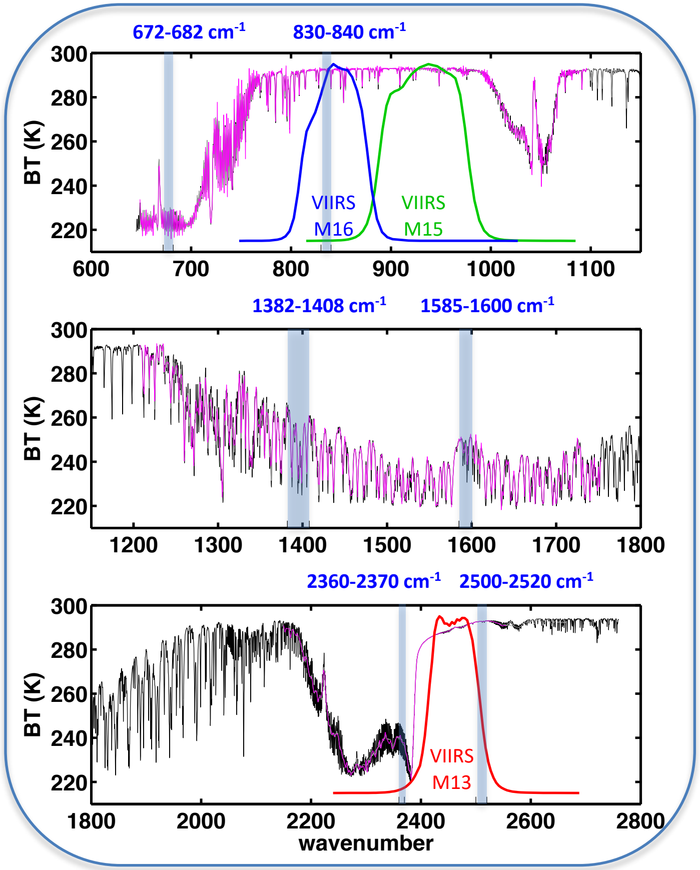
- 2km IFOVs provide much higher probability of cloud-free soundings
- FPA units available from IRAD in mid-2018
- Minimal changes to CrIS passive cooler
- No changes to CrIS optical design or any optical/structural modules
- Higher level of onboard processing can be used to maintain similar data rates
  - Onboard conversion to Principal Components of calibrated spectra

New HIRAS Sounder from China on FY-3E/F/G

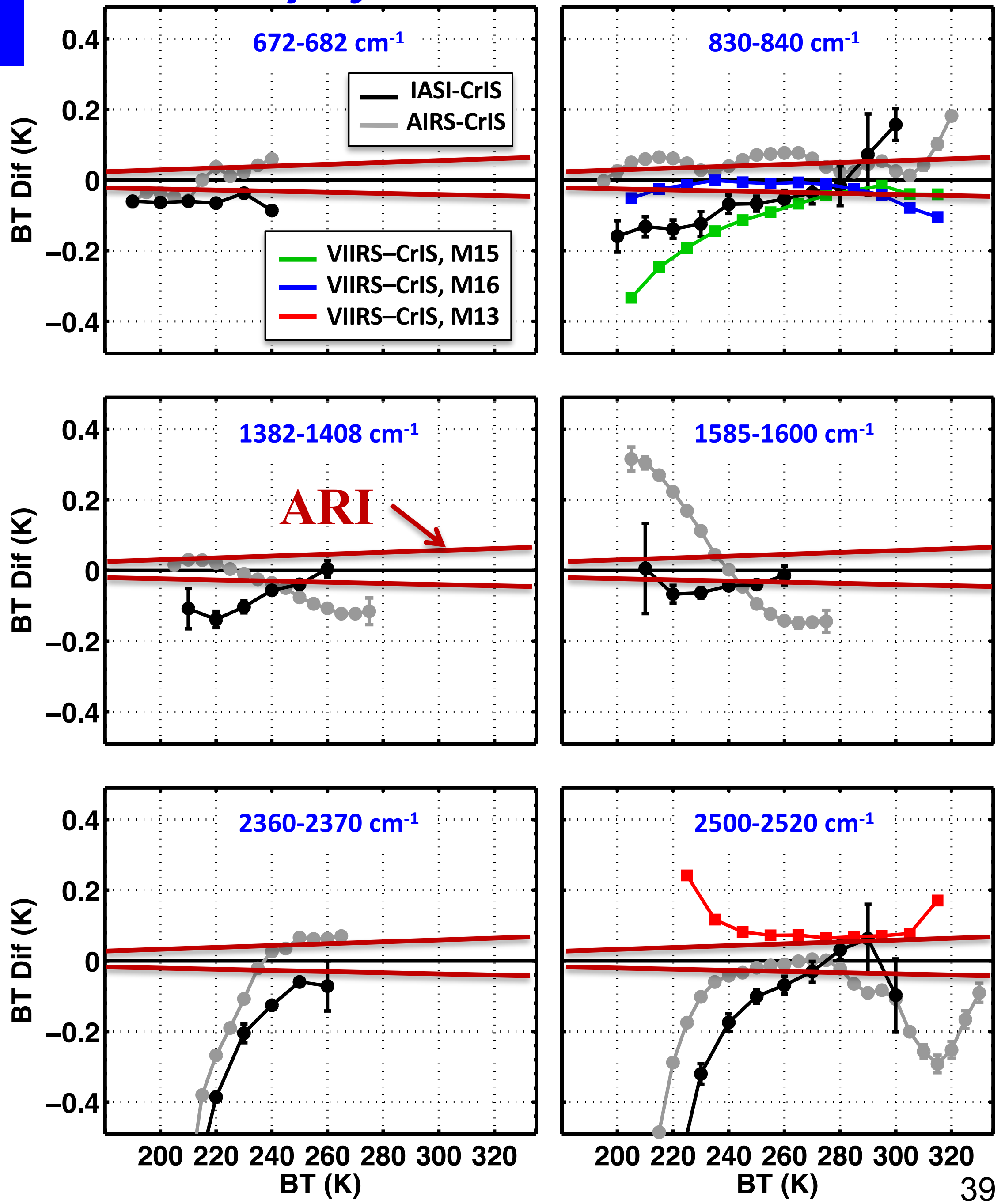
N0.	Sensor Siute	Sensor \ Satellite	FY-3E (05) EM Satellite	FY-3F (06) AM Satellite	FY-3G (07) PM Satellite	FY-3R (08) Rainfall Satellite
		Scheduled Launch Date	2018	2019	2021	2020
1	Optical Imagers	MERSI	√（LL）	√（III）	√（III）	√（III-Simplified）
2	**Passive Microwave Sensors**	**MWTS**	√	√	√	
		MWHS	√	√	√	
		MWRI		√	√	√
3	**Occultation Sounder**	**GNOS**	√	√	√	√
4	Active Microwave Sensors	**WindRAD**	√	√		
		Rainfall RAD	Early Morning	AM	PM	√
5	Hyperspectral Sounding Sensors	**HIRAS**	√	√	√	
		GAS (Greenhouse Gases Absorption Spectrometer)			√	
		OMS (Ozone Mapping Spectrometer)		√		
6	Radiance Observation Sensor Suite	ERM		√		
		SIM	√	√		
		SSIM (Solar Spectral Irradiation Monitor)	√			
7	Space Weather Sensor Suite	SEM	√			
		Wide Angle Aurora Imager			√	
		Ionosphere photometer	√(Multi-angle)		√	
		Solar X-EUV Imager	√			

