Calibration of the Scanning High-resolution Interferometer Sounder (S-HIS) Infrared Spectrometer: Overview (Part 1)

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Calibration of Airborne Sensor Systems
Utah State, 22 August 2005

TOPICS

1. S-HIS Summary
2. S-HIS Radiometric & Spectral Calibration
3. Tests of High Spectral Resolution Calibration
   (including S-HIS comparison to AIRS)
4. The Promise of CrIS for NPOESS

1. S-HIS Summary

UW Scanning HIS: 1998-Present

(HIS: High-resolution Interferometer Sounder, 1985-1998)

Characteristics

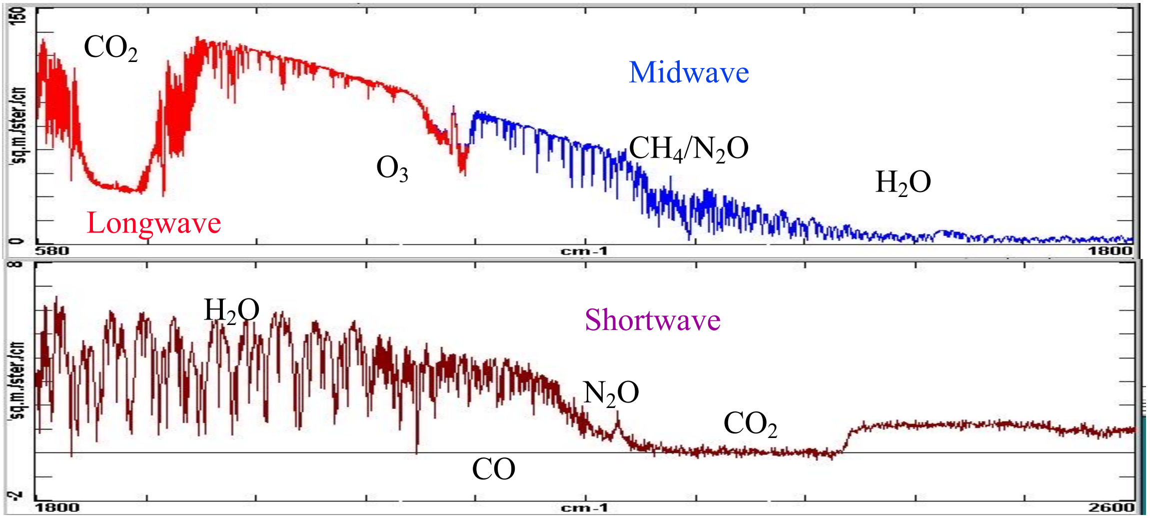
Spectral Coverage: 3-17 microns

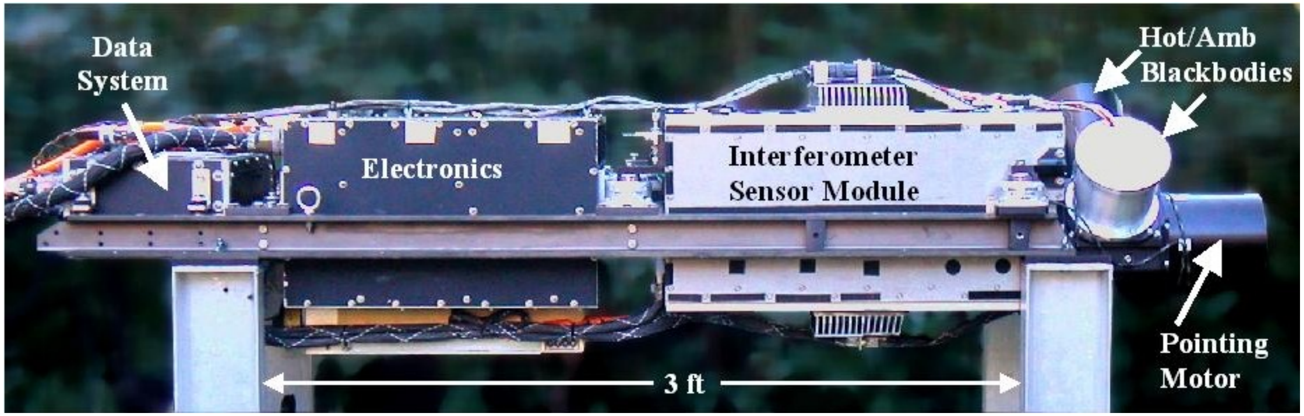
Spectral Resolution: 0.5 cm^{-1}

Resolving power: 1000-6000

Footprint Diam: 1.5 km @ 15 km

Cross-Track Scan: Programmable including uplooking zenith view



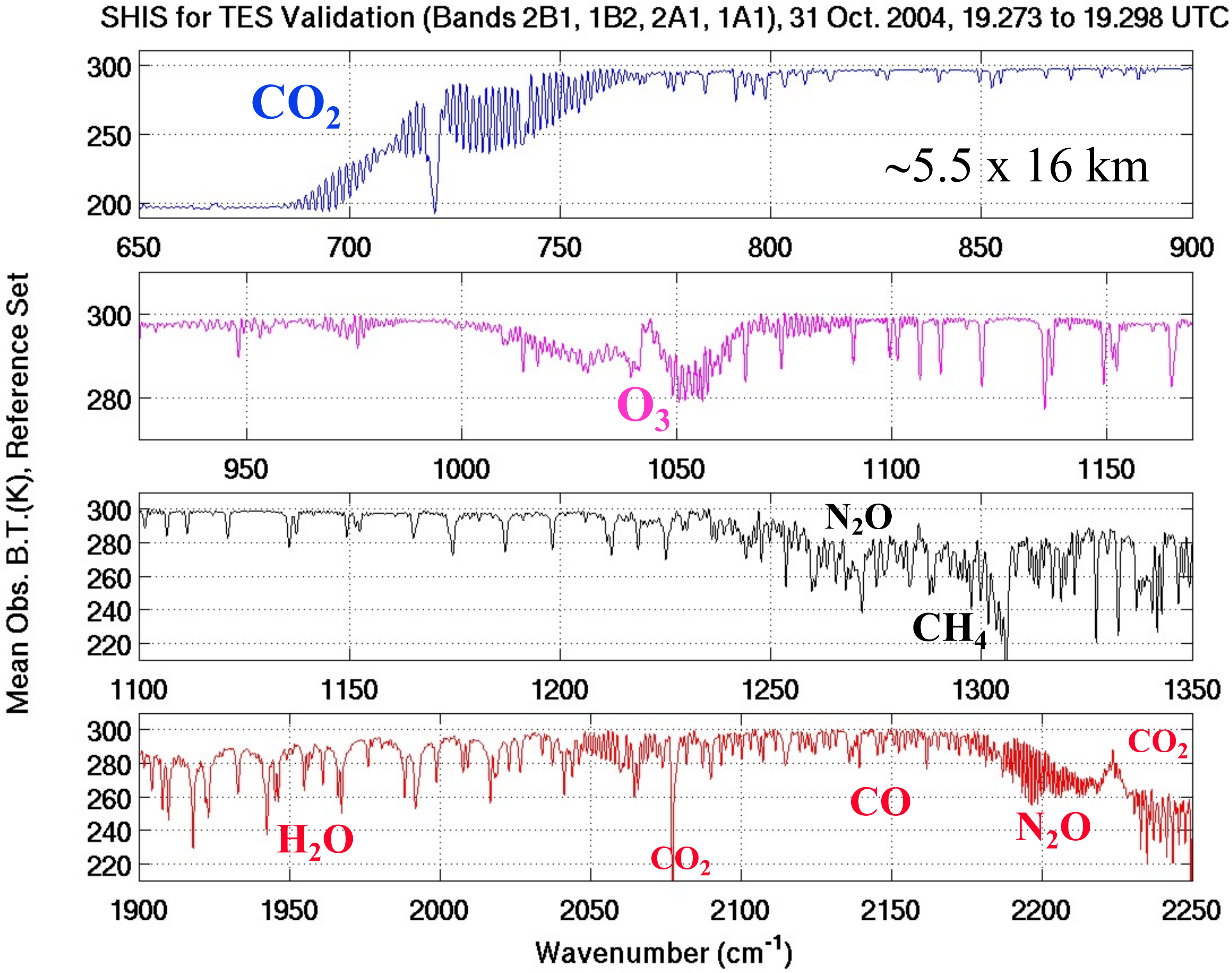


Applications:

- ◆ Radiances for Radiative Transfer
- ◆ Temp & Water Vapor Retrievals
- ◆ Cloud Radiative Prop.
- ◆ Surface Emissivity & T
- ◆ Trace Gas Retrievals

S-HIS –Tropospheric Emission Spectrometer (TES) Bands

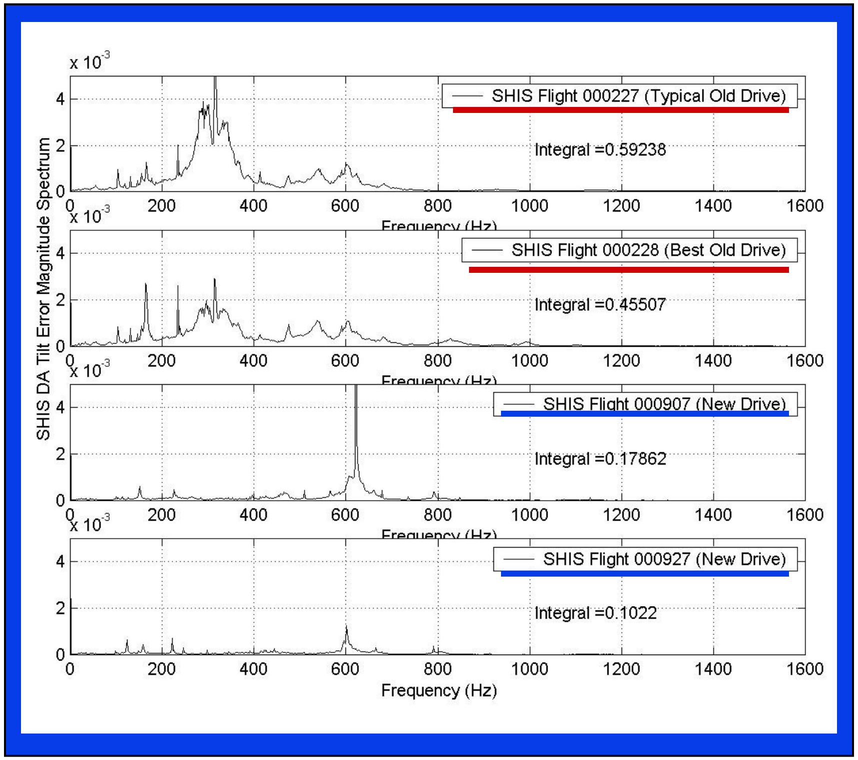
near 31 Oct overpass



Scanning HIS Interferometer: with Telescope, Collection optics, & Detectors/Cooler

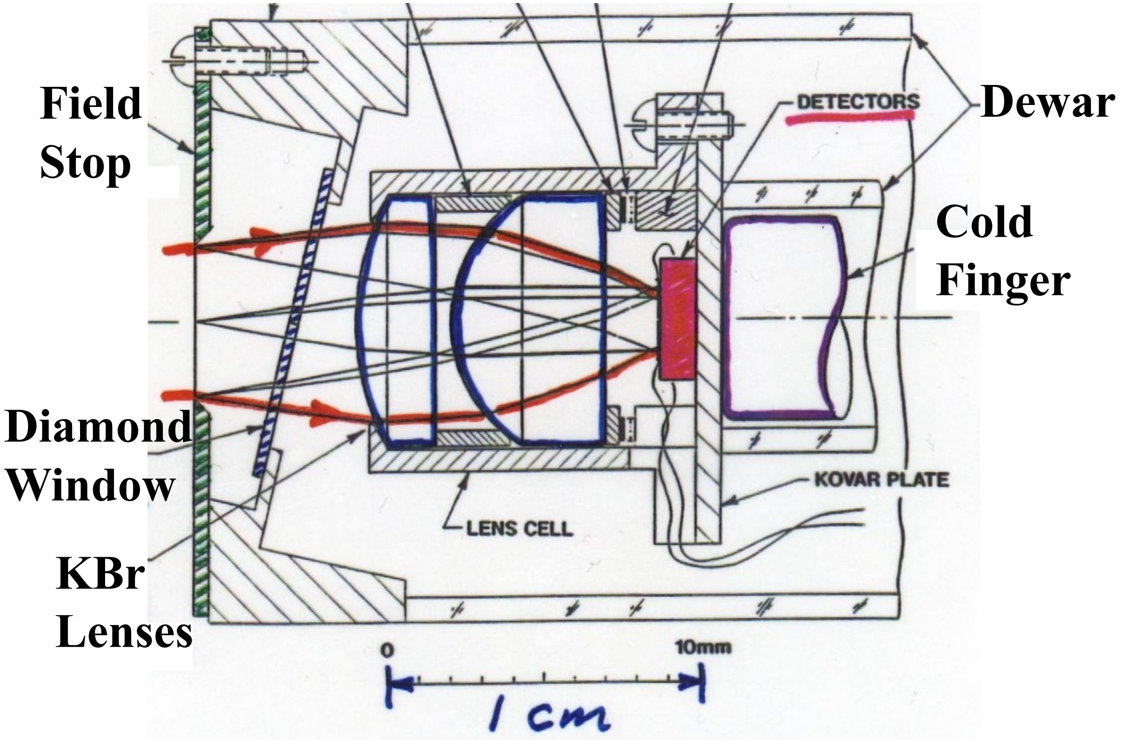
Laser metrology located on bottom of optical bench

S-HIS Linear Bearing Based Michelson Drive

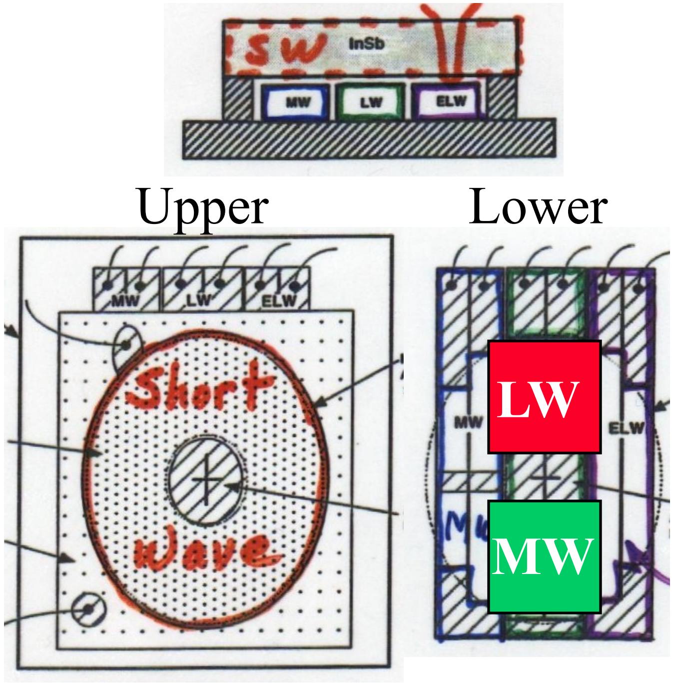


Comparison of Tilt Spectra measured during flight form the **old** and **new** Michelson Drive assemblies as measured by the S-HIS laser based dynamic Alignment system. The new drive eliminates significant tilt dynamic amplitude Below 600 Hz. In addition, the overall tilt magnitude is lower by almost a factor 6 with the new drive.

Scanning HIS Detector/Dewar Configuration



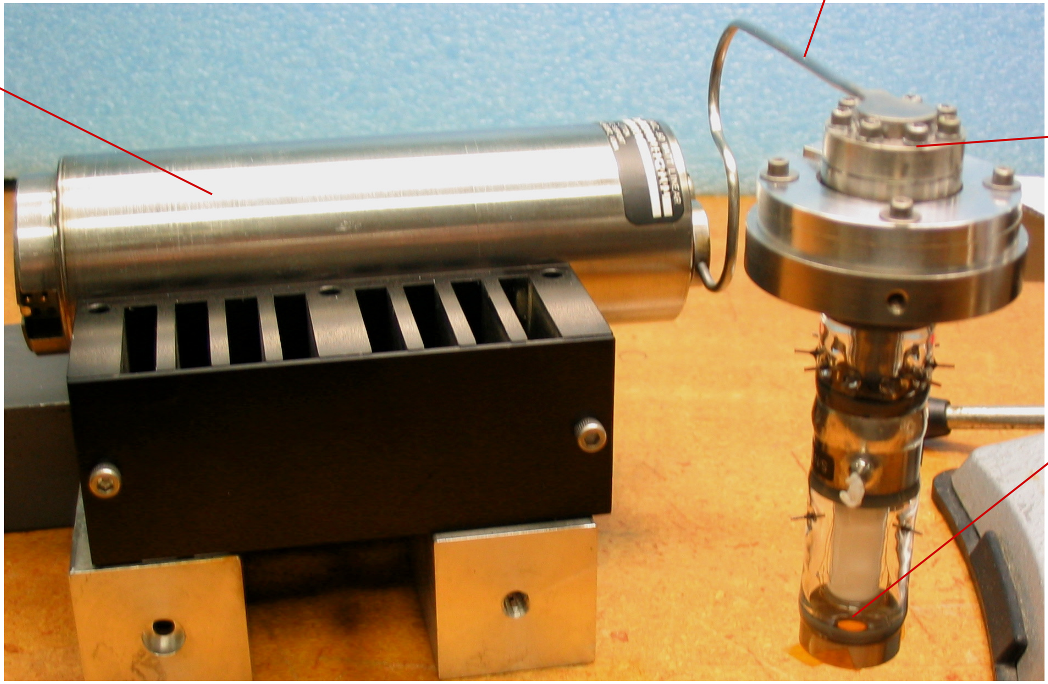
Dewar with tilted diamond window & KBr lenses



Sandwich Detectors: Shortwave InSb on top MW & LW below

S-HIS Split Cycle Stirling Cooler

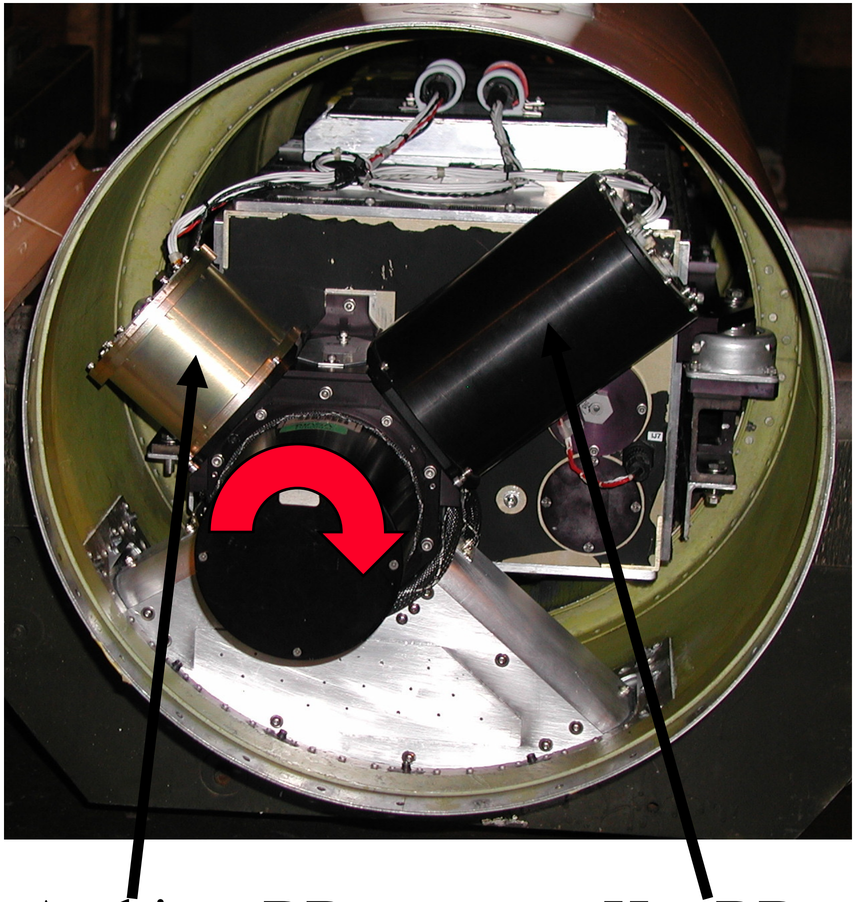
- Allows vibration isolation
- Simplifies cooler replacement

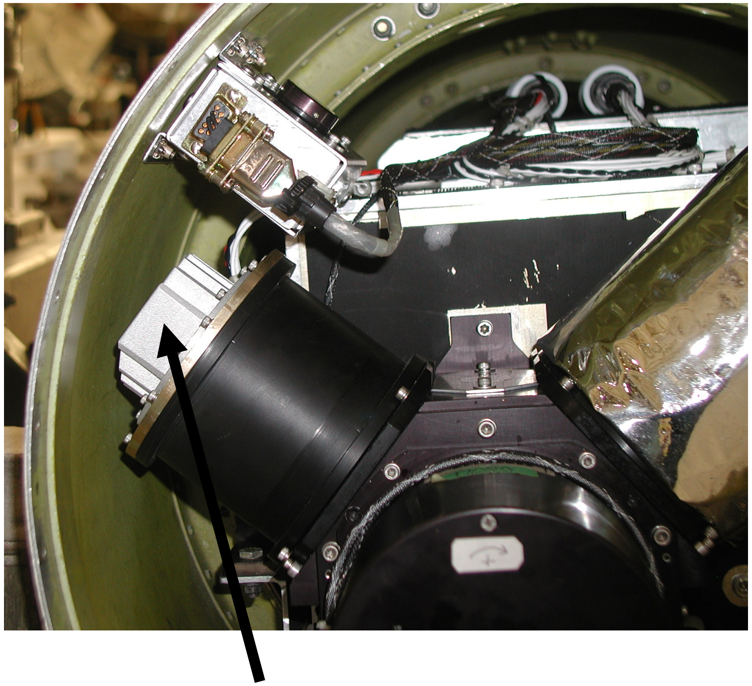


Litton cooler with dewar

S-HIS In-Flight Calibration

- Hot and Cold onboard BBs viewed every x-track scan (12 sec).

