AIRS Radiance Validation

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CalTech

Calibration Emphasis

Make full use of the fundamental advantage of high resolution infrared spectra to provide a new standard of accuracy for weather and climate applications

- High spectral resolution does offer inherent advantages for calibration accuracy (Goody and Haskins, 1998)
- S-HIS verifies highly accurate AIRS radiometric calibration-better than originally specified
- Characterizing the nature of small differences should lead to improvements in remote sensing
- The high resolution calibration advantage has also been transferred to lower resolution IR instruments, like MODIS

Now concerned with tenths of K, not 1 K!

Topics

- **S-HIS summary**
- **Radiometric Calibration**
- **AIRS Radiance Validation with S-HIS**
  5 cases cover Tropics to Arctic,
  Day and Night, Land and Sea
  (thanks to IPO, DOE, and NASA AURA
  validation & science support)
- **Artifacts of Individual Spectra**
- **Summary**

1. S-HIS summary

UW Scanning HIS: 1998-Present

HIS: High Resolution Interferometer Sounder (1985-1998)

Characteristics

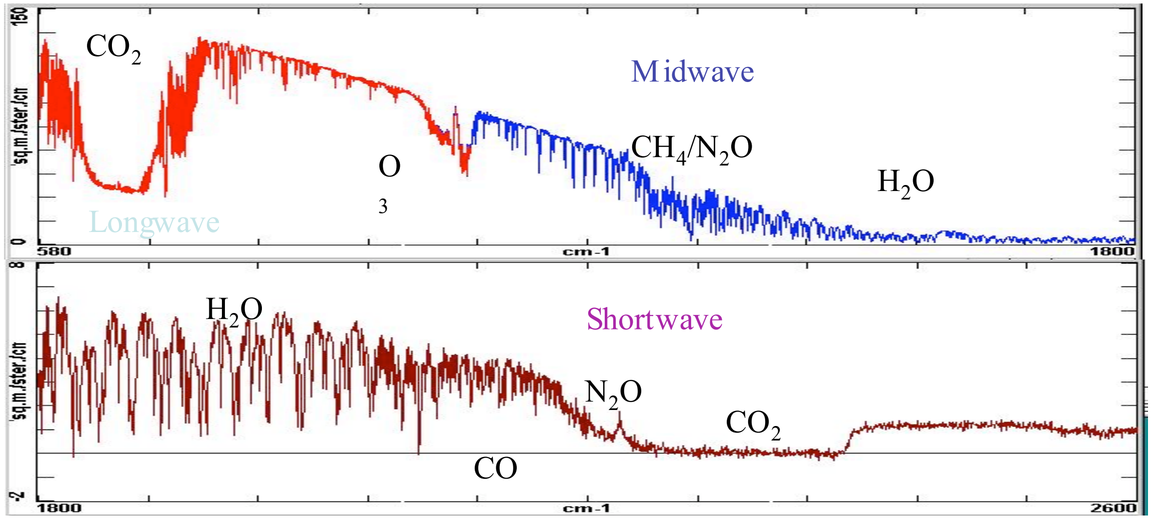
Spectral Coverage: 3-17 microns

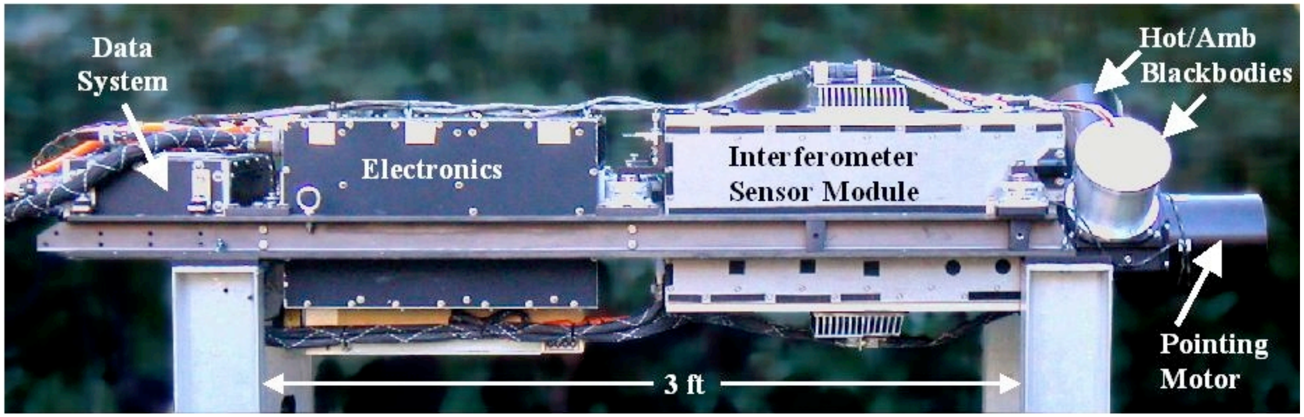
Spectral Resolution: 0.5 cm^{-1}

Resolving power: 1000-6000

Footprint Diam: 1.5 km @ 15 km

Cross-Track Scan: Programmable including uplooking zenith view





Applications:

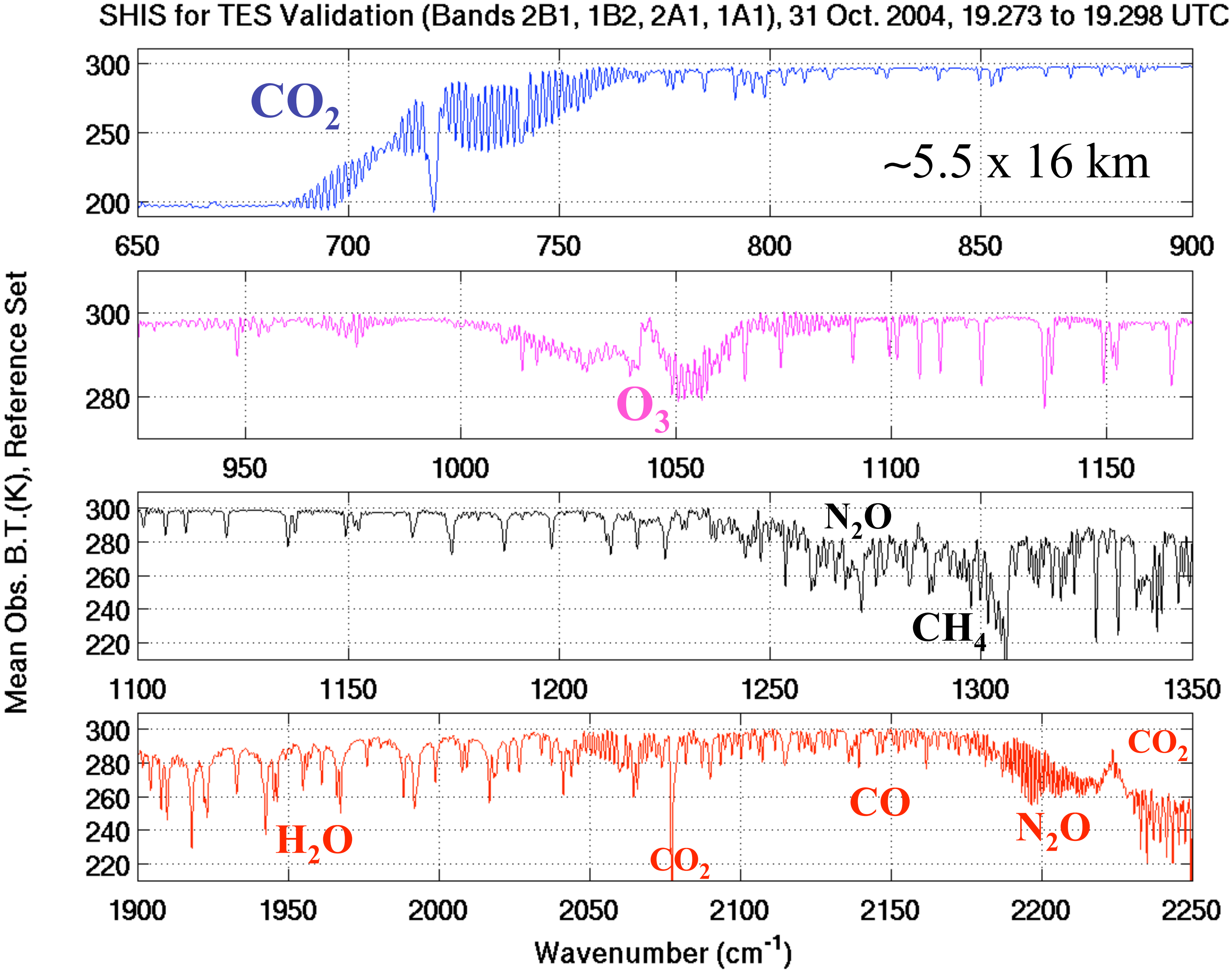
- Radiances for Radiative Transfer
- Temp & Water Vapor Retrievals
- Cloud Radiative Prop.
- Surface Emissivity & T
- Trace Gas Retrievals

S-HIS for CRAVE
January 2006

AURA Validation Experiment-Costa Rica

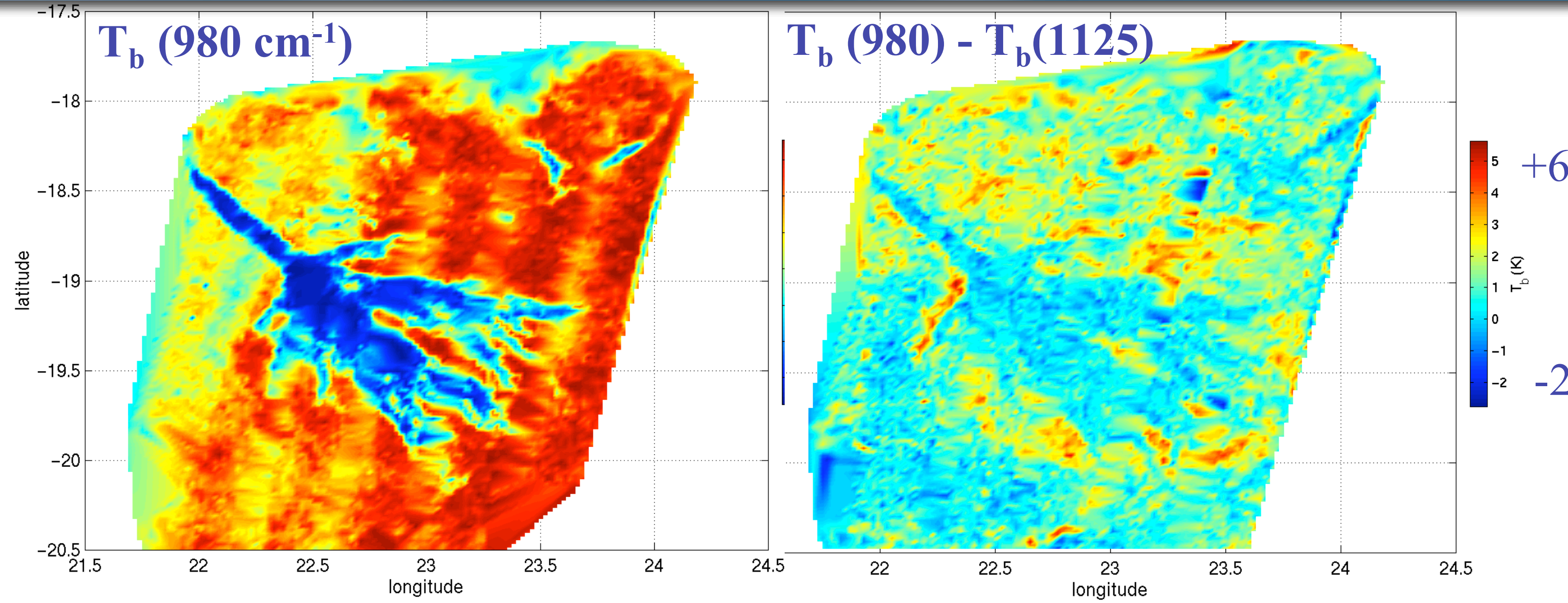
S-HIS
scans cross-track downward & looks upward

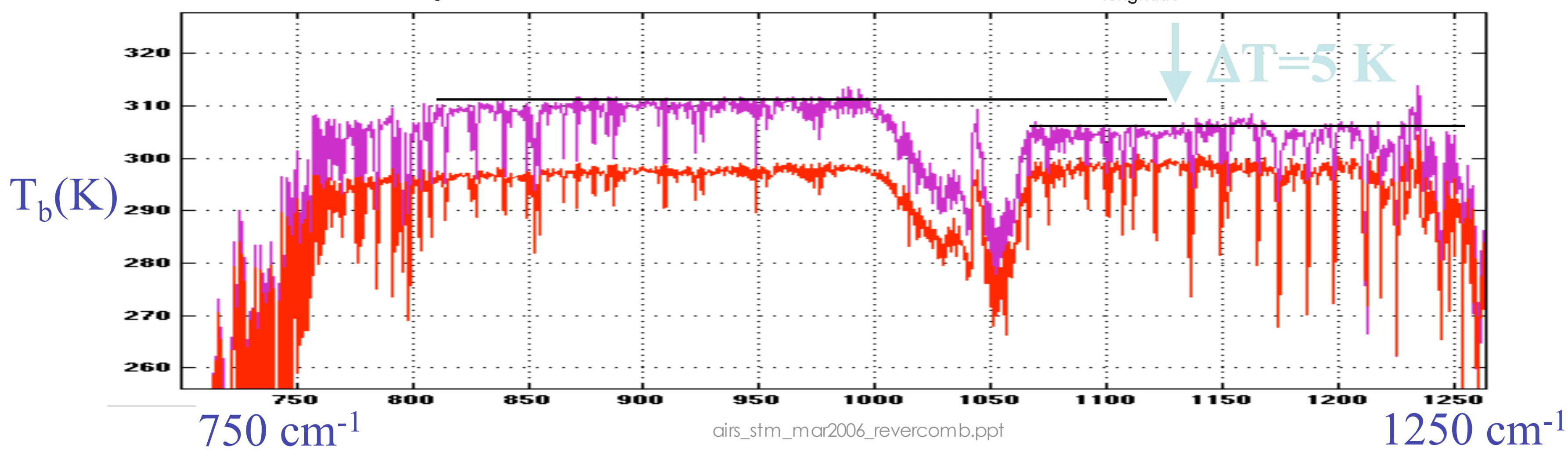
S-HIS –Tropospheric Emission Spectrometer (TES) Bands
near 31 Oct 2004 overpass



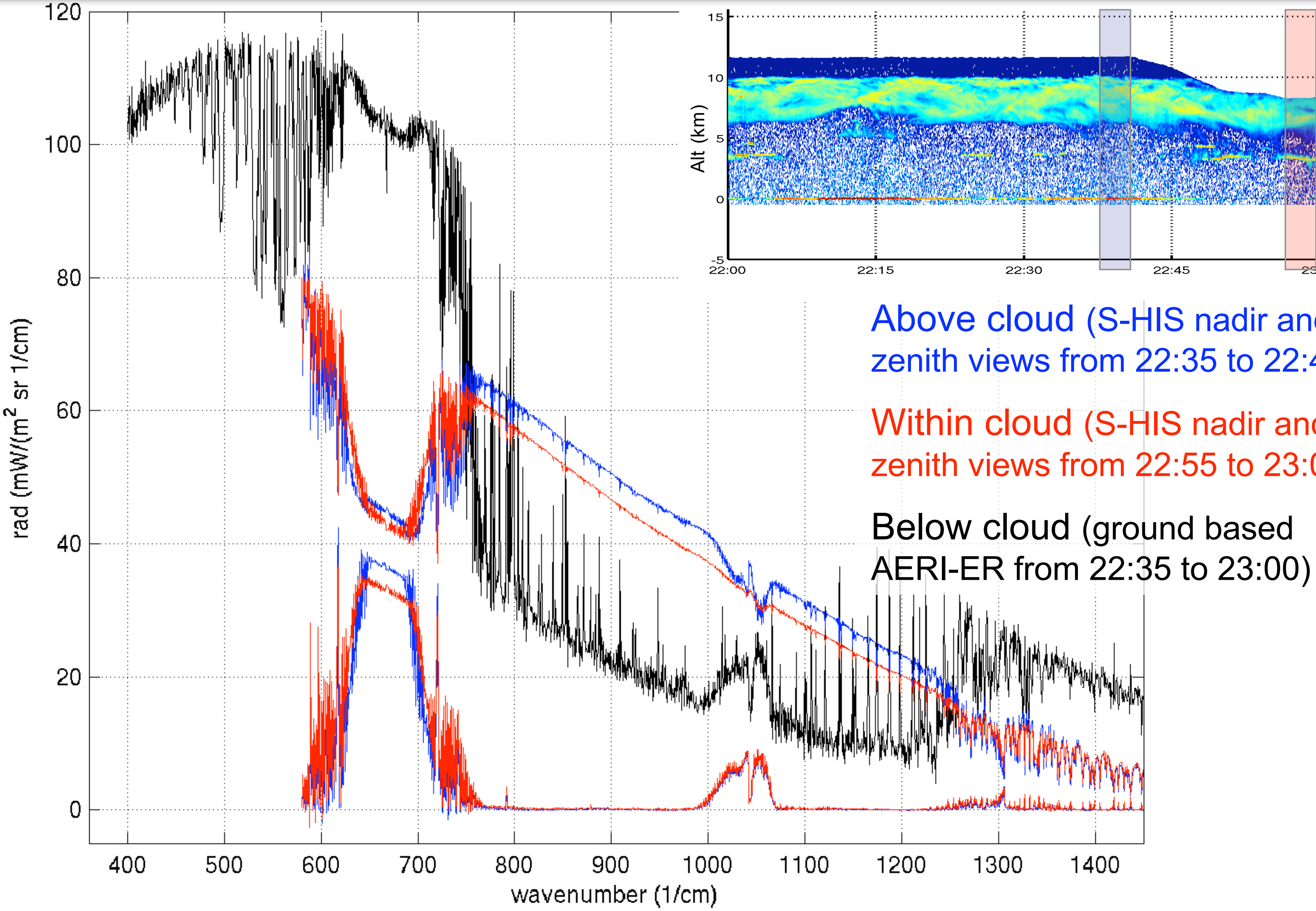
Cross-track Mapping Capability:

Okavanga Delta Surface Emissivity (27 August 2000)





Uplooking: MPACE Example 10/17/04 with SHIS & AERI-ER



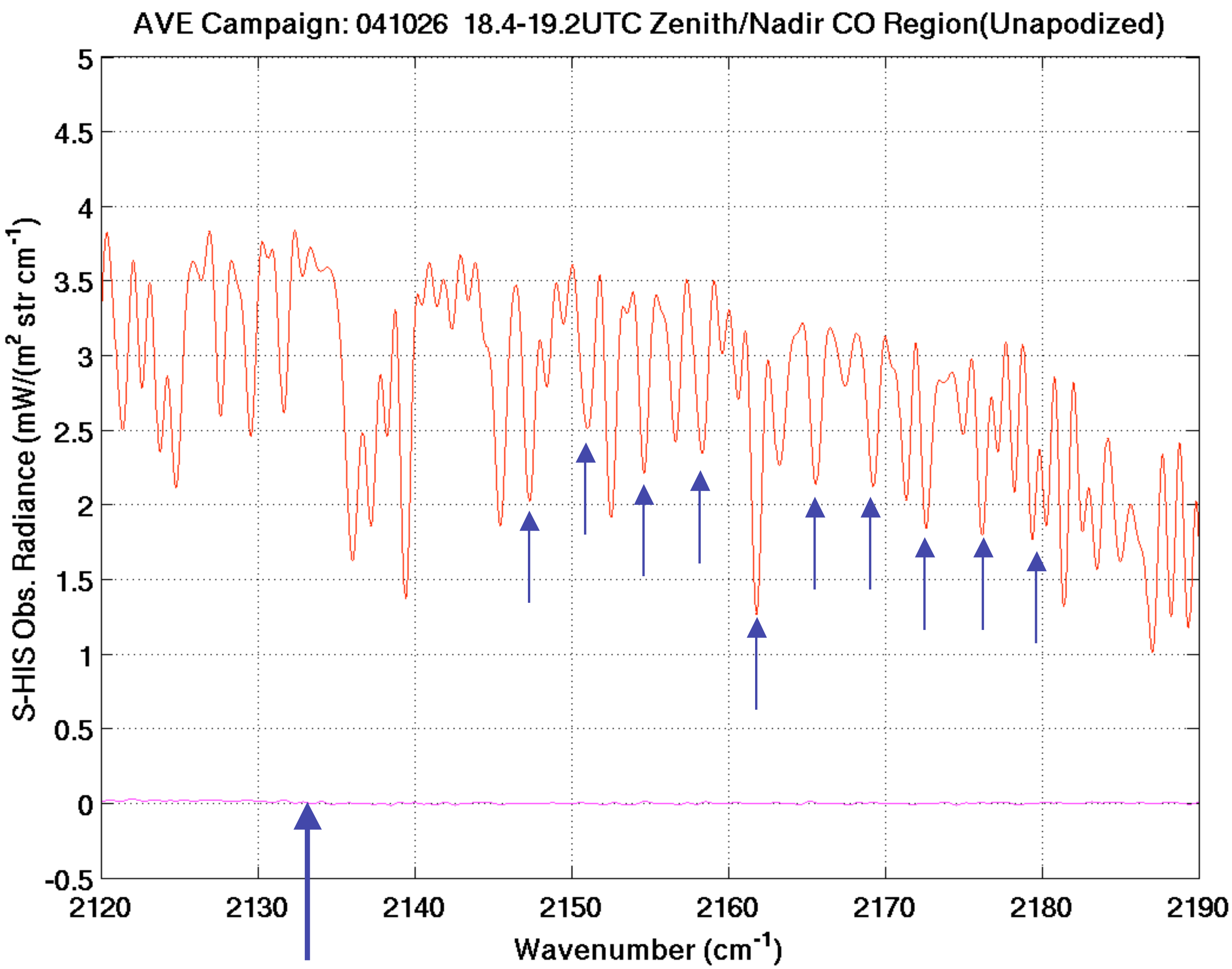
Above cloud (S-HIS nadir and zenith views from 22:35 to 22:40)

Within cloud (S-HIS nadir and zenith views from 22:55 to 23:00)

Below cloud (ground based AERI-ER from 22:35 to 23:00)