CLARREO Mission Offers highly Valuable On-orbit Standard

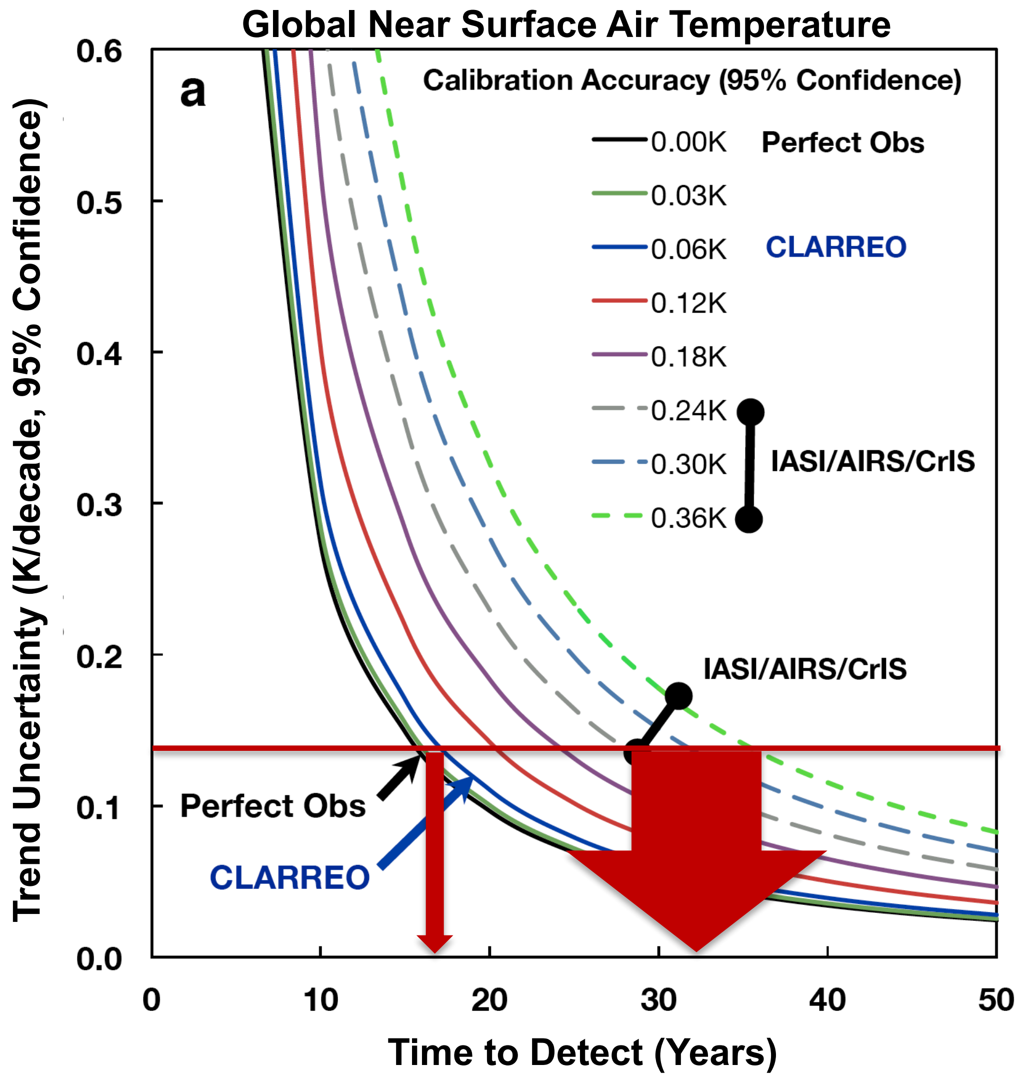
- **ARI 0.1 K not-to-exceed RU provides better "truth"**
- **Residual from CrIS for:**
  - AIRS
  - IASI
  - VIIRS: M13, M15, M16



Summary of Inter-calibrations Results



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



Example with ~ factor of 2 shorter Time to Detect

Wielicki et al., BAMS, 2013

Huge Financial benefit shown by Cooke and Wielicki

CrIS: Its high accuracy & special properties for climate

SSEC

A. CrIS Radiometri… racy

B. C… n

C. A… gh Accuracy ar…

D. Co…

CrIS Rests on a Strong Foundation of high accuracy FTS instruments

➡ <u>Backup</u>: Background on Accuracy Advance from High Spectral Resolution

Since the mid 1980's, we have been learning that Spectrally Resolved Radiances in the IR can be measured with very high accuracy

(Potential accuracy actually improves as Spectral Resolution increases, contrary to some conventional wisdom, Goody & Haskins, J Climate,1998)

Because of this, High Resolution IR radiance observations are now concerned with <u>tenths of K, not degrees K</u> and are well suited to climate observing!

A long list of IR spectrometers since IRIS & SIRS (1969) have taught us a lot about Calibration

- **High-resolution Interferometer Sounder (HIS):** UW aircraft Instrument for NASA & NOAA
- **Atmospheric Emitted Radiance Inteferometer (AERI):** UW ground-based for DOE ARM Program
- **Scanning HIS (S-HIS):** UW aircraft instrument for DOE, NASA, & IPO
- **NPOESS Airborne Sounder Testbed (NAST-I):** MIT/LL, NASA LaRC, UW
- **Interferometer for Monitoring Greenhouse Gases (IMG):** Japanese ADEO
- **Michelson Interferometer for Passive Atmospheric Sounding (MIPAS):** ESA Envisat
- **Atmospheric IR Sounder (AIRS):** NASA EOS Aqua
- **Tropospheric Emission Spectrometer (TES):** NASA EOS Aura
- **Infrared Atmospheric Sounding Interferometer (IASI): EUMETSAT MetOp-A**
- **Atmospheric Chemistry Experiment (ACE):** Canadian Space Agency
- **TANSO-FTS:** Greenhouse Gases Observing Satellite (GOSAT), JAXA
- **Cross-track Infrared Sounder (CrIS): ITT for NPP/NPOESS**
- **Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS):** NASA New Millennium Program

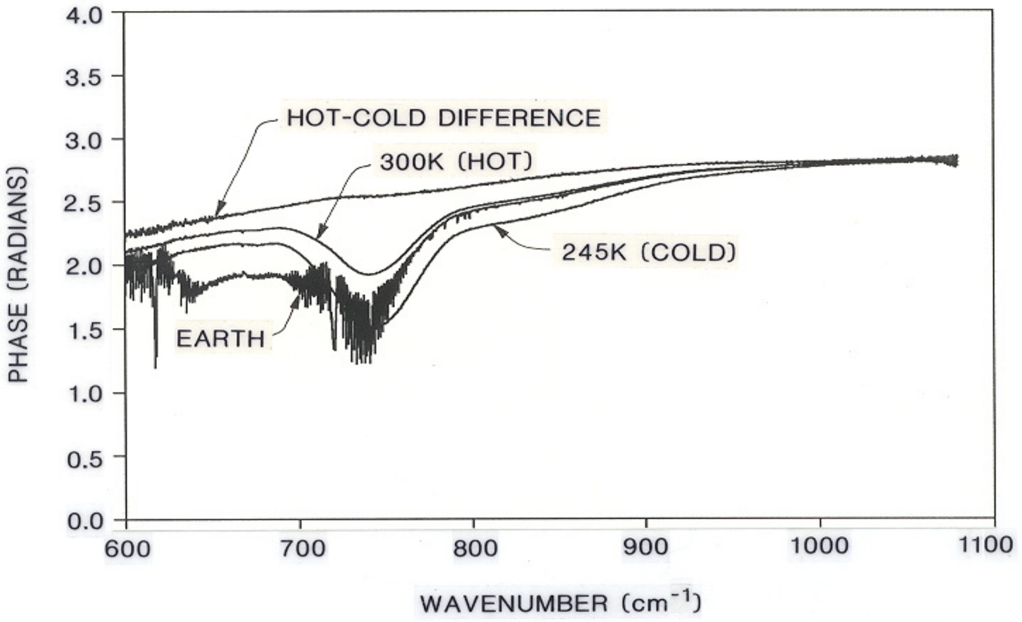
All, except AIRS, are FTS based interferometers