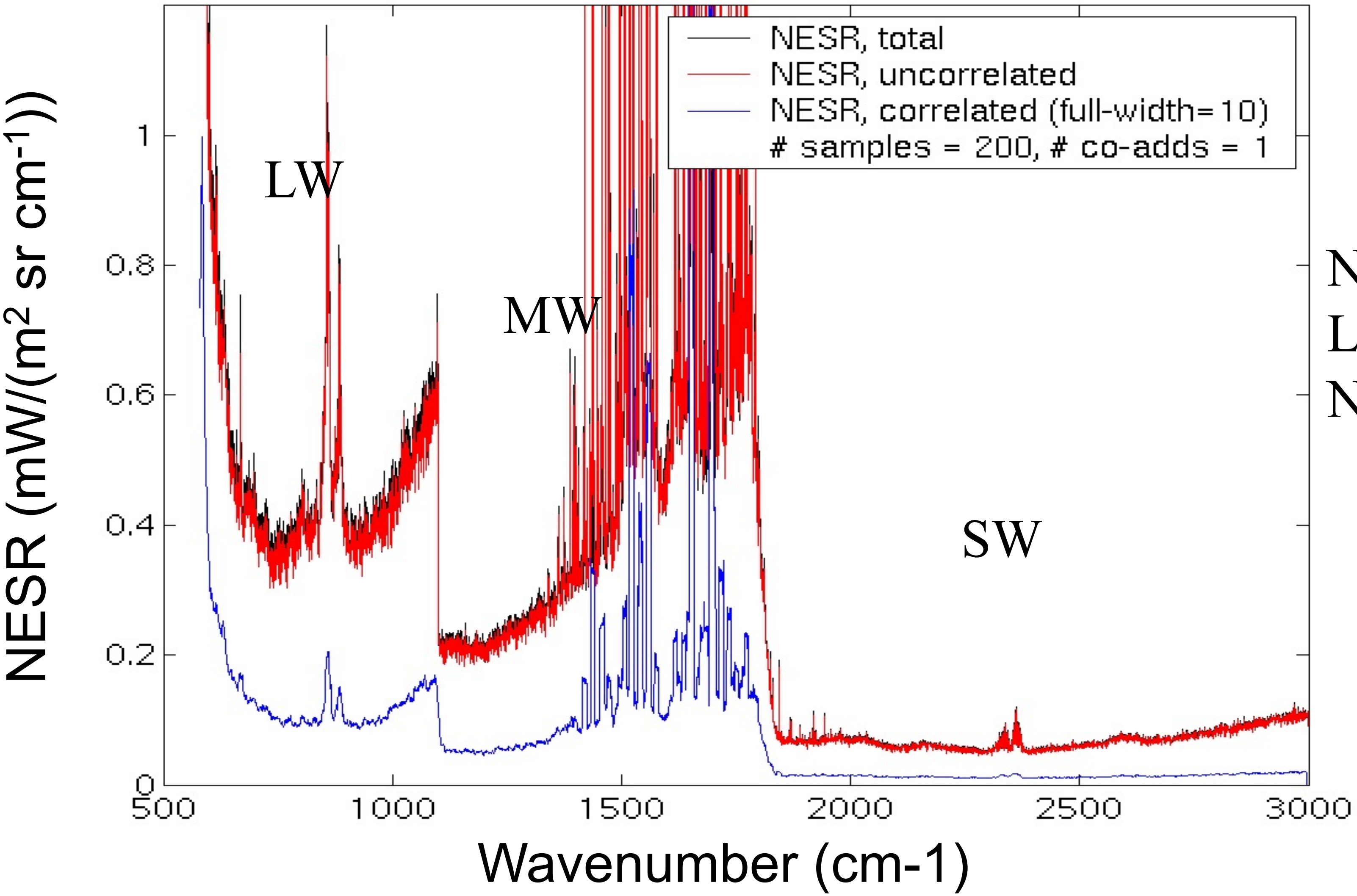




Cooling fins closely couple the Cold Blackbody to the Pod Ambient Air Temperature.

Instrument Characteristics

UW Pre-Mission Cal. Verification



Noise Levels Nominal

SSEC Scanning HIS on 1st ARM-UAV Mission with Proteus, October 2002

S-HIS scans cross-track downward & looks upward

Aura Validation Expt

AVE, Oct/Nov 2004

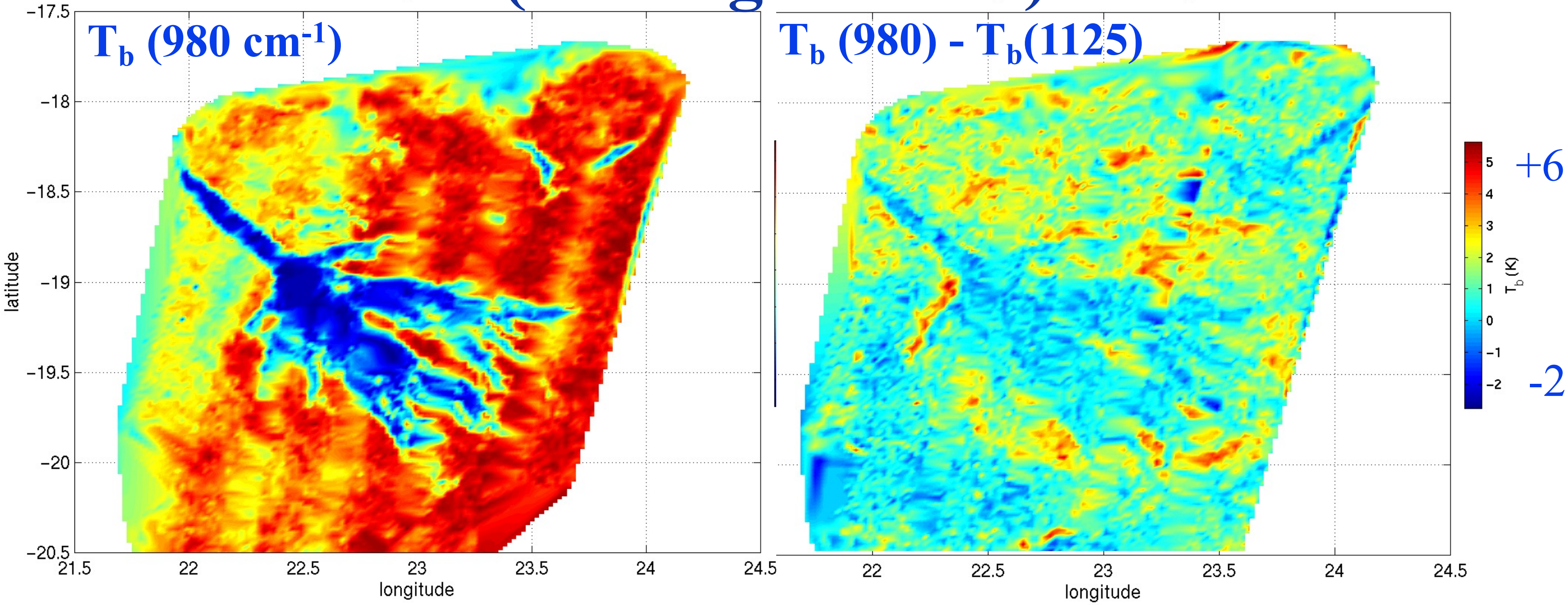
Left Wing Pod

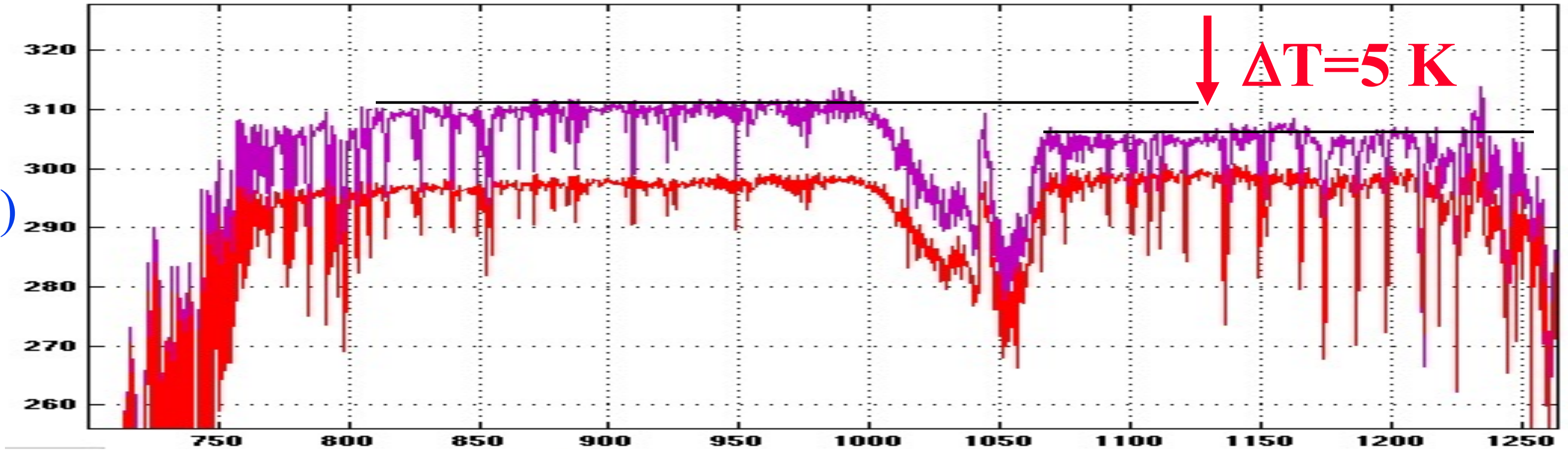
S-HIS

scans cross-track downward
&
looks upward

Okavanga Delta Surface Emissivity

(27 August 2000)





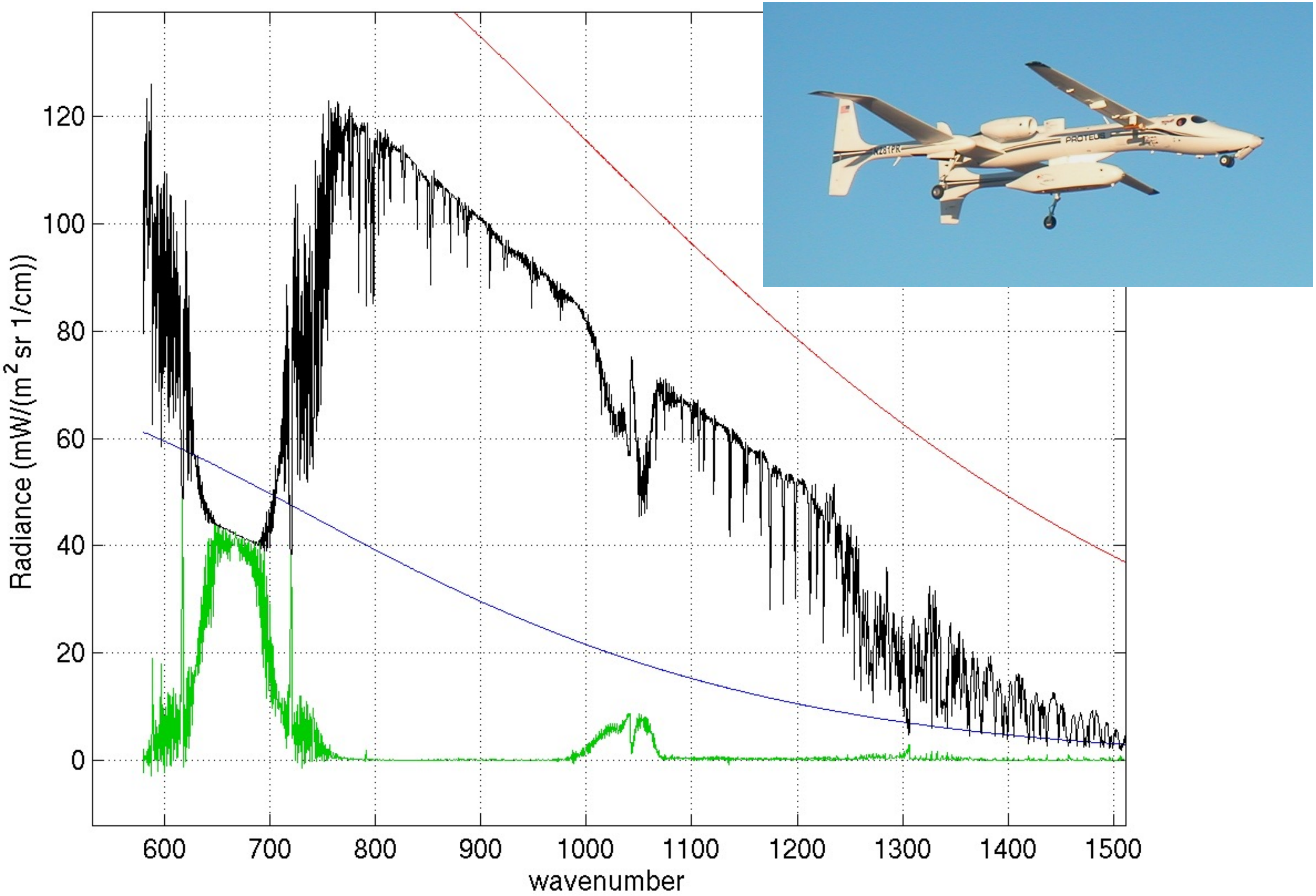
ΔT=5 K

T_b(K)

750 cm^{-1}

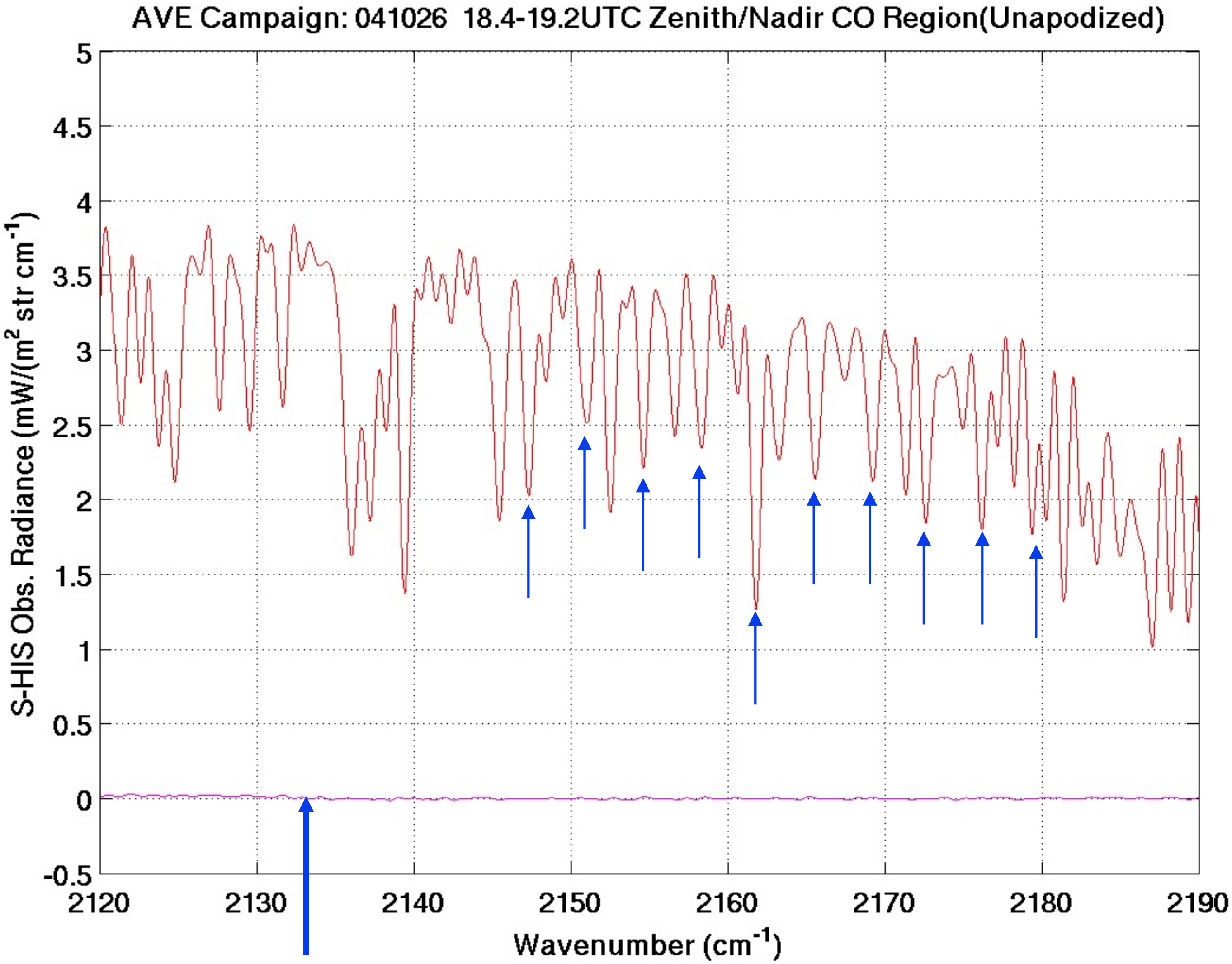
1250 cm^{-1}

S-HIS zenith and cross-track scanning Earth views 11-16-2002 from Proteus @ ~14km