S-HIS Spectra, 4.67 μm CO

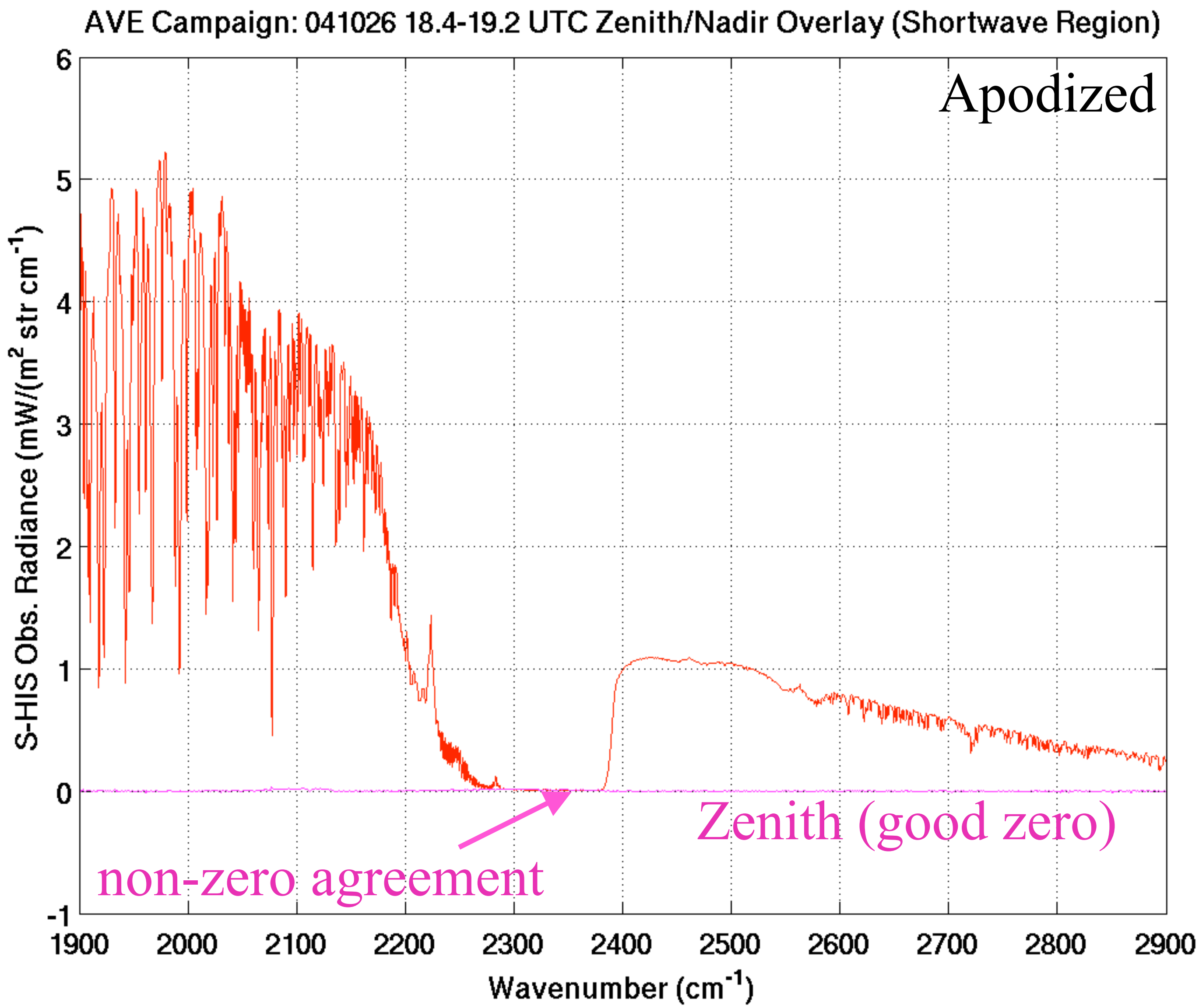
AVE, 26 October 2004



Note good uplooking zero

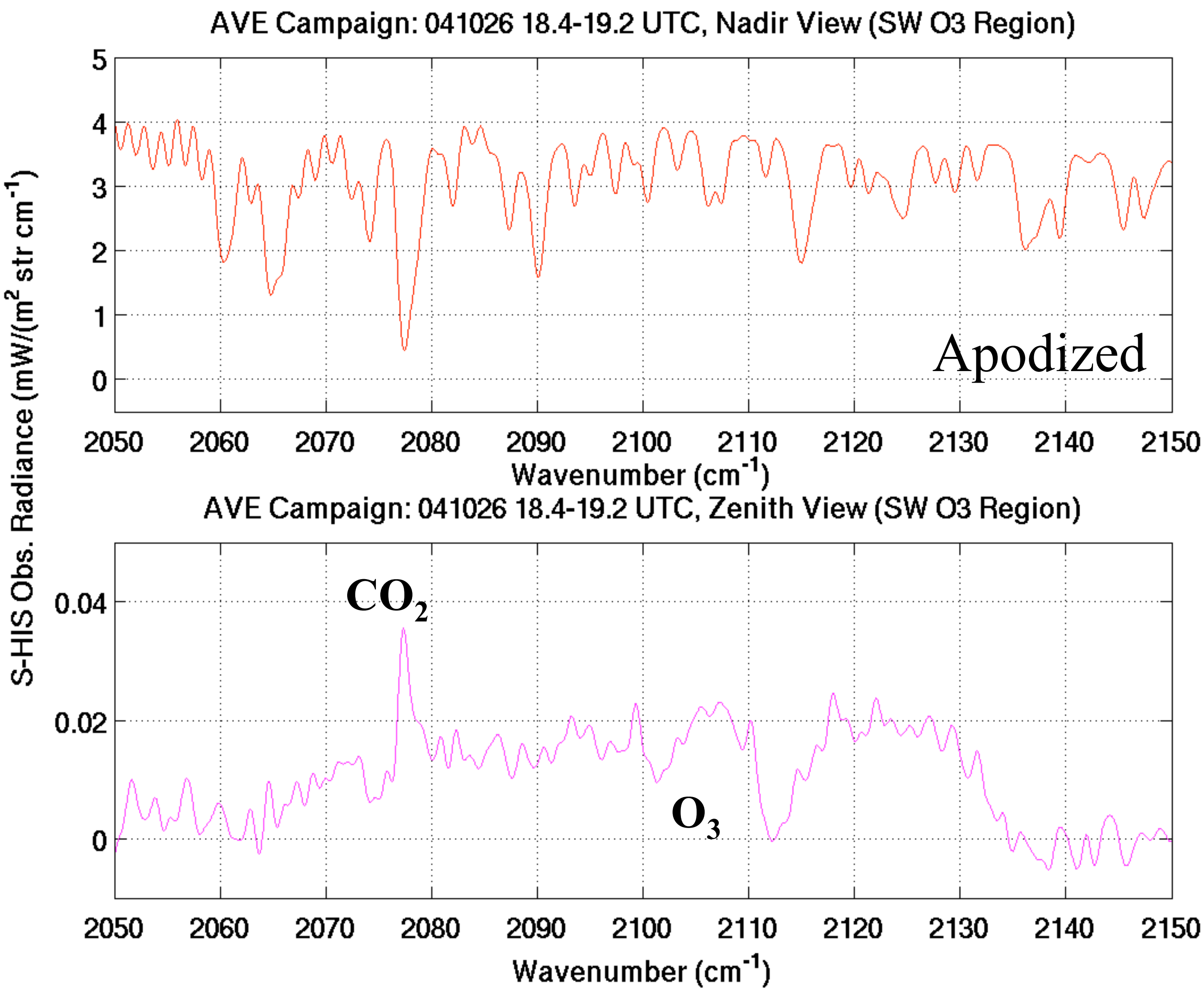
S-HIS Spectra, SW/4.3 μm CO_2

AVE, 26 October 2004



S-HIS Spectra, 4.73 μm O_3

AVE, 26 October 2004



2. Radiometric Calibration

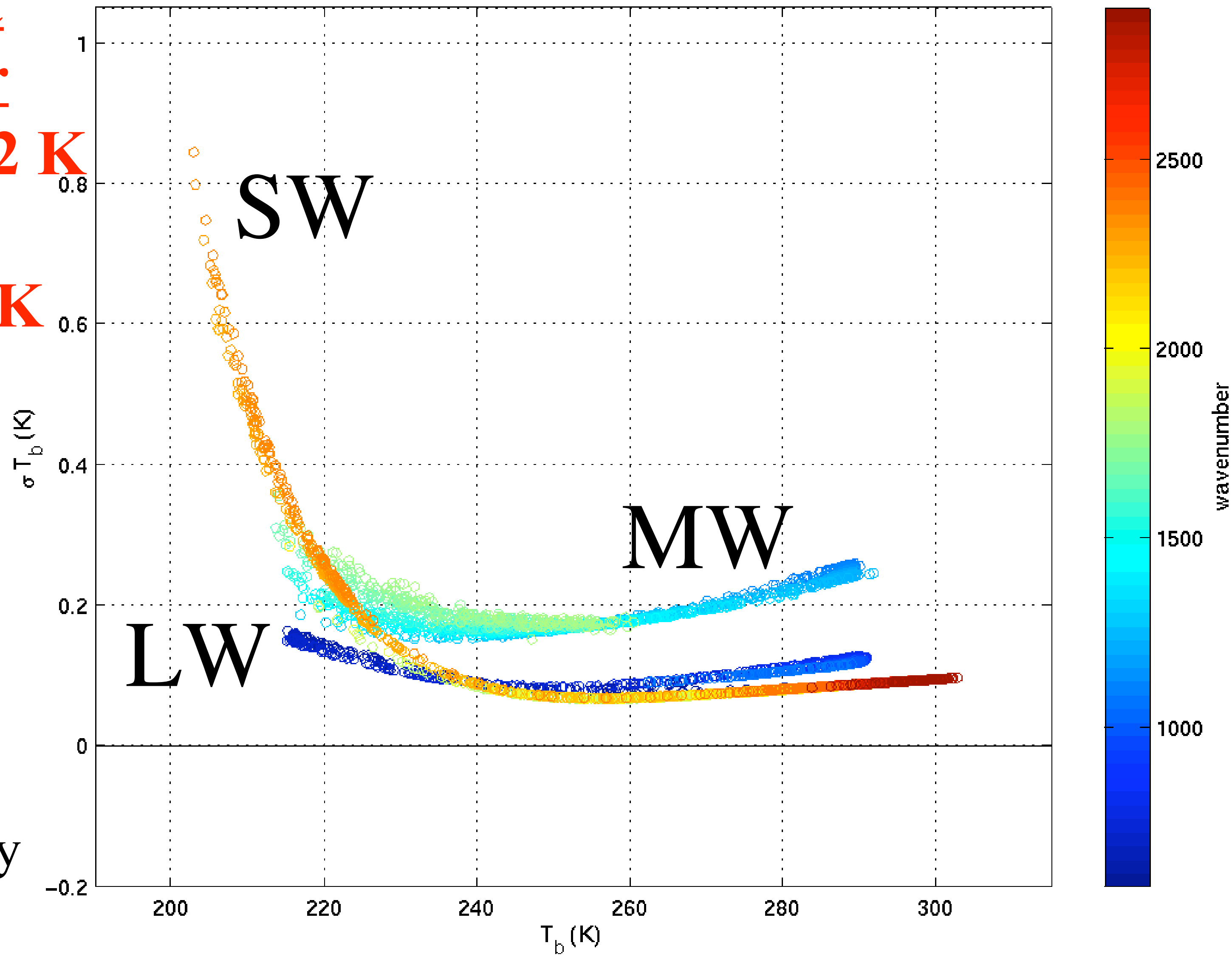
Scanning-HIS Radiometric Calibration Budget

TABB= 227, THBB=310, 11/16/02 Proteus

Similar to AERI description in Best, et al., CALCON 2003

3-sigma
Tb error
mostly < 0.2 K
for
Tb >220 K

RSS of
Errors in
T_{HBB}, T_{ABB}
T_{Rfl}
ε_{HBB}, ε_{ABB}
+ 10% of
non-linearity
correction



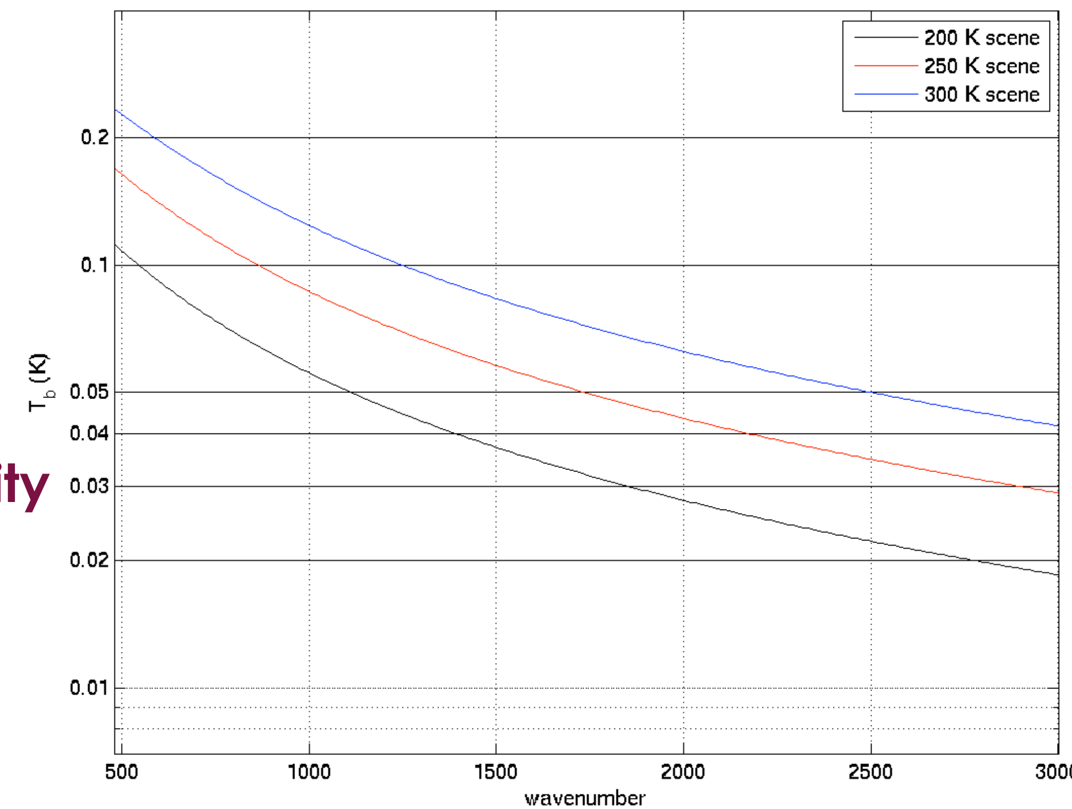
AIRS Radiometric Calibration: A better error estimate is needed

The statement of an AIRS Radiometric Calibration of <u><0.2% absolute error</u> in the AIRS Technical Fact Sheet* is indicative of the problem

The difference between absolute error (3-sigma or at least 2-sigma) and reproducibility or repeatability needs to be clarified

*http://www-airs.jpl.nasa.gov/press/AIRS_tech_factsheet.pdf

Brightness temperature errors for 0.2% radiance errors are unrealistic in the SW band; 0.2 K is entirely different



The NIST Connection

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

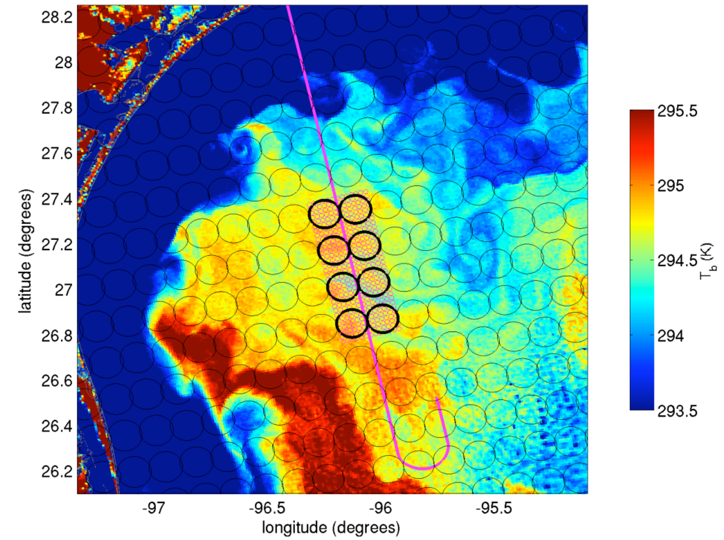
Max Difference
< 0.055°C Longwave
< 0.035°C Shortwave
between 293 & 333 K

- Direct test of S-HIS planned for 2006 using NIST Transfer Radiometer (TXR) at aircraft flight temperatures

3. AIRS Radiance Validation with S-HIS

AIRS / S-HIS Comparison Methodology

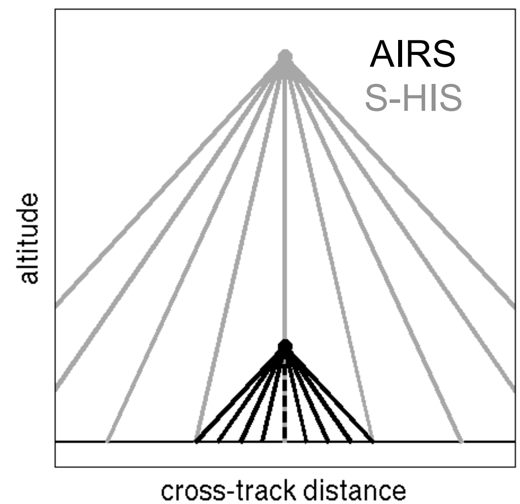
$$(Obs_{AIRS}-Calc_{AIRS}) \otimes SRF_{SHIS} - (Obs_{SHIS}-Calc_{SHIS}) \otimes SRF_{AIRS}$$

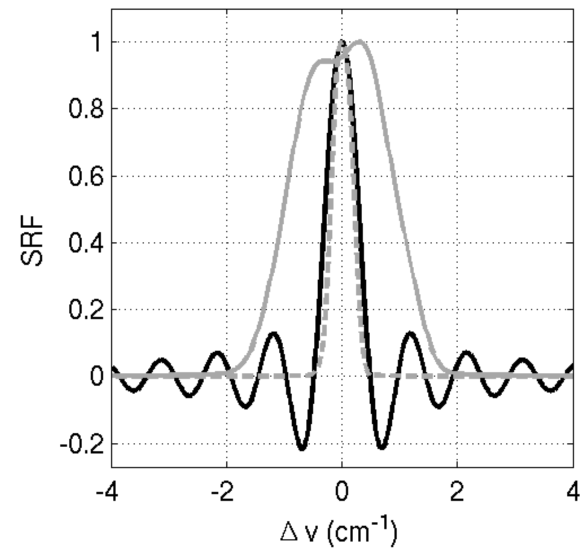


Spatial colocation is achieved by selecting scenes with low variability and covering the full AIRS FOVs with SHIS observations

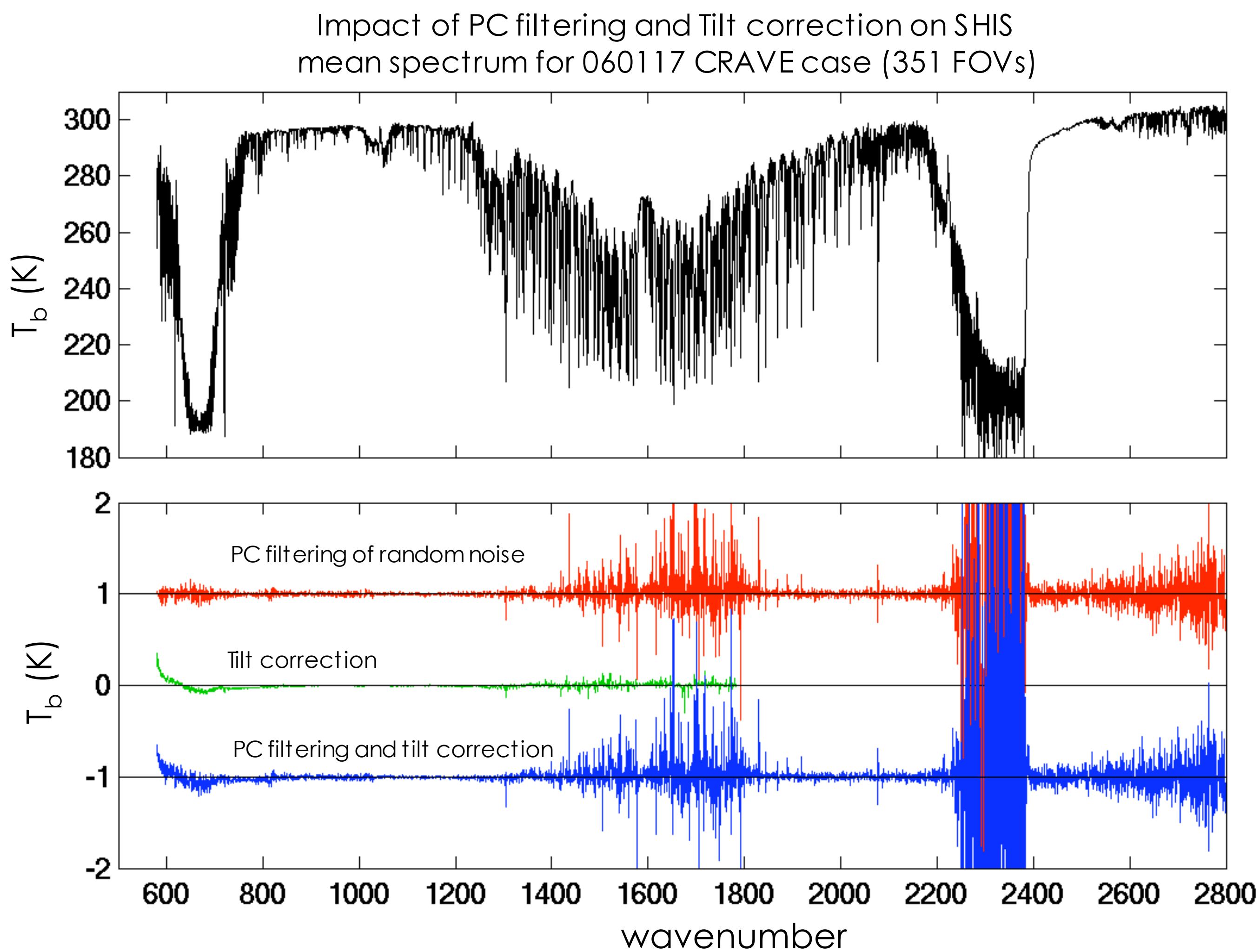
The double obs-calc method accounts for altitude and view angle differences and differences in instrument lineshapes

Channels with high sensitivity above the aircraft altitude are excluded from the final comparisons





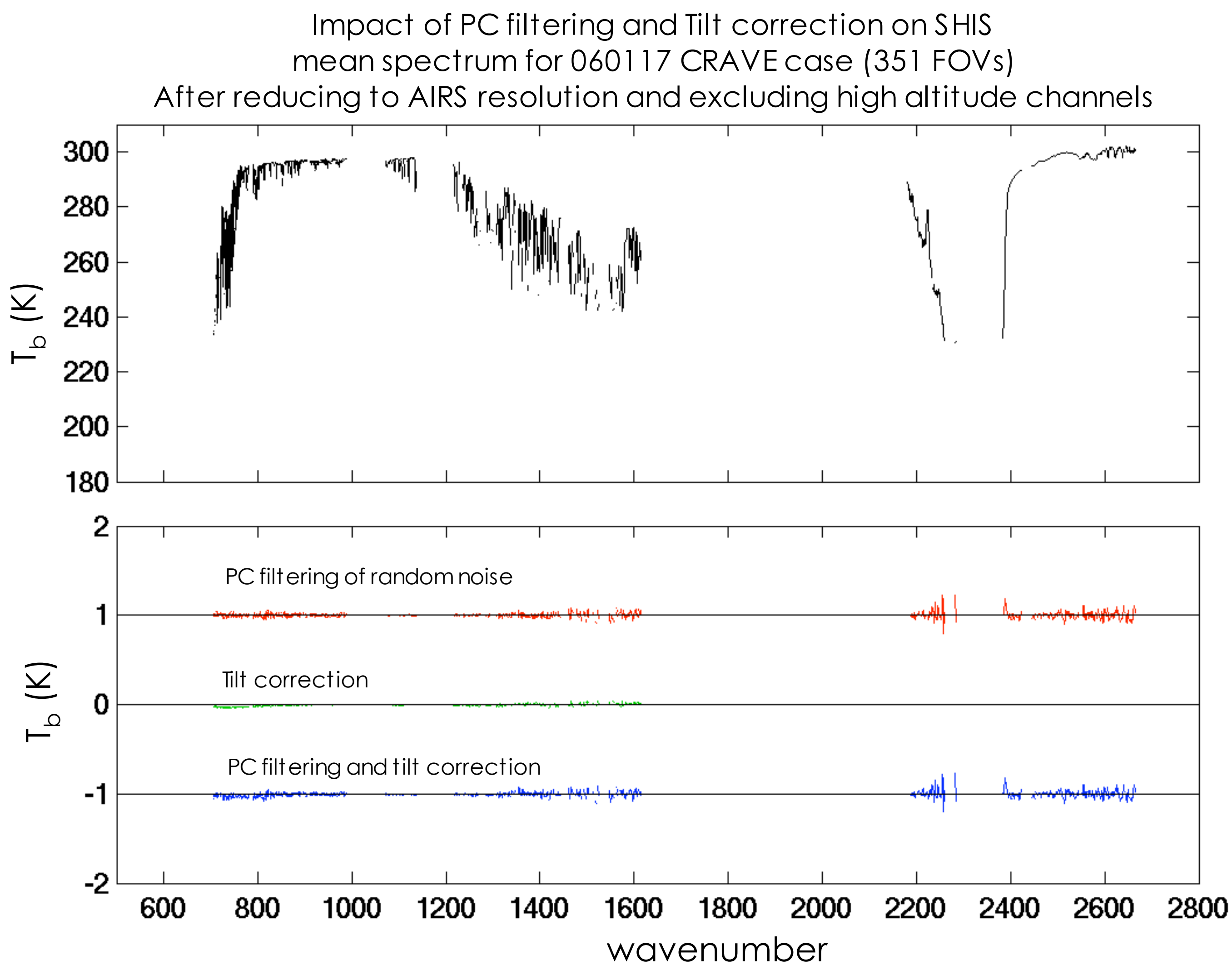
Impact of S-HIS PC Filtering and Tilt Correction



Full S-HIS spectral coverage & resolution:

Mainly noise reduction (bias for only LW < 650 cm^{-1} tilt correction)