HIS Aircraft Instrument: 13 very successful missions, 1986-

Bomem DA2 interferometer (Henry Buijs), precursor to CrIS

HIS Lesson Learned

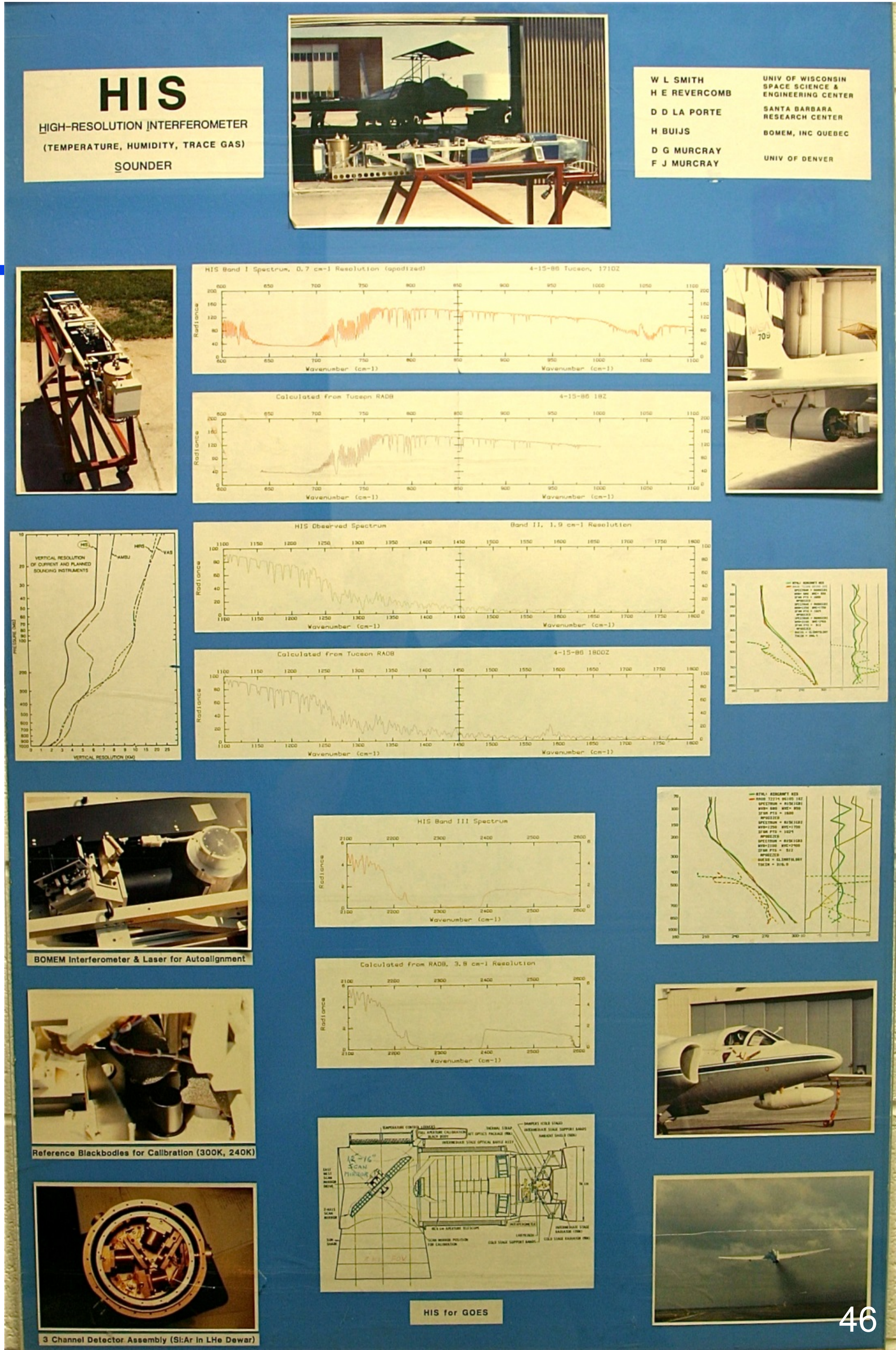
- **Learned to avoid errors from Phase source dependence (Revercomb, et al., 1988)**



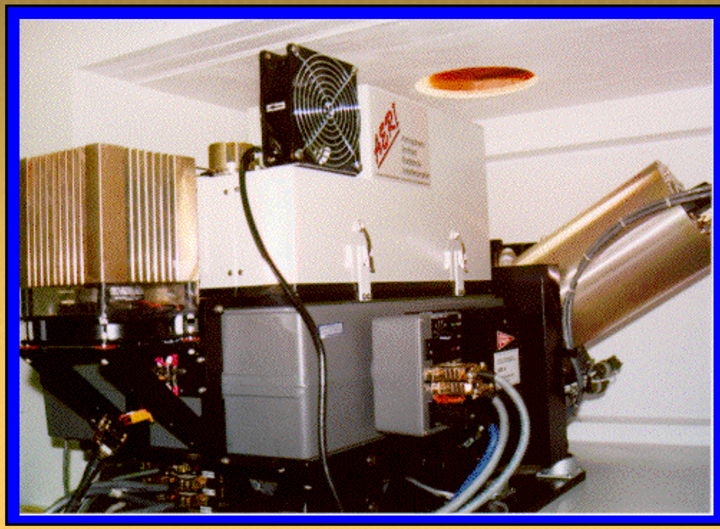
- **State-of-the-art FTS well suited to achieving accurate calibration**

Early Calibration

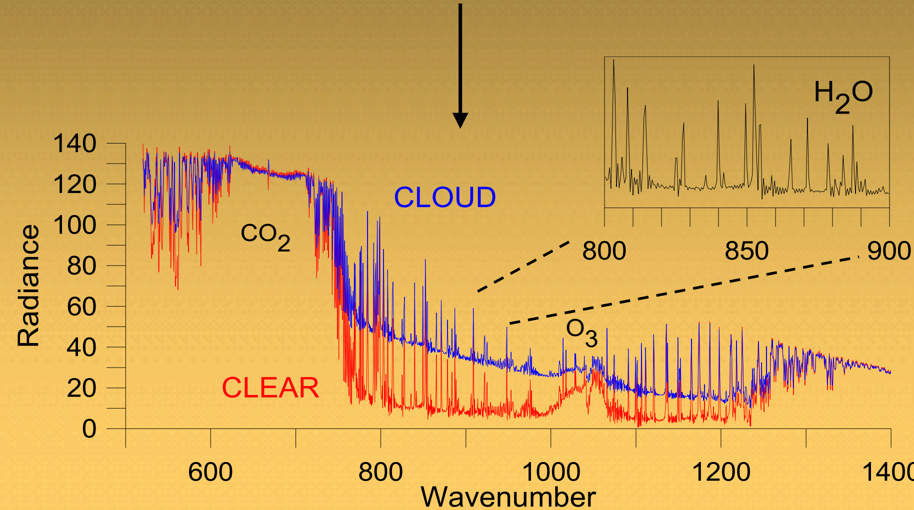
- < 0.5 K 3-sigma made radiative transfer issues apparent
- Tony Clough got real excited about the spectroscopy potential of HIS from this 1st poster in 1986