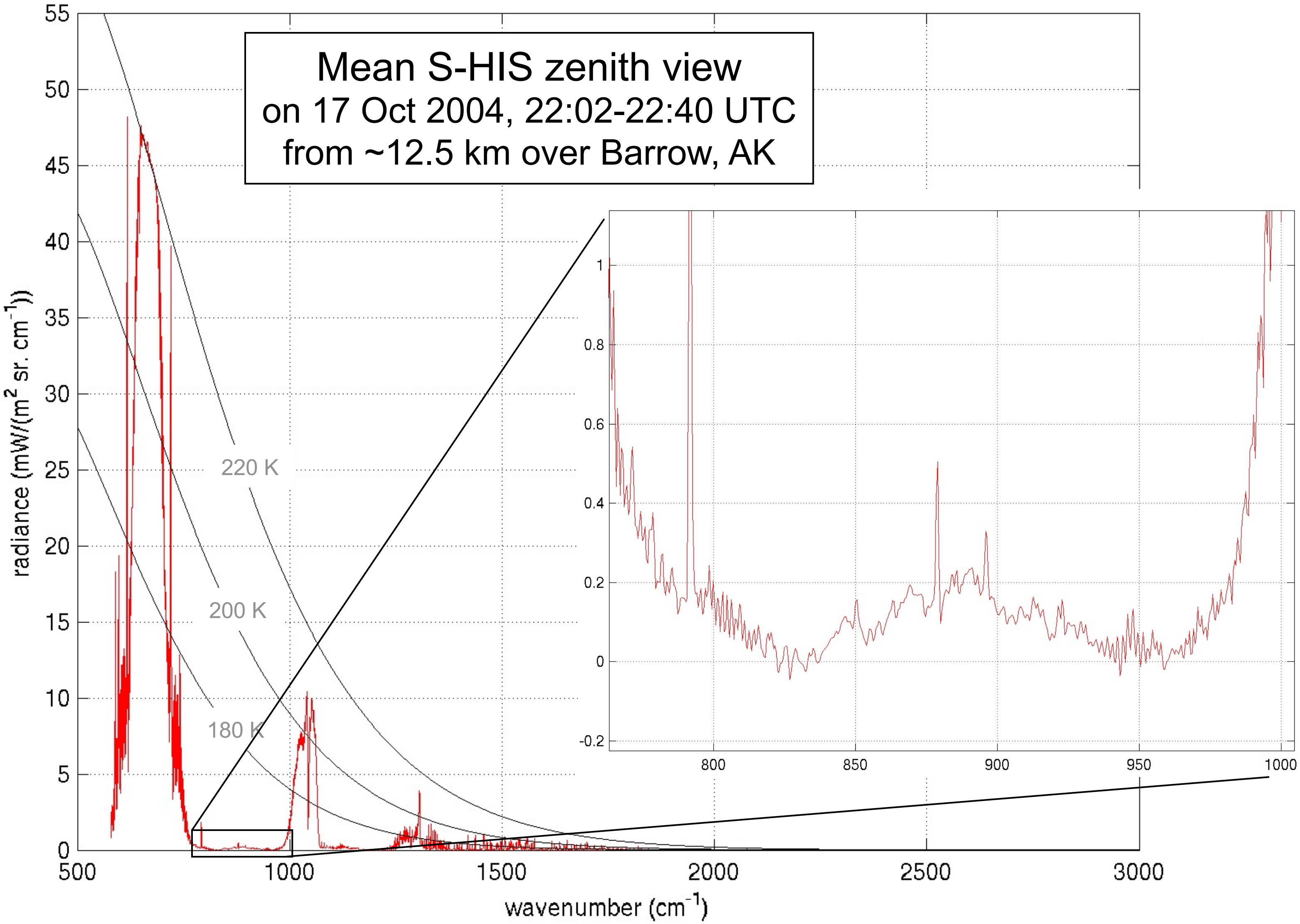
S-HIS Spectra, 4.67 μm CO

AVE, 26 October 2004



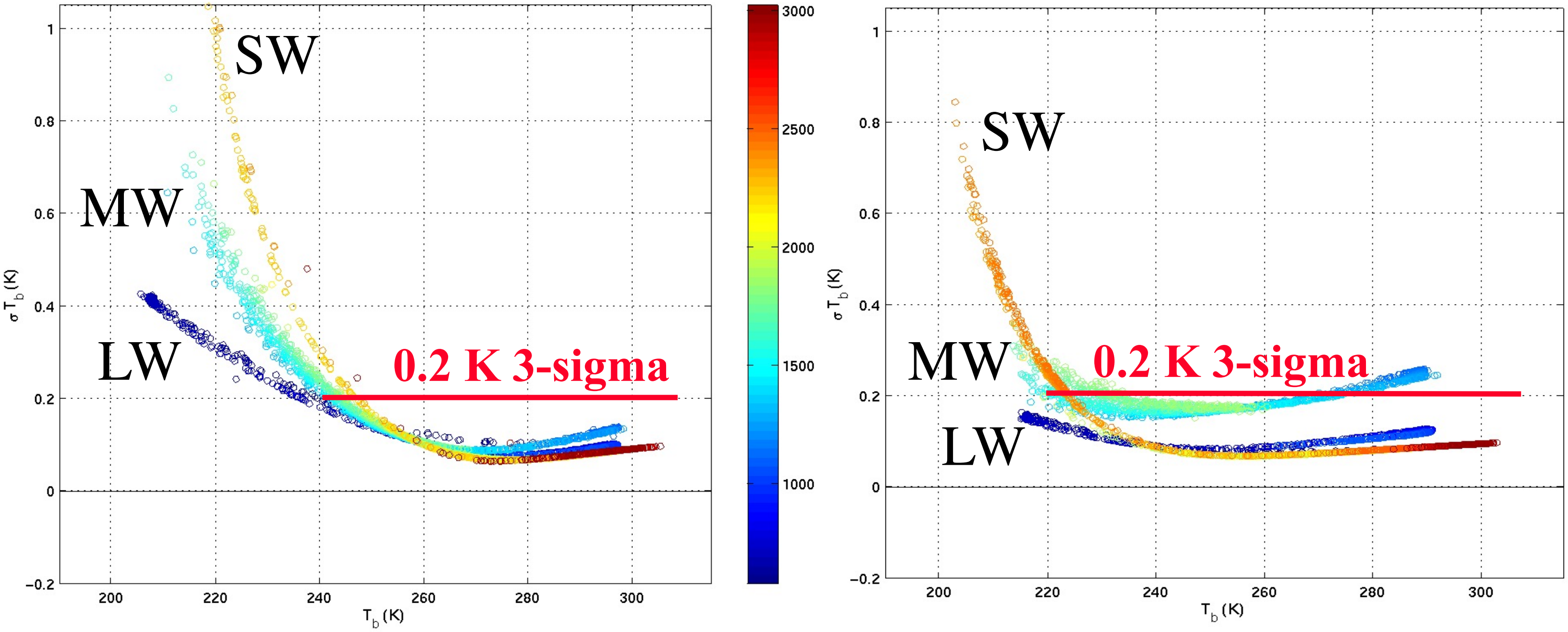
Note good uplooking zero

HNO_3 in S-HIS Zenith views



2. S-HIS Radiometric & Spectral Calibration

Scanning-HIS Radiometric Calibration 3-sigma Error Budget



240K 310K

220K 310K

Scene Brightness temperature

ER2, 21 Nov 2002

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

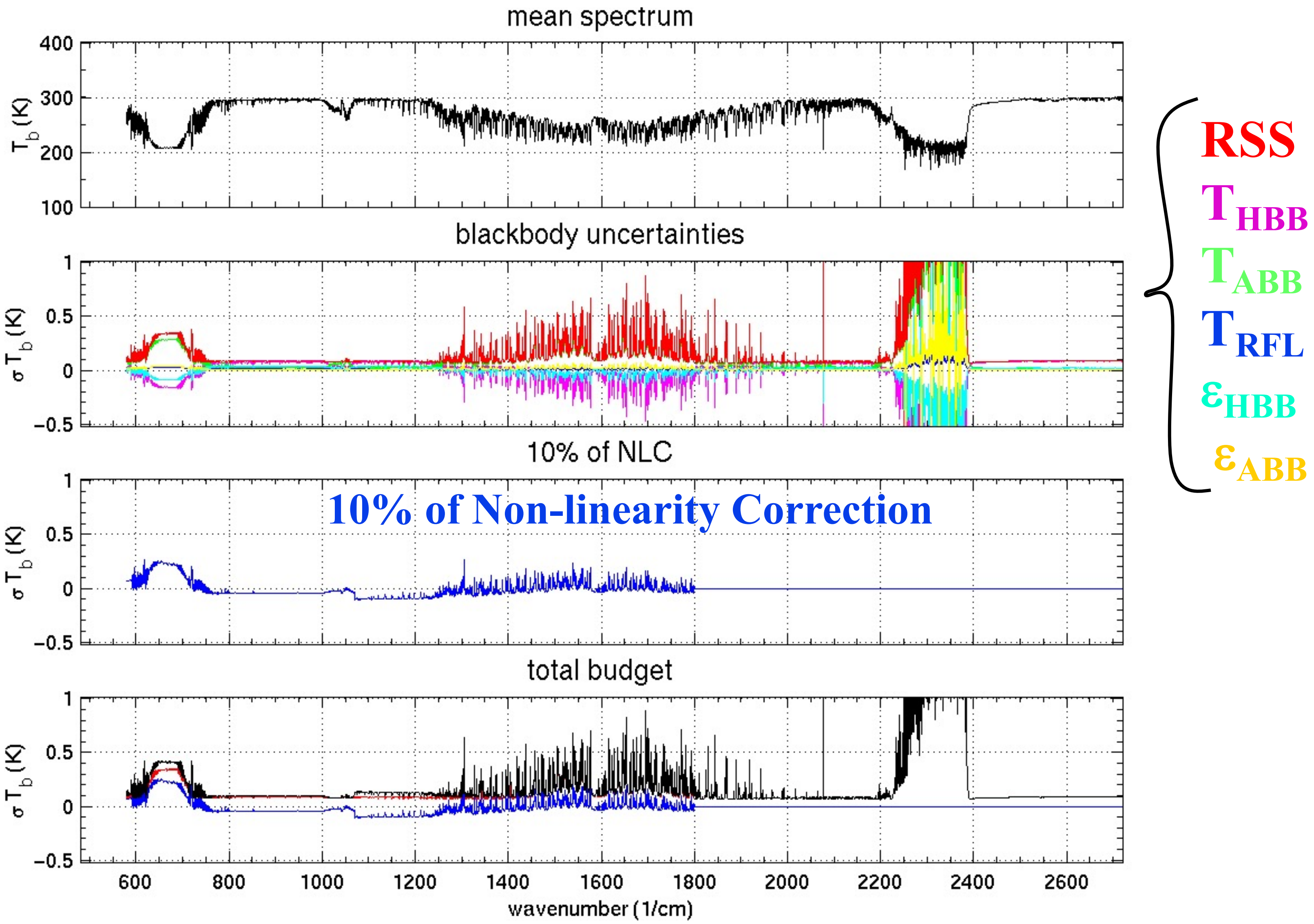
Proteus, 16 Nov 2002

$T_{ABB} = 227K, T_{HBB} = 310K$

Scanning-HIS Radiometric Calibration Budget

TABB= 260, THBB=310, 11/21/02 ER2

****3-sigma Uncertainties, similar to Best, et al., CALCON 2003 for AERI**



10% of Non-linearity Correction

Non-linearity Correction

- Physical model is basis for correction needing one key coefficient per band
- Band-to-band overlaps are used to constrain the LW and MW band coefficients
  - SW band detector is highly linear, allowing SW overlap with MW to constrain or test the MW non-linearity
  - MW overlap with LW can then constrain or test the LW non-linearity
- Up-looking constraints also used to refine non-linearity coefficients and their uncertainties
- AERI comparisons used for Validation

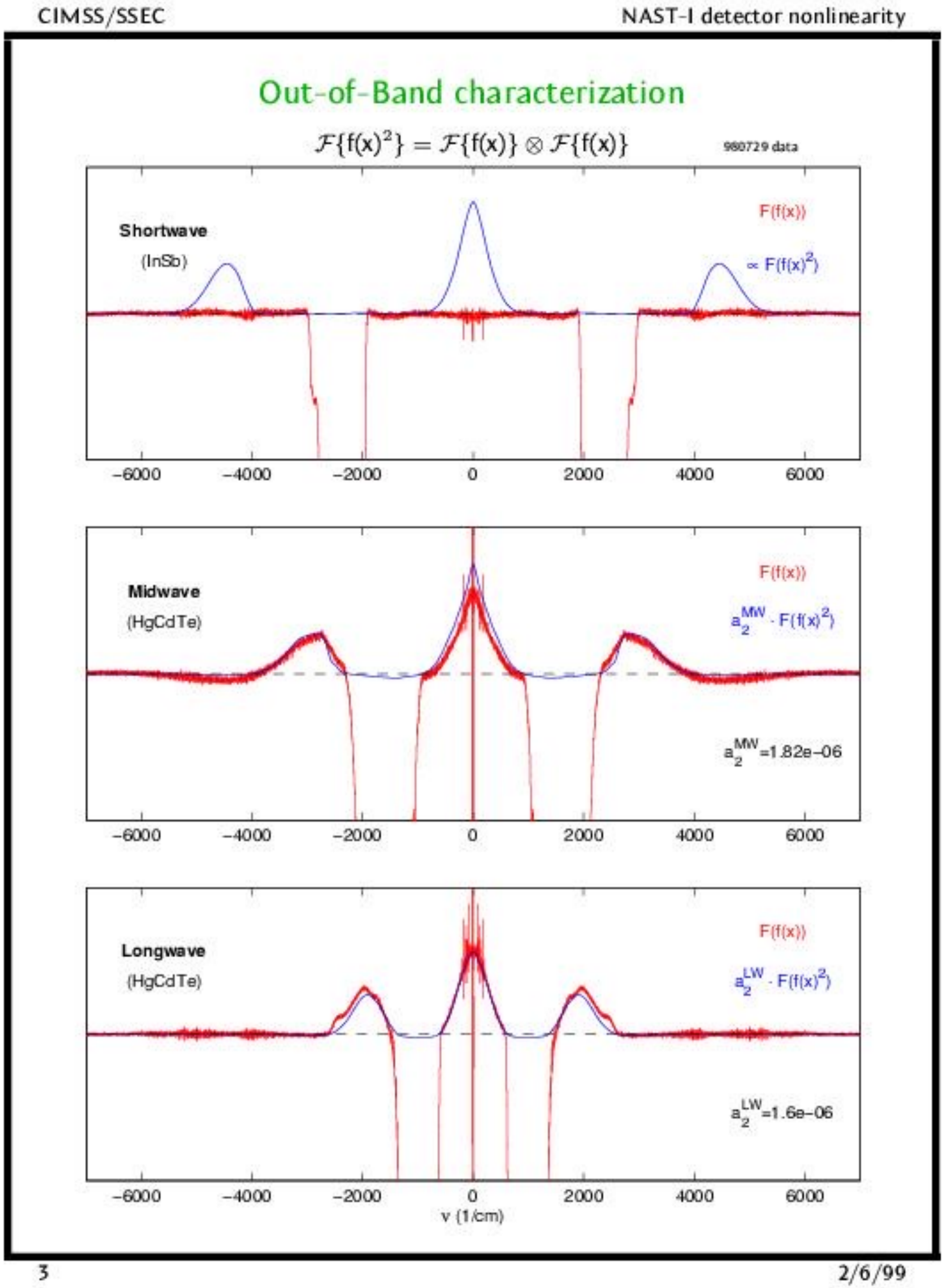
Example Non-linearity: NAST Aircraft Instrument

Out of band response is a good test of linearity & helps define correction

Photo-voltaic InSb detector demonstrates expected high degree of linearity in SW

Photo-conductive HgCdTe demonstrates expected non-linearity in MW & LW

Supports expected quadratic non-linearity of PC detectors



CIMSS/SSEC NAST-I detector nonlinearity

Out-of-Band characterization

$\mathcal{F}\{f(x)^2\} = \mathcal{F}\{f(x)\} \otimes \mathcal{F}\{f(x)\}$ 980729 data

3 2/6/99

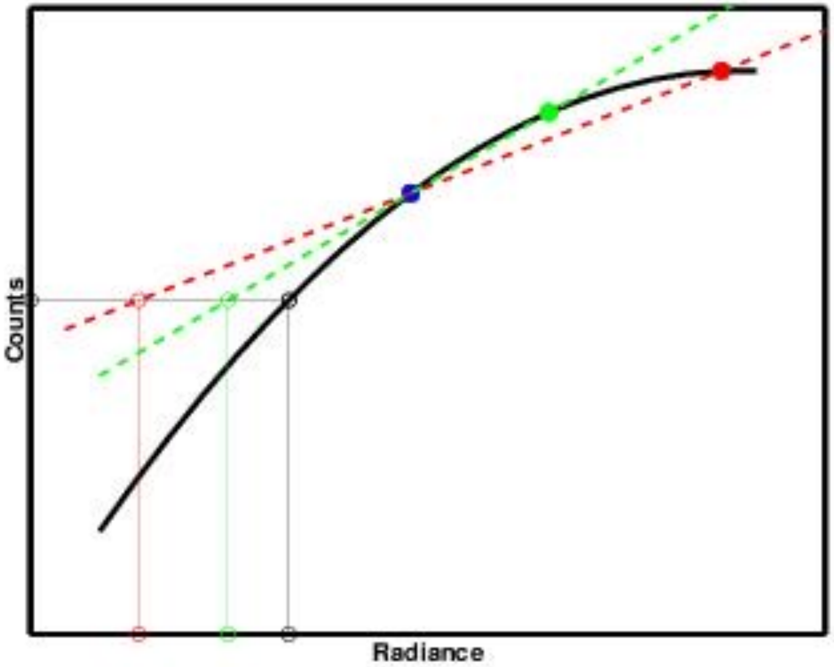
Physical Non-linearity Model, General Principle

- HgCdTe detector theory predicts
  $Q = c_1 \Delta n + c_2 (\Delta n)^2 + c_3 (\Delta n)^3$
  where Q is the incident photon flux density and Δn is the photo-generated conduction band electron concentration. (Marion B. Reine, 1979)
- The measured signal, I_m, is proportional to Δn, and the corrected linear signal, I_c, is proportional to Q:
  $I_c = I_m + a_2 (I_m)^2 + a_3 (I_m)^3$
- Separating I_m into an AC interferogram, $f(x)$, and a DC offset, V, gives:
  $I_c = (f + V) + a_2 (f + V)^2 + a_3 (f + V)^3$

Primary Term-Linear in Spectrum

$$\rightarrow \widetilde{I_c} = (1 + 2a_2 V + 3a_3 V^2) \widetilde{f} + (a_2 + 3a_3 V) \widetilde{f^2} + a_3 \widetilde{f^3}$$

$$\rightarrow V = \frac{V_a}{e} + \frac{V_a}{e} \frac{k + 2r_{dw}}{\frac{B_a}{B_i}(t_{fw} + r_{fw} - r_{dw})}$$



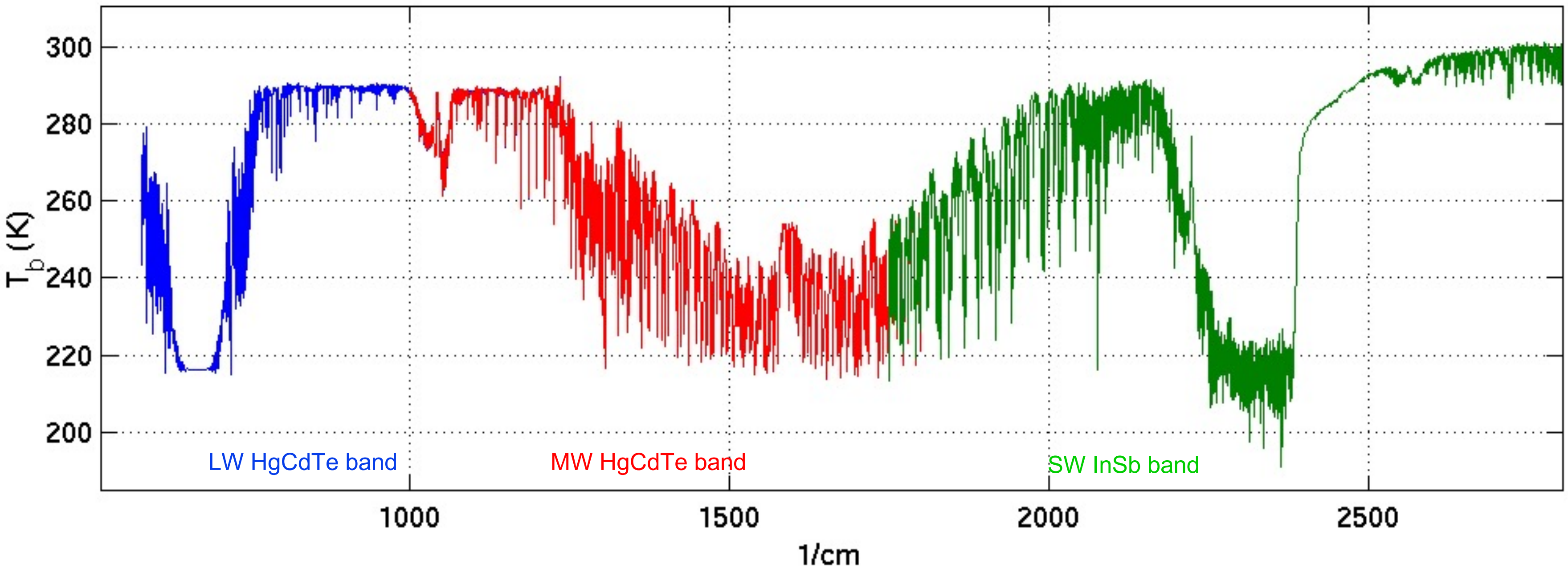
a_2 determined from

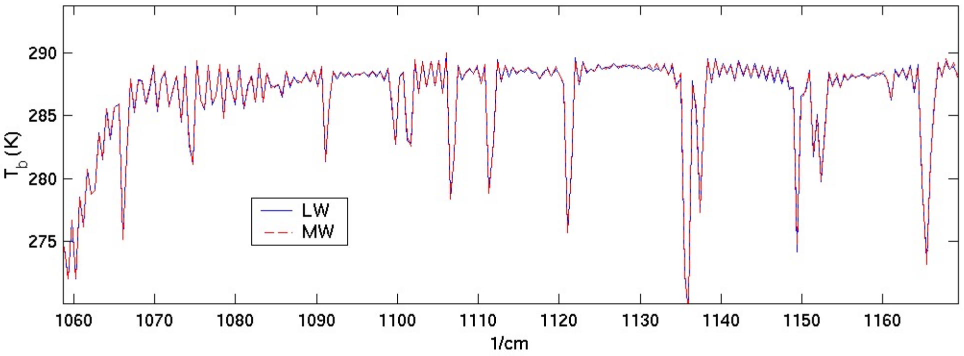
- Out of Band: $\widetilde{I_c} = 0 \rightarrow |a_n| = \widetilde{I_m} / \widetilde{I_m^n}$
- uplooking clear sky comparisons with AERI
- in-flight clear sky comparisons with HIS
- comparisons with external blackbodies

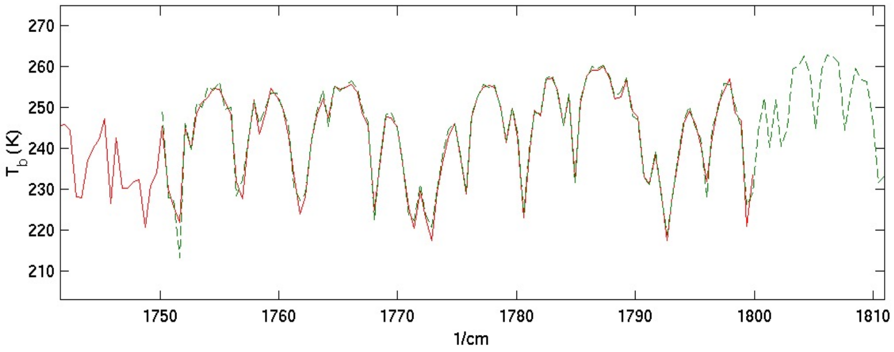
Correction applied before Complex Radiometric Calibration