Impact of S-HIS PC Filtering and Tilt Correction

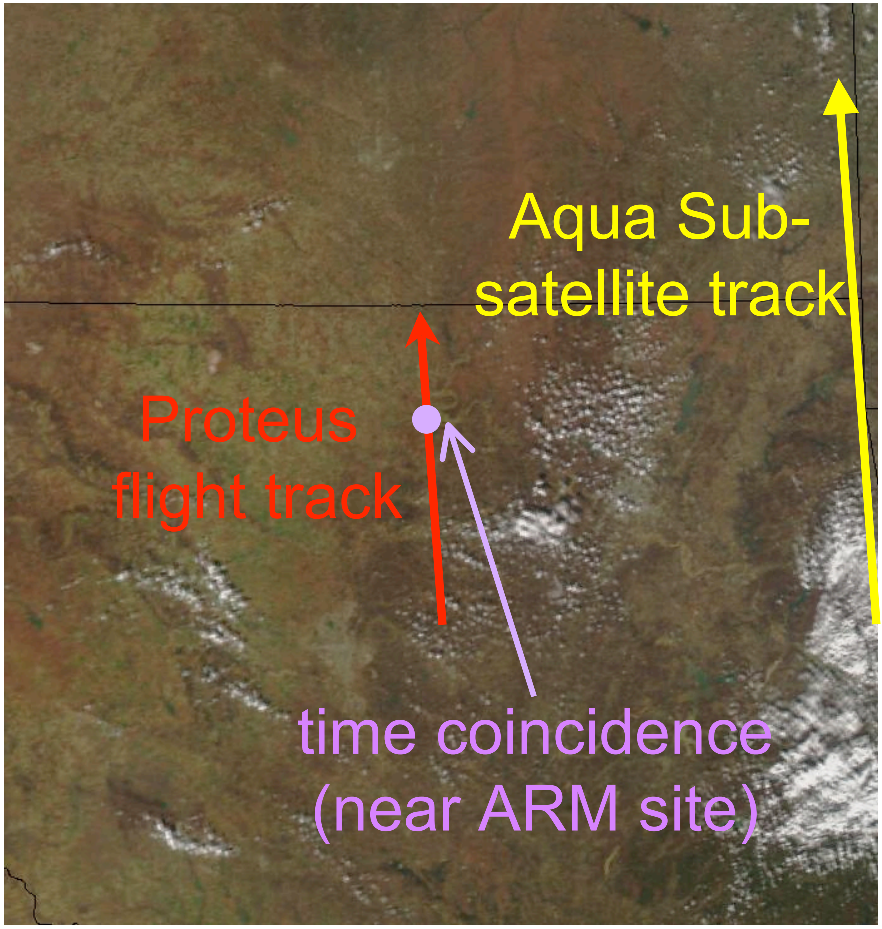


For final comparison conditions:

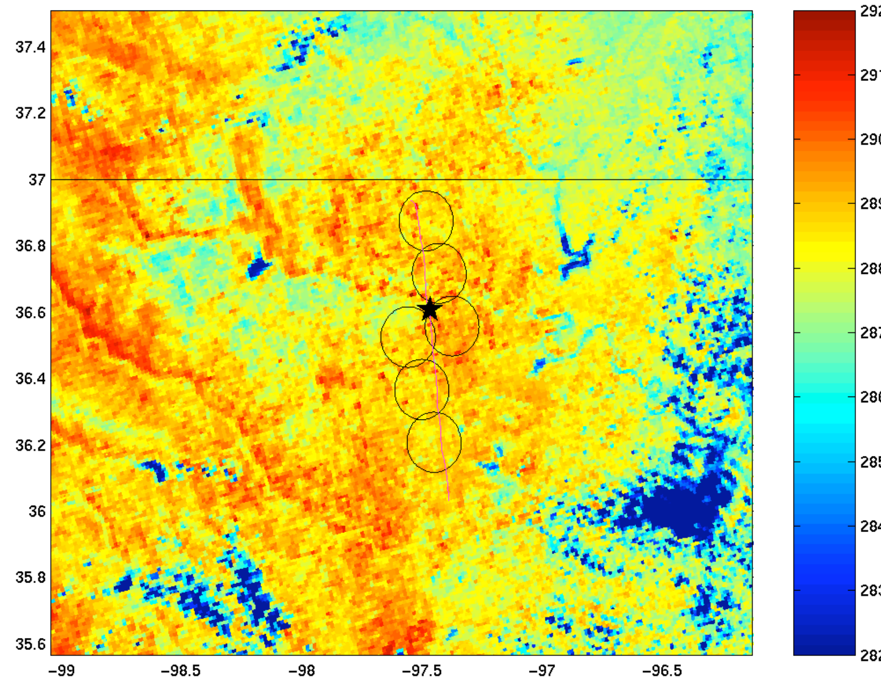
No biases, just noise reduction

ARM-SGP Validation case: 2002.11.16

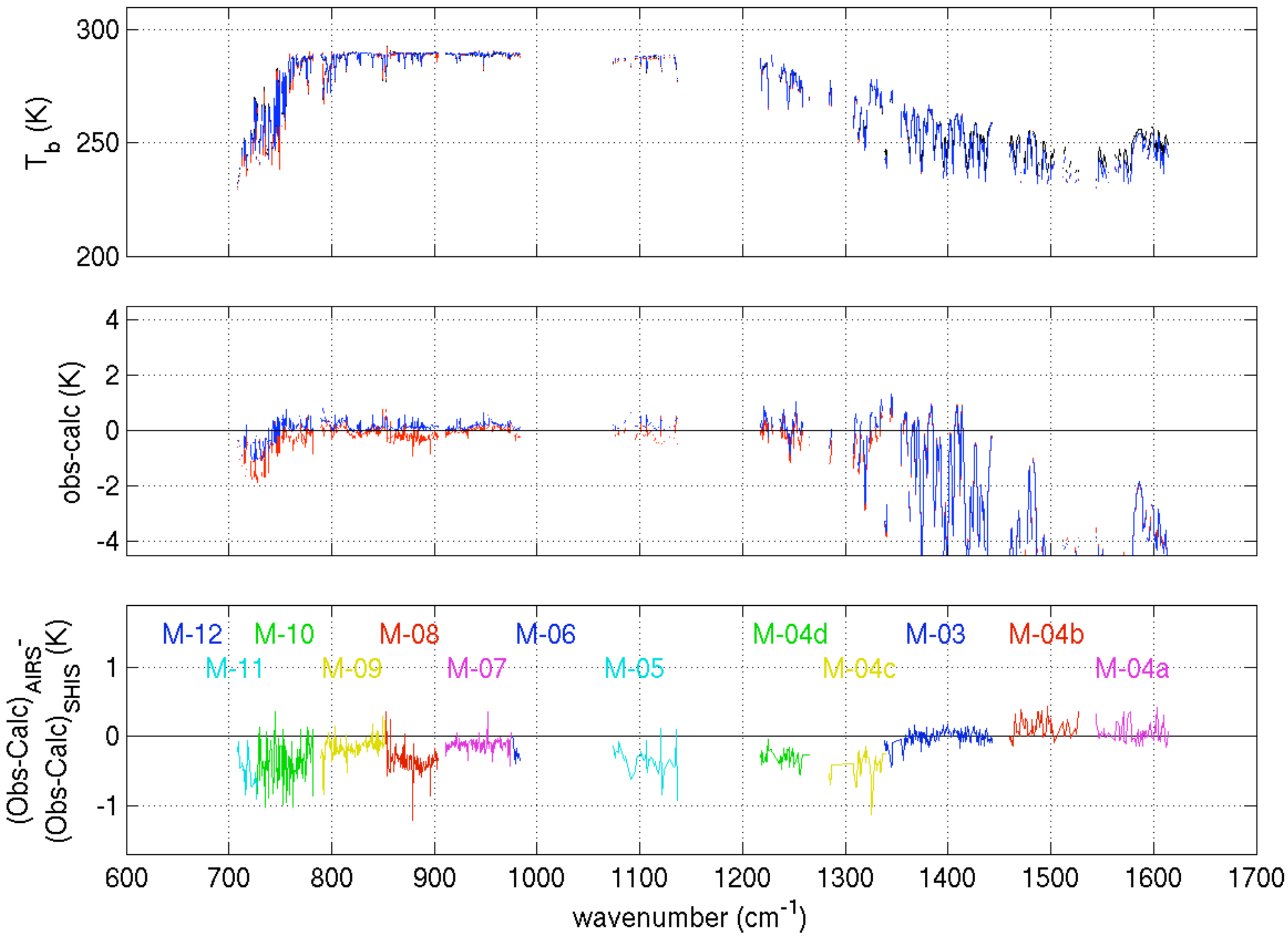
ARM UAV Campaign, S-HIS on Proteus
@ ~14km near ARM SGP CF, 19:24 UTC



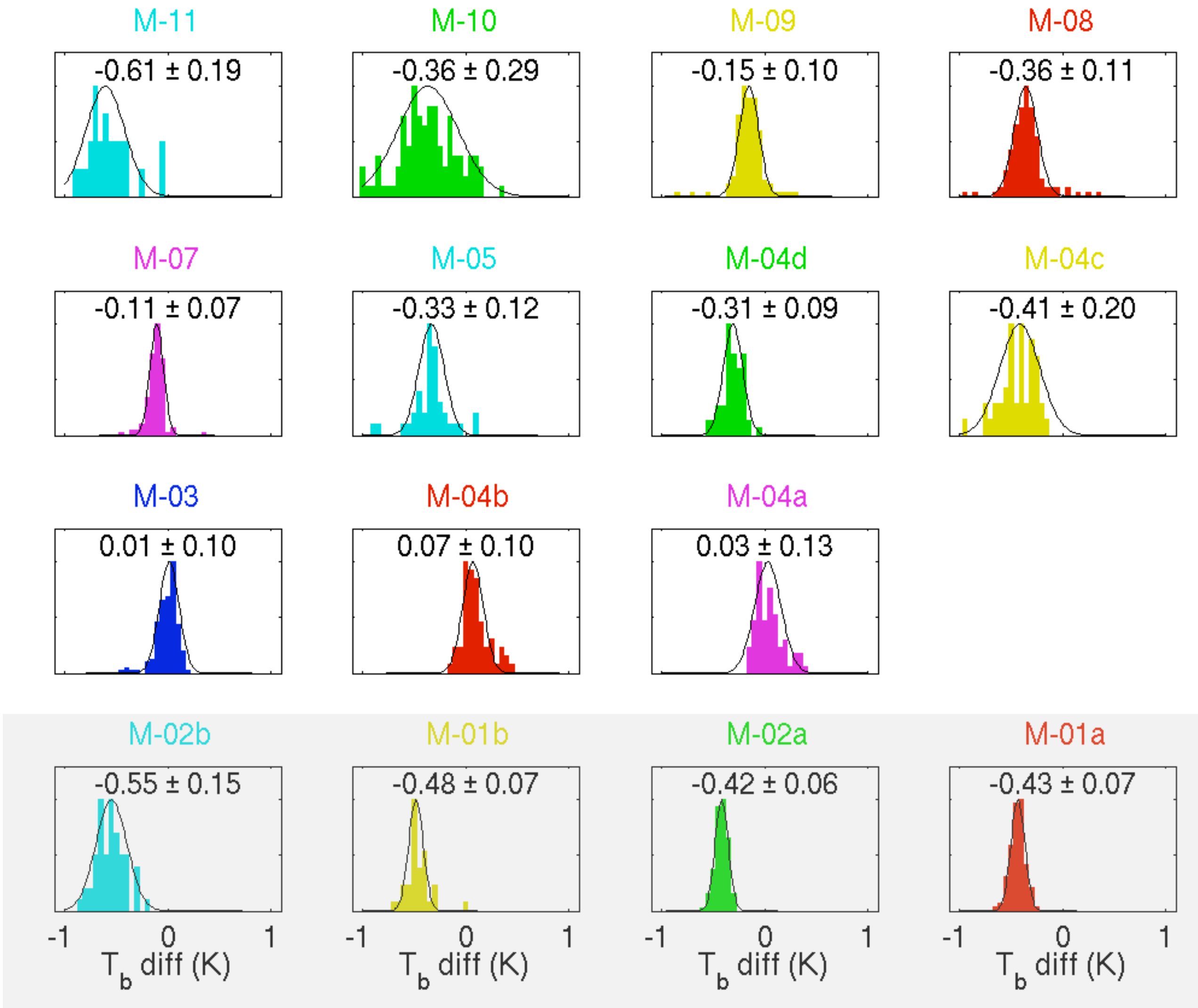
MODIS 12 μm brightness temperatures and AIRS FOV locations:



ARM-SGP Validation case: 2002.11.16



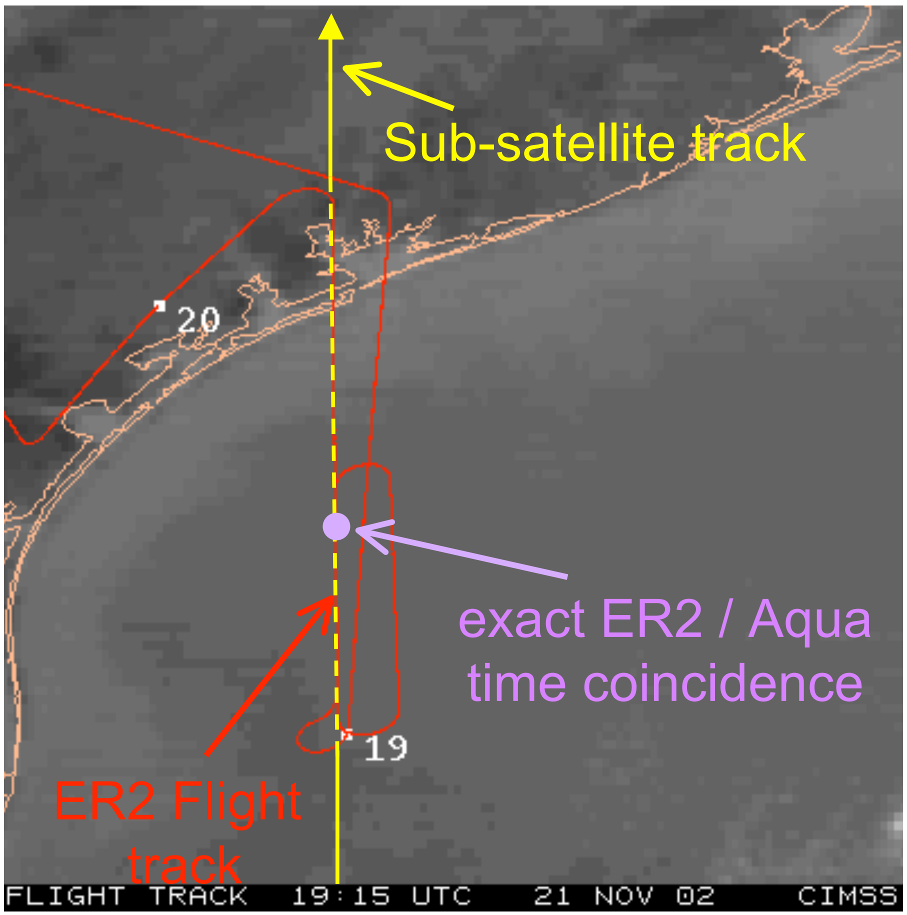
ARM-SGP Validation case: 2002.11.16



SW Modules

Gulf of Mexico Validation case: 2002.11.21

Texas 2002 Aqua Validation Campaign
S-HIS on ER-2 @ ~20km over Gulf of Mexico
at 19:40 UTC



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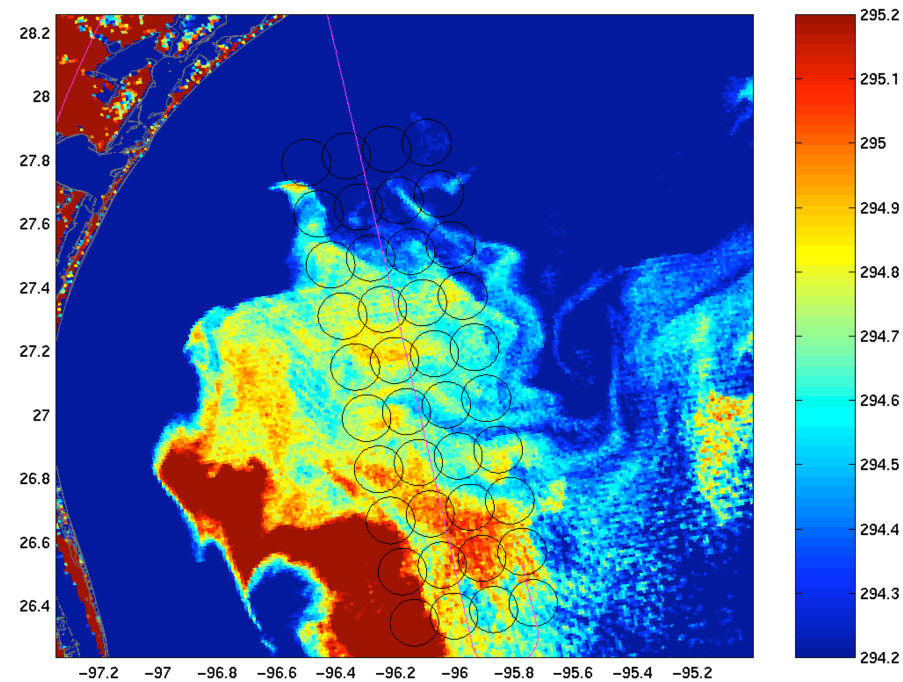
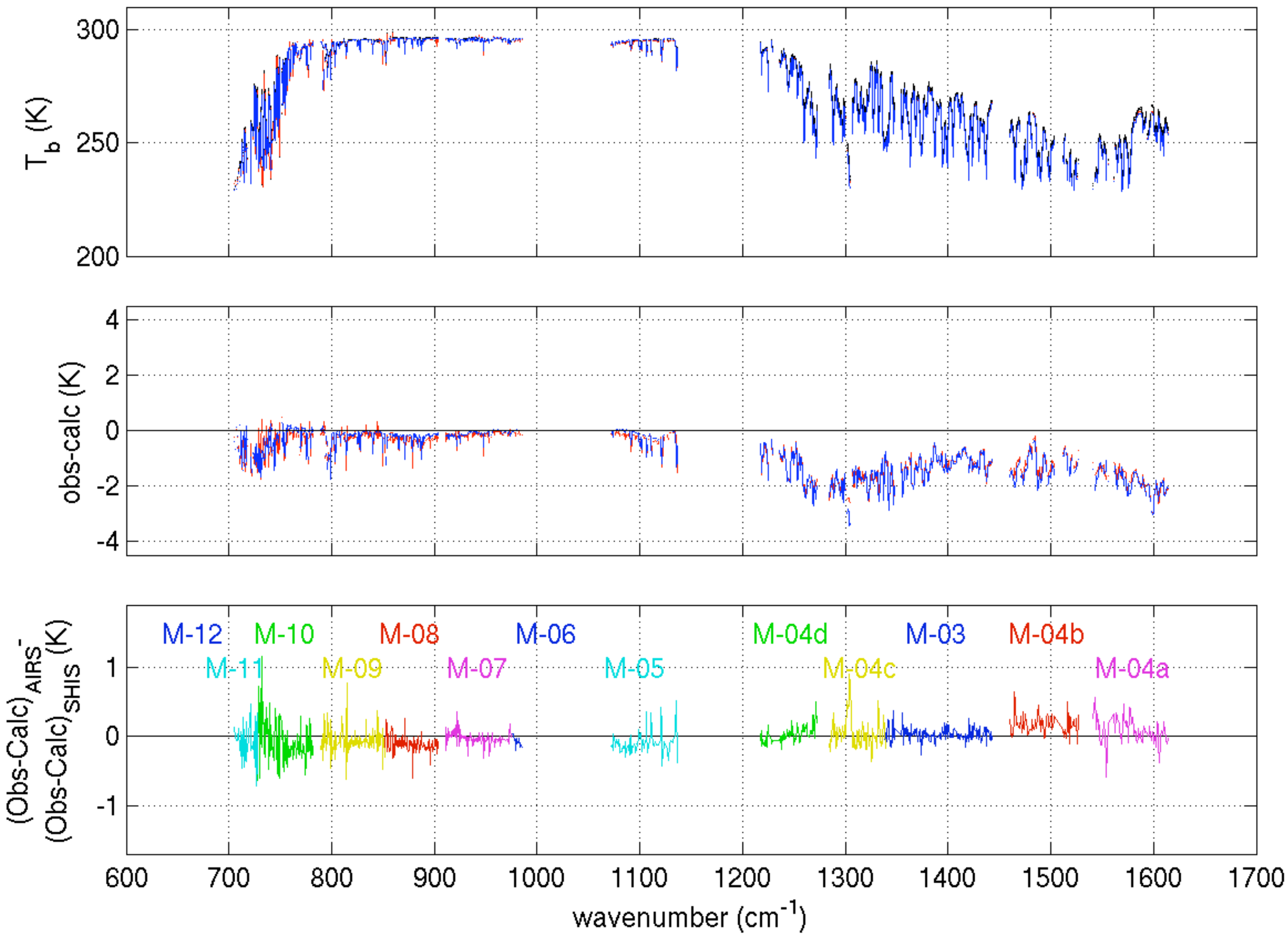
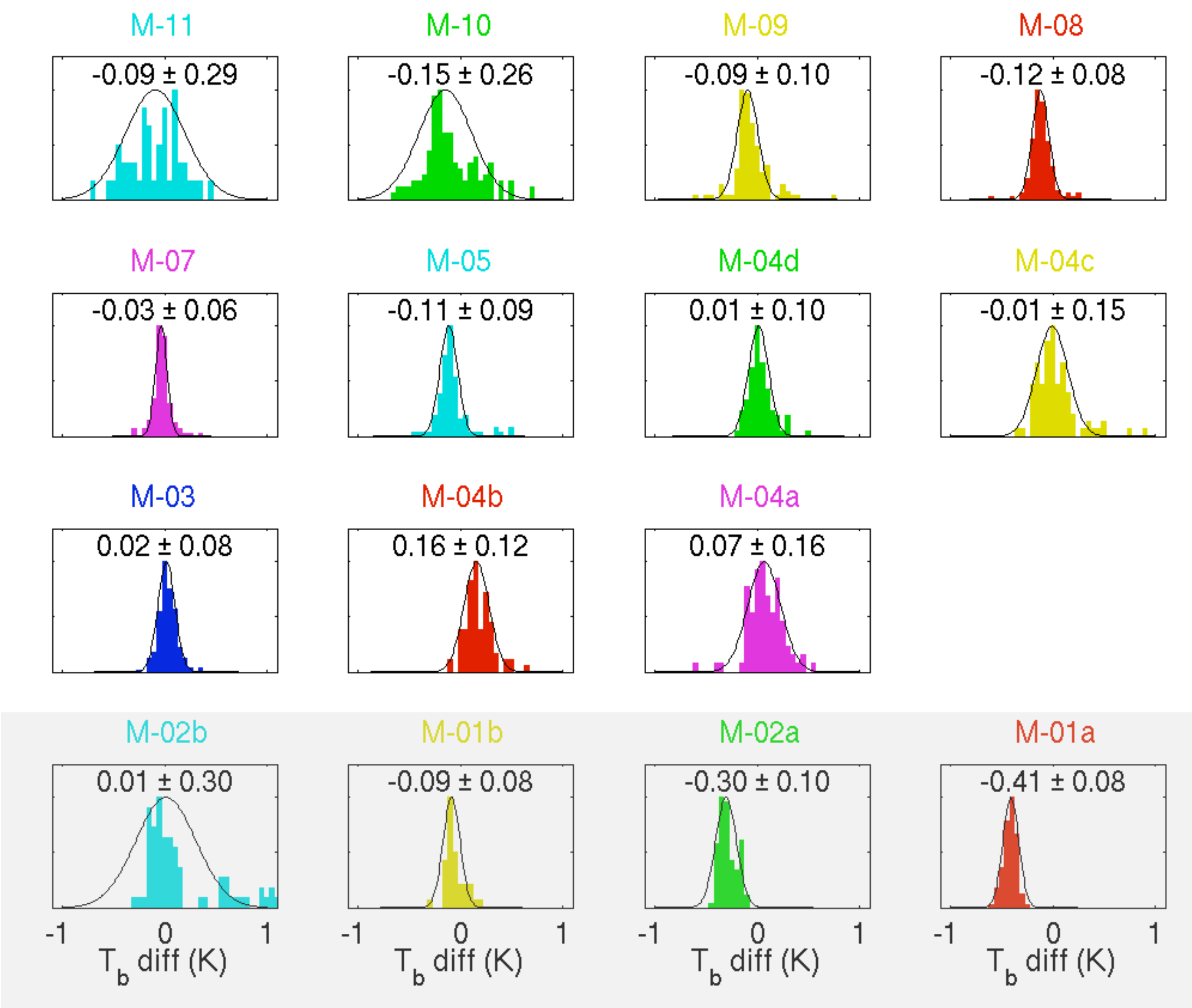


Gulf of Mexico Validation case: 2002.11.21



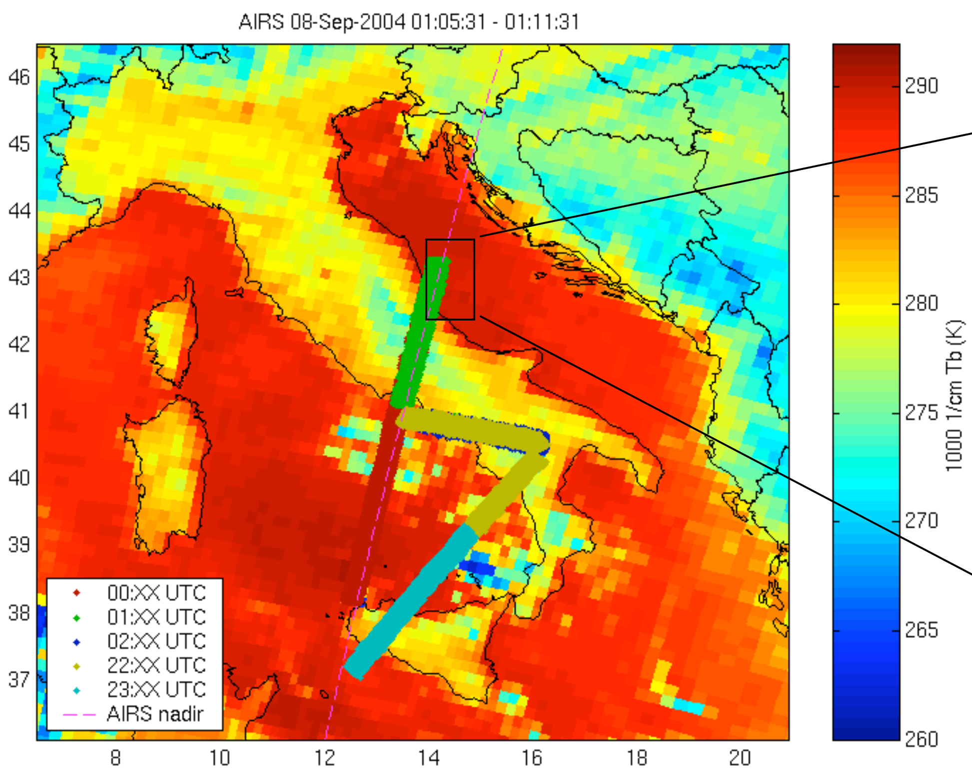
Gulf of Mexico Validation case: 2002.11.21