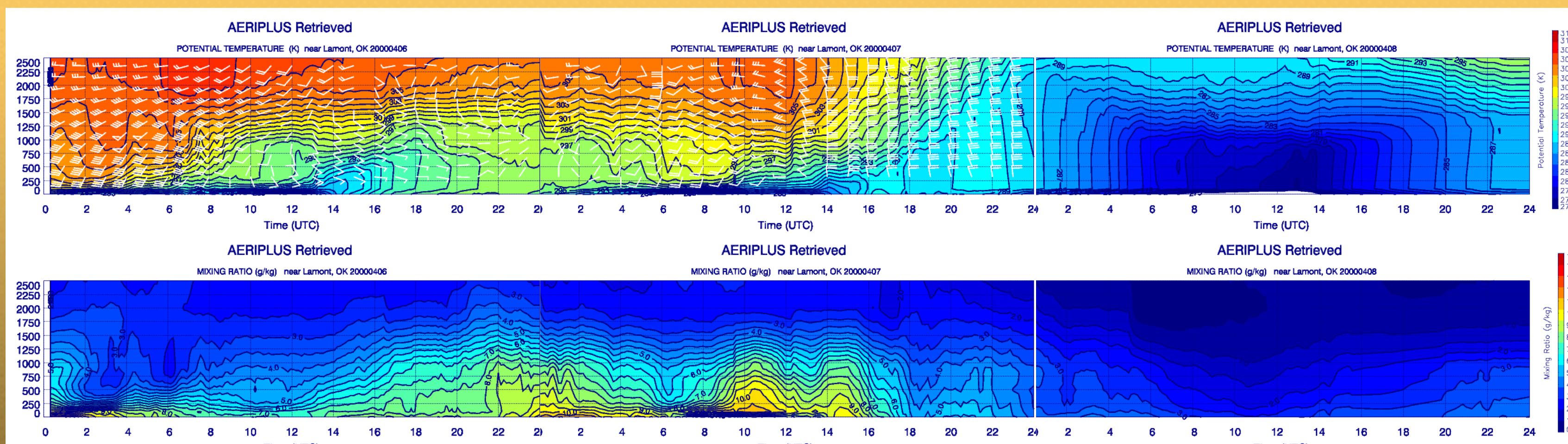
ATMOSPHERIC EMITTED RADIANCE INTERFEROMETER (AERI)



Operational at DOE ARM



Accurate High Resolution Radiometry

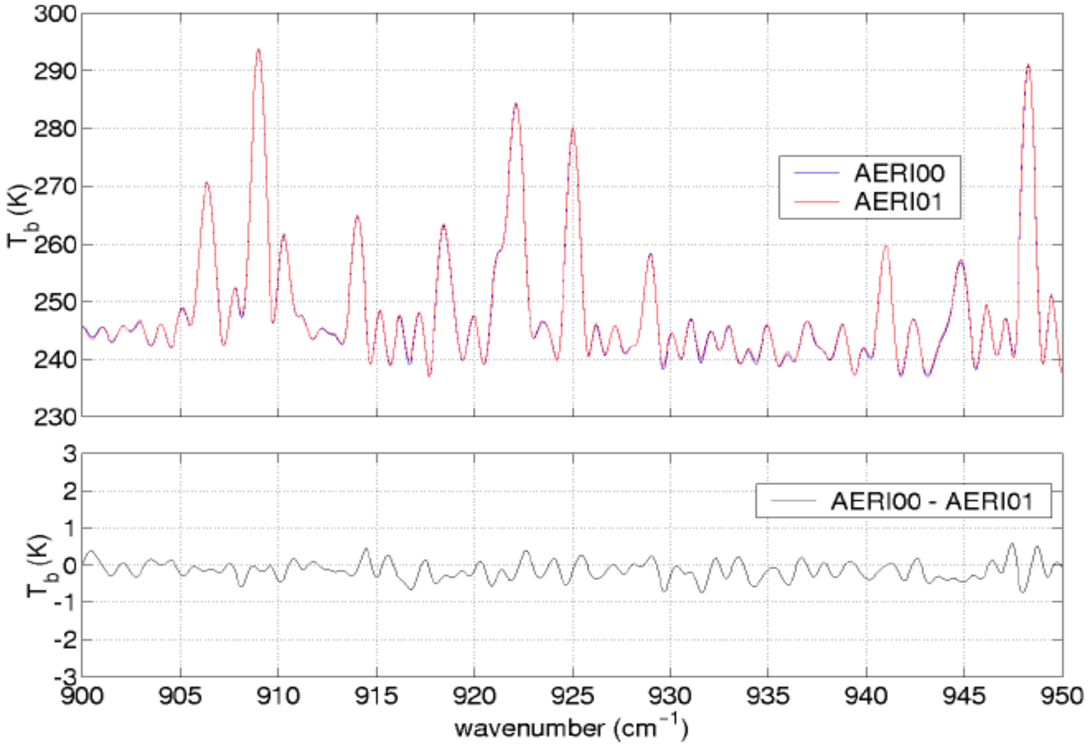


Continuous Atmospheric Profiling - Temperature and Water Vapor

Bomem Michelson Series Interferometer

AERI (1990-) Lessons Learned

- **Radiance calibration uncertainty consistently lower than uncertainty of radiative transfer and atmospheric state-led to improvements**
- **Accurate Non-linearity correction technique developed**
- **≥2 instruments are invaluable for assessing calibration uncertainty**



AERI/AERI comparison
9/16/1997
04:05-04:58
SGP ARM site

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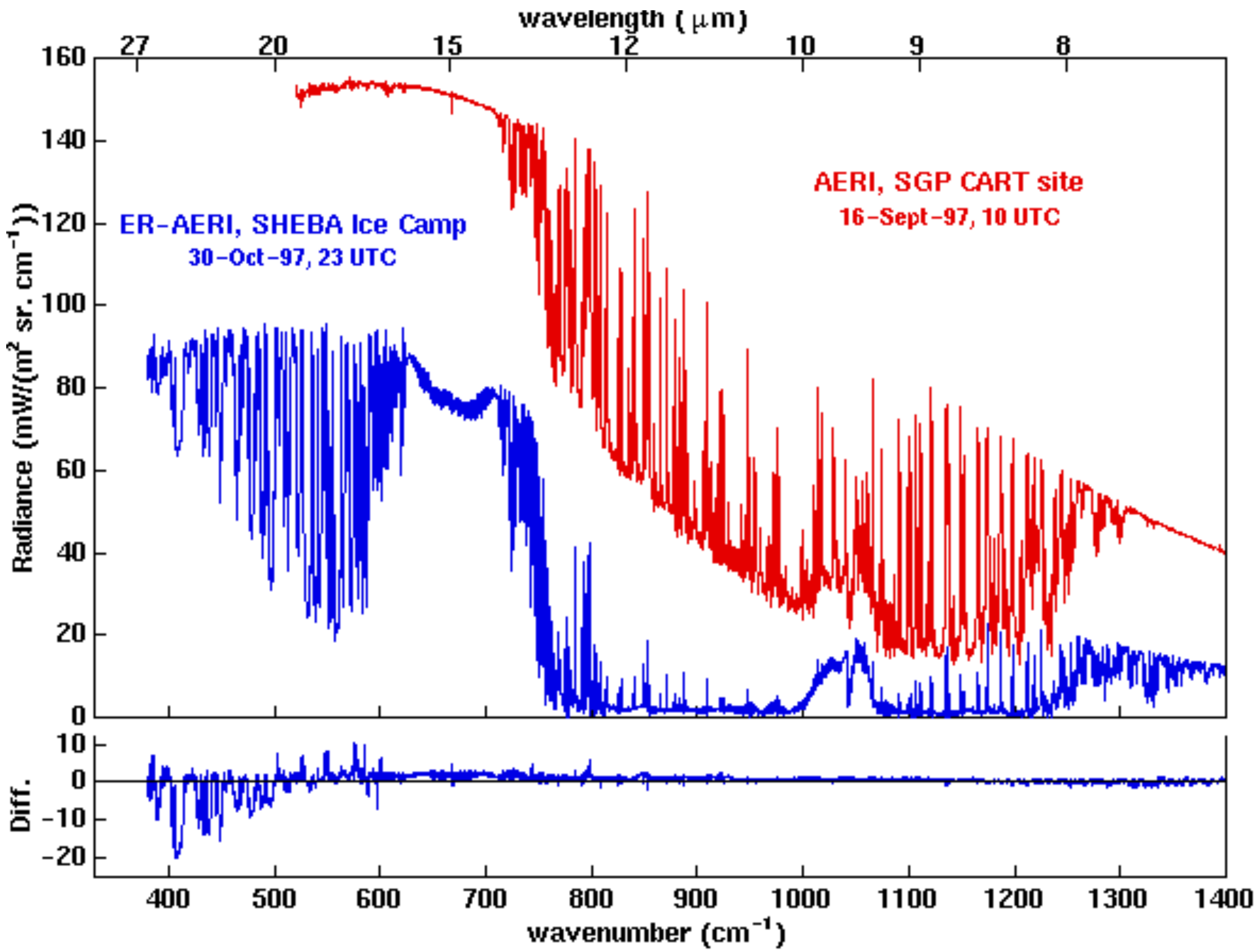
Water Vapor Continuum Improvement in Rotational Band