Scanning-HIS LW/MW and MW/SW Band Overlap

11-16-2002



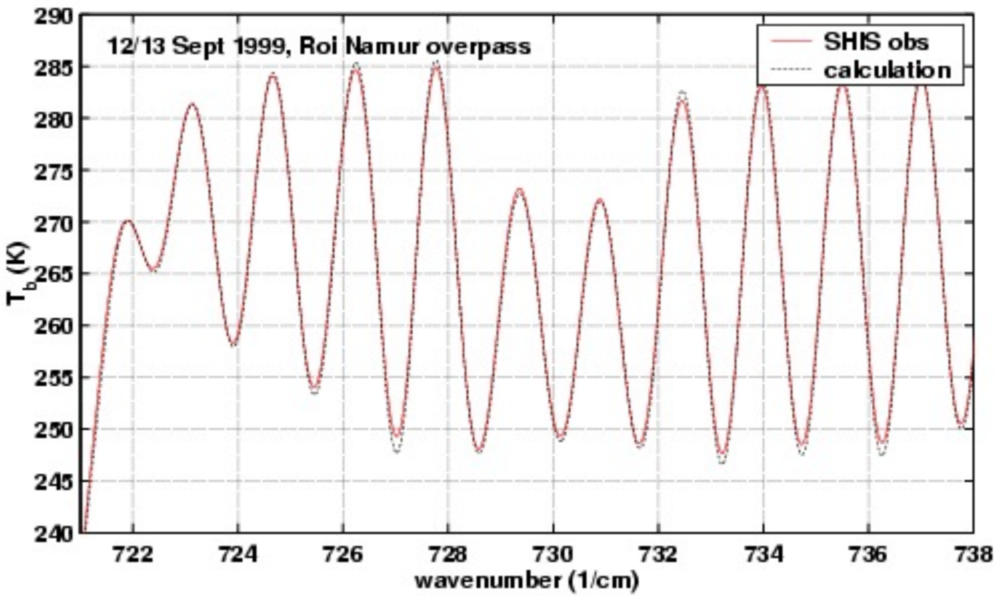

LW/MW overlap


MW/SW overlap

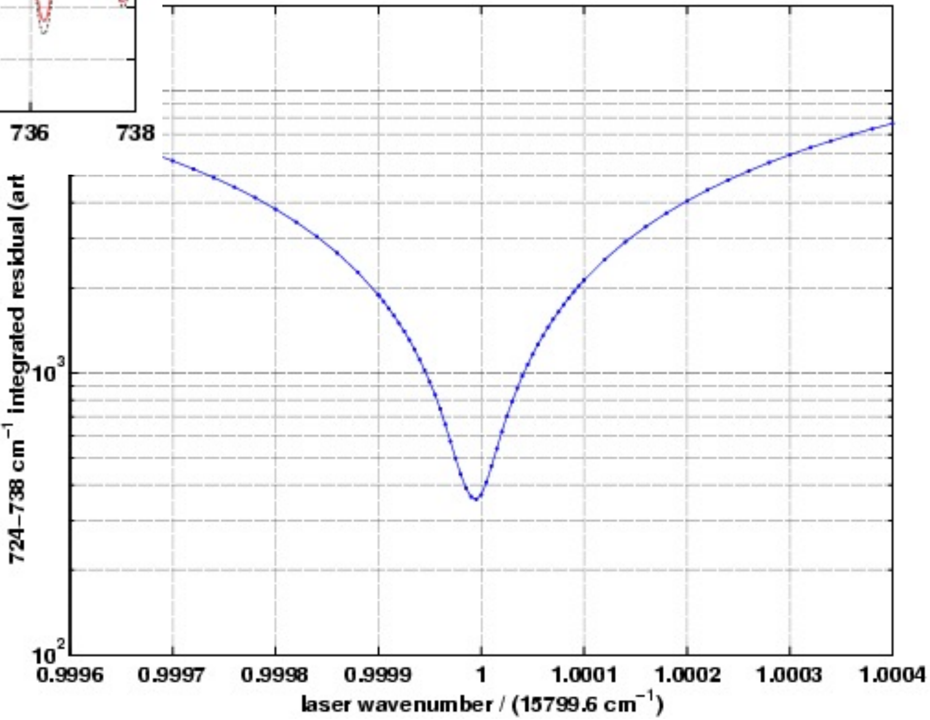
Spectral Calibration and Standardization

- FTS approach determines the spectral scale for a whole spectral band to within a single multiplicative “scale-stretching” factor
- The factor is a function of the reference laser wavelength, and the alignment of the laser & IR beams to the interferometer axis, all of which are very stable, even without thermal control
- **Spectral calibration uses well-known regions of calculated atmospheric spectra off-line & infrequently**
- **Instrument Line Shape is normalized to an ideal sinc function based on known geometry and refinement using atmospheric nitrous oxide lines near 2195 cm^{-1}**
- Calibration is followed by procedures to standardize the spectral characteristics

Example Spectral Calibration: S-HIS



Atmospheric CO_2 lines

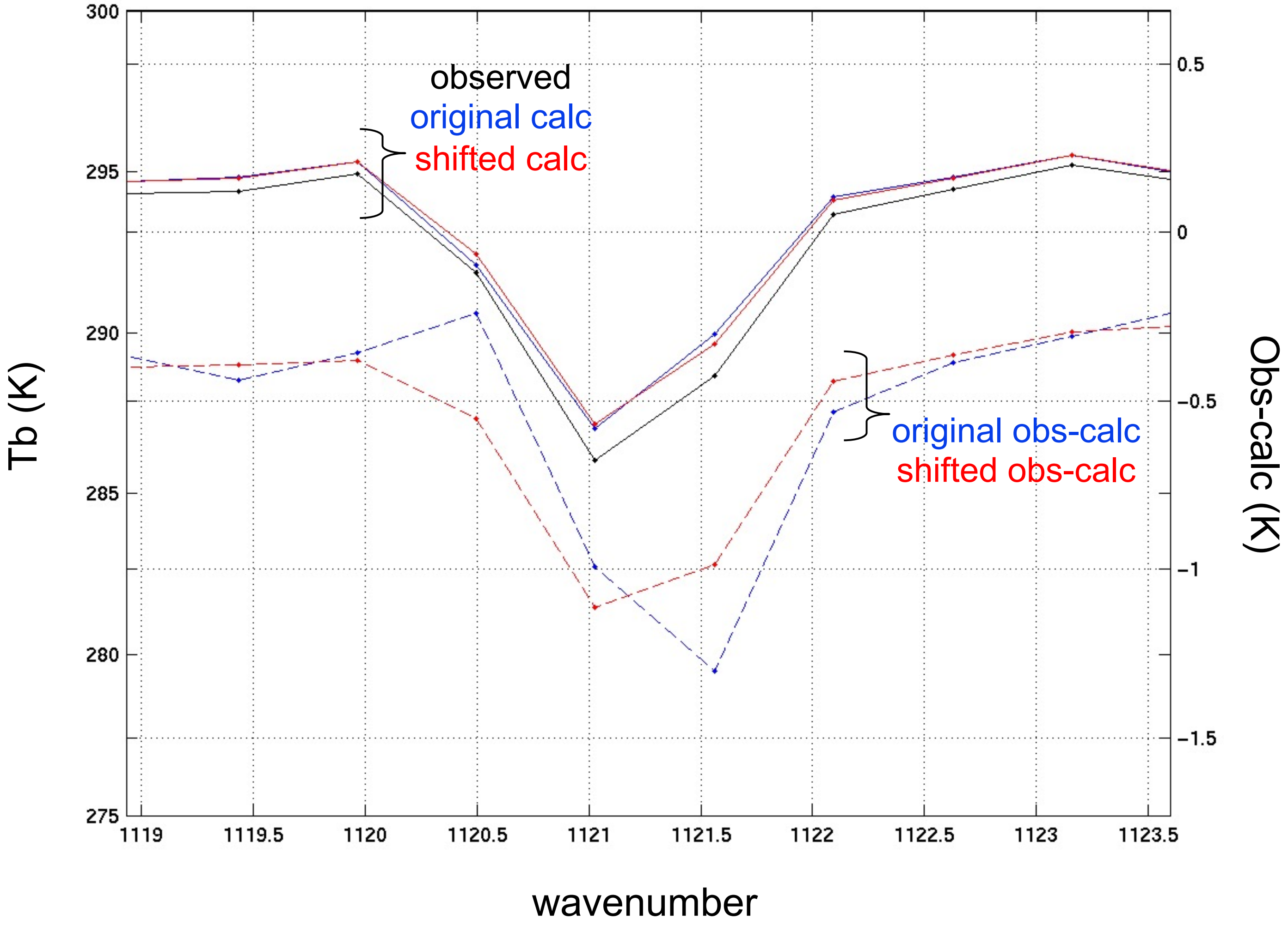


Wavenumber Scale chosen to minimize difference

Estimated accuracy =1.2 ppm (1 sigma)

With many samples, the accuracy is even higher

Small Spectral Shift (3% of resolution) in AIRS Module-05 identified from S-HIS Validation



Tobin, et al., CALCON 2003, presented S-HIS Spectral Calibration

Self-Apodization is removed to standardize the Instrument Line Shape (ILS)

Self-apodization function is expanded in a Taylor Series to separate OPD and ν dependence, allowing rigorous relationships in terms of Fourier transforms

- In expression for the measured interferogram, *F(x)*, expand sinc function as a power series of $(\pi\nu x b^2/2)$:

- Compute perturbation terms and subtract from measured interferogram.

This process is used for AERI, HIS, S-HIS, NAST-I

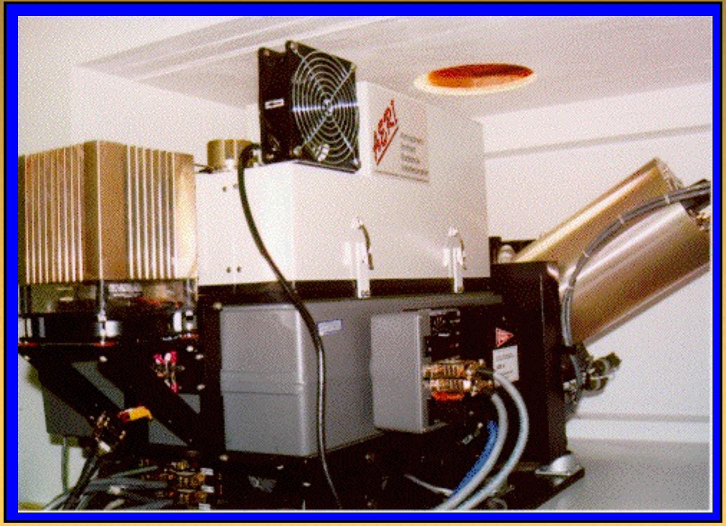
Spectral Scale Standardization

- Producing instrument-independent spectra requires interpolation from the specific instrument scale (determined by spectral calibration) to a standardized scale
- AERI, HIS, S-HIS and NAST processing implements this interpolation following the self-apodization correction.

  [A densely sampled spectrum, from which linear interpolation can be performed accurately, is constructed by double FFT (FFT calibrated spectrum to interferogram, zero fill to a large effective optical path difference, FFT back to a densely sampled spectrum, and linearly interpolate)]

3. Tests of High Spectral Resolution Calibration

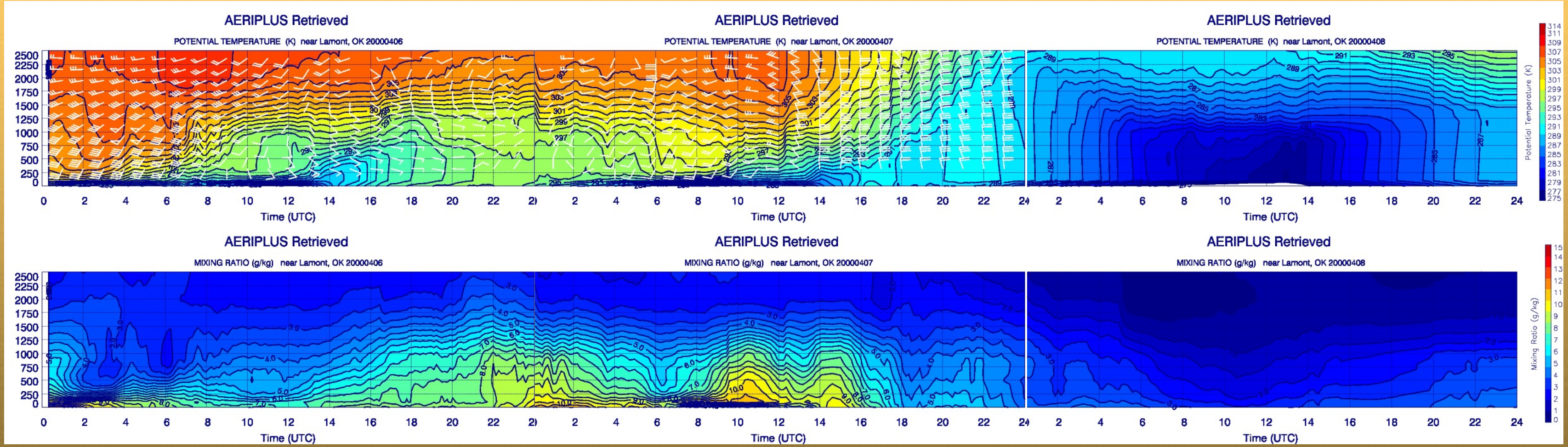
ATMOSPHERIC EMITTED RADIANCE INTERFEROMETER (AERI)



Operational at DOE ARM

Clear Sky and Cloud Downwelling Emission

Accurate High Resolution Radiometry



Continuous Atmospheric Profiling - Temperature and Water Vapor

The NIST Connection

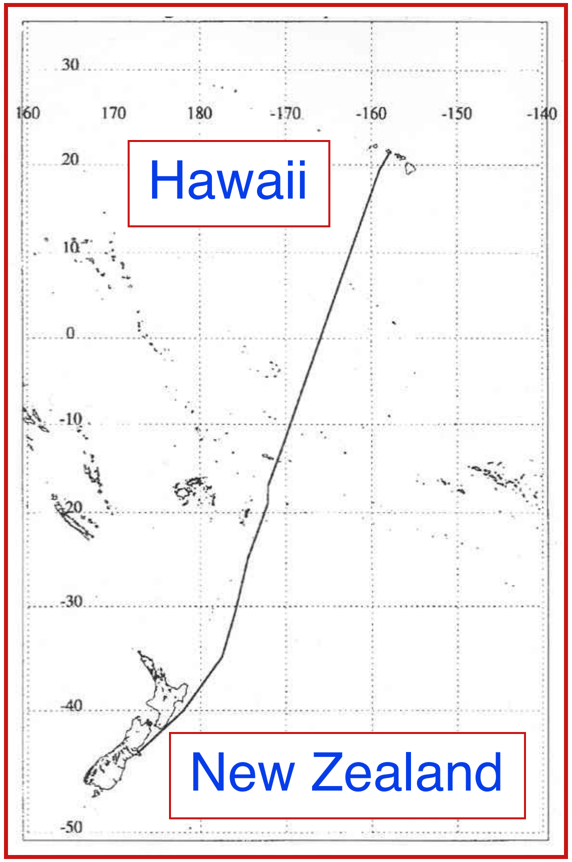
- Comparisons with NIST maintained blackbodies conducted with ground-based AERI. S-HIS employs the same calibration approaches

Miami, 1998

Max Difference
< 0.055°C Longwave
< 0.035°C Shortwave
between 293 & 333 K

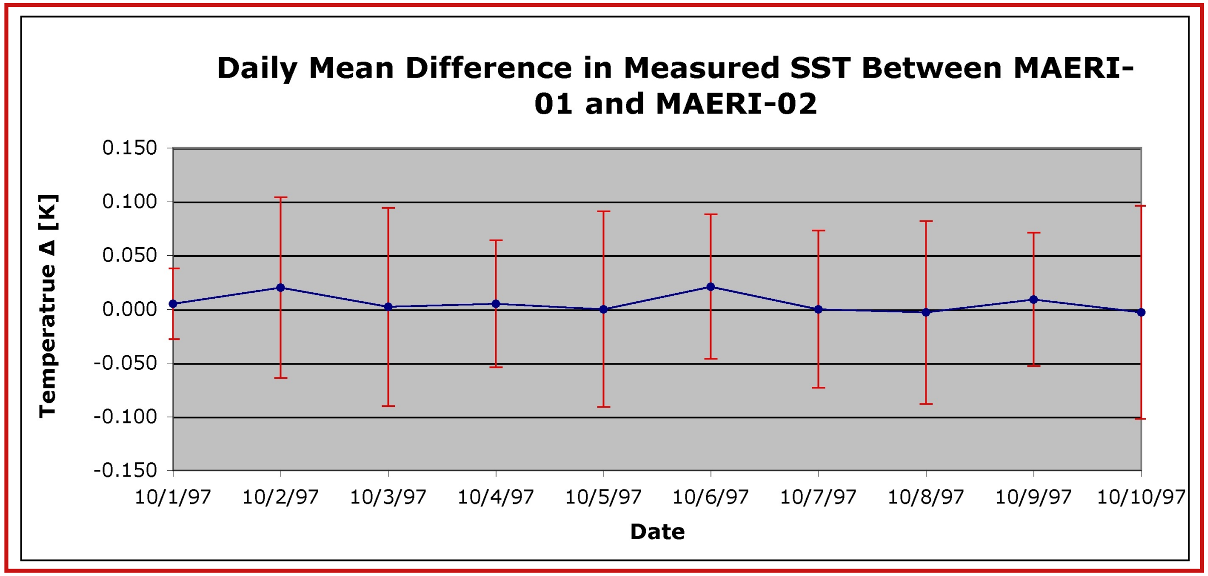
- Direct test of S-HIS planned using NIST Transfer Radiometer (TXR) at aircraft flight temperatures