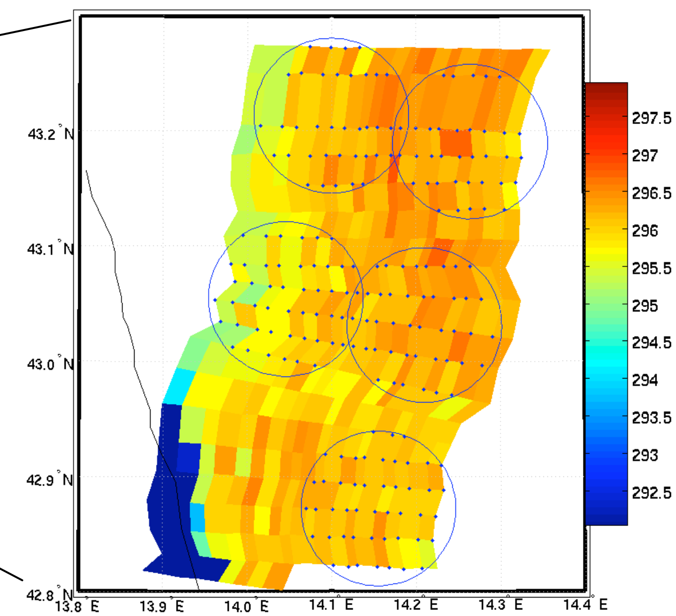
SW Modules

Italy Validation case: 2004.09.07

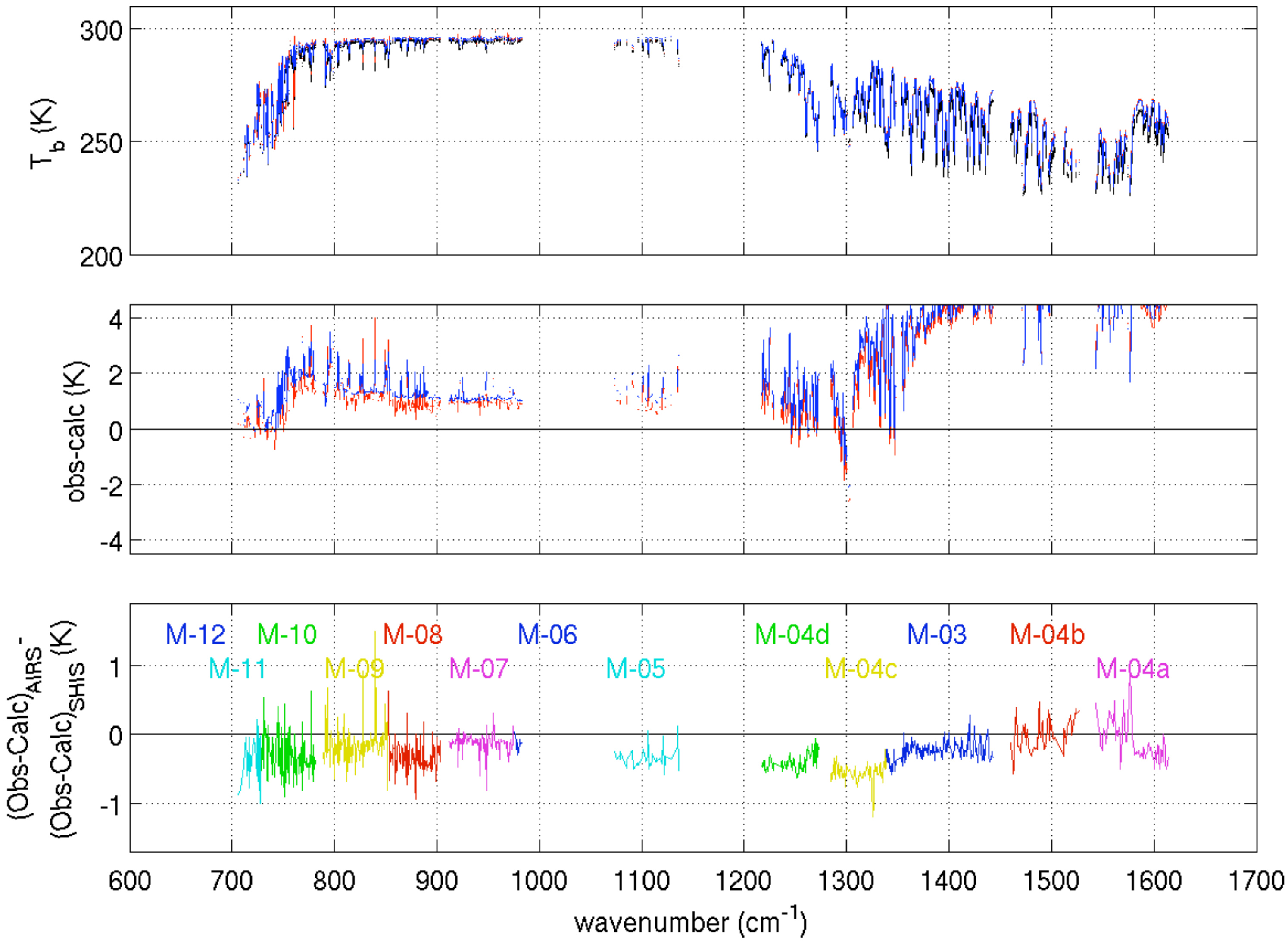
ADRIEX (EAQUATE) Campaign
S-HIS on Proteus @ ~16km over Adriatic Sea
2004.09.08, 01:10 UTC (Nighttime)



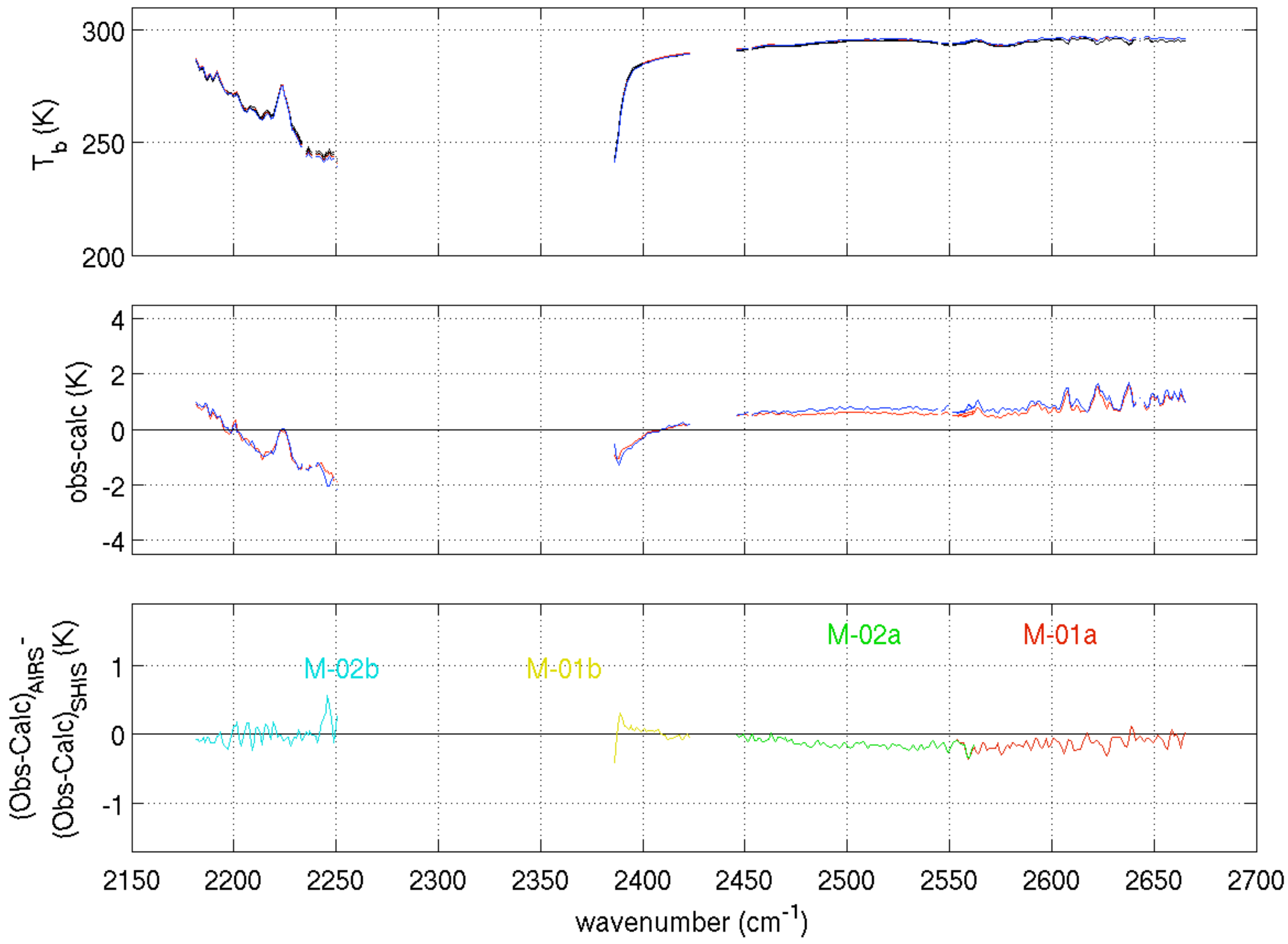
S-HIS 12 μm brightness temperatures and AIRS FOV locations:



Italy Validation case: 2004.09.07

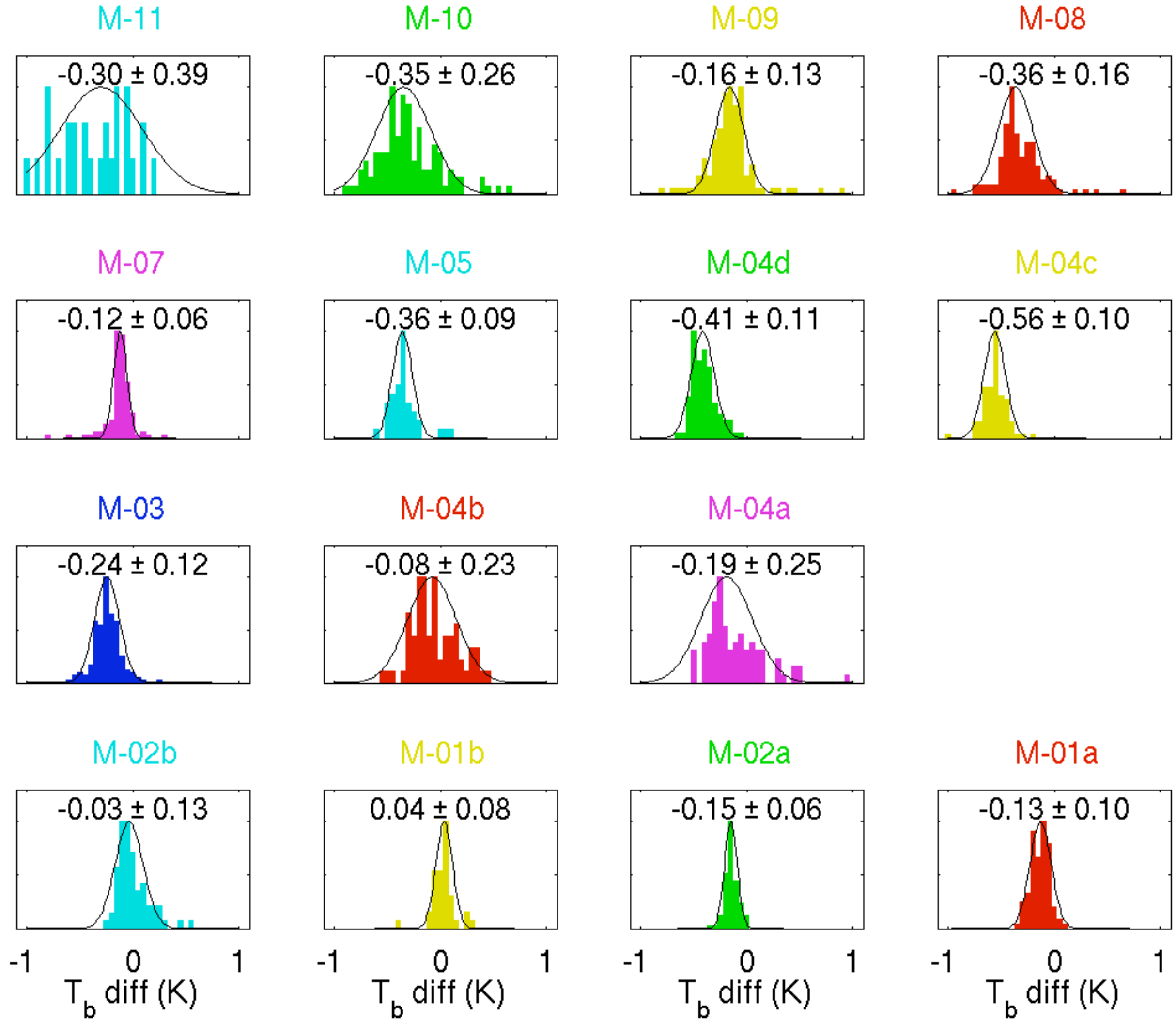


Italy Validation case: 2004.09.07



Night Flight Shortwave validation is Excellent

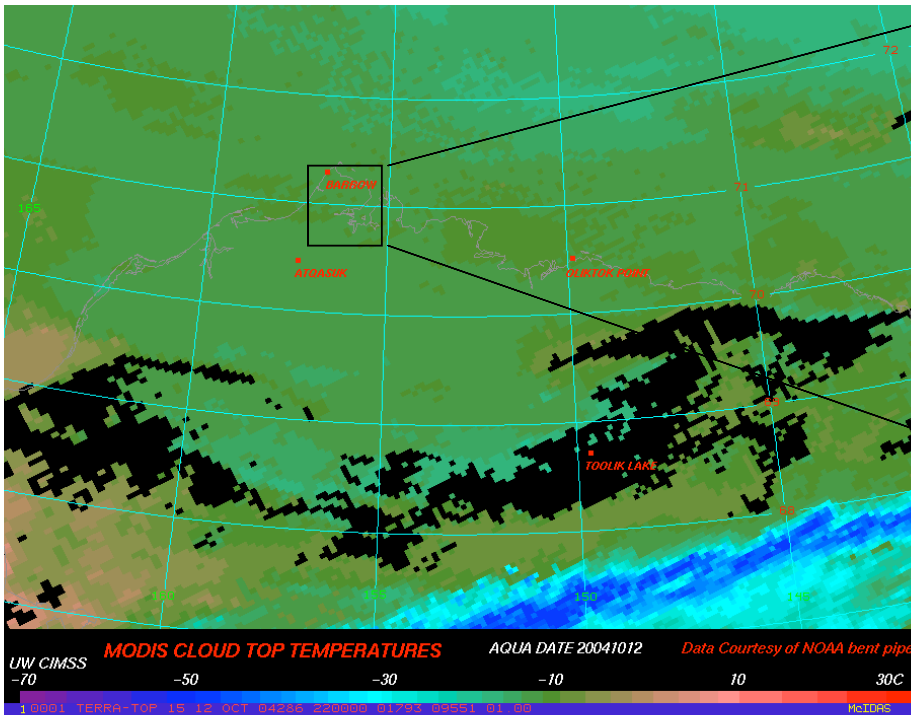
Italy Validation case: 2004.09.07



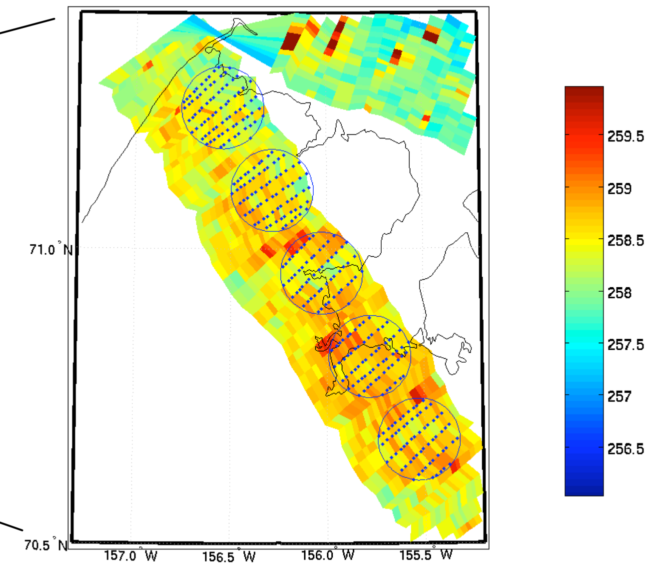
SW Modules

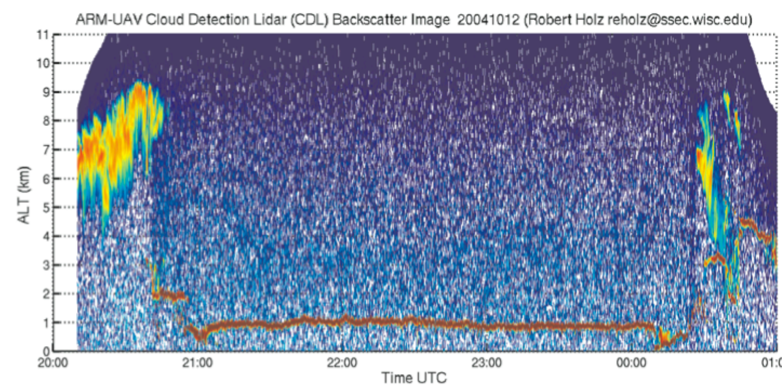
Arctic Validation case: 2004.10.21

MPACE Campaign
S-HIS on Proteus @ ~16km over low stratus clouds near Barrow, AK at 22:00 UTC

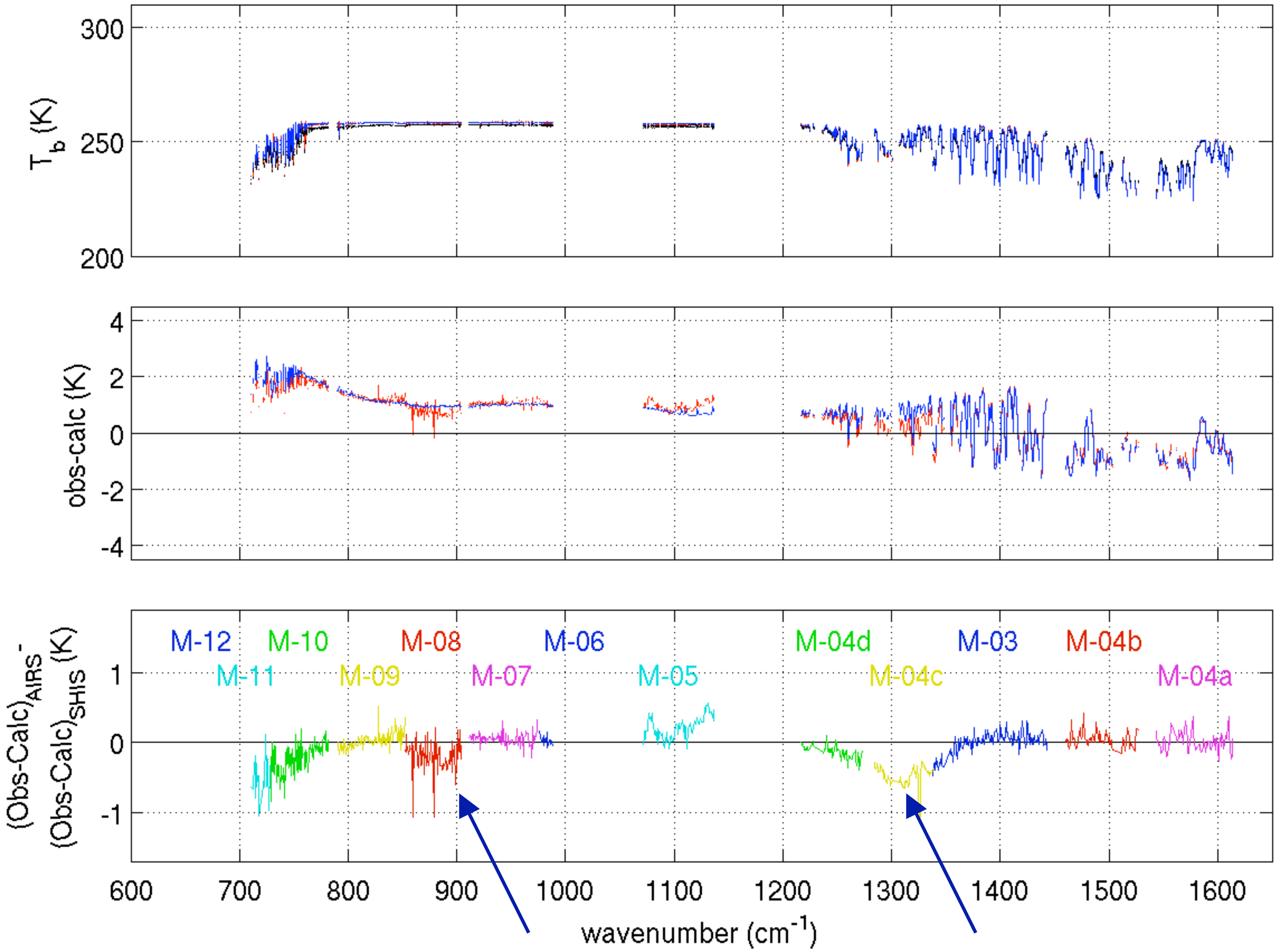


S-HIS 12 μm brightness temperatures and AIRS FOV locations:



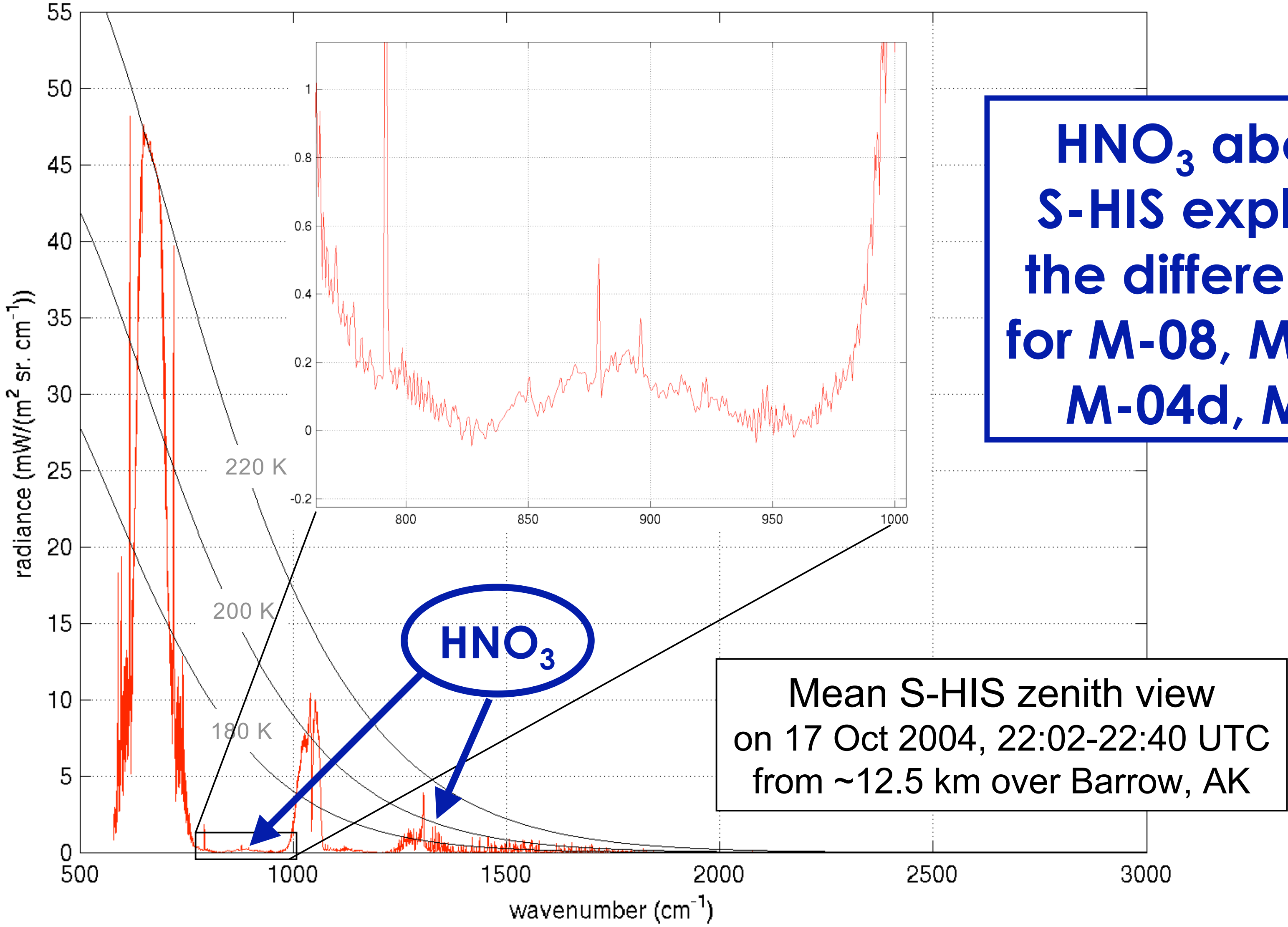


Arctic Validation case: 2004.10.21



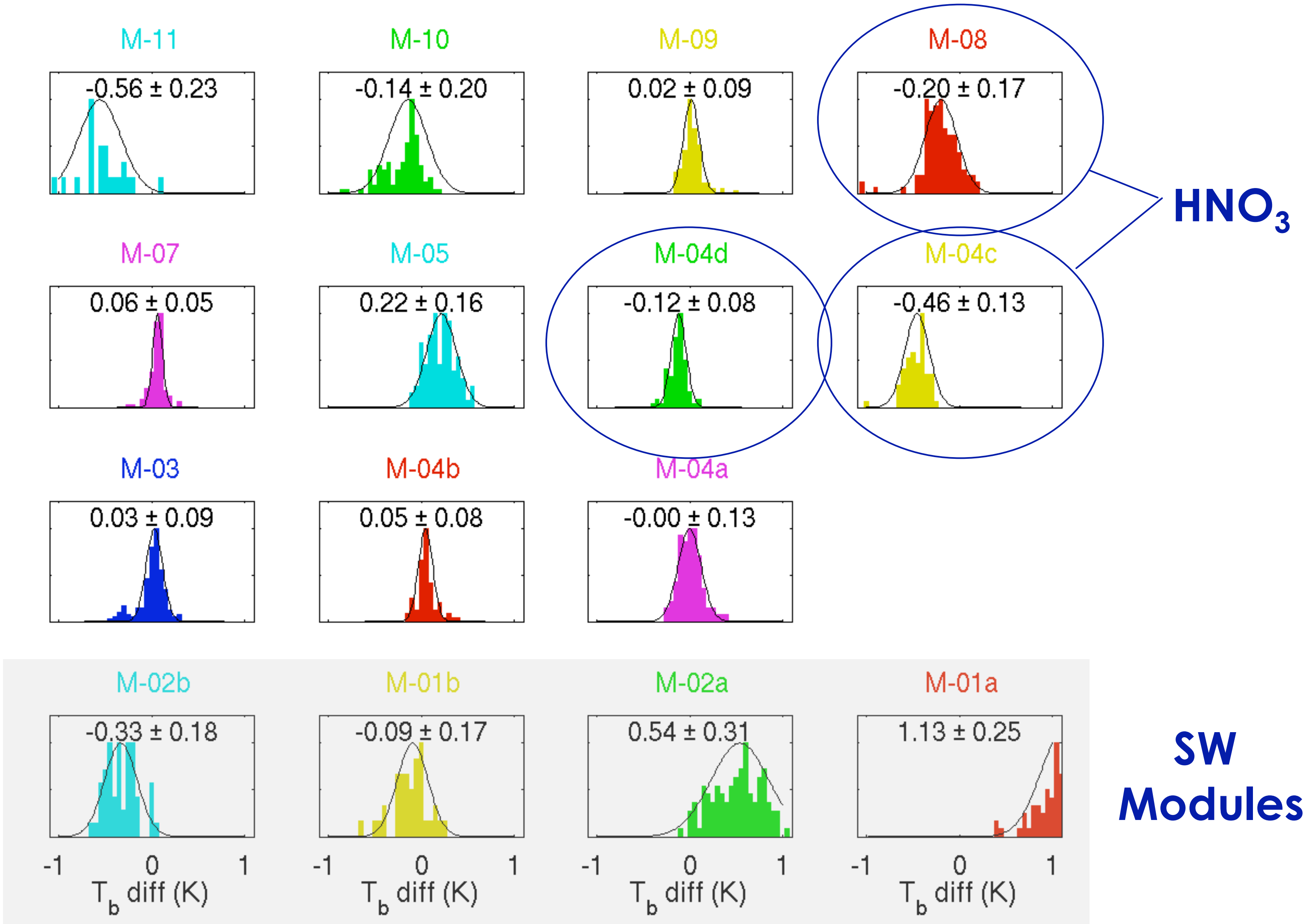
How do we explain these differences?

HNO_3 in S-HIS zenith views



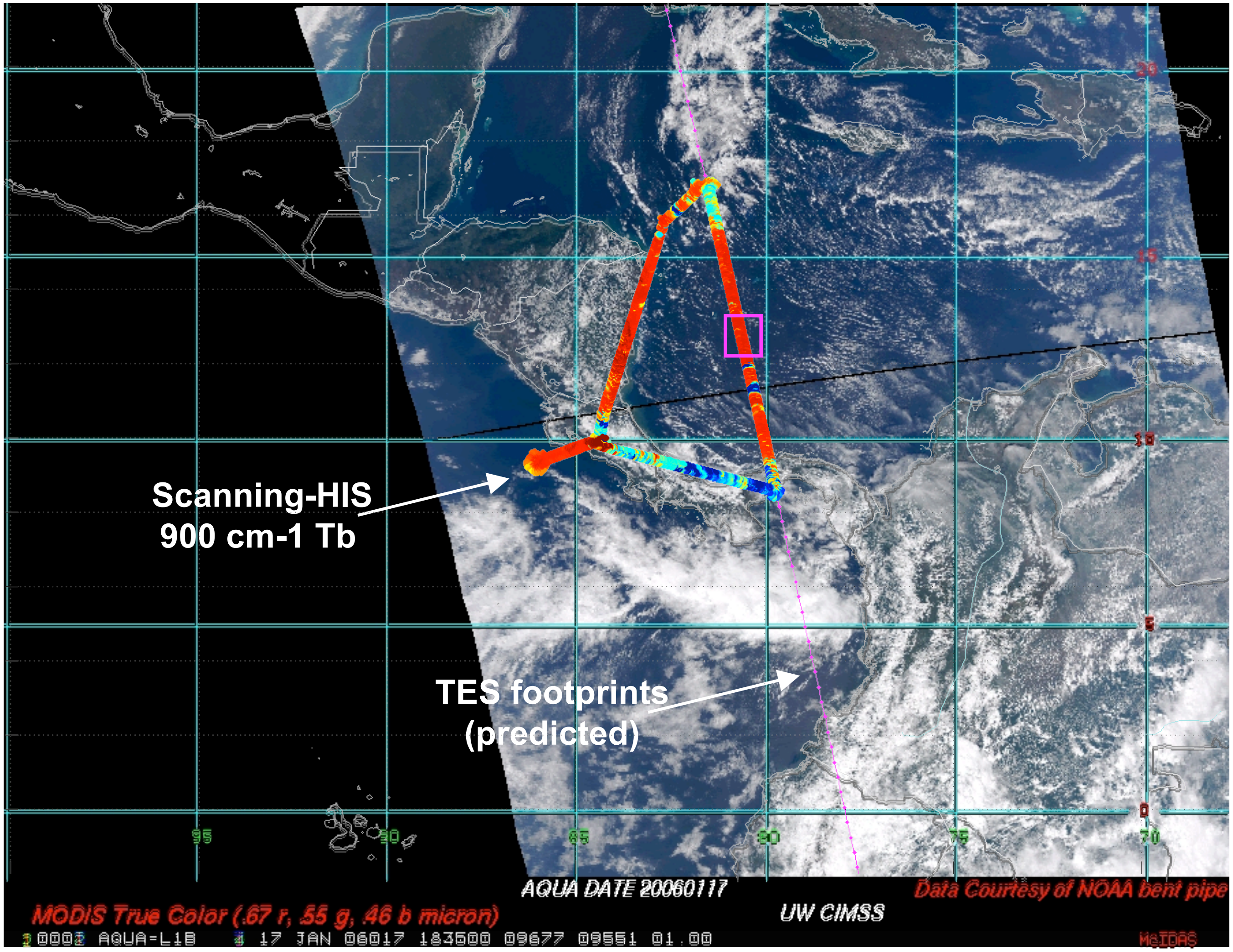
HNO_3 above S-HIS explains the differences for M-08, M-04c, M-04d, M03

Arctic Validation case: 2004.10.21

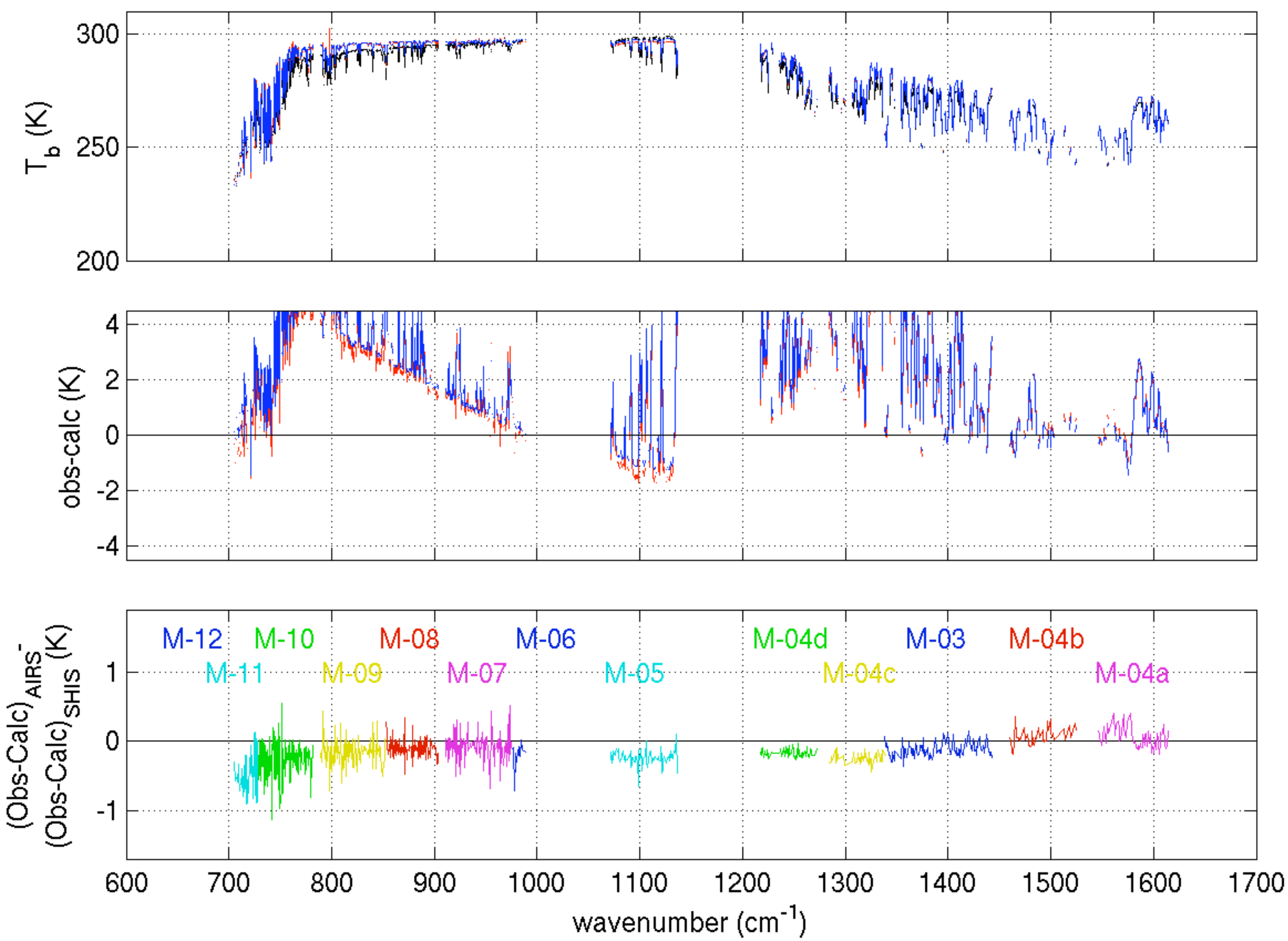


Tropical Validation case: 2006.01.17

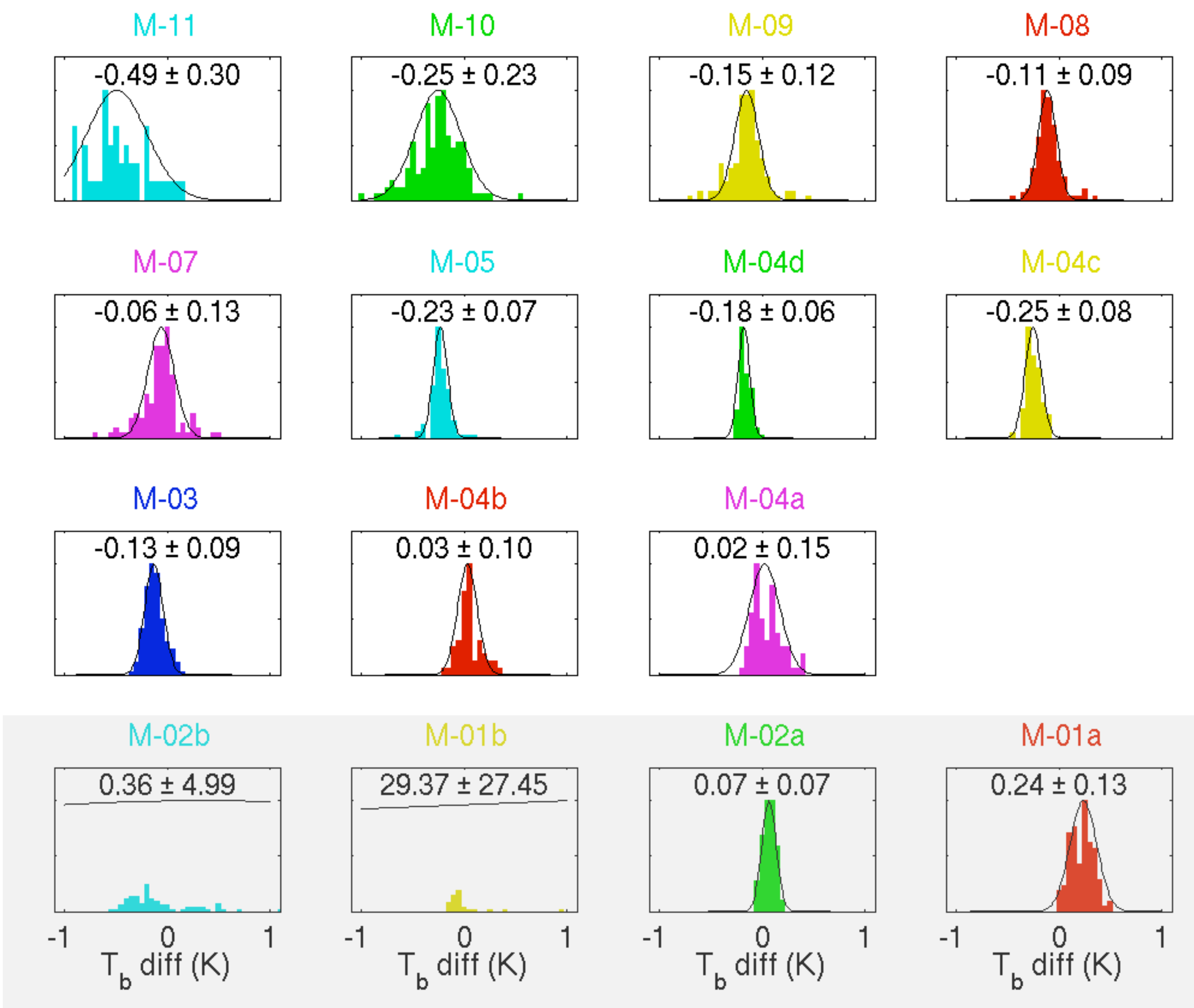
CRAVE Campaign, S-HIS on WB-57 at ~17 km over the Caribbean



Tropical Validation case: 2006.01.17



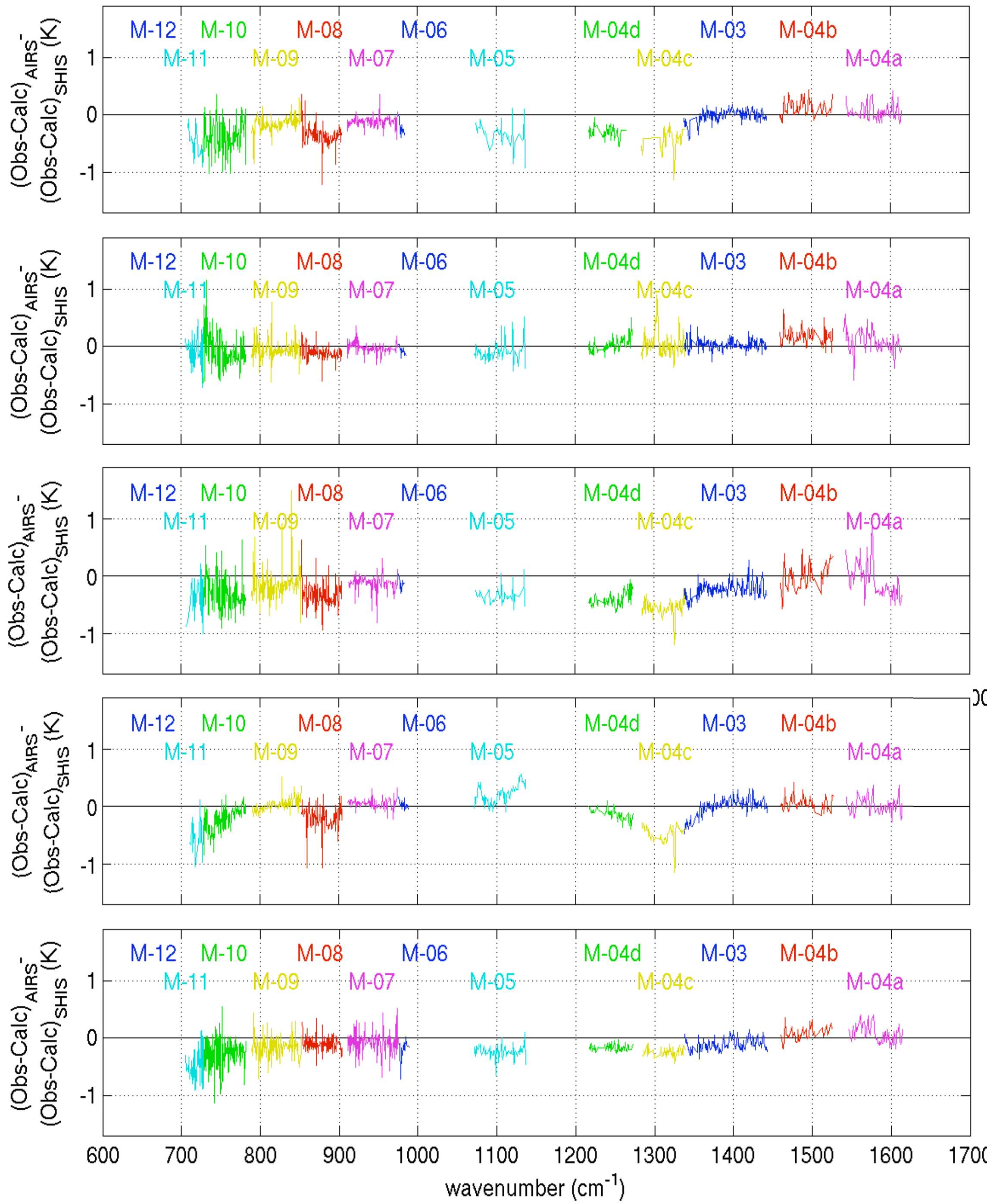
Tropical Validation case: 2006.01.17



SW Modules

AIRS-SHIS Summary

- **Radiance validation is remarkably good**
- **Includes Tropical to Arctic atm.**
- **Extends over > 3 years**
- **HNO_3 creates 08, 04c, 04d biases**
- **Small 05=O_3?**
- **Small LW CO_2 diffs: above plane contributions?**



2002.11.16 ARM-SGP

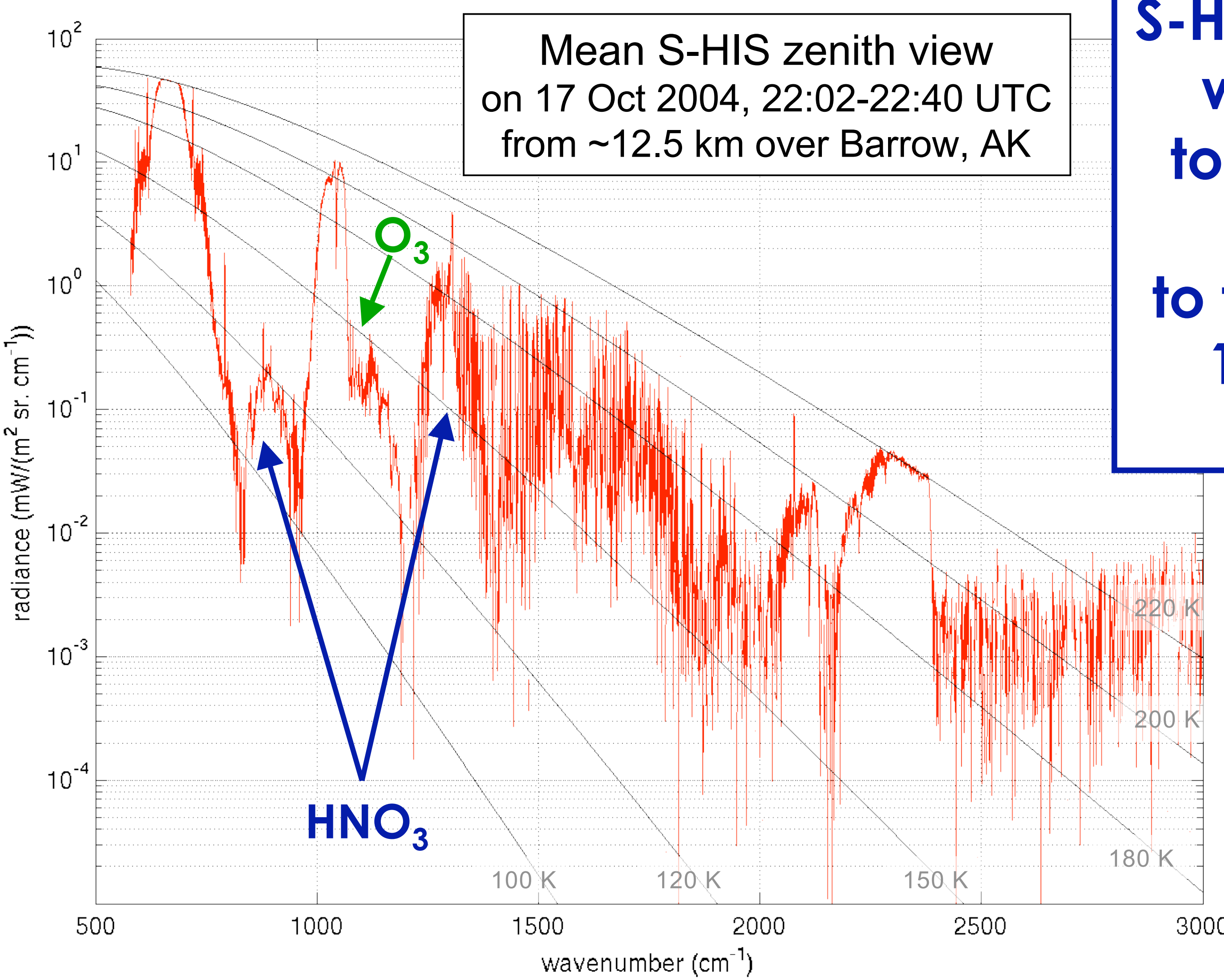
2002.11.21 Gulf of Mex

2004.09.07 Italy

2004.10.21 Arctic

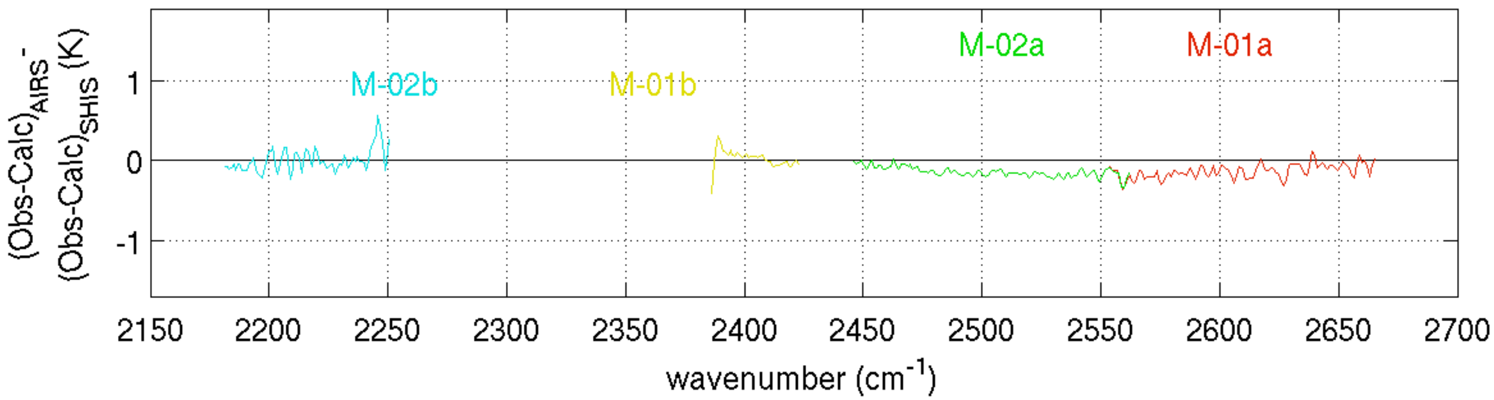
2006.01.17 Tropical

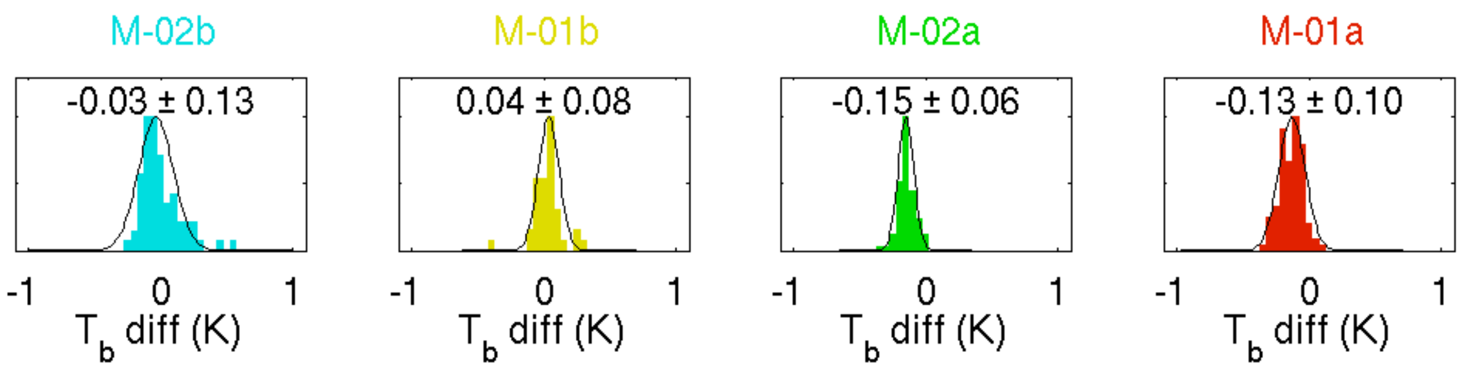
S-HIS zenith views are very revealing



S-HIS zenith view will be used to account for HNO_3 and to test the O_3 & 15 μm CO_2 regions