Clear sky **SGP** and **SHEBA AERI** spectra (top panel)
And SHEBA obs-calc using CKDv2.1

Key Radiative Forcing Result


nature International weekly journal of science

2015

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Research > Letters > Article

NATURE | LETTER

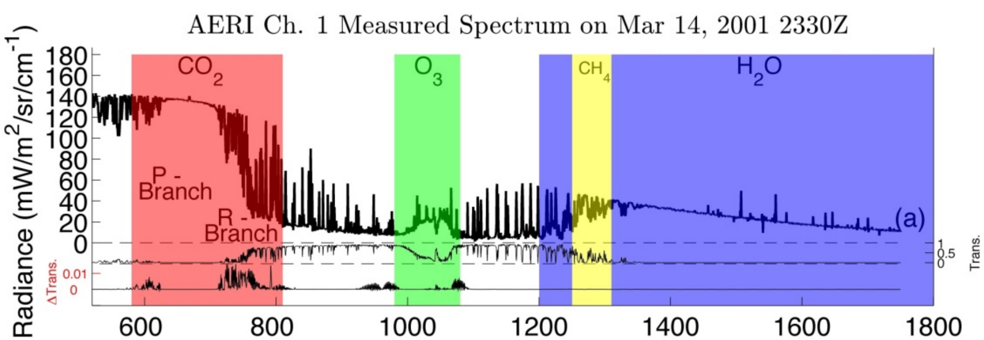
Observational determination of surface radiative forcing by CO_2 from 2000 to 2010

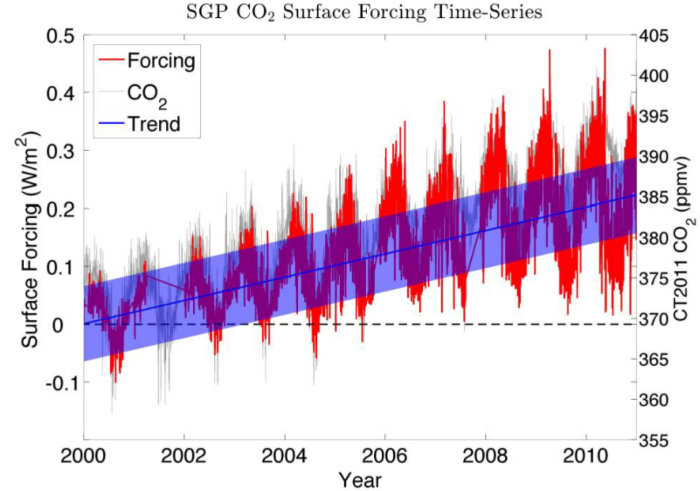
D. R. Feldman, W. D. Collins, P. J. Gero, M. S. Torn, E. J. Mlawer & T. R. Shippert

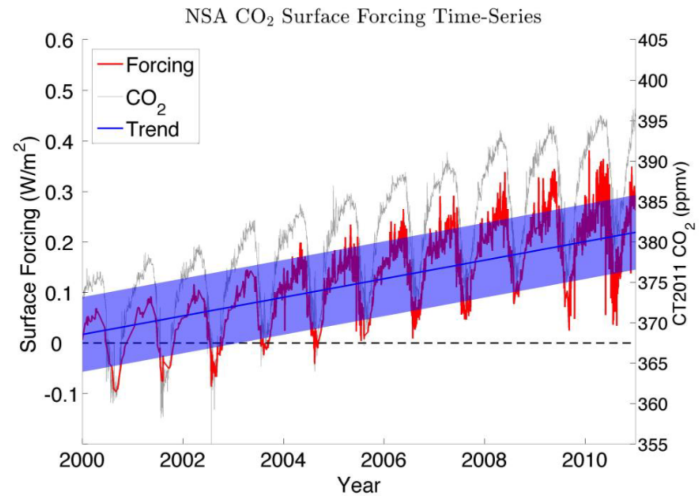
Affiliations | Contributions | Corresponding author

Nature (2015) | doi:10.1038/nature14240

Received 09 June 2014 | Accepted 15 January 2015 | Published online 25 February 2015