Intercomparison of 2 Marine AERIs Measuring Sea Surface Temperature



Track of the R/V Roger Revelle
28 Sept. - 14 Oct. 1997

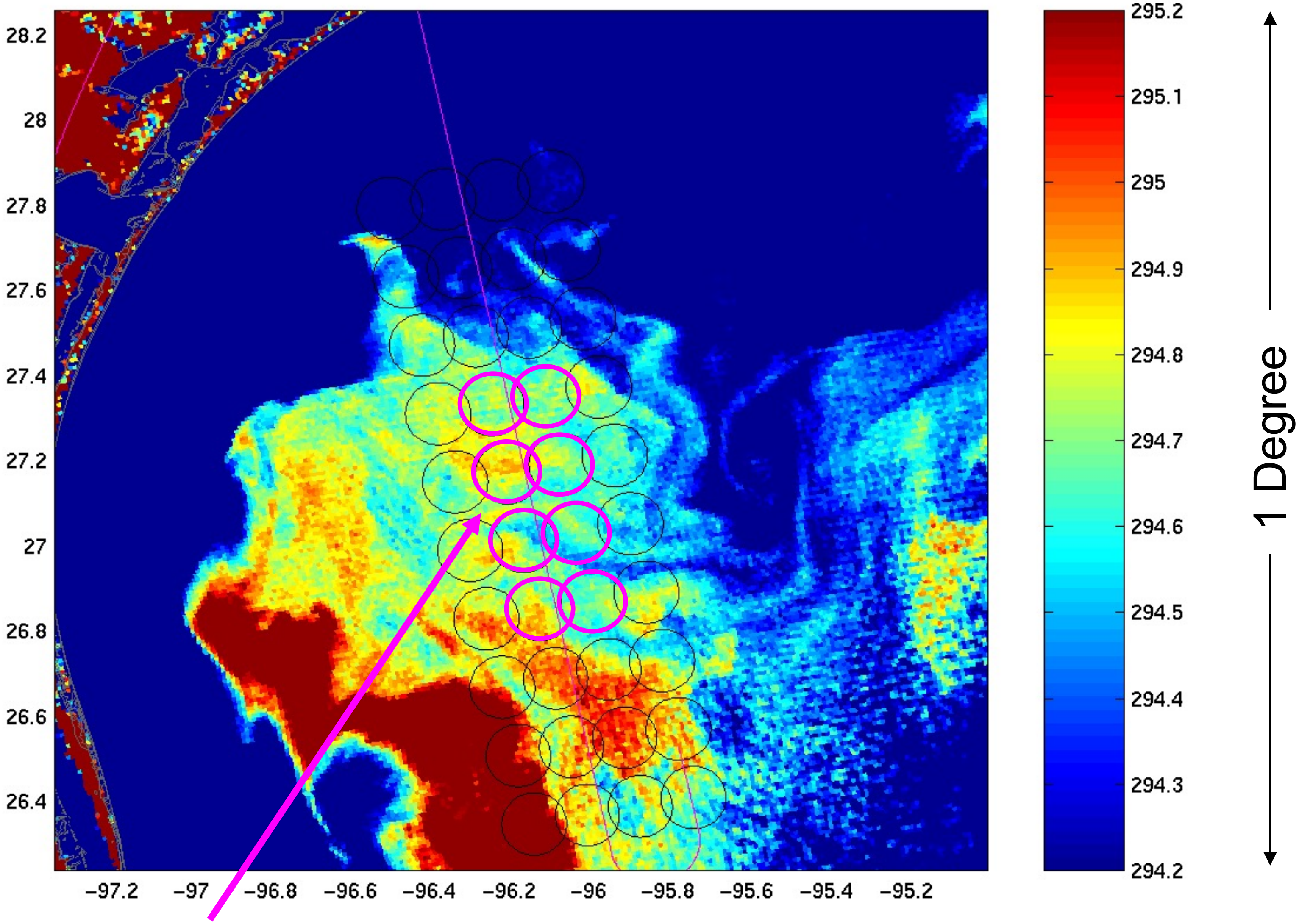
16 Day Cruise



Largest Daily Mean Difference: 0.020 K
Ten Day Mean Difference: 0.005 K

AIRS Validation with UW Scanning HIS

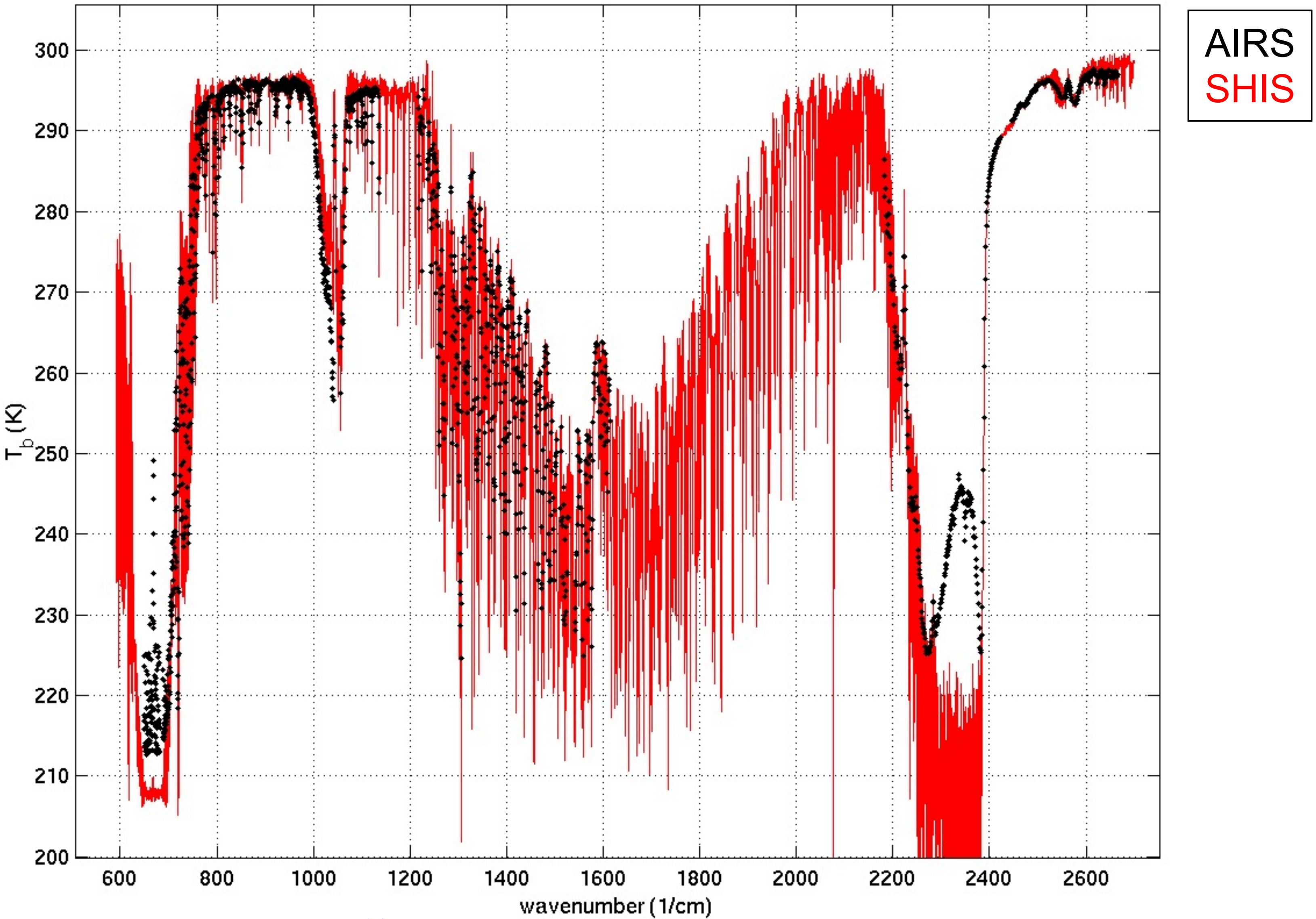
21 November 2002, NASA ER2



8 AIRS FOVs used in the following comparisons (shown in MODIS 12 micron image)

2002 Gulf of Mexico Comparison

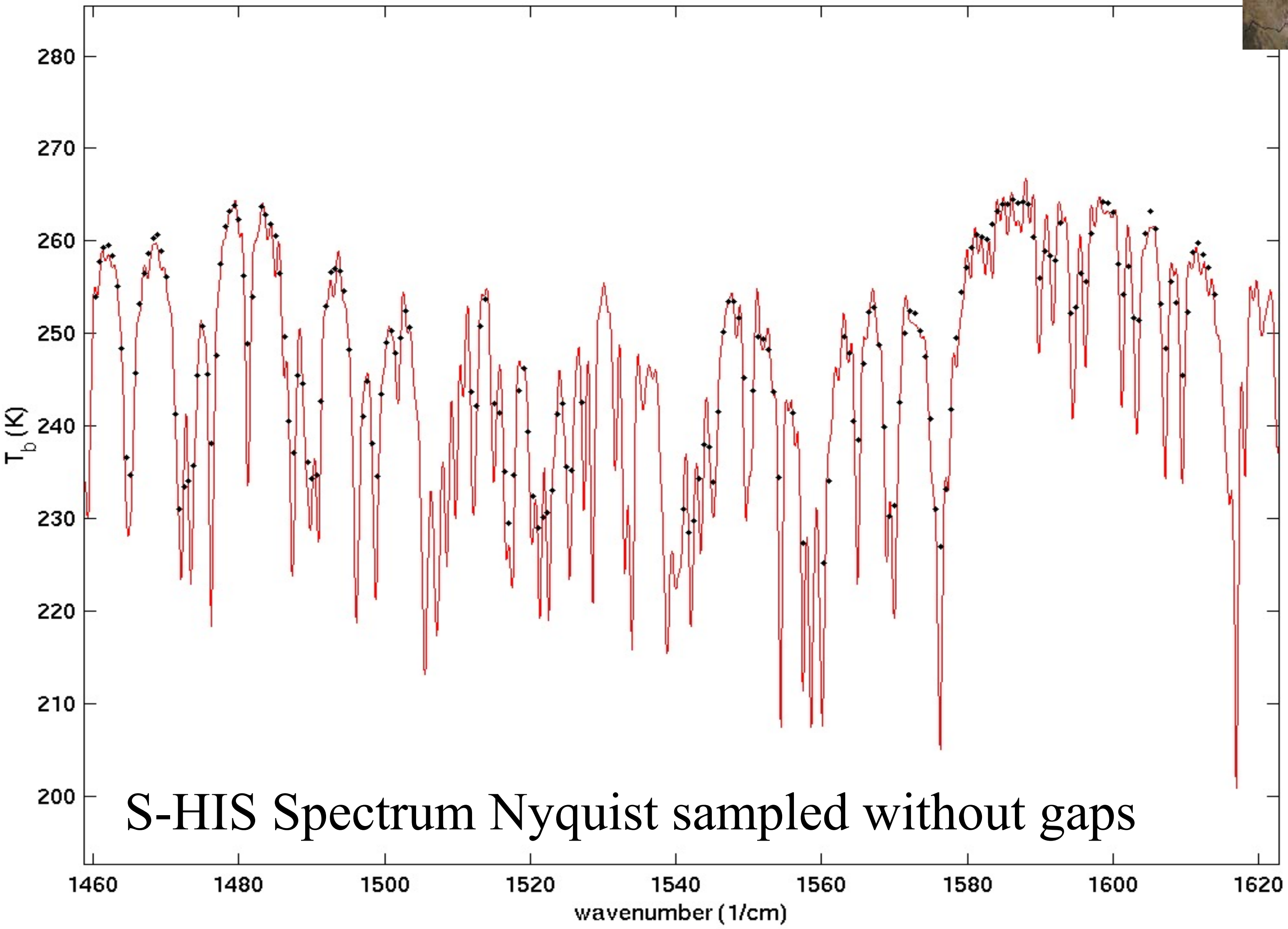
8 AIRS FOVs, 448 SHIS FOVs, PC filtering



“comparison 0”

“comparison 0”

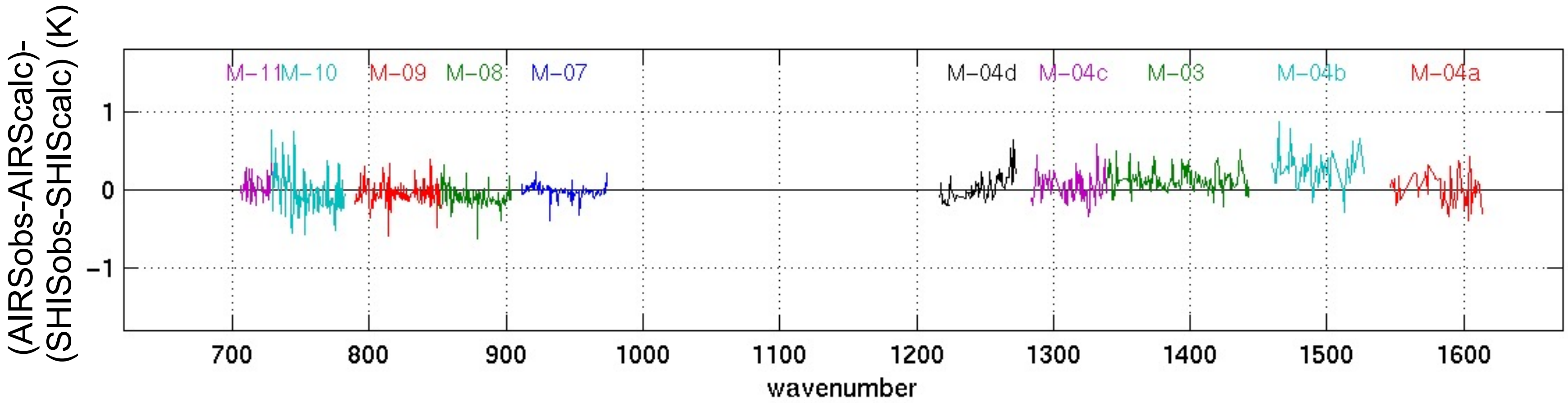
8 AIRS FOVs, 448 SHIS FOVs, PC filtering

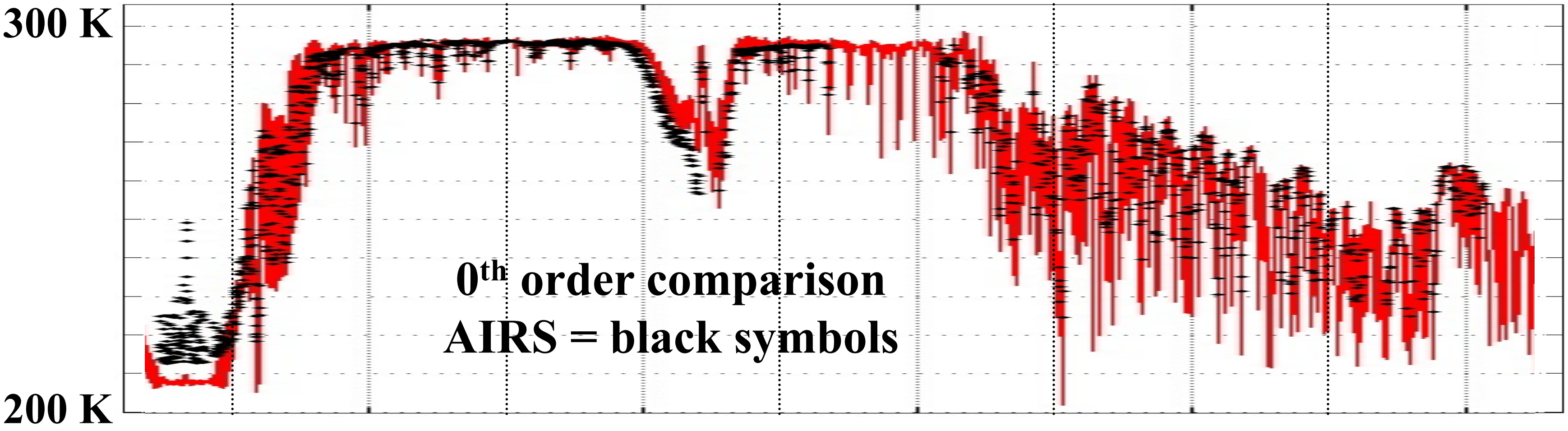


S-HIS Spectrum Nyquist sampled without gaps

Detailed Radiance Comparison: Spectrally normalized AIRS-HIS Residuals

Mean over AIRS modules (same color) generally <0.1 K!



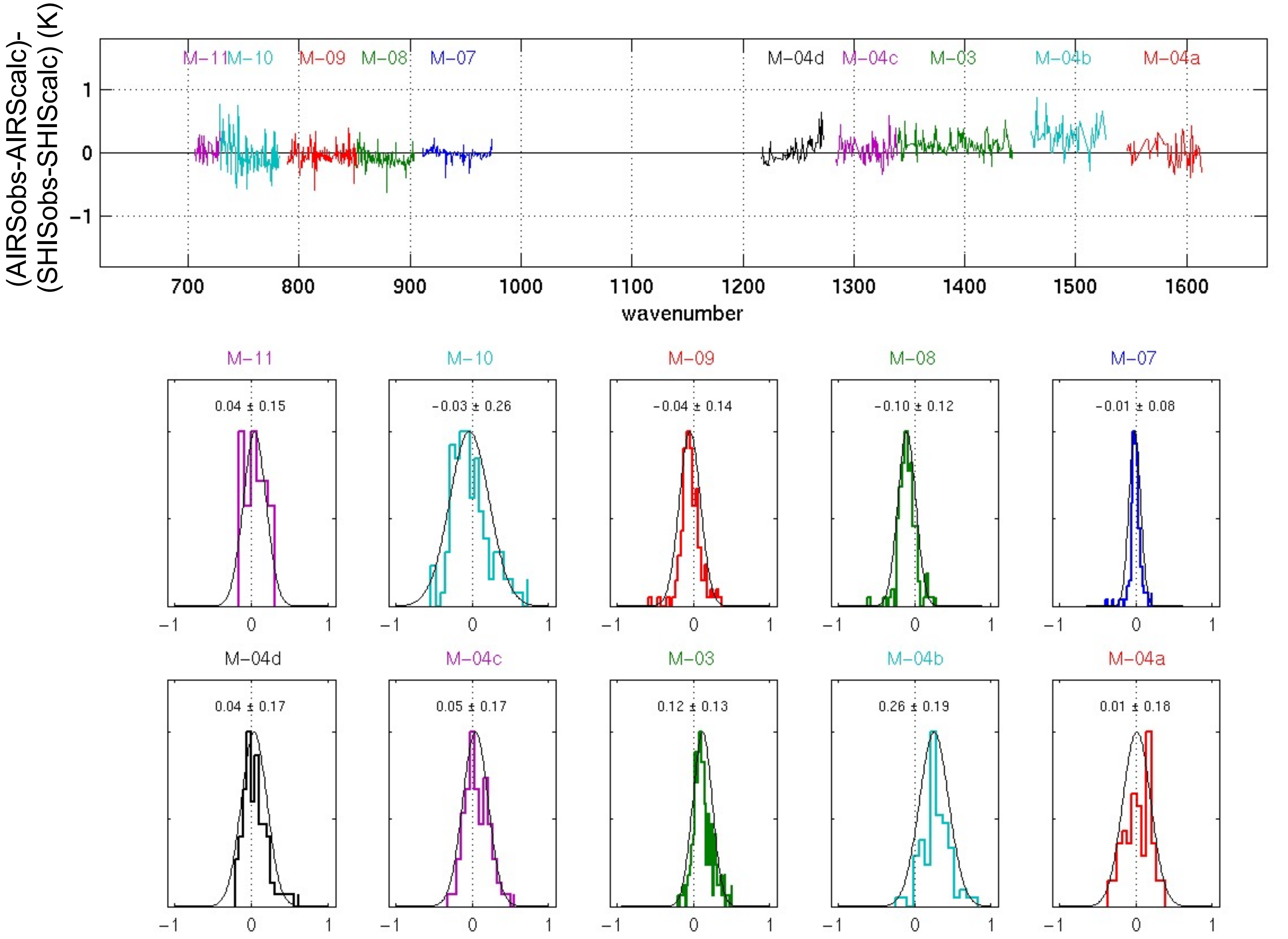


0^{th} order comparison
AIRS = black symbols

Excluding channels strongly affected by atmosphere above ER2

Statistical Properties of AIRS-SHIS Residuals

Mean generally < 0.1 K & Standard Deviation < 0.2 K over AIRS modules



New Comparisons from 2004 Field Experiments

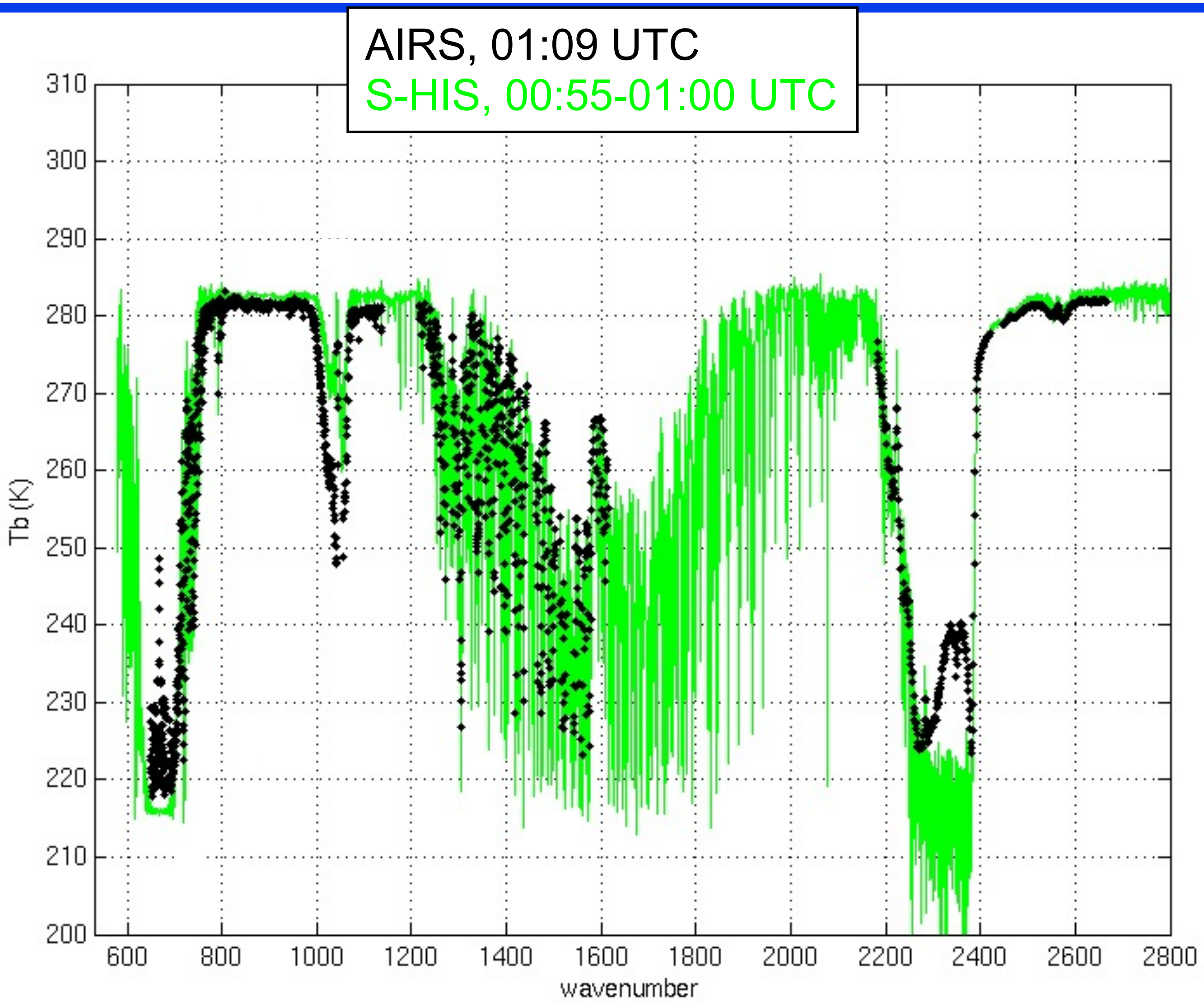
EAQUATE: **European Aqua Thermal Experiment (Italy & UK)**