AIRS-SHIS Summary: SW (2004.09.07)



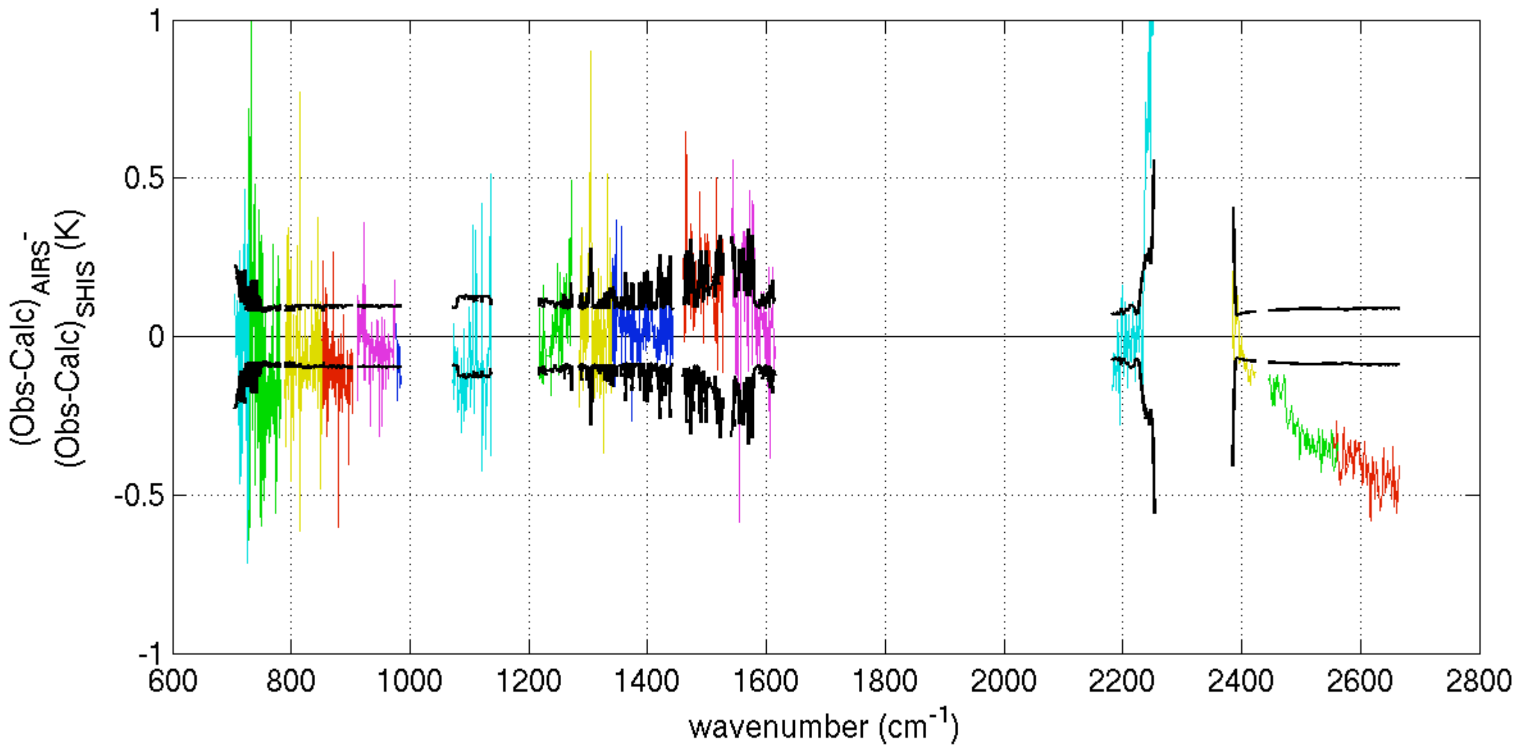


<u>1st Direct SW Radiance Validation</u>

Excellent agreement for night-time comparison from Adriex in Italy

Summary of AIRS/SHIS cases

2002.11.21 Differences and S-HIS 3-sigma calibration uncertainty

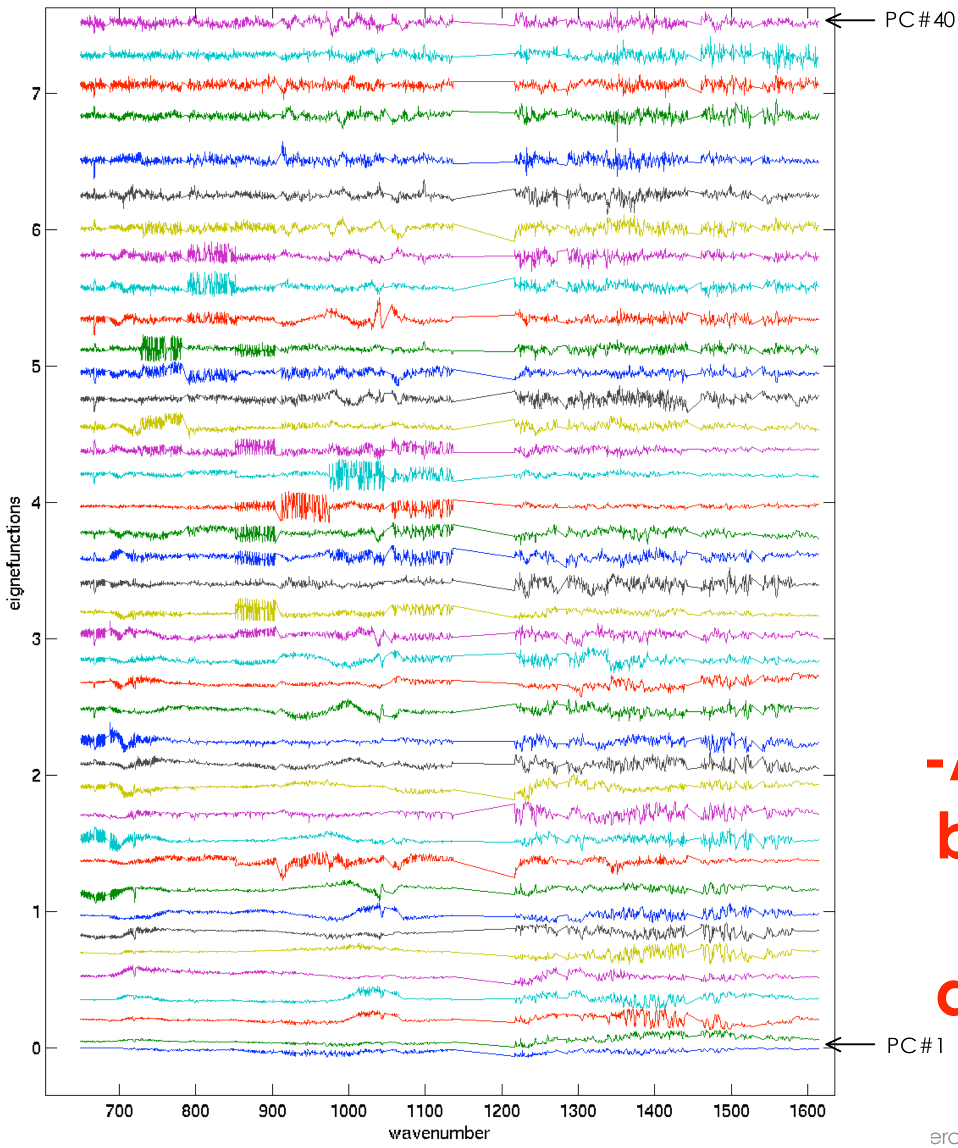


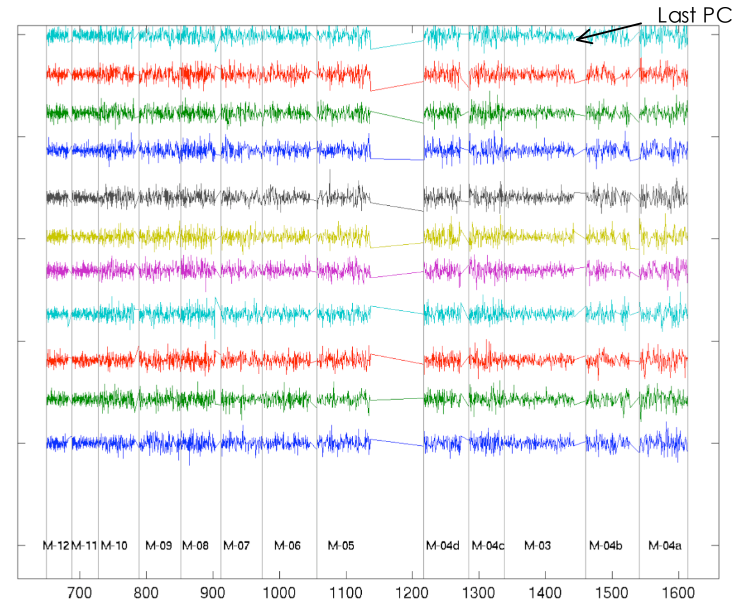
4. Artifacts of Individual Spectra

Non-Random (spectrally correlated) and Temporally Variable Spectral Artifacts

- These are effects that lie in the less understood domain between calibration (long average) and spectrally random, repeatable noise
- Principal Component Analysis (PCA) proves to be a good technique for identifying statistical indicators of these types of effects
- Examining differences from mean observations over uniform scenes reveal more details

AIRS eigenfunctions-LW & MW
for Granule 2005.04.20.196

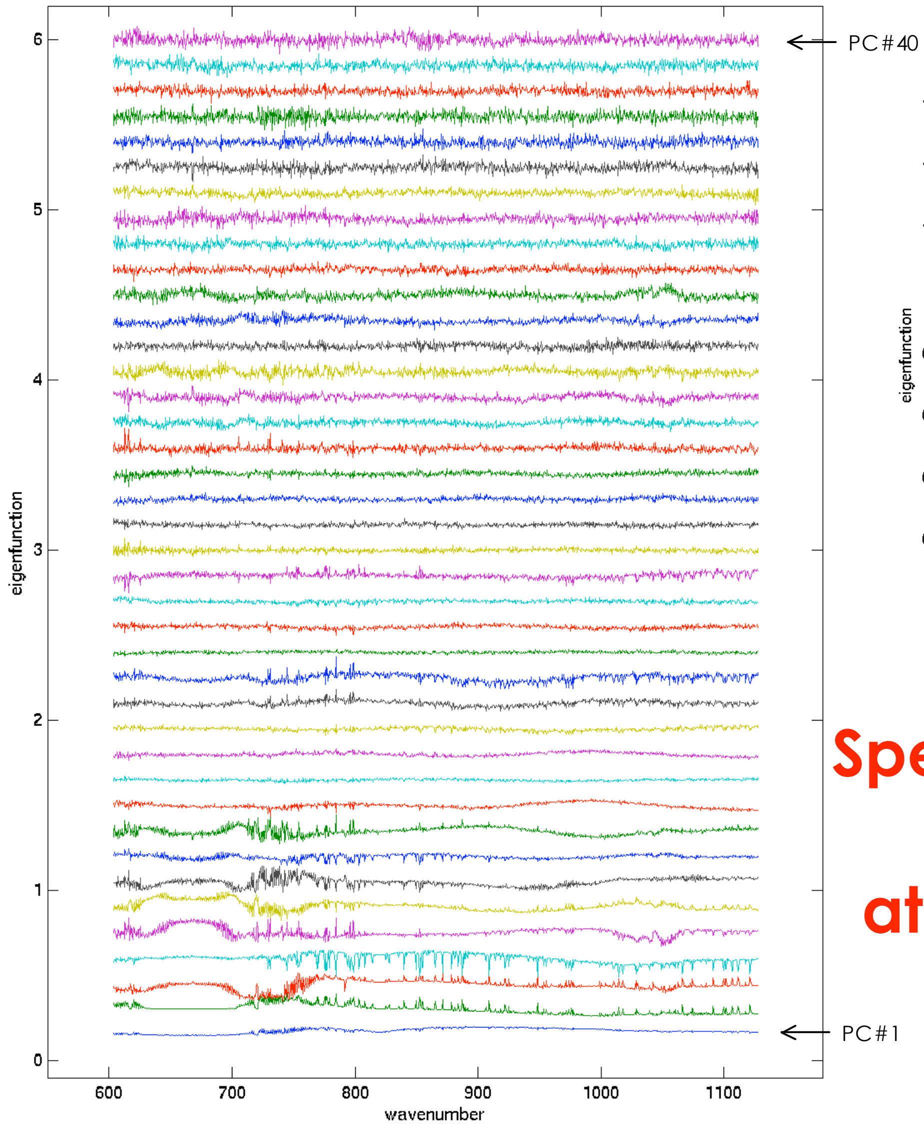


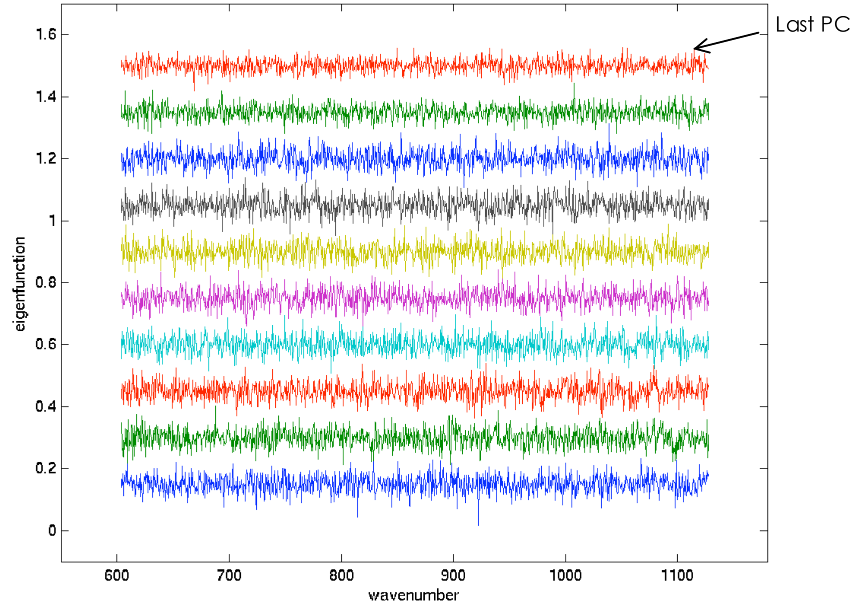


Early PCs look clean

-Array module-to-module biases & noise variations are apparent at low levels (higher PCs) from 730-1120 cm^{-1}

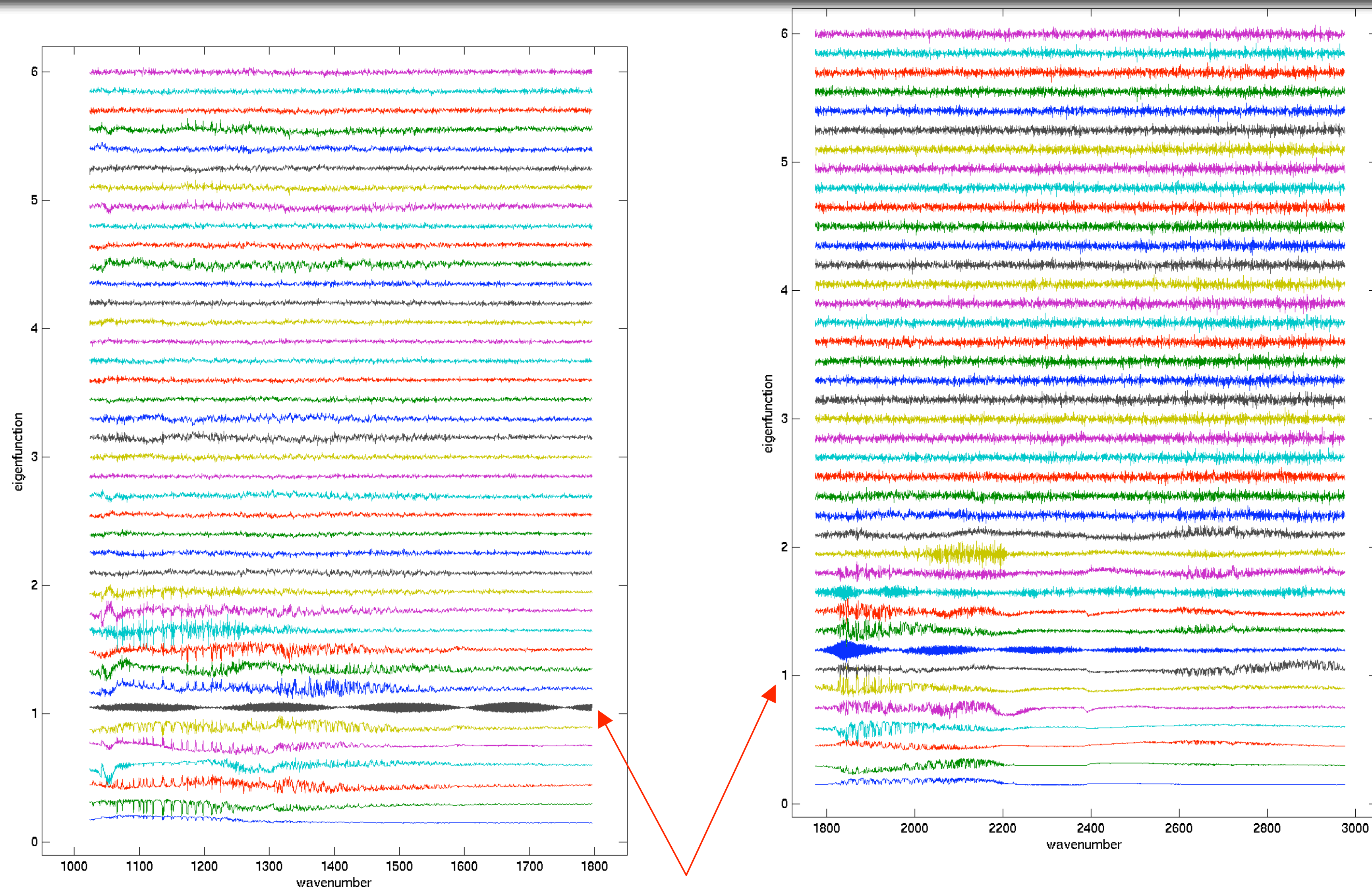
S-HIS eigenfunctions-LW Band
2006.01.17 CRAVE flight





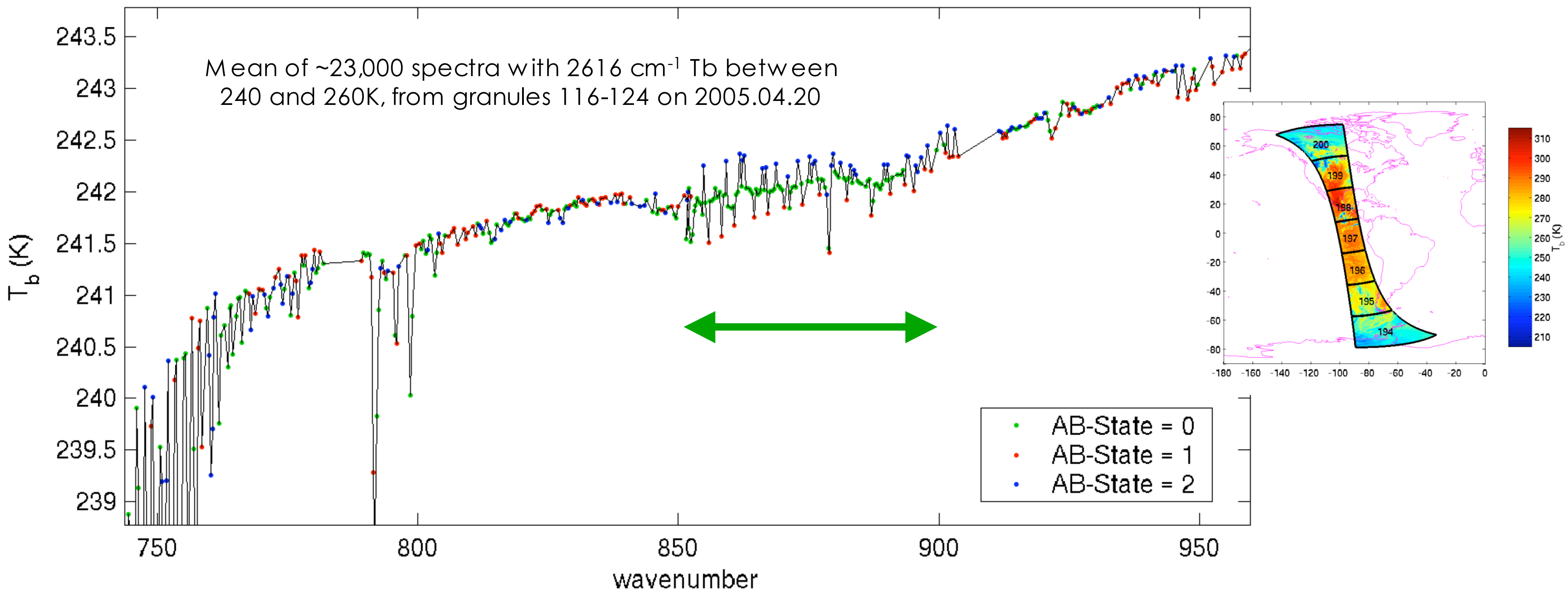
Spectral signatures are clean, indicative of real atmospheric characteristics