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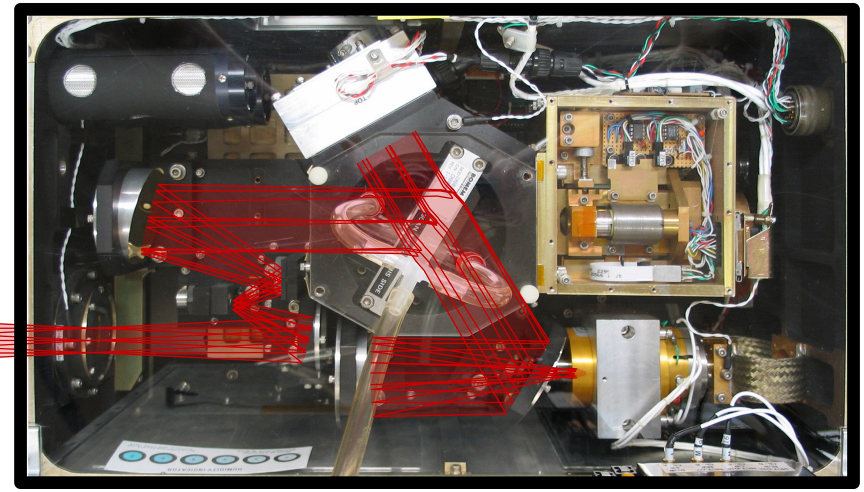
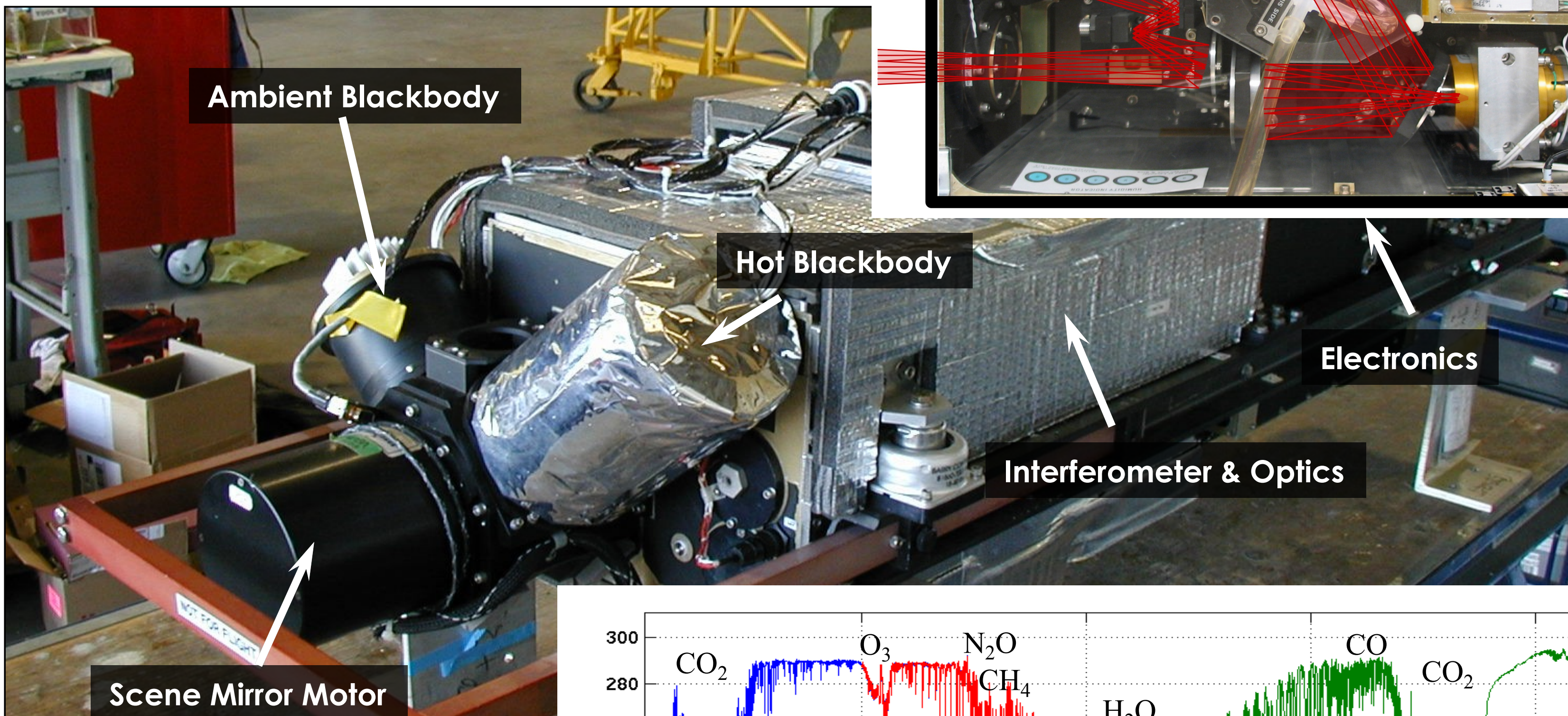
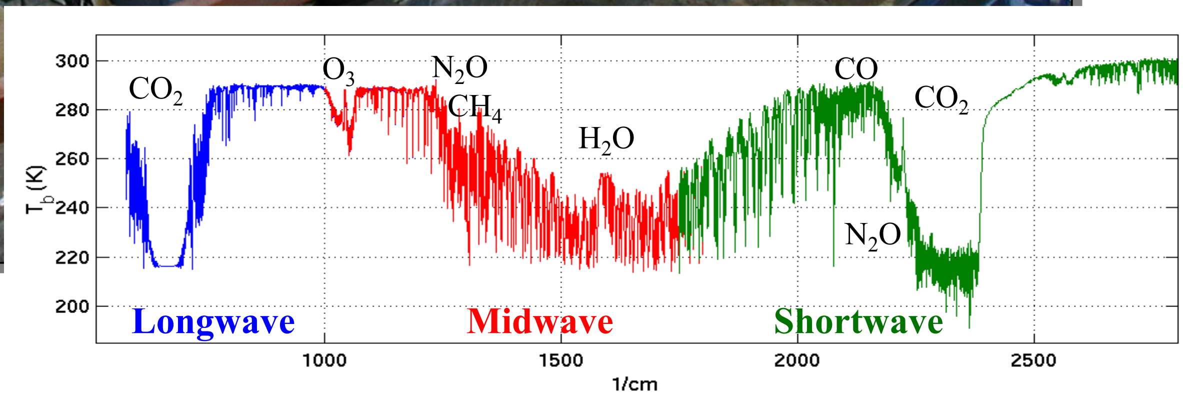
UW Scanning HIS