MPACE: **Mixed-Phase Arctic Cloud Experiment**

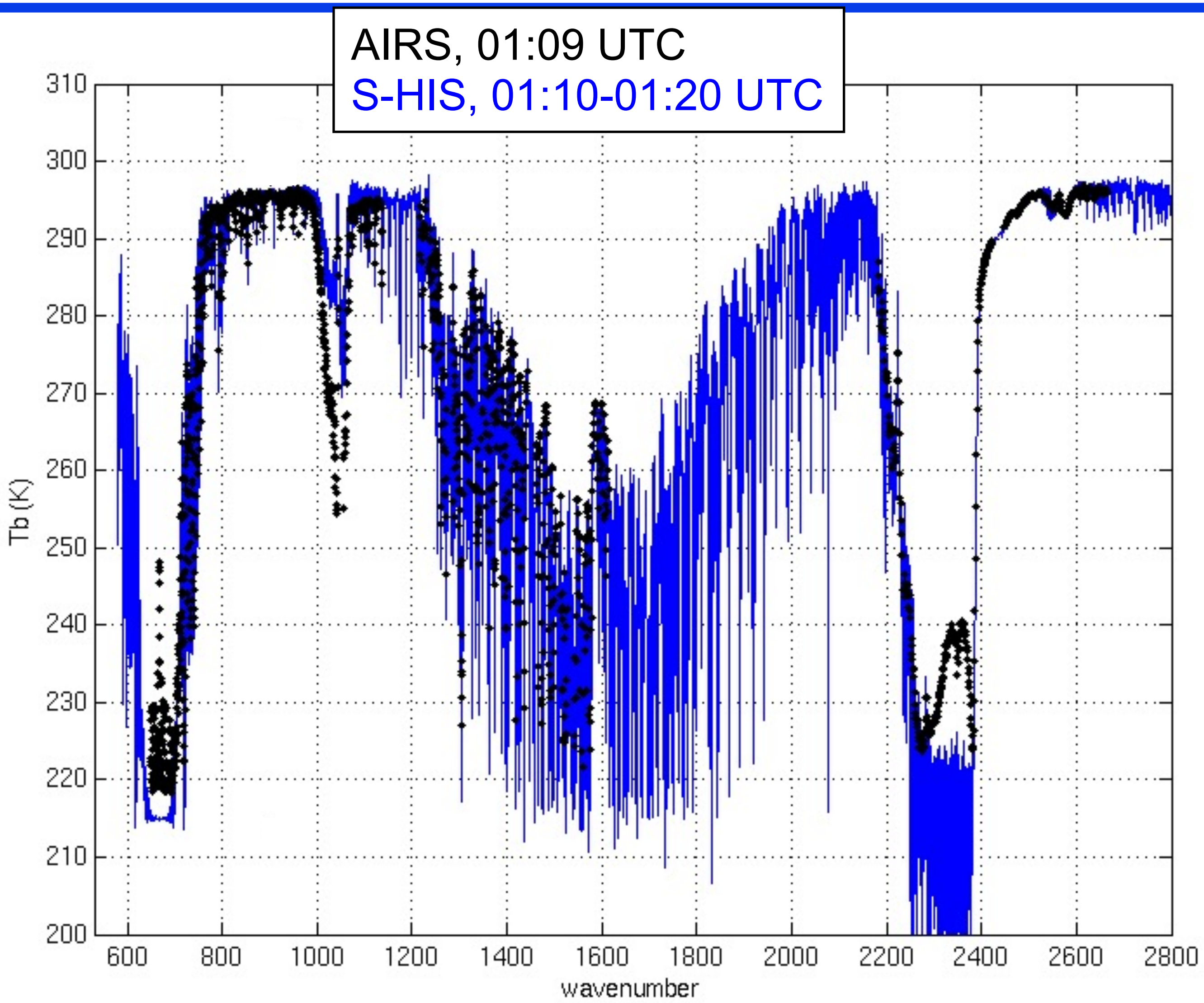
AVE: **Aura Validation Experiment**

Only Processed through 0th order comparison

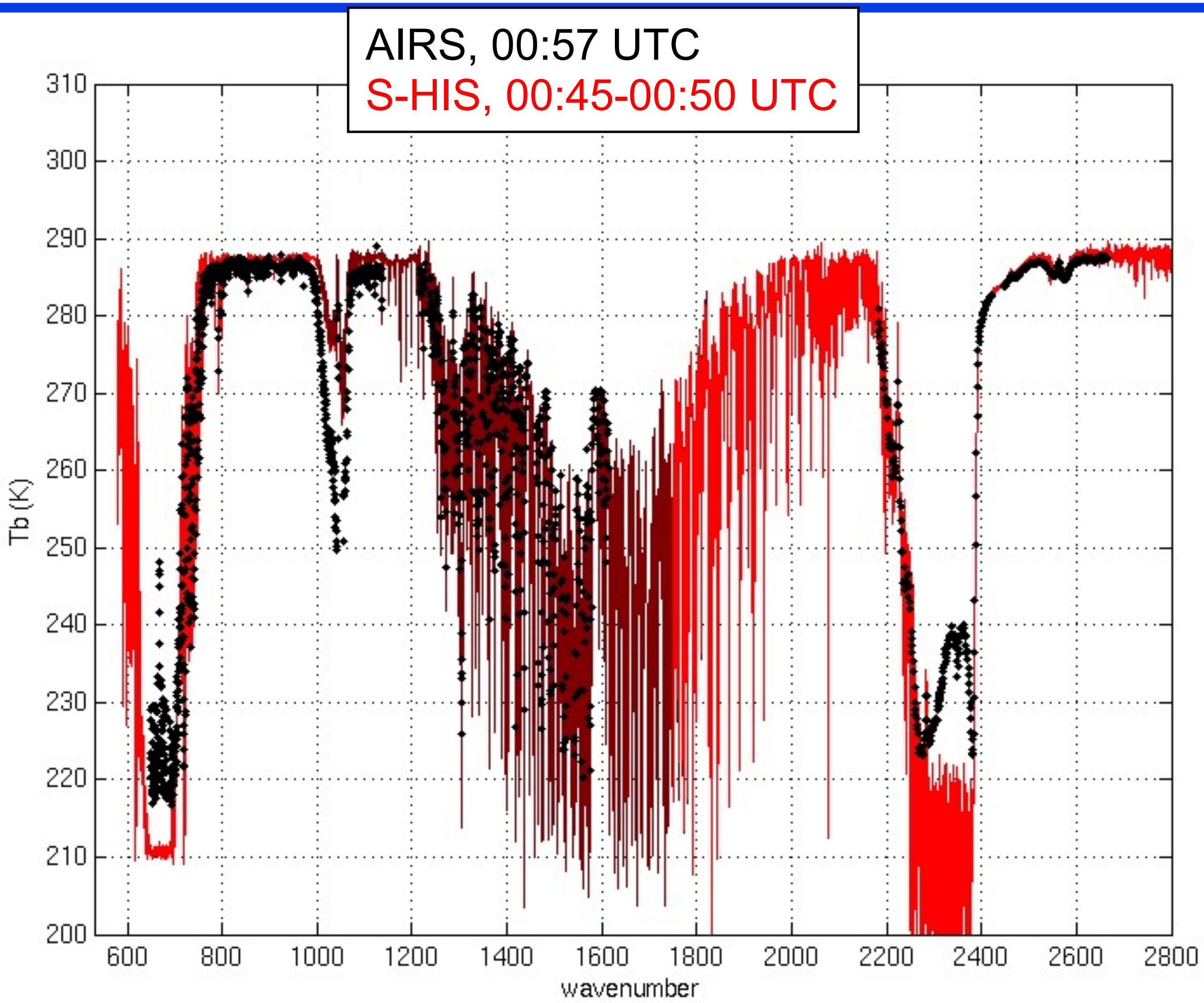
EAQUATE (Italy) 040907- Mountains



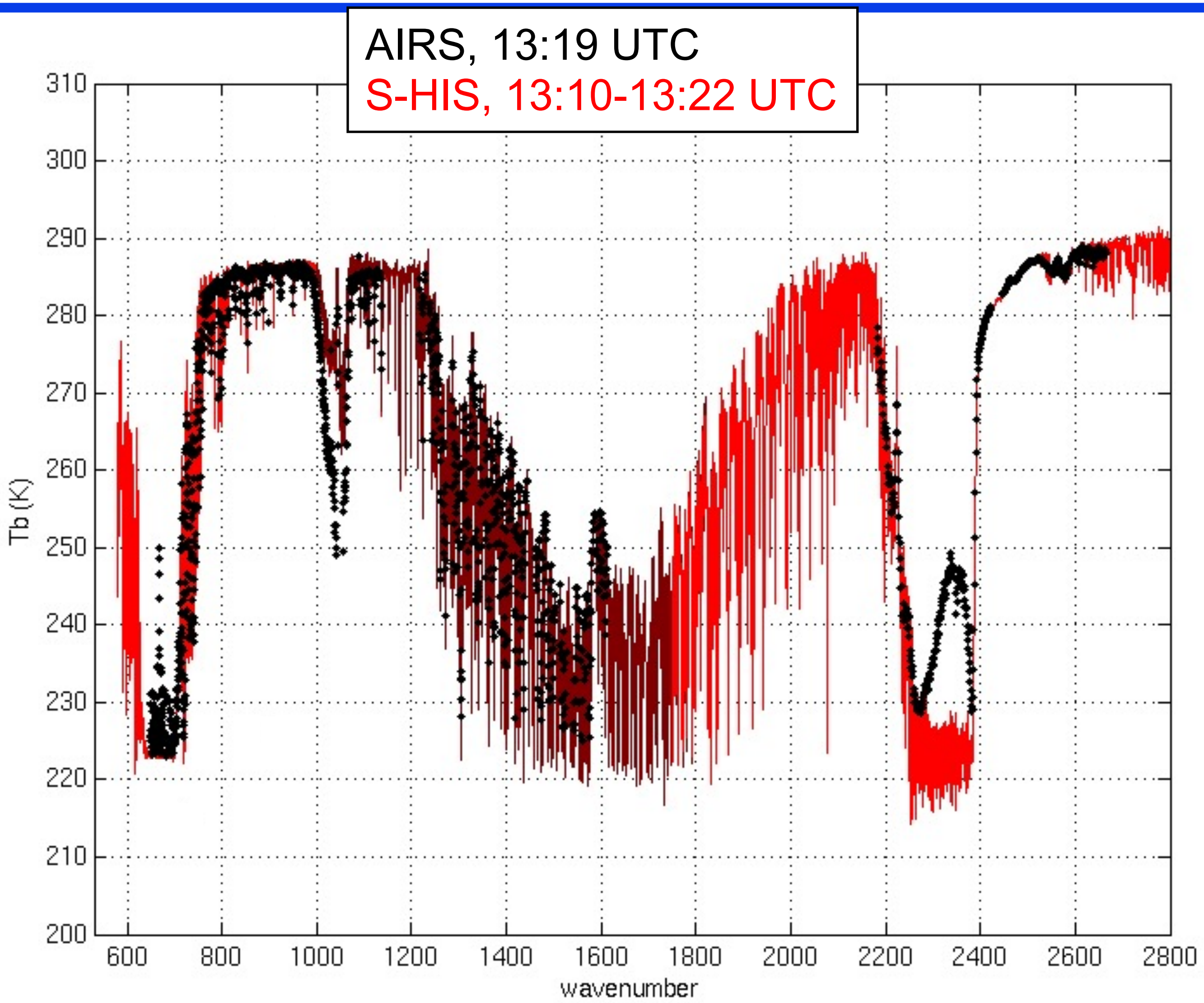
EAQUATE (Italy) 040907- Ocean



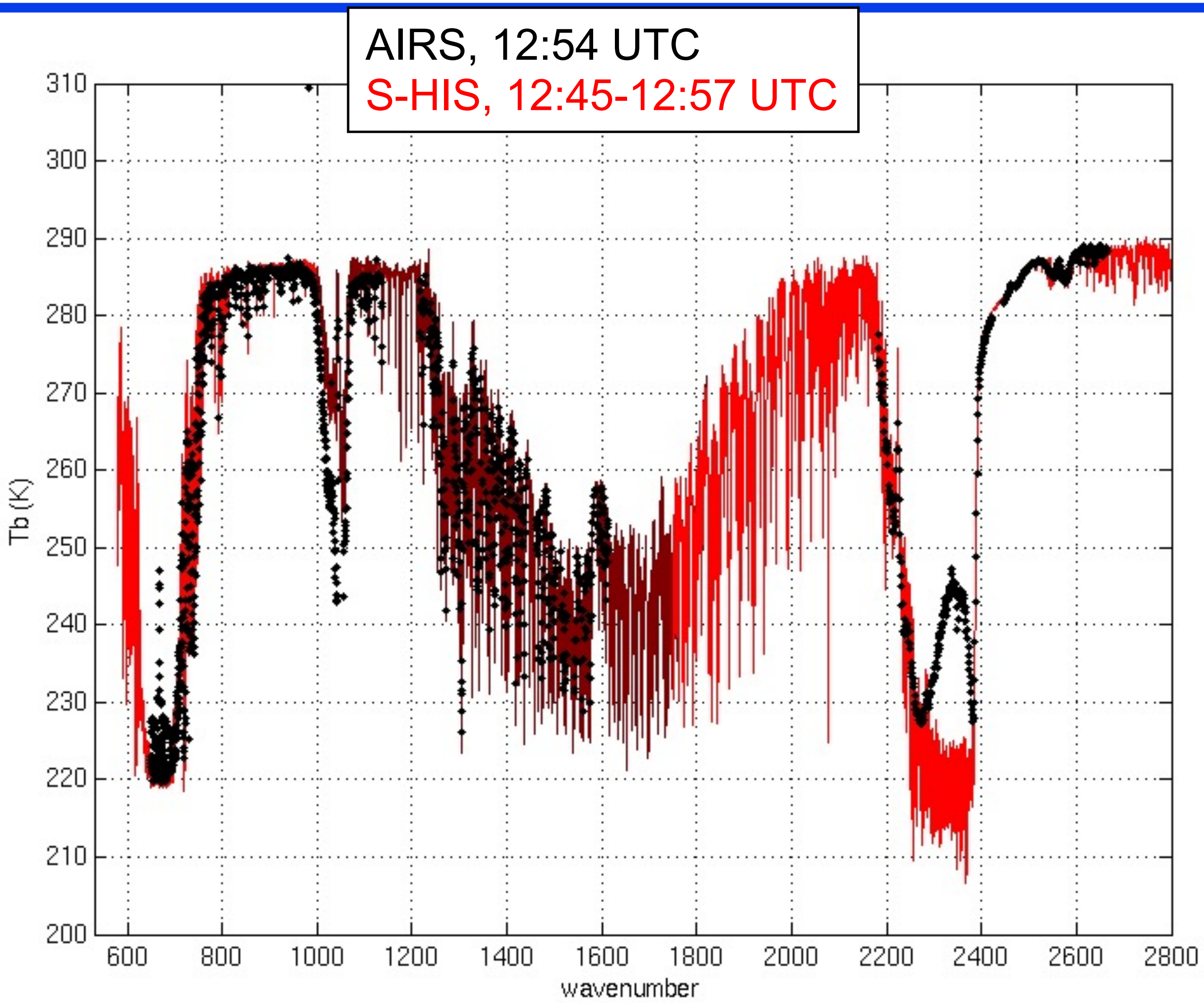
EAQUATE (Italy) 040909



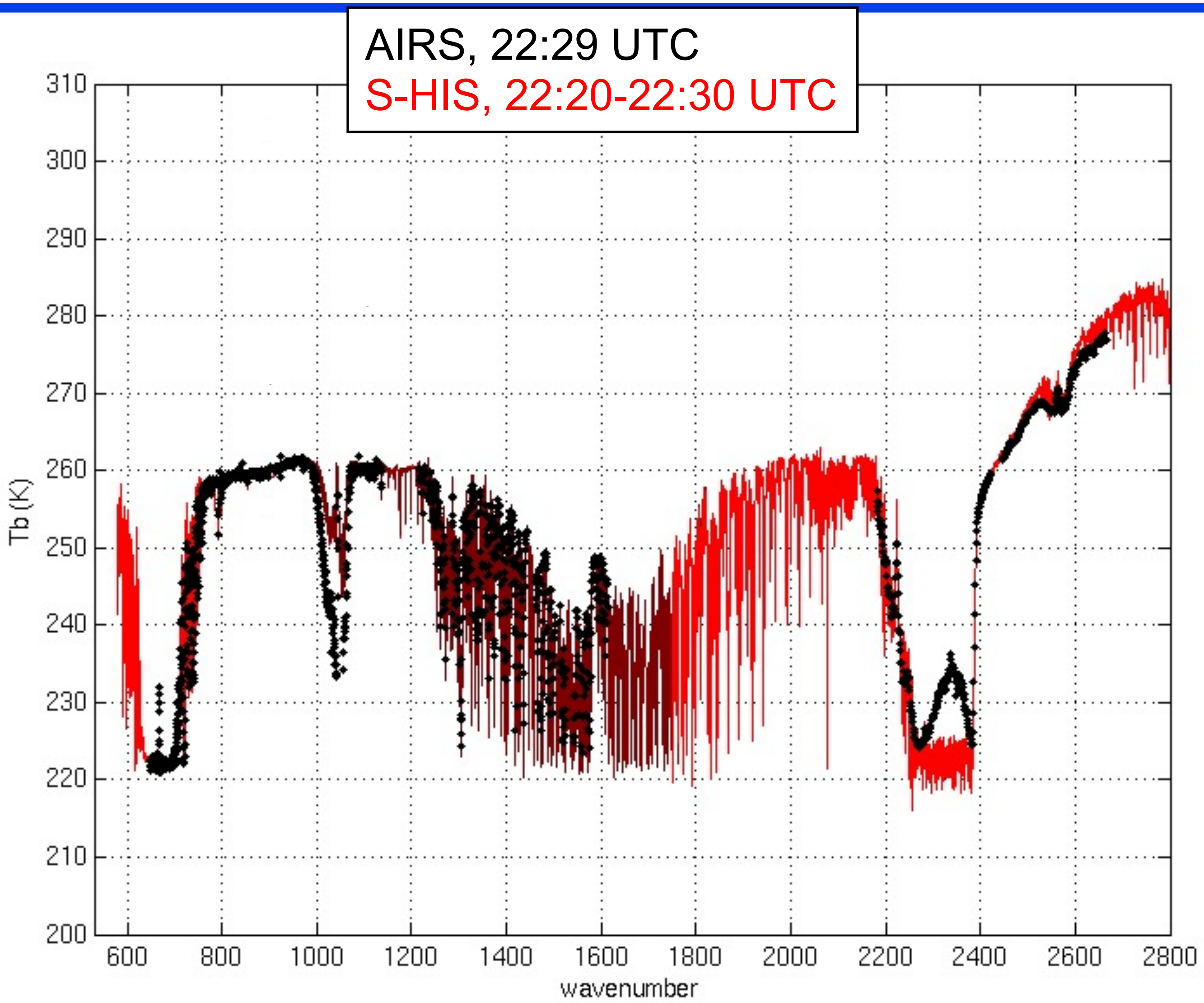
EAQUATE (UK) 040914



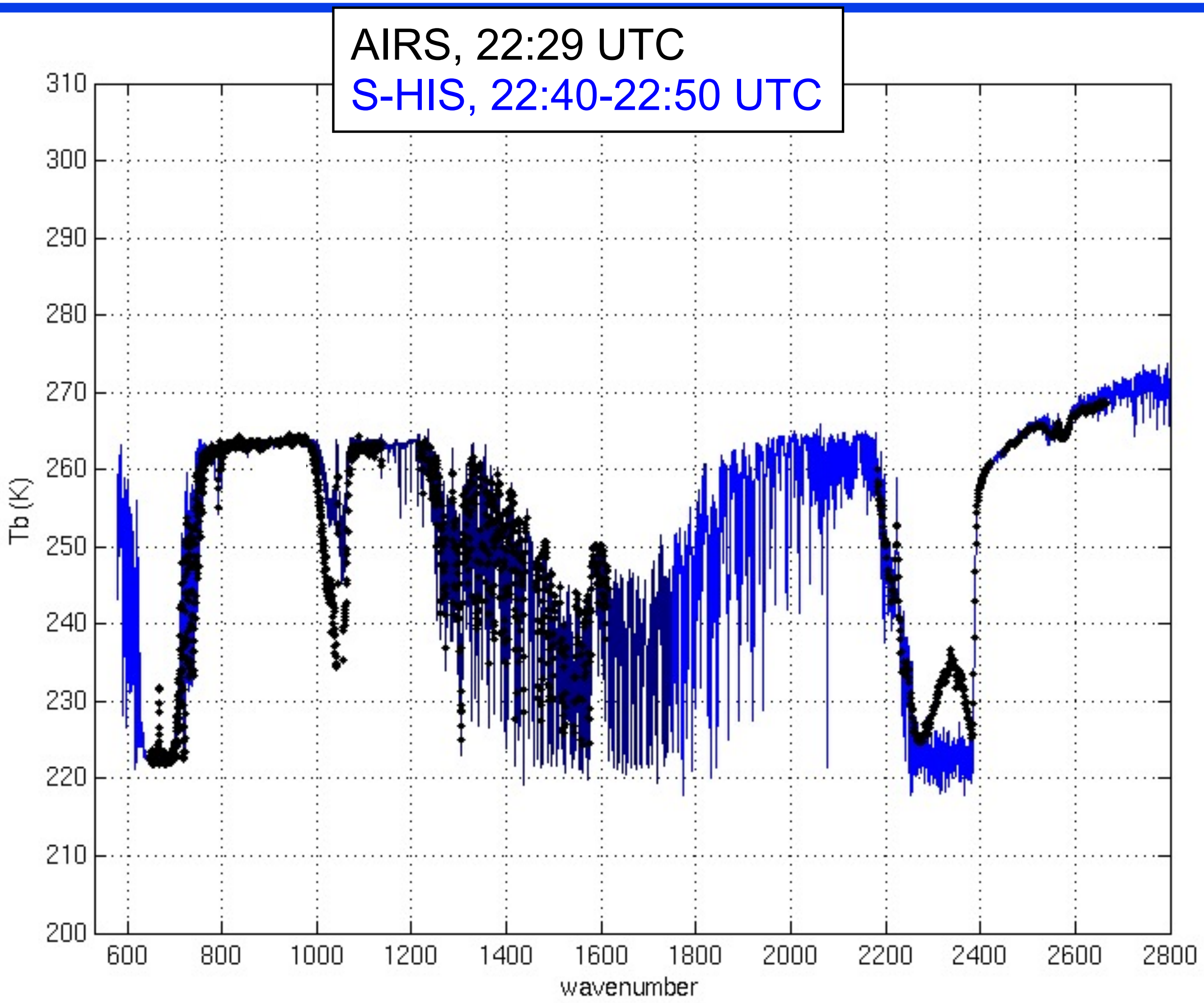
EAQUATE (UK) 040918



MPACE 10/08

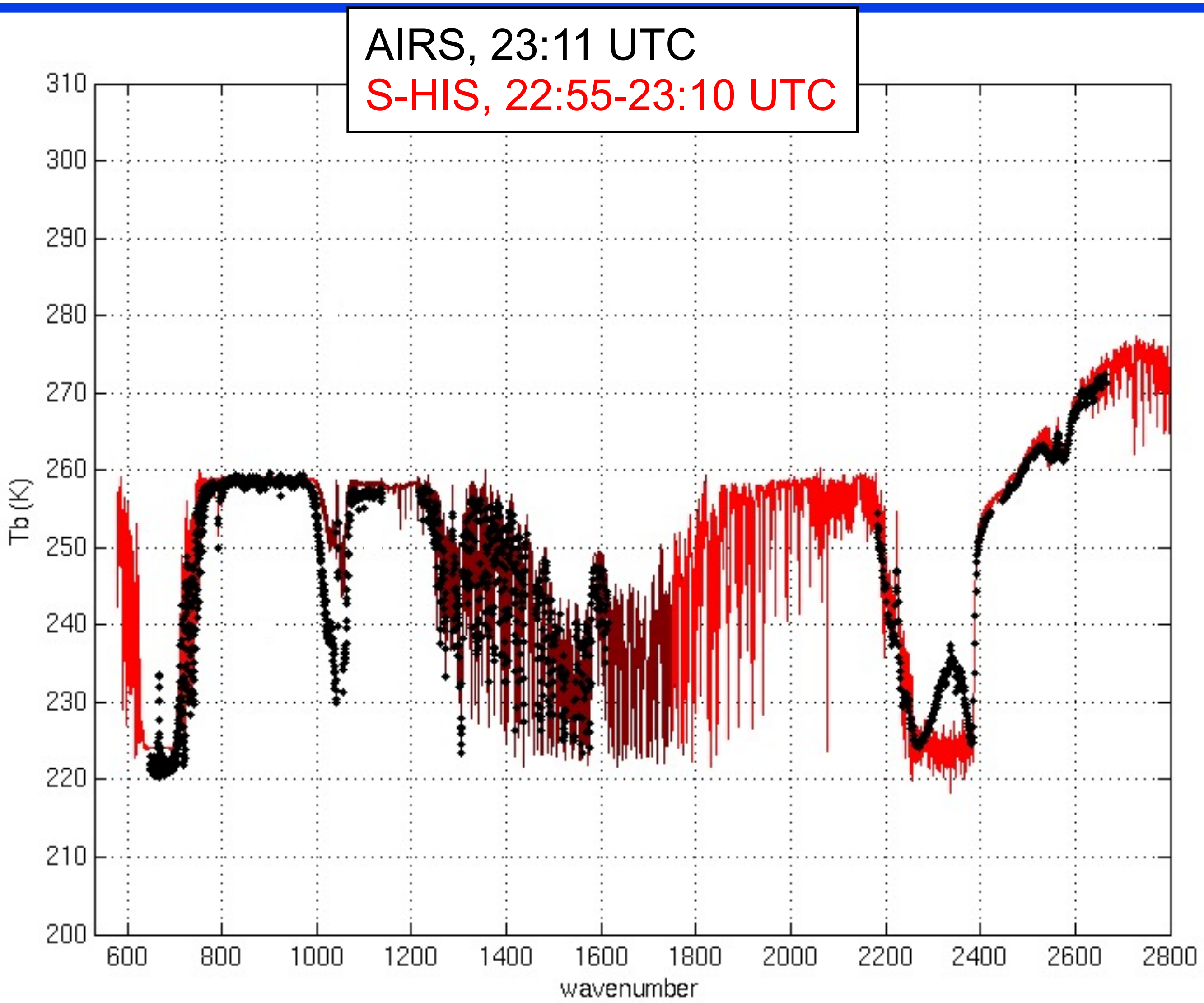

AIRS, 22:29 UTC
S-HIS, 22:20-22:30 UTC
Tb (K)
wavenumber
310
300
290
280
270
260
250
240
230
220
210
200
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

MPACE 10/08

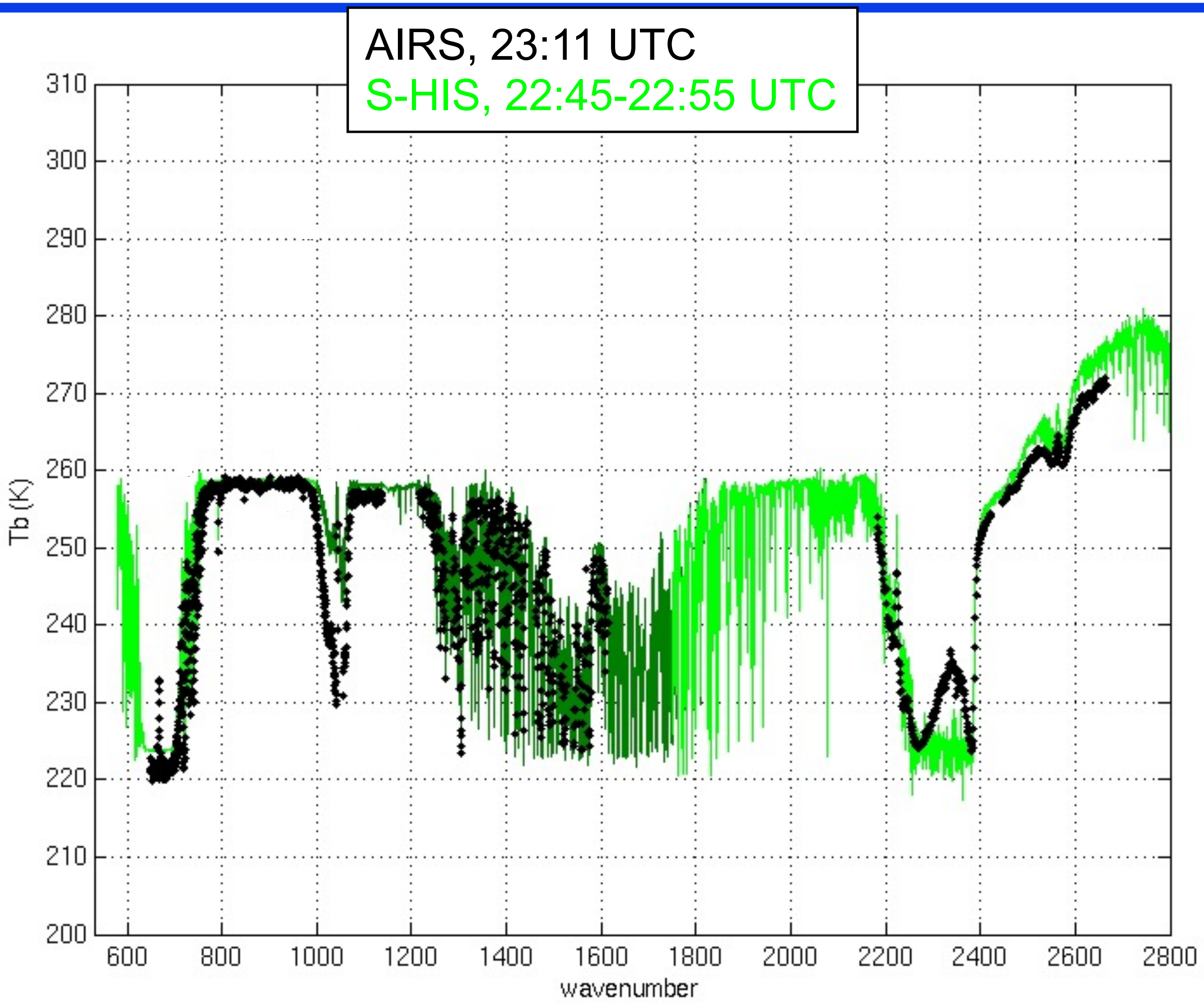