S-HIS eigenfunctions-MW & SW Bands



Ringing is indicative of processing artifact- easily fixed by roll-off mod

A/B-state dependent calibration in M-08

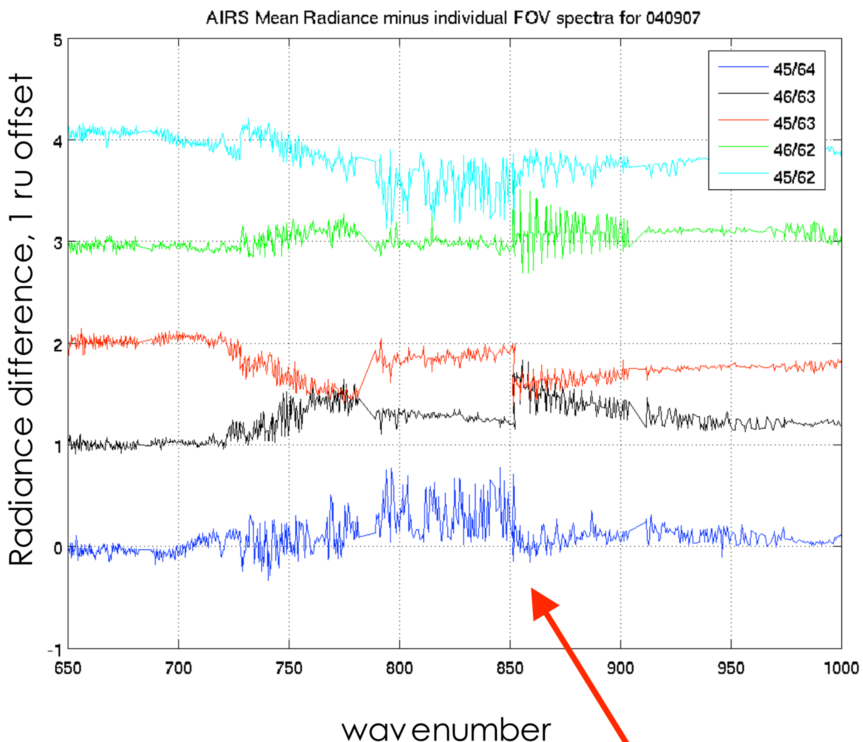


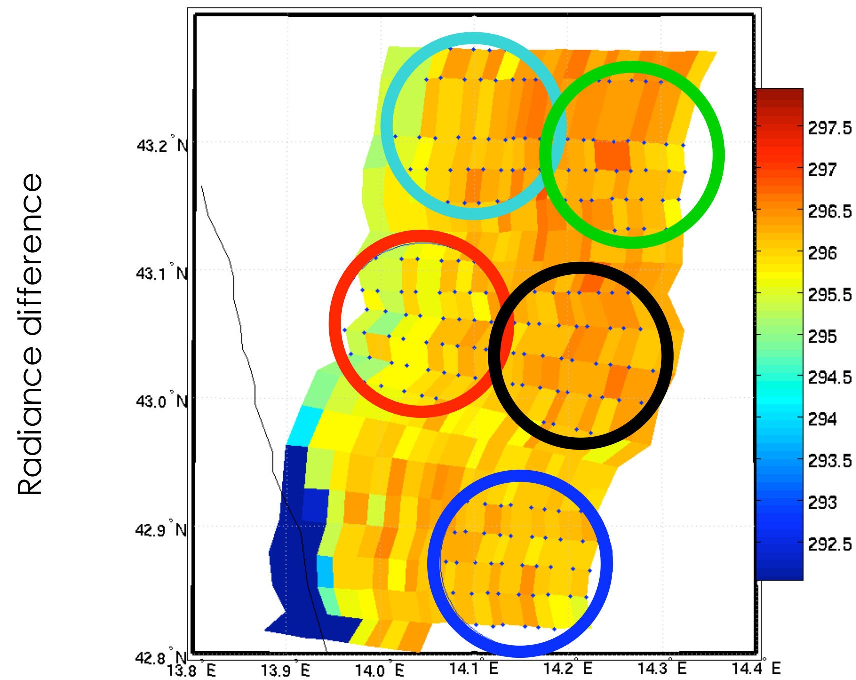
- Similar behavior observed for similar scenes throughout the mission
- Less evident in mean spectra at colder (e.g. Dome C.) and warmer (e.g. clear ocean) scenes.

- Notes

Variability of Single Spectra, LW region
2004.09.07 (Italy)

AIRS Spectra - mean

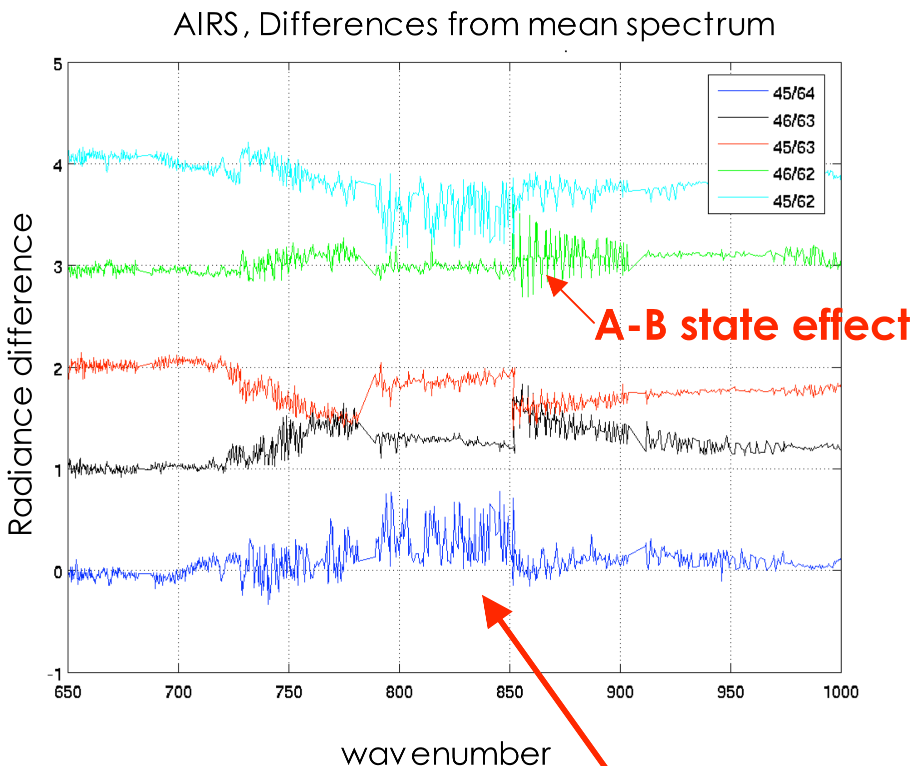




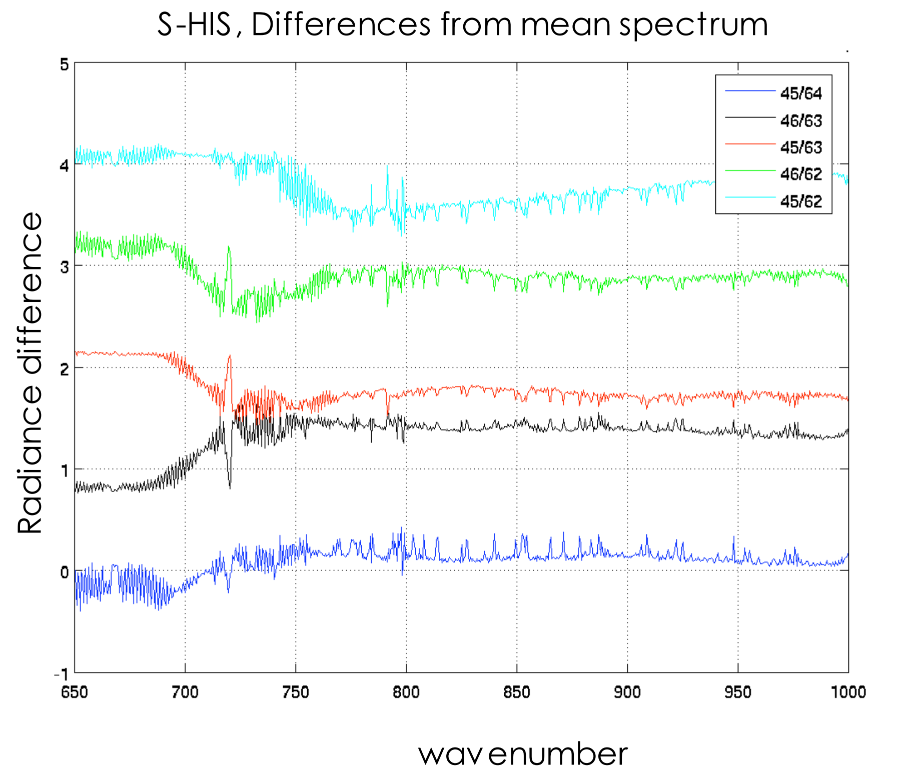
Note large Spectrum-to-Spectrum jumps (±0.4 K) for uniform scene

Variability of Single Spectra, LW region
2004.09.07 (Italy)

AIRS



S-HIS

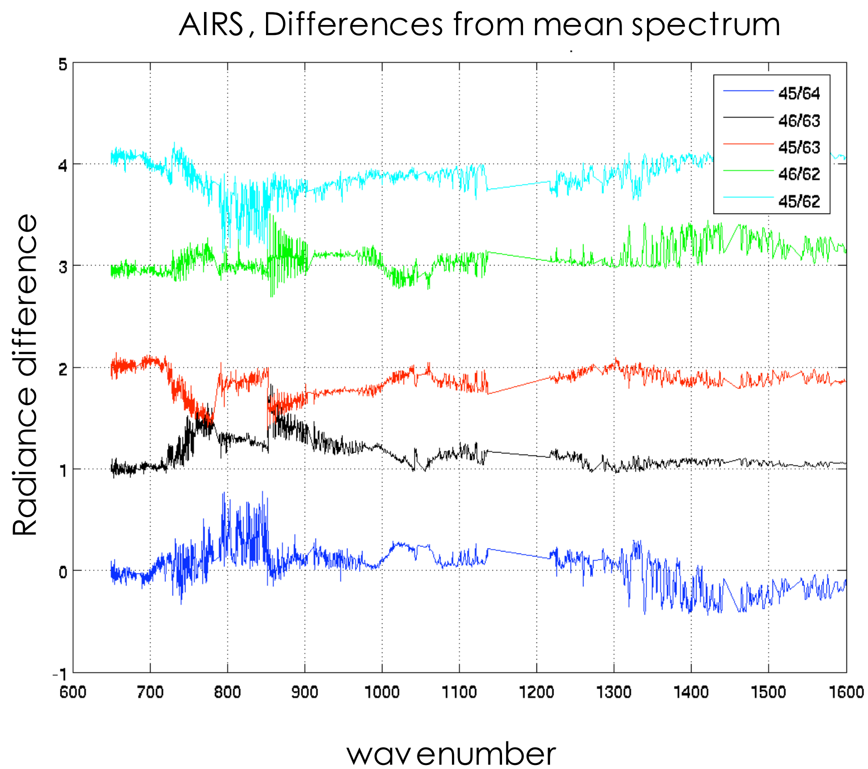


Smooth & physically reasonable

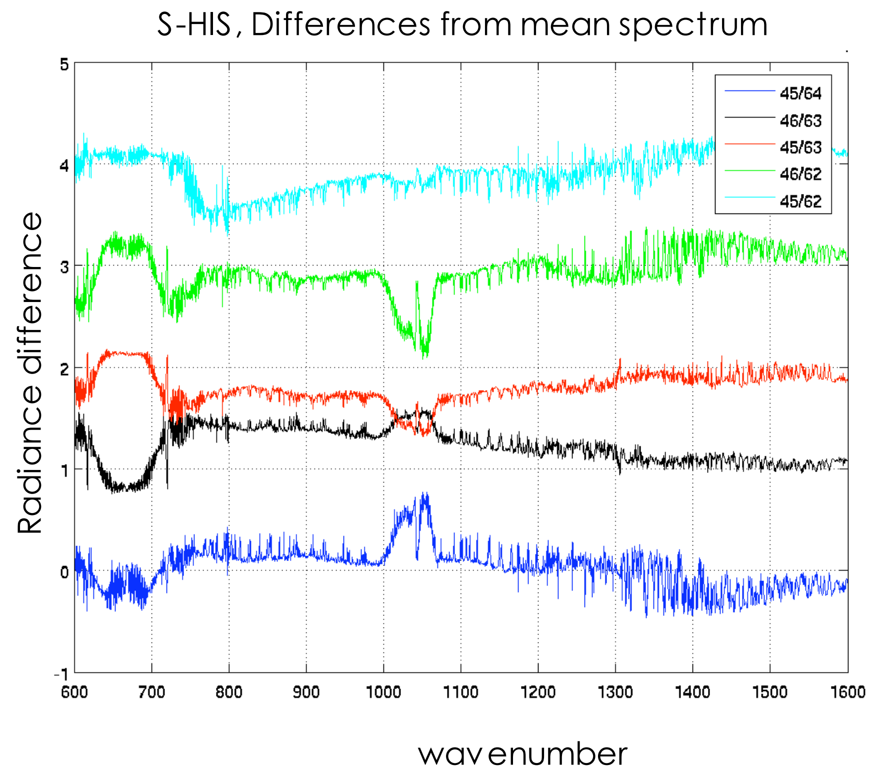
Note large differences in noise (±0.4 K) as well as jumps in M-09

SHIS and AIRS Variability, LW and MW regions
2004.09.07 (Italy)

AIRS



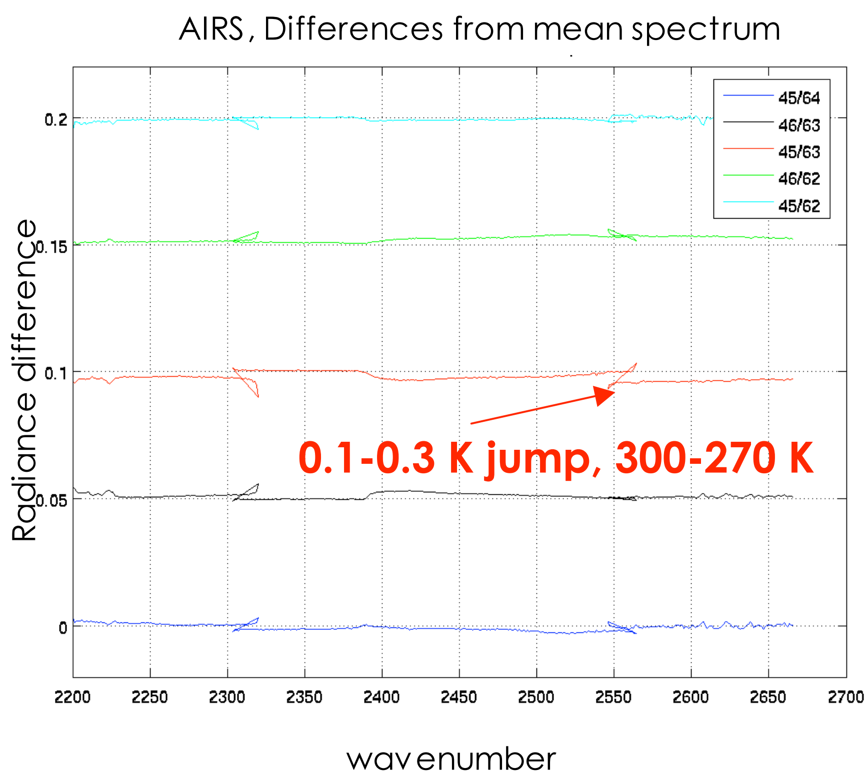
S-HIS



Generally good agreement in MW region, with little sign of module-to-module jumps

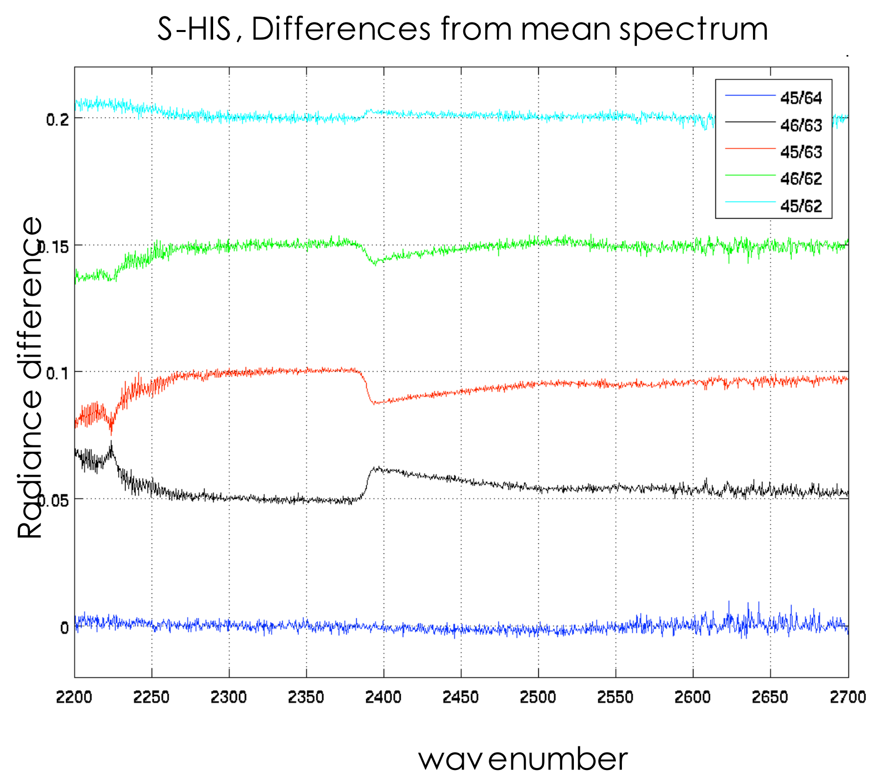
SHIS and AIRS Variability, SW region
2004.09.07 (Italy)

AIRS



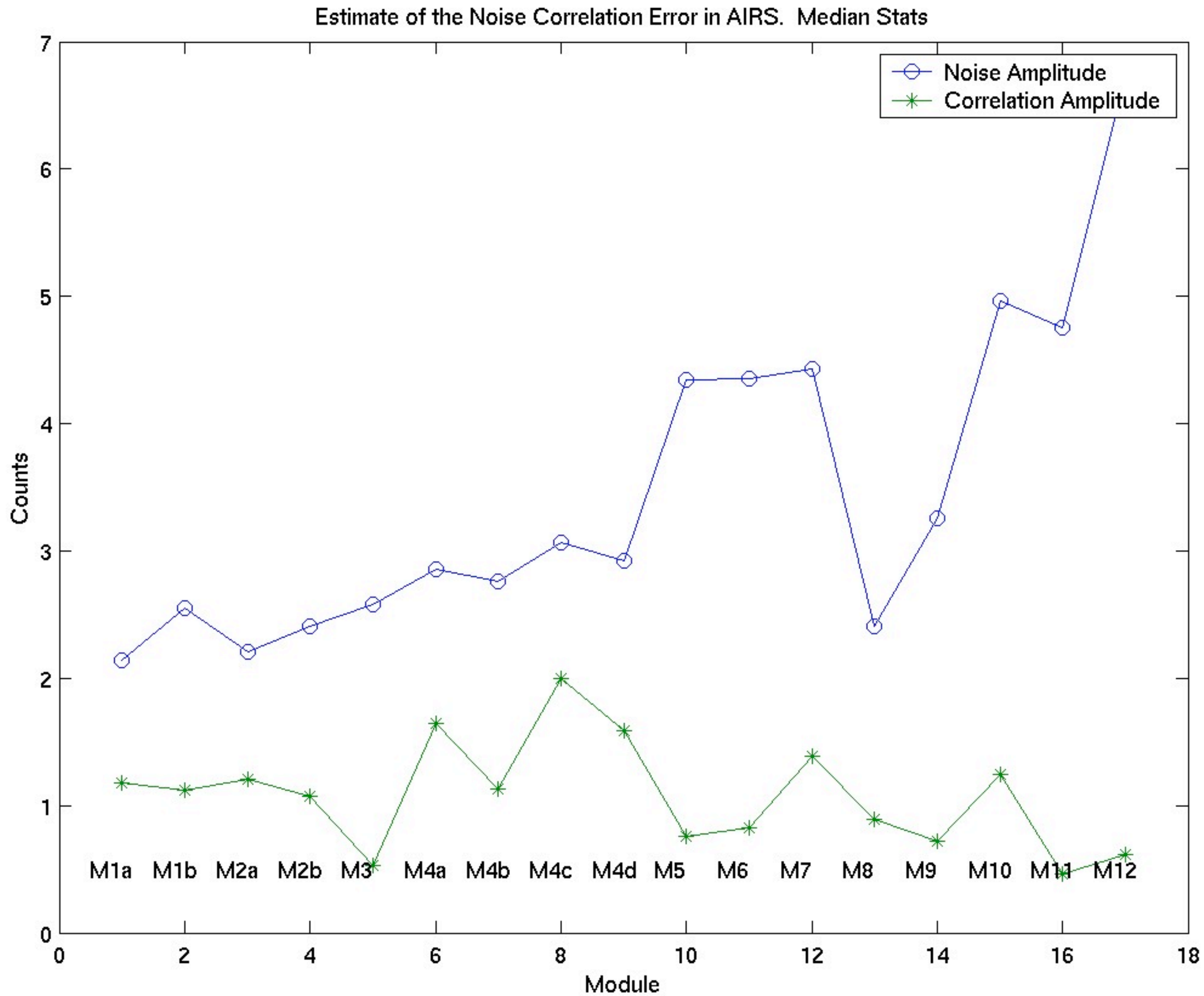
AIRS shows low noise, but evidence of significant module-to-module jumps

S-HIS



S-HIS is noisier, but 4x higher resolution & spectrally smooth

AIRS Correlated Noise Level by Module as determined by BAE



Summary of AIRS Radiance Validation for climate

- **S-HIS and AIRS Radiances are in excellent overall agreement**
  - S-HIS Validation of AIRS radiances (averaged over several FOVs) for 5 diverse atmospheres yields mean differences over AIRS modules that are generally < 0.2 K, with many smaller examples
  - HNO_3 above the aircraft explains some larger differences that are expected to be < 0.2 K after further analysis using S-HIS zenith views **(and we need to handle HNO_3 for retrieval. i.e. include it in the forward radiative transfer model)**
  - Other exceptions occur in spectral regions where the above-aircraft influence also needs further analysis (15 μm CO_2 band & M-05 ozone)
- **The expected 3-sigma calibration performance of AIRS should be carefully assessed from parameter-characterization uncertainties to complement this validation record**
- **Validation over the lifetime of AIRS is needed to assure the long-term stability of the AIRS climate record**
- **The value of aircraft observations for direct radiance validation has now been definitively proven**

Summary of AIRS Single-Spectrum Artifacts

- **The radiometric performance of AIRS at the level of the NEN contains artifacts not described by spectrally and temporally random noise, or by long-term calibration uncertainty**
  - Spectrum-to-spectrum jumps of radiances (±0.4K) for some detector modules do not seem to be atypical
  - Apparent "noise" levels for some modules (after PC filtering) seem to change dramatically from one spectrum to the next (from very small values up to 0.5 K p-p)
  - Module M-08 (at least) suffers from a peculiar behavior related to A/B detector states that seems to be highly variable from one spectrum to the next (±0.5K)
- **Principal Component Analyses (PCA) are very valuable at revealing these artifacts; supplementation by inspection of individual spectra seems necessary for more complete characterization**
- **Achieving optimum retrieval performance for cloud clearing and for individual FOVs probably depends on successfully characterizing the temporal and spectral character of this behavior**