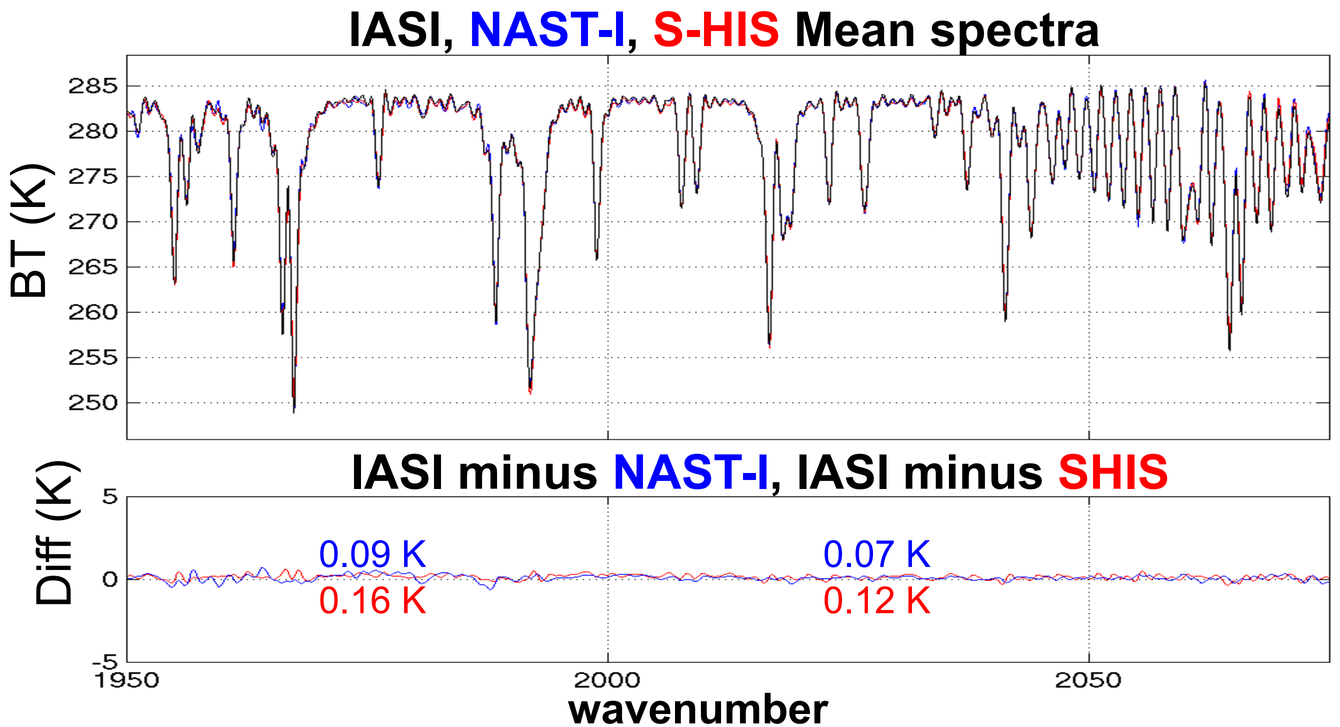






S-HIS / NAST (1998-) Lessons Learned

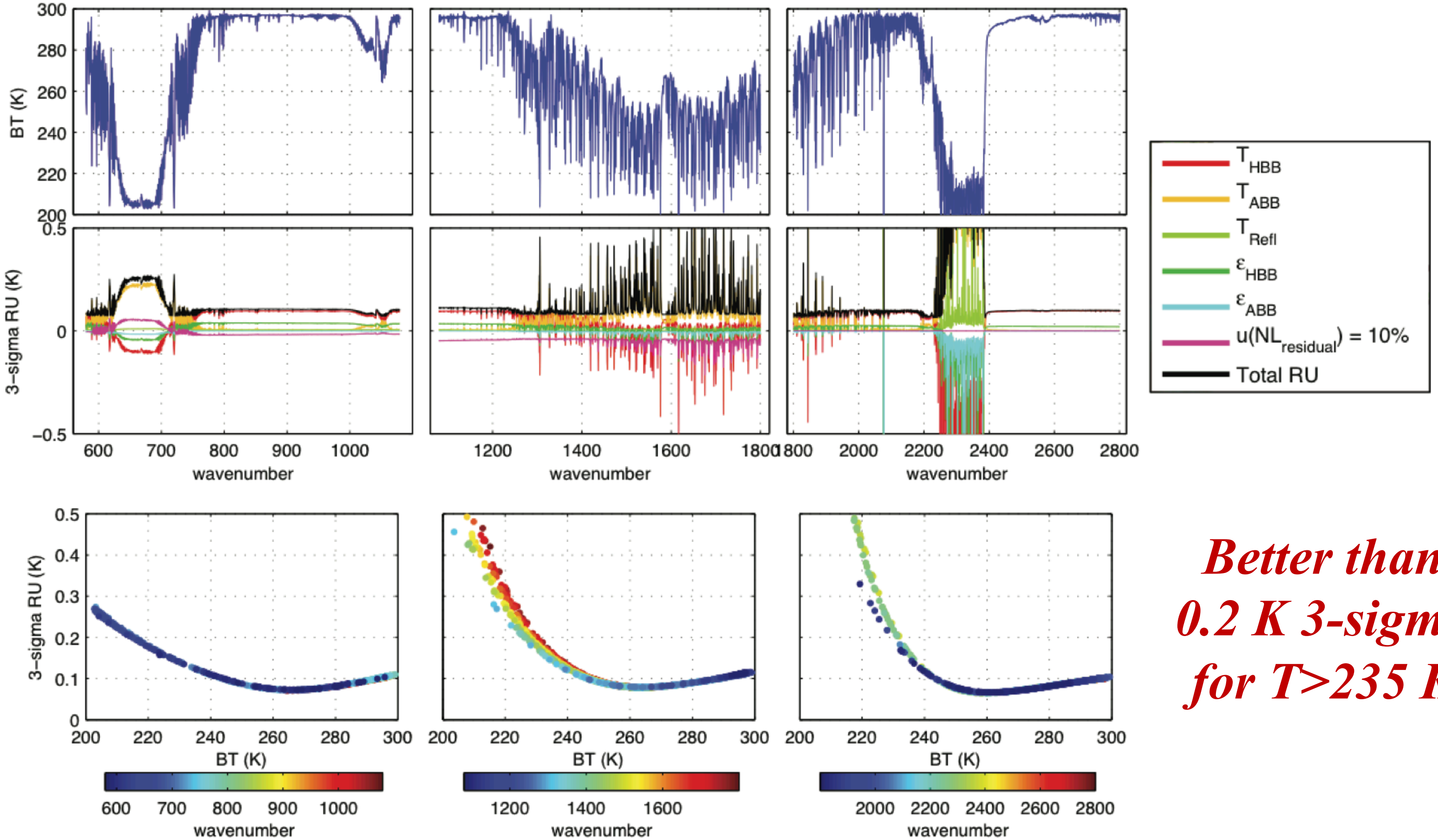
- More about Non-linearity correction techniques
- Re-enforced value of comparing 2 or more instruments
- Tilt induced Sample Position Error correction developed



IASI Validation
4/19/2007
SGP ARM

S-HIS Radiometric Uncertainty (RU)

S-HIS Brightness Temperature Spectrum and 3-sigma RU
(for clear sky conditions encountered during a S-NPP overpass on 2013-06-01)

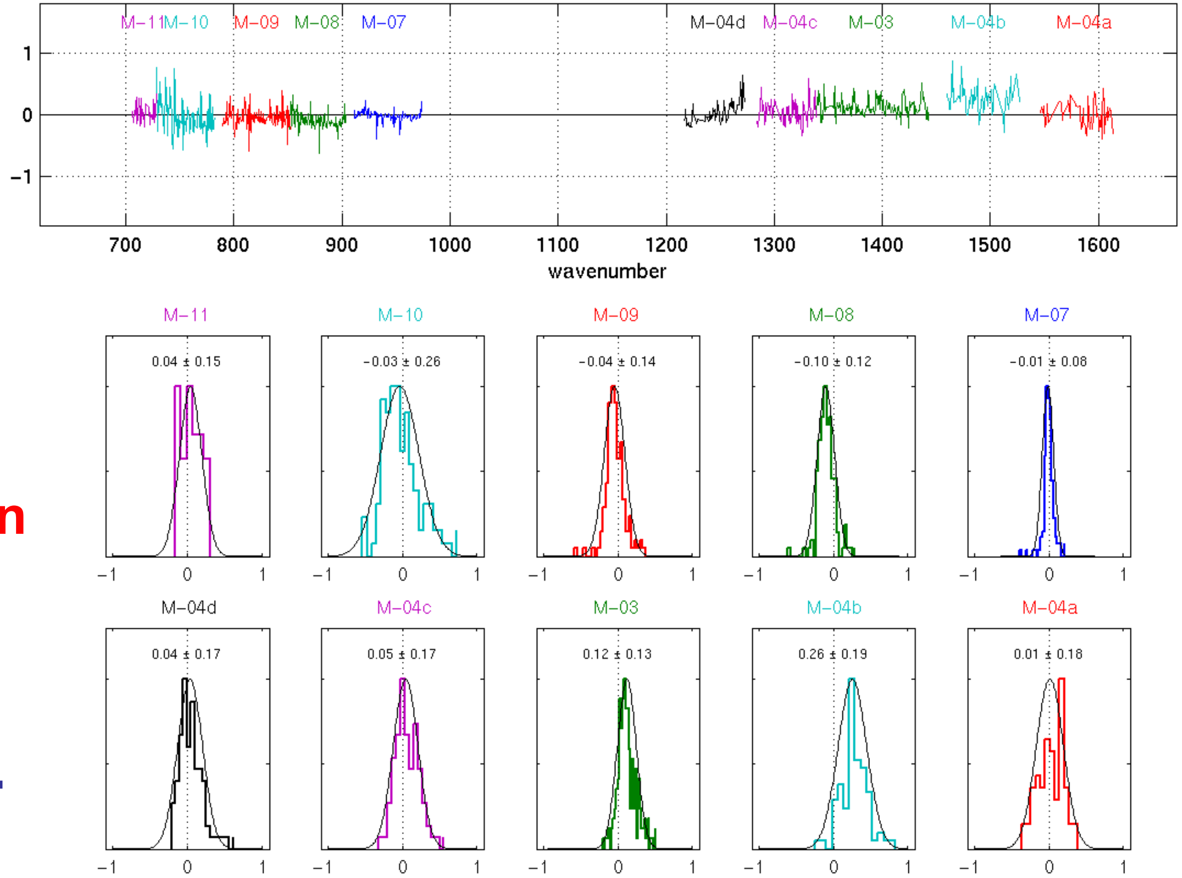


Better than 0.2 K 3-sigma for T>235 K

e.g. Tobin, D. C. (2007), High-Altitude Aircraft Observations Providing NIST-Traceable Benchmark Infrared Observations for GSICS, *in the October 2007 GSICS Newsletter*.