AIRS, 22:29 UTC
S-HIS, 22:40-22:50 UTC
310
300
290
280
270
260
250
240
230
220
210
200
Tb (K)
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
wavenumber

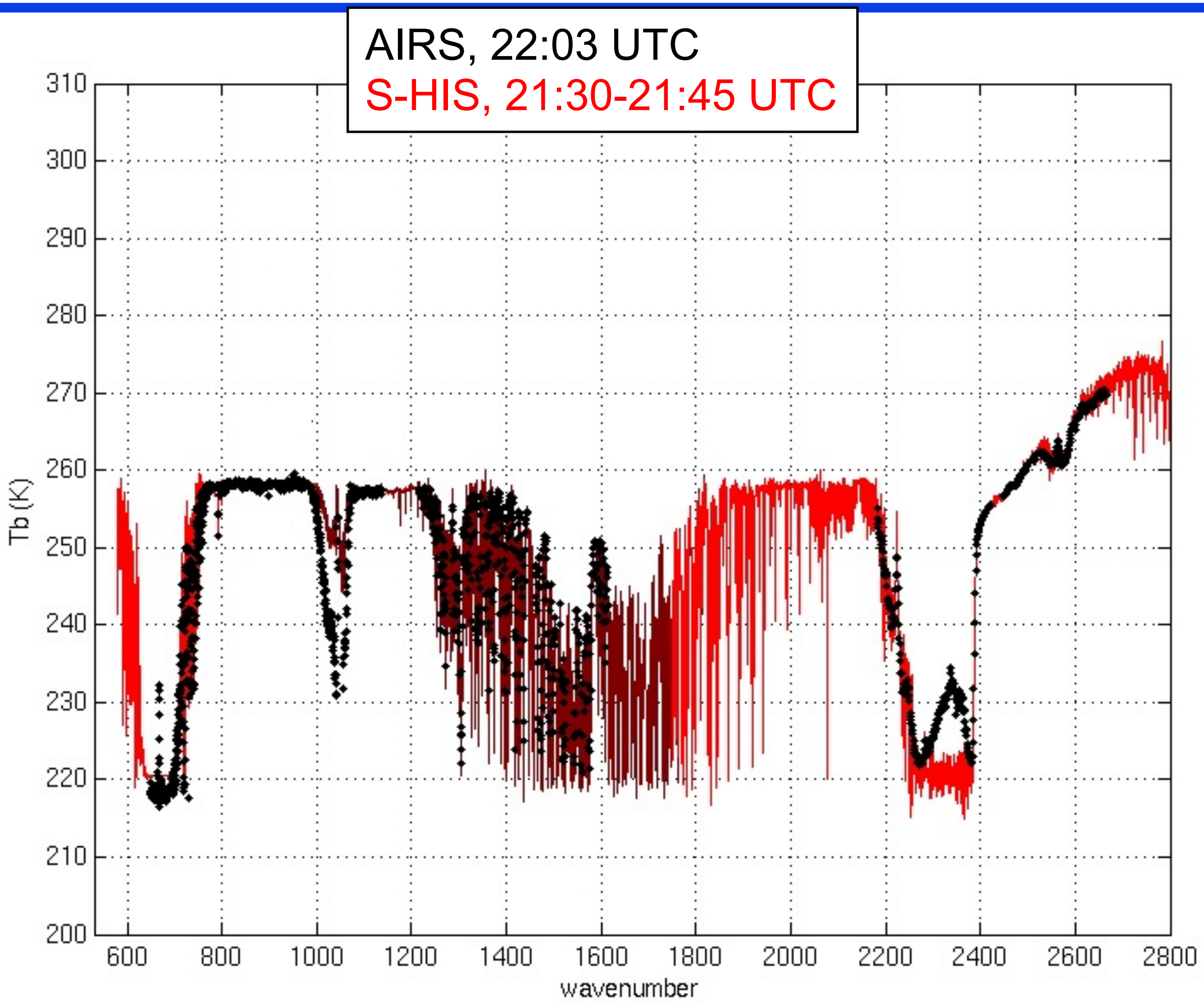
MPACE 10/09


AIRS, 23:11 UTC
S-HIS, 22:55-23:10 UTC
Tb (K)
310
300
290
280
270
260
250
240
230
220
210
200
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
wavenumber

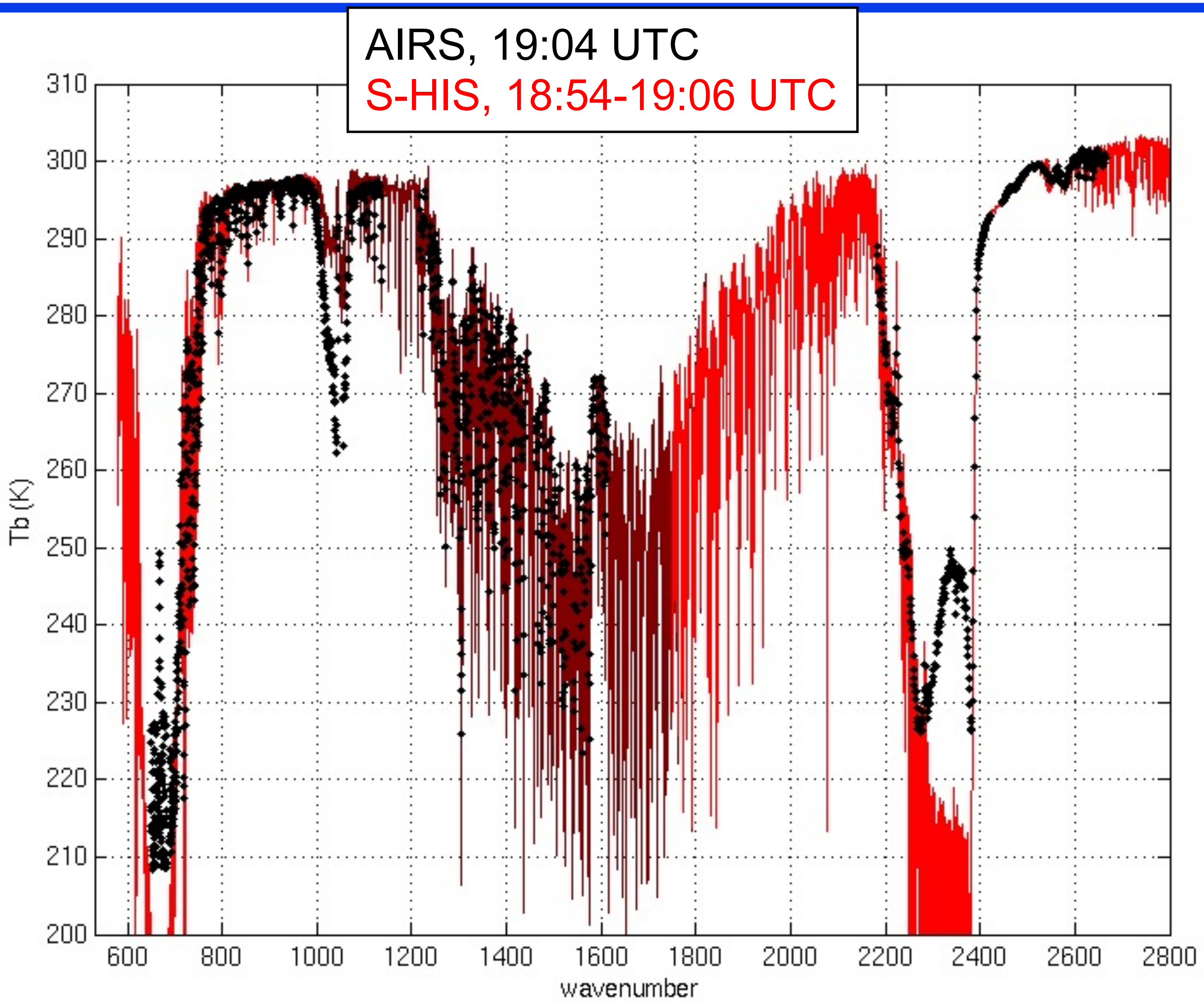
MPACE 10/09


AIRS, 23:11 UTC
S-HIS, 22:45-22:55 UTC
Tb (K)
310
300
290
280
270
260
250
240
230
220
210
200
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
wavenumber

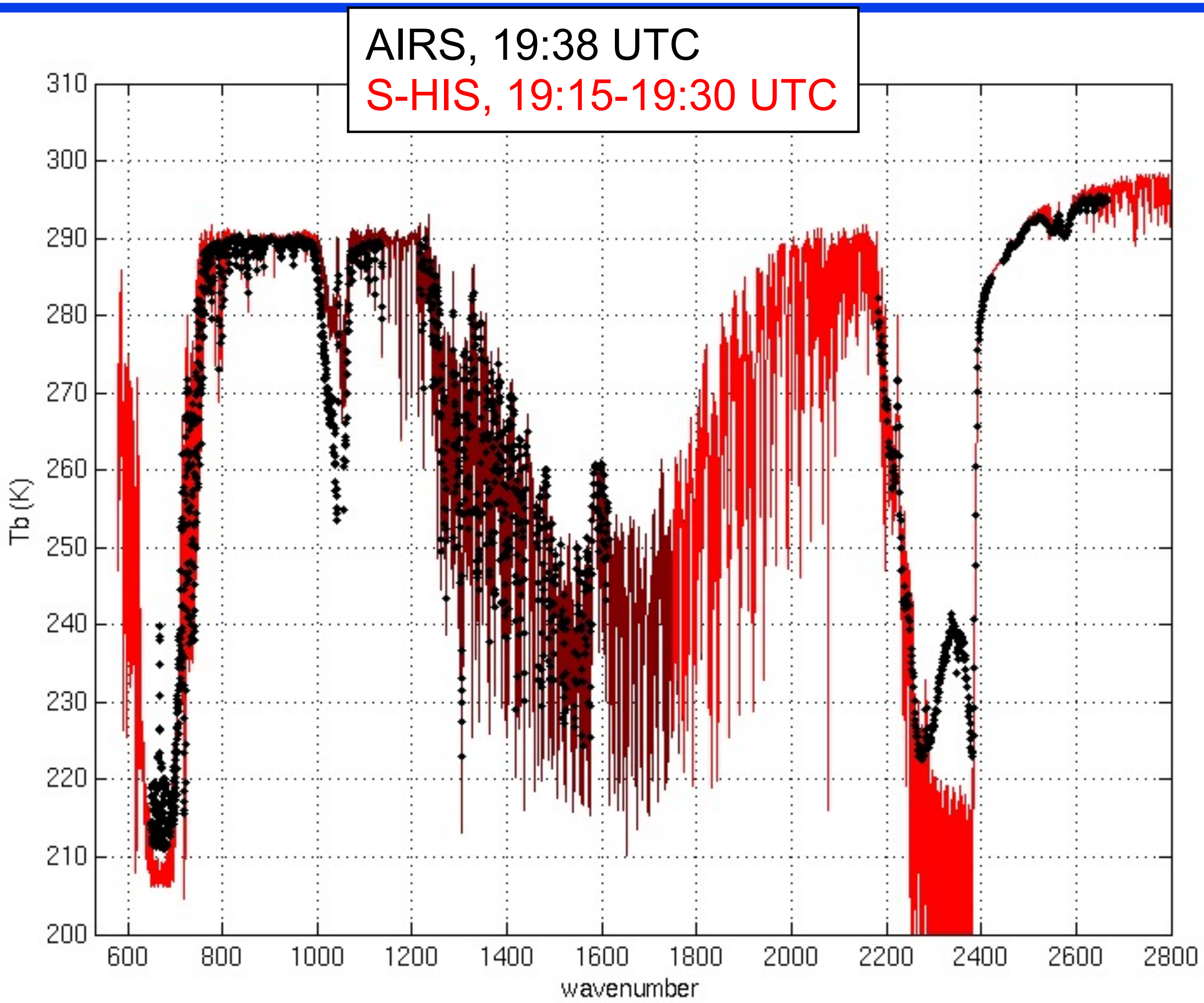
MPACE 10/12


AIRS, 22:03 UTC
S-HIS, 21:30-21:45 UTC
Tb (K)
310
300
290
280
270
260
250
240
230
220
210
200
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
wavenumber