S-HIS Backup Slides

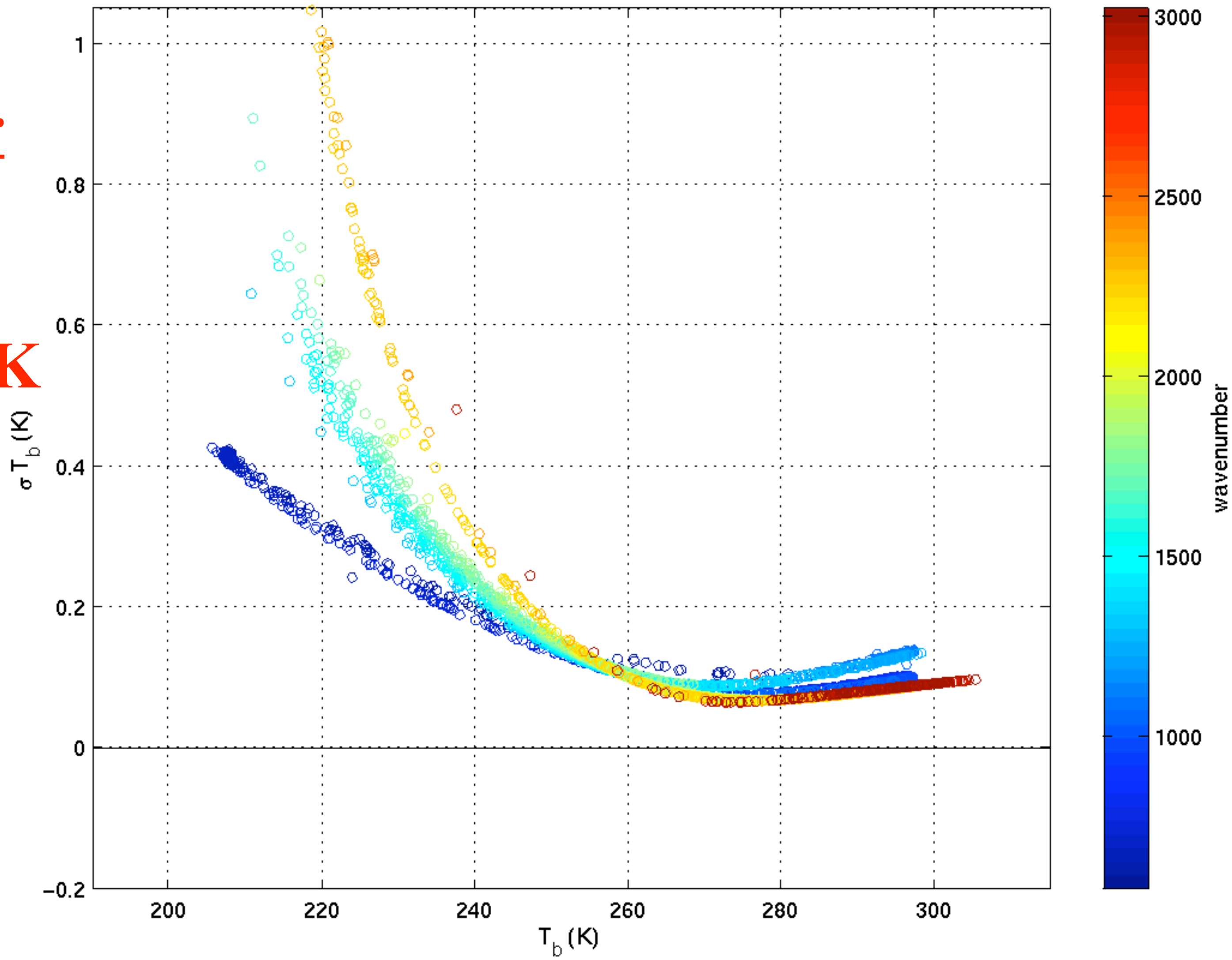
- More Radiometric Calibration
- Non-linearity Correction
- Spectral Calibration and Normalization

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

3-sigma Tb error < 0.2 K for Tb >250 K



Scanning-HIS Radiometric Calibration Budget

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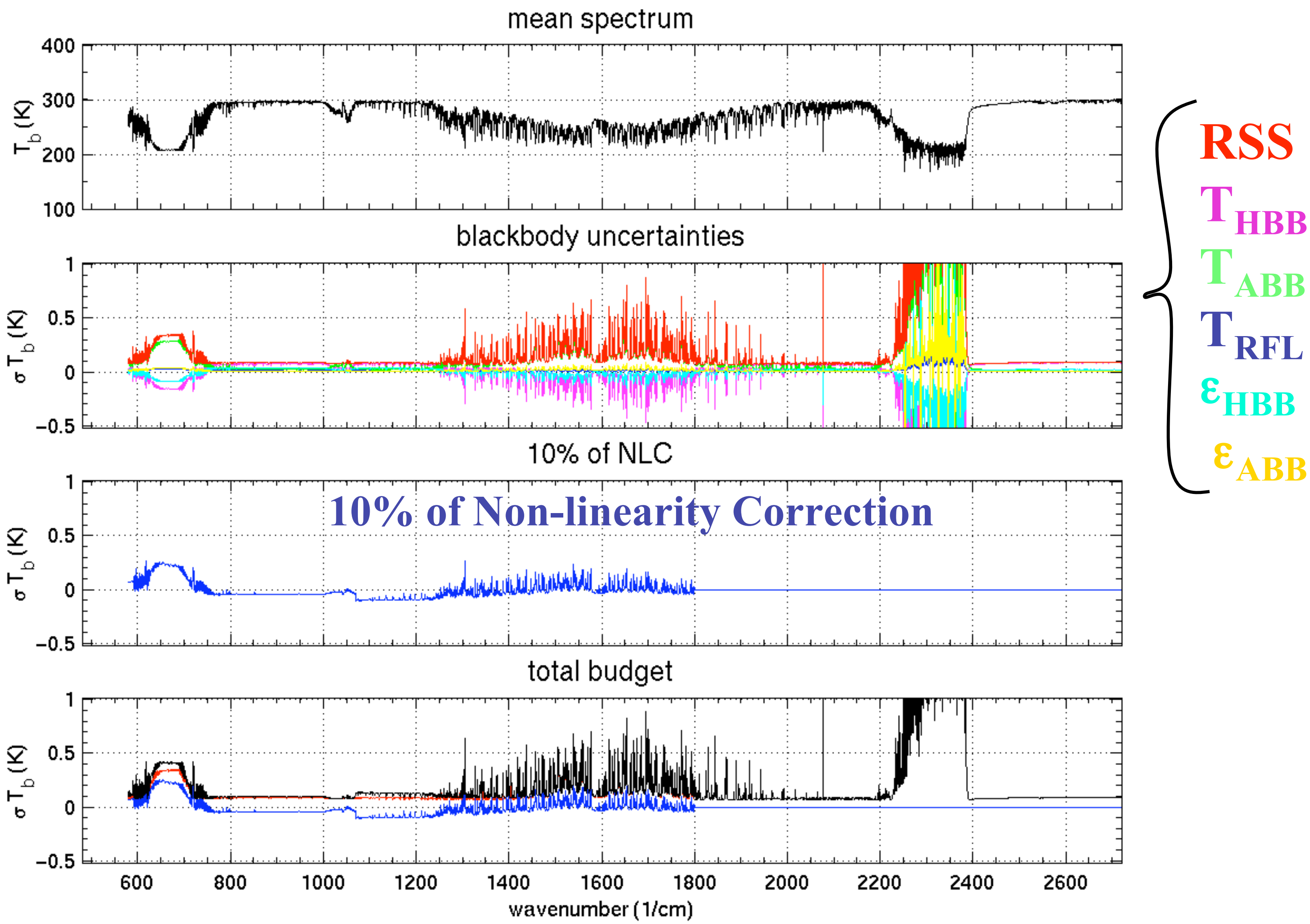


Non-linearity Correction

- 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

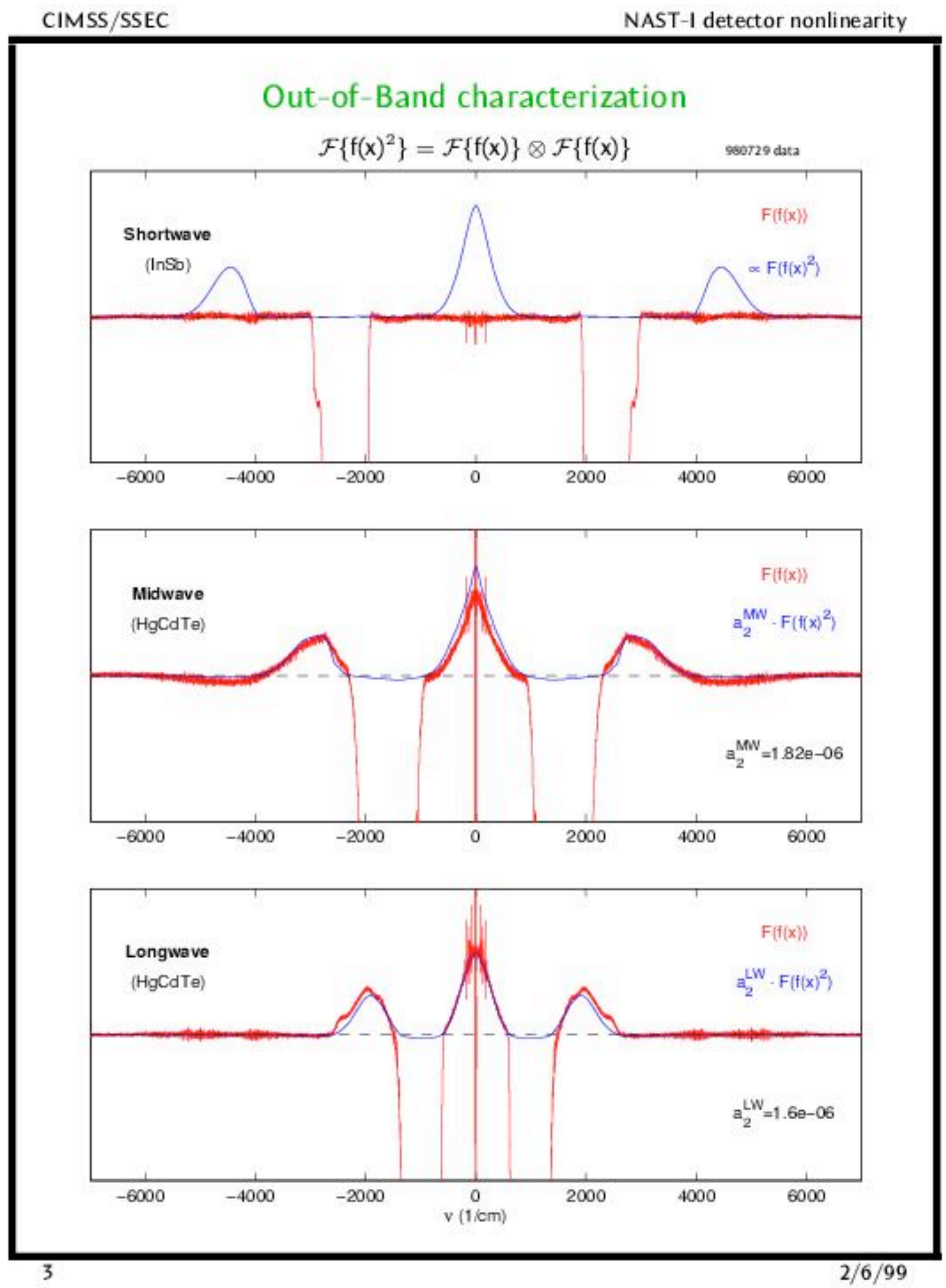
Example Non-linearity: NAST Aircraft Instrument

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



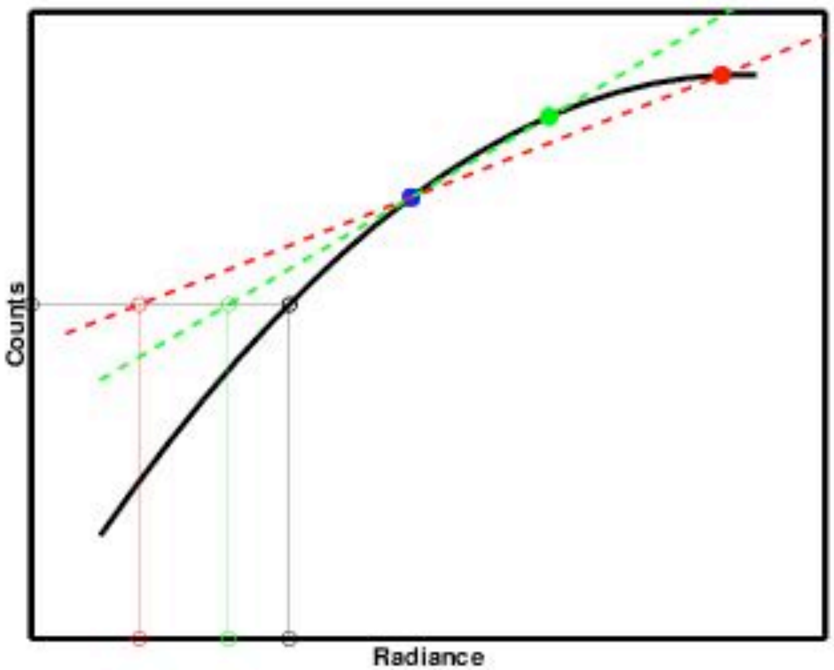
Physical Non-linearity Model, General Principle

- 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

$$\rightarrow \tilde{I}_c = (1 + 2a_2V + 3a_3V^2)\tilde{f} + (a_2 + 3a_3V)\widetilde{f^2} + a_3\widetilde{f^3}$$

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



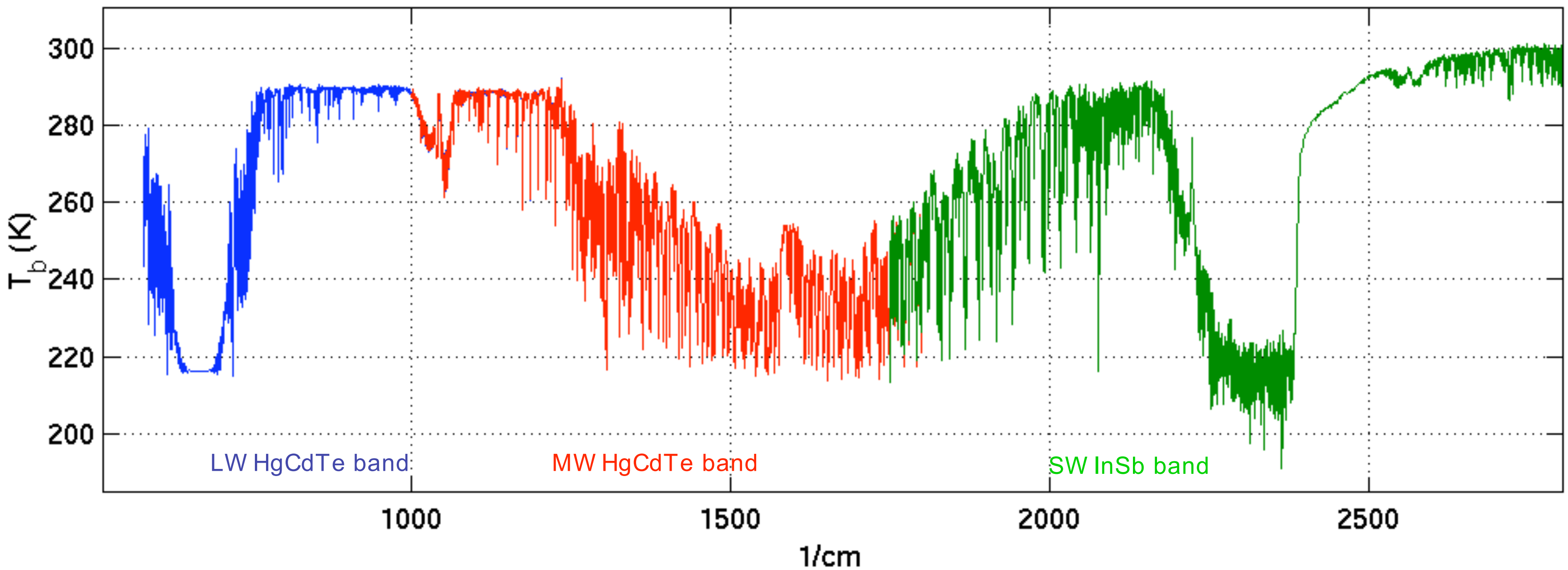
a_2 determined from

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

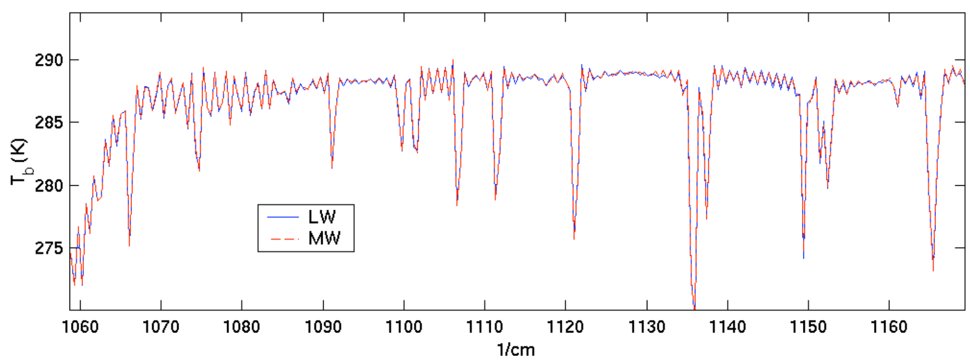
Correction applied before Complex Radiometric Calibration

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

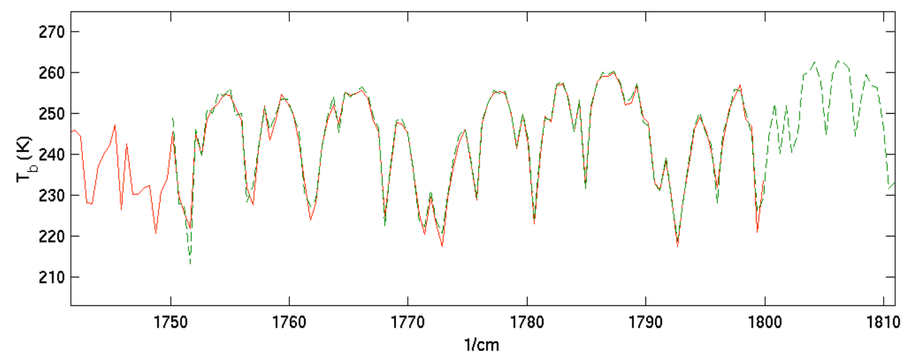
11-16-2002



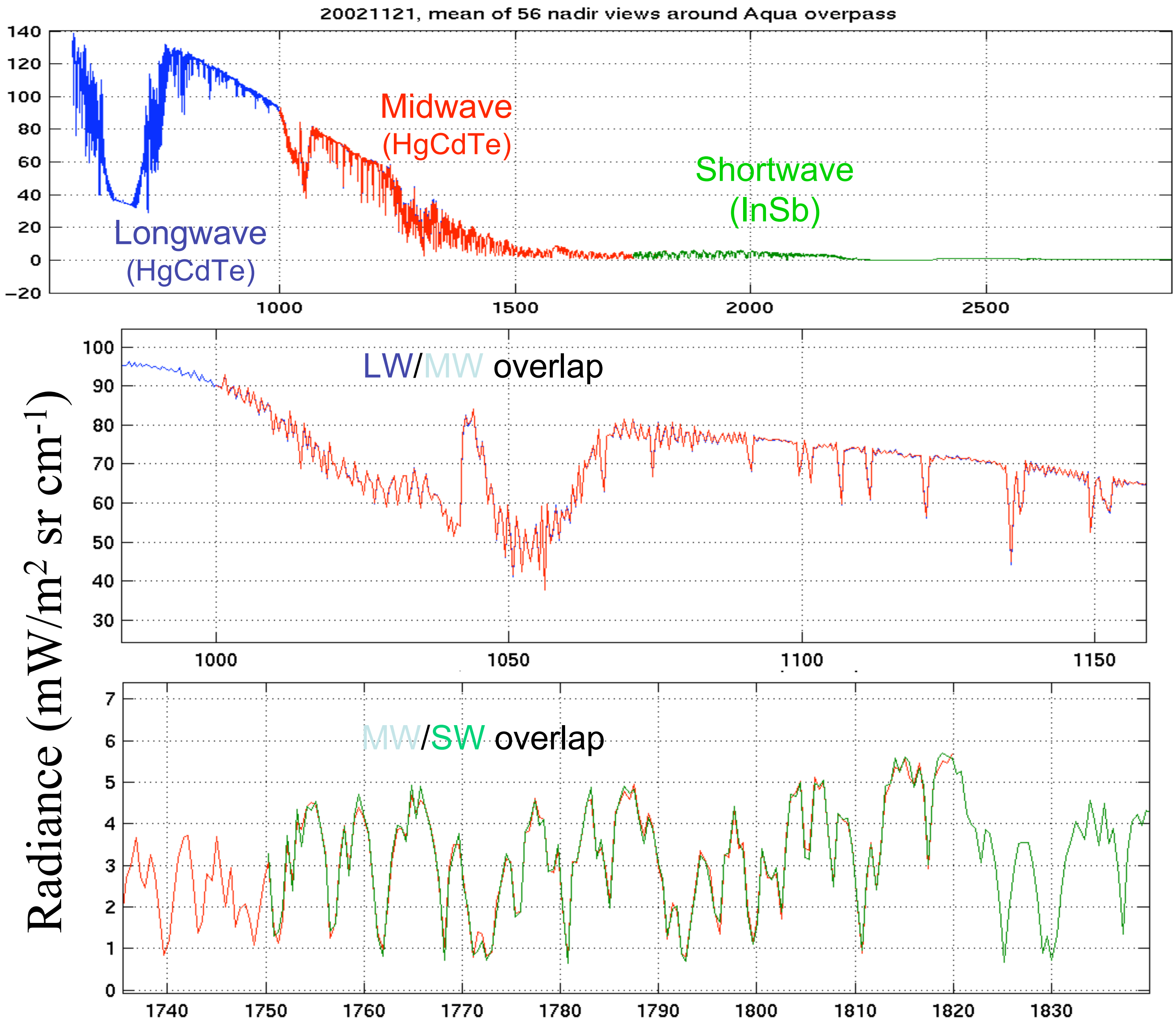
LW/MW overlap



MW/SW overlap



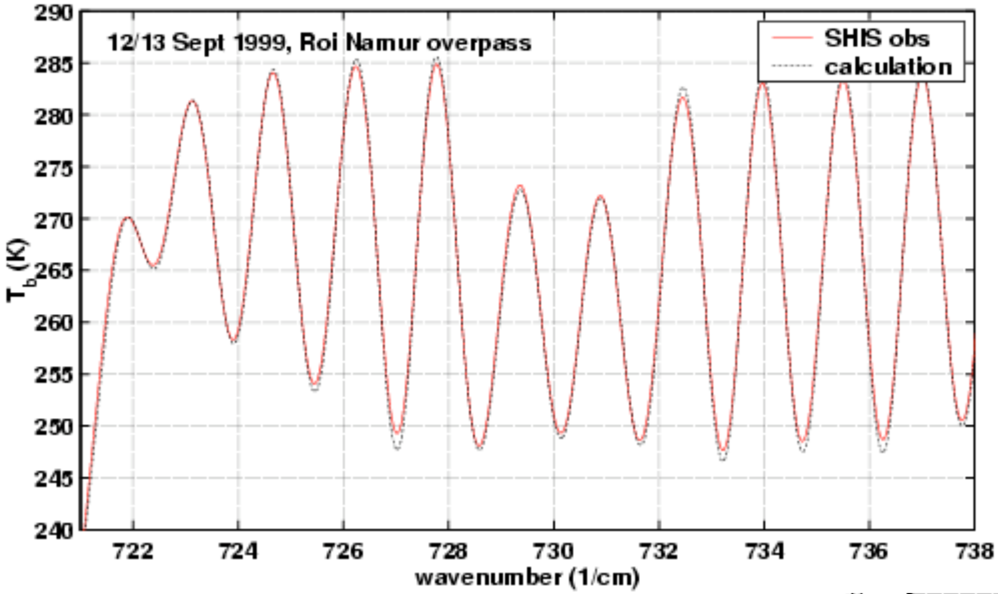
Scanning-HIS Band Overlap Agreement



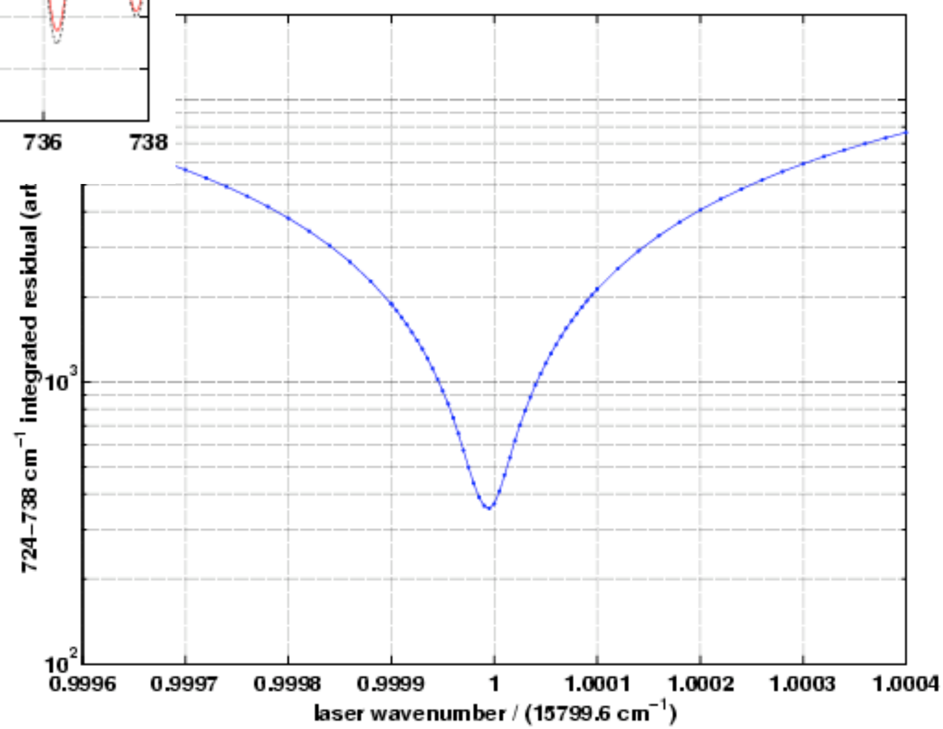
Spectral Calibration and Standardization

- 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}**

Example Spectral Calibration: S-HIS



Atmospheric CO_2 lines