AIRS (2002-) Lessons Learned

- Highly accurate calibration can be achieved with a grating too
- Detector-induced correlated noise is an issue
- Extreme thermal control needed for ILS stability



1st demo of direct airborne validation

AIRS Validation with S-HIS

11/21/2002

Gulf of Mex

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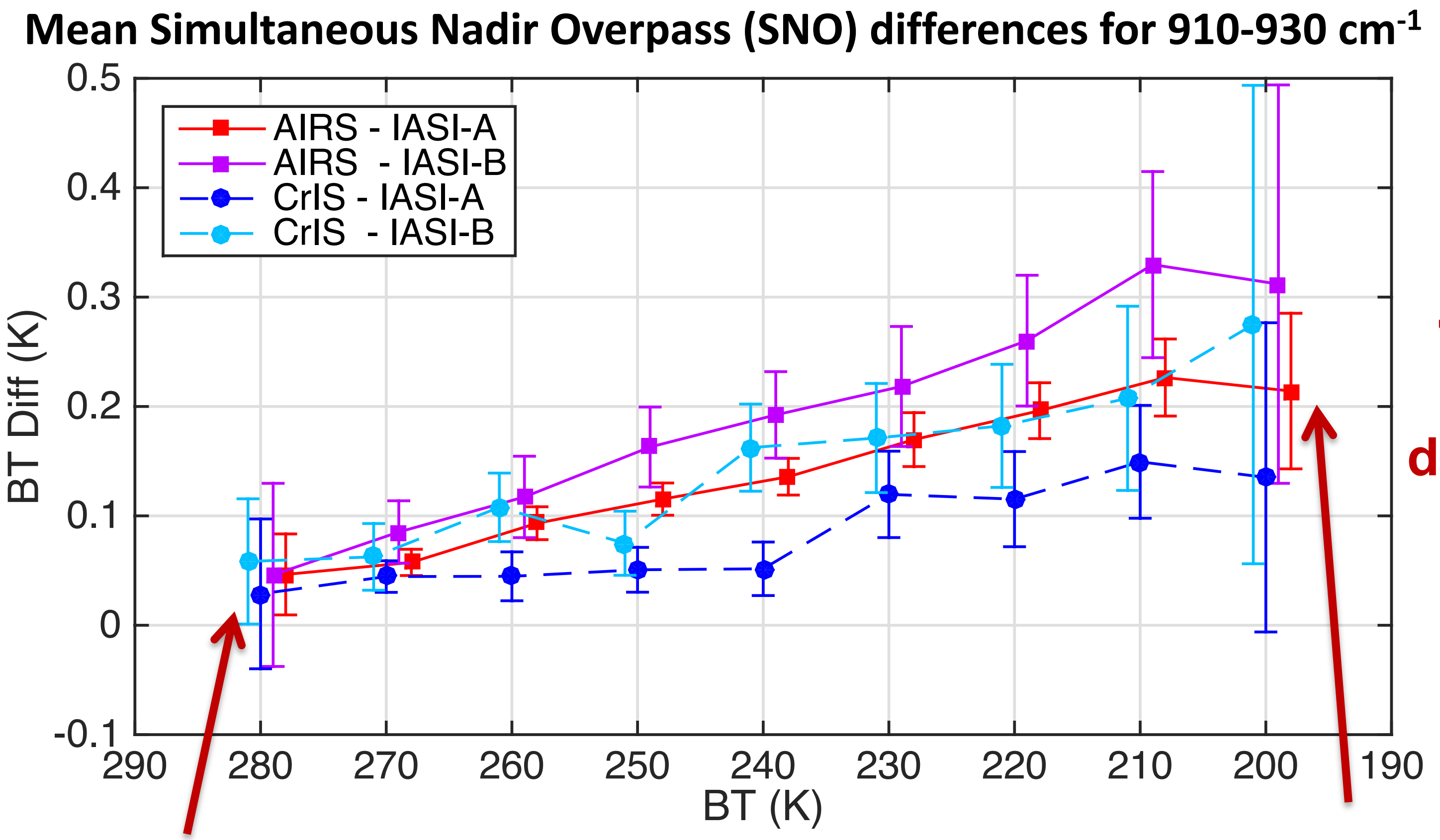
Sounders SNOs Show Good Agreement



< 0.3 K relative differences

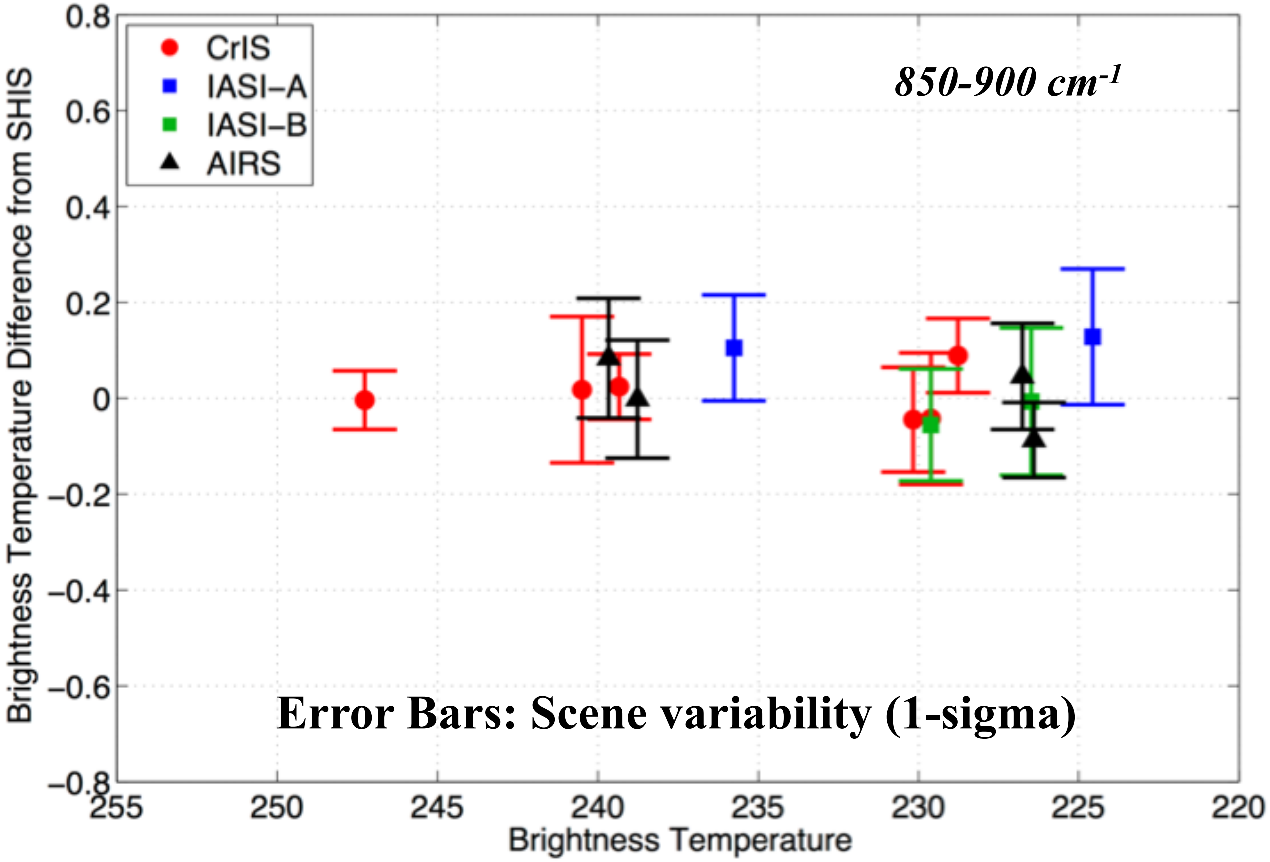
0.050 K Agreement

Error-bars represent statistical matchup uncertainty, not sensors uncertainty

SNOs: AIRS-IASIA, CrIS-IASIA
AIRS-IASIB, CrIS-IASIB

CrIS and AIRS radiances agree exceptionally well, even at cold temperatures

2015 Scanning-HIS aircraft validation of AIRS, CrIS, and IASI over



- ***Agreement better than 0.2K over a range of cold scenes***

IR Calibration Accuracy

- **Order of Magnitude advancement** over past filter radiometers offered by new high spectral resolution sounders (AIRS on EOS Aqua, IASI on MetOp A & B, CrIS on Suomi NPP)
- **Accurate knowledge of Spectral ILS** (Instrument Line Shape) is largely responsible
- **Important for forecast model assimilation & climate**
- **Advanced Sounders have reasonable agreement on recent multi-year brightness temperature trends**
- UW **Absolute Radiance Interferometer (ARI) for CLARREO** uses this advantage and **novel on-orbit standards** to offer a new absolute reference for climate