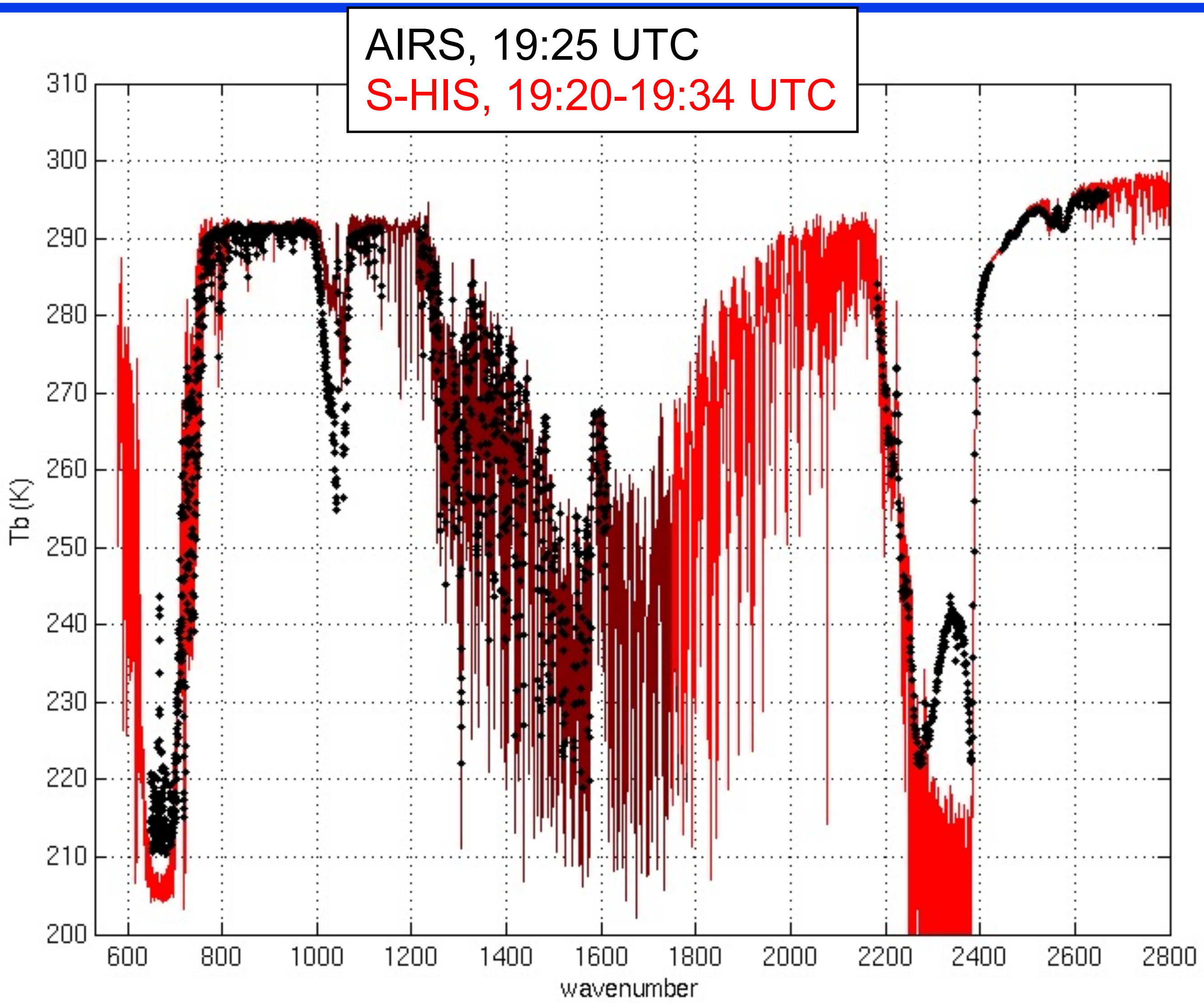
AVE Flight 10/31



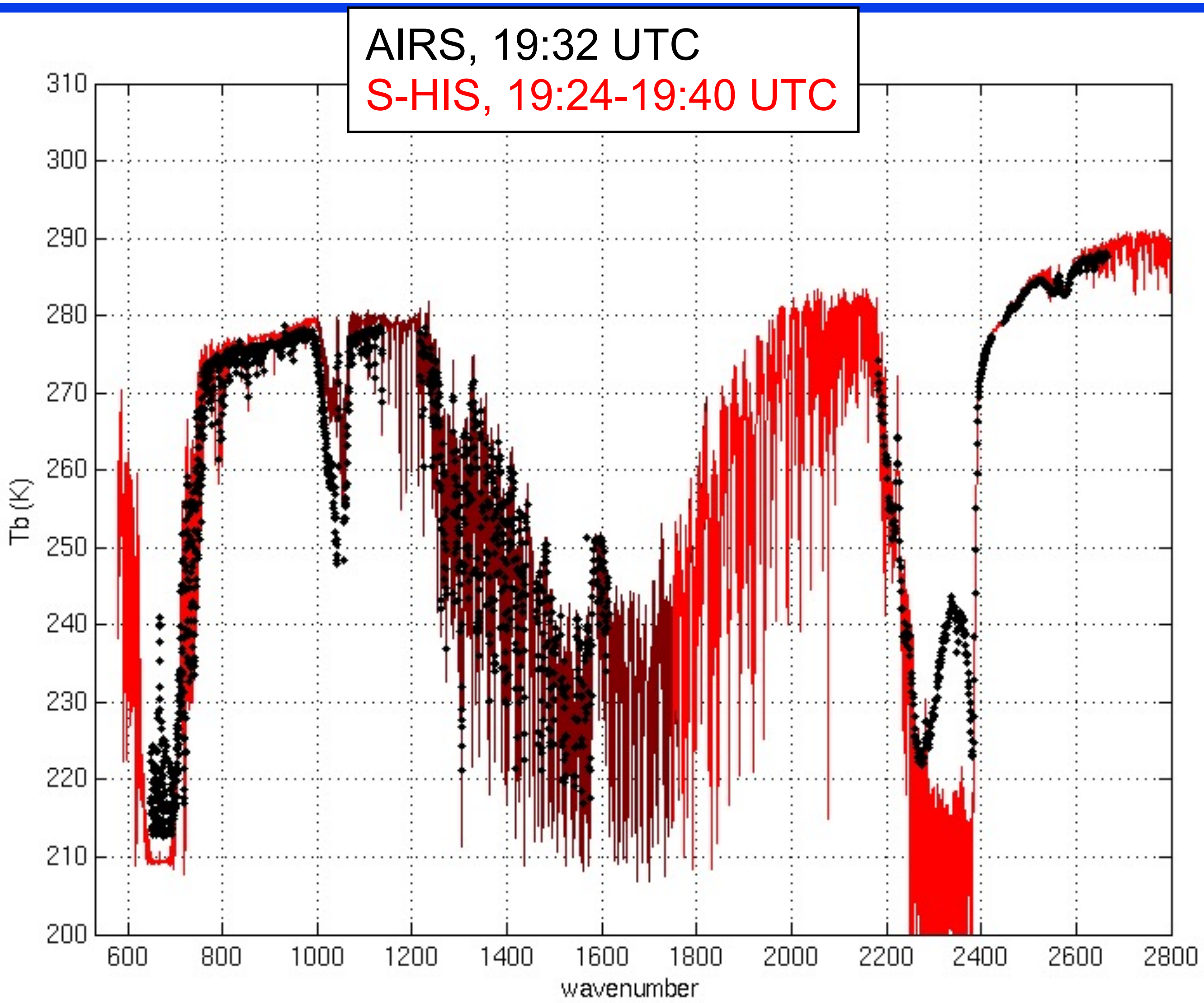
AVE Flight 11/03



AVE Flight 11/05



AVE Flight 11/12



4. The Promise of CrIS for NPOESS

CrIS, AIRS Successor for NPOESS will be even better

1. **Radiometric Calibration**: < 0.4 K 3-sigma
   (Design specs: < 0.45%, LW, 0.58% MW, 0.77% SW)

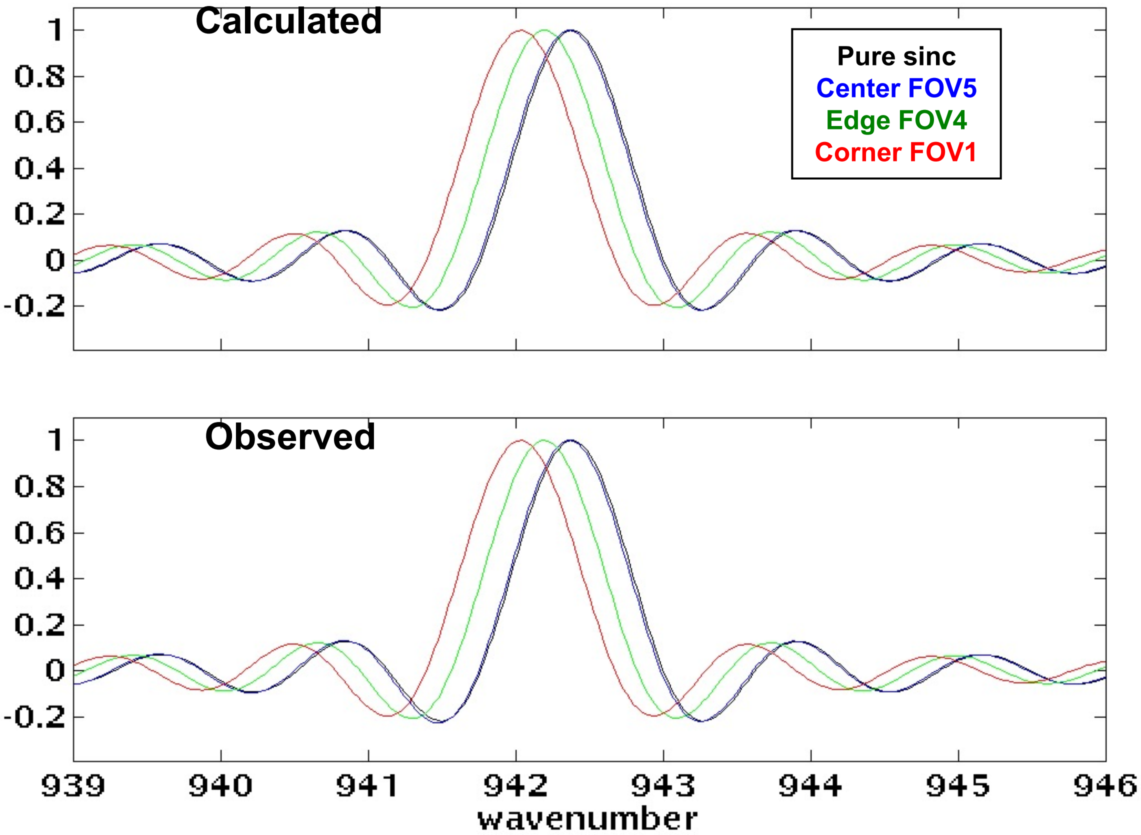
2. **Spectral Calibration**:
   Instrument Line Shape (ILS) extremely well known and stable from first principles

3. **Noise**:
   4x smaller than AIRS in the LW CO_2 region

CrIS Observed and Calculated Instrument Line Shape (ILS)

CO$_2$ laser source, Center, Edge & Corner Pixels of 3x3 array

(λ_{laser} = 775.18765 nm, $\nu_{CO2laser}$ = 942.383333 cm^{-1}, dx=-0.7mrad, dy=0.1 mrad)

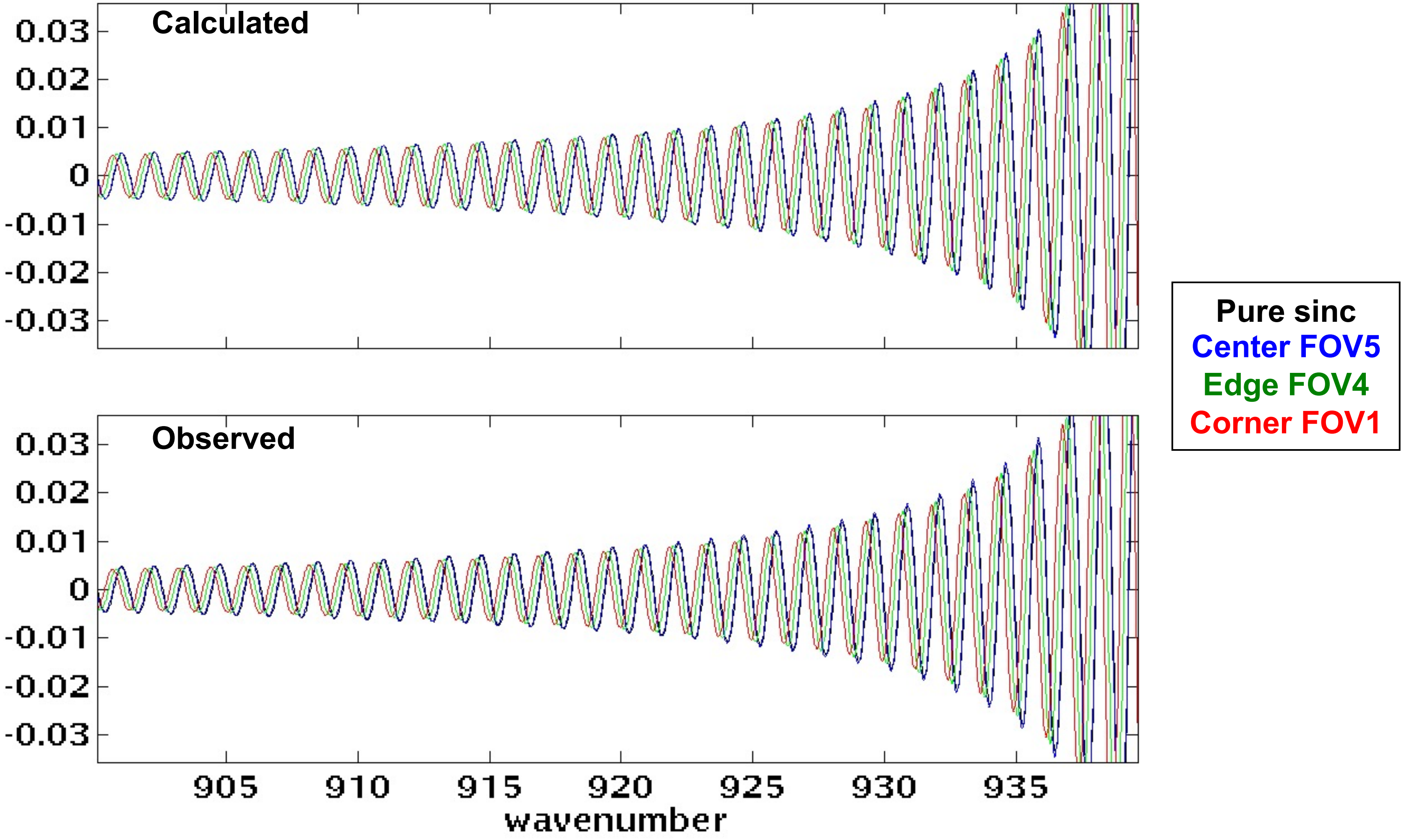


		Center FOV	Edge FOV	Corner FOV
centroid (cm^{-1})	Obs	942.367	942.195	942.034
	Calc	942.366	942.195	942.034
FWHM (cm^{-1})	Obs	0.747	0.757	0.767
	Calc	0.751	0.759	0.767
Lfoot	Obs	0.358	0.329	0.313
	Calc	0.347	0.328	0.313
Rfoot	Obs	0.347	0.326	0.311
	Calc	0.345	0.329	0.313

FTS design expectations confirmed

Observed and Calculated ILSs for Run1, FOVs 5, 4, and 1

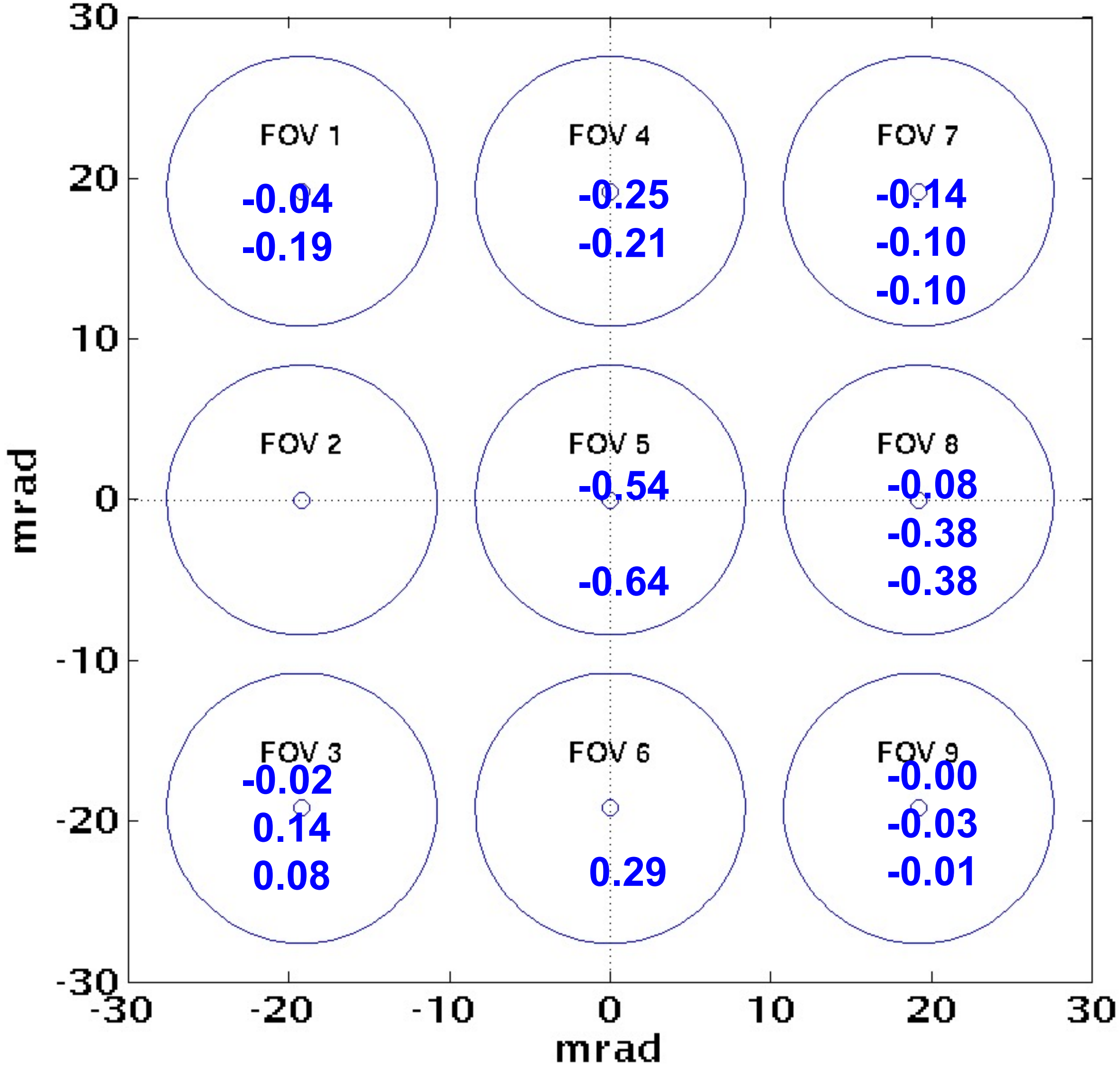
λ_{laser} = 775.18765 nm, $\nu_{CO2laser}$ = 942.383333 cm^{-1}, dx=-0.7mrad, dy=0.1 mrad



CrIS ILS Quantitative Verification

Δwidth (%) for all FOVs

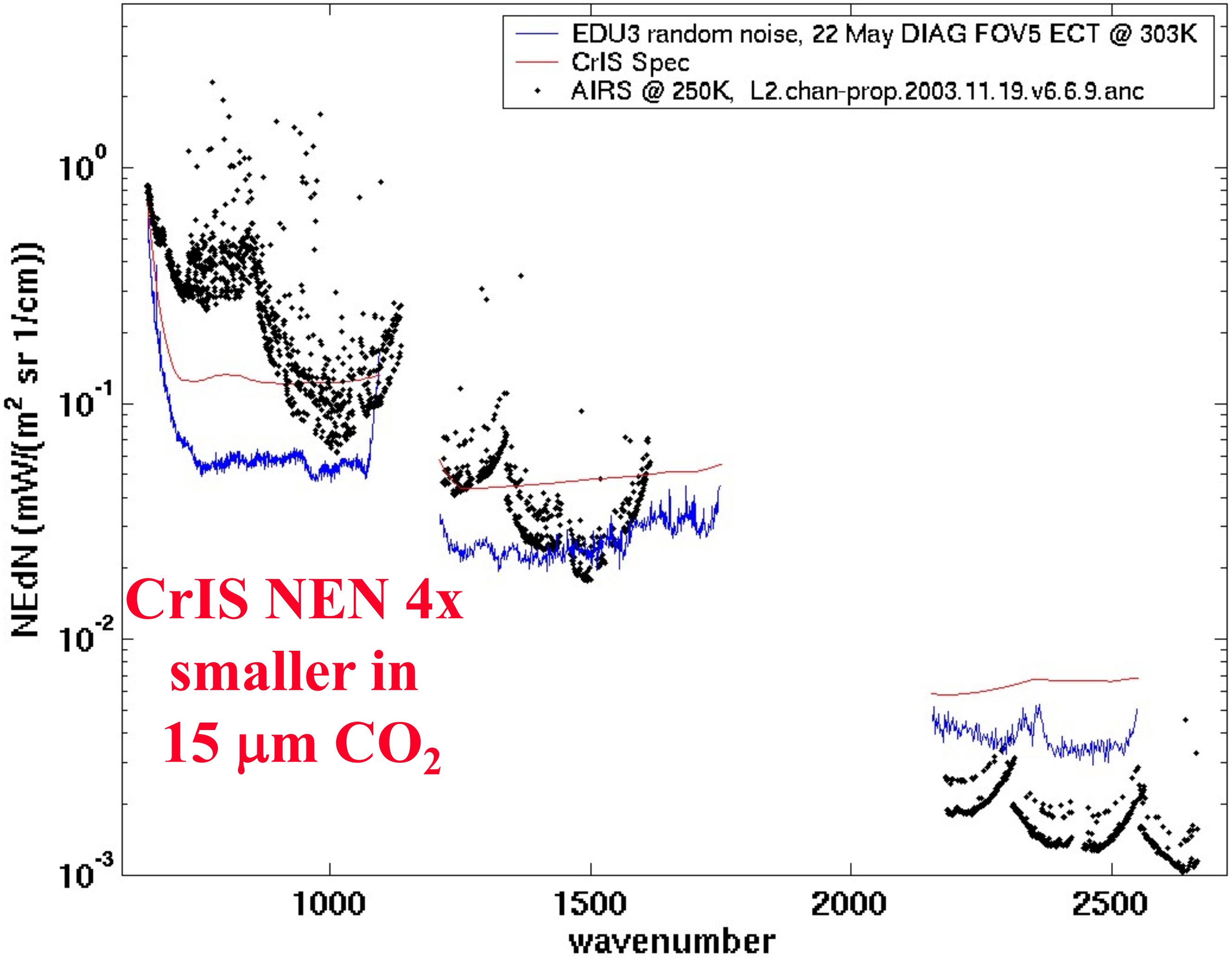
with small overall array shift dx= -0.7mrad, dy= 0.1 mrad



Normal Spec

Δwidth < 1%

NEN Comparion with AIRS (AIRS, CrIS random, CrIS Spec)



CrIS NEN 4x smaller in 15 μm CO_2

AIRS for 250K scene, CrIS for 303 K (SW NENs similar for 300K scene)

Calibration and Validation of upwelling IR radiance observations are now concerned with
tenths of K, not degrees K !

High Spectral Resolution is an important part of the reason
(Goody & Haskins, J Climate,1998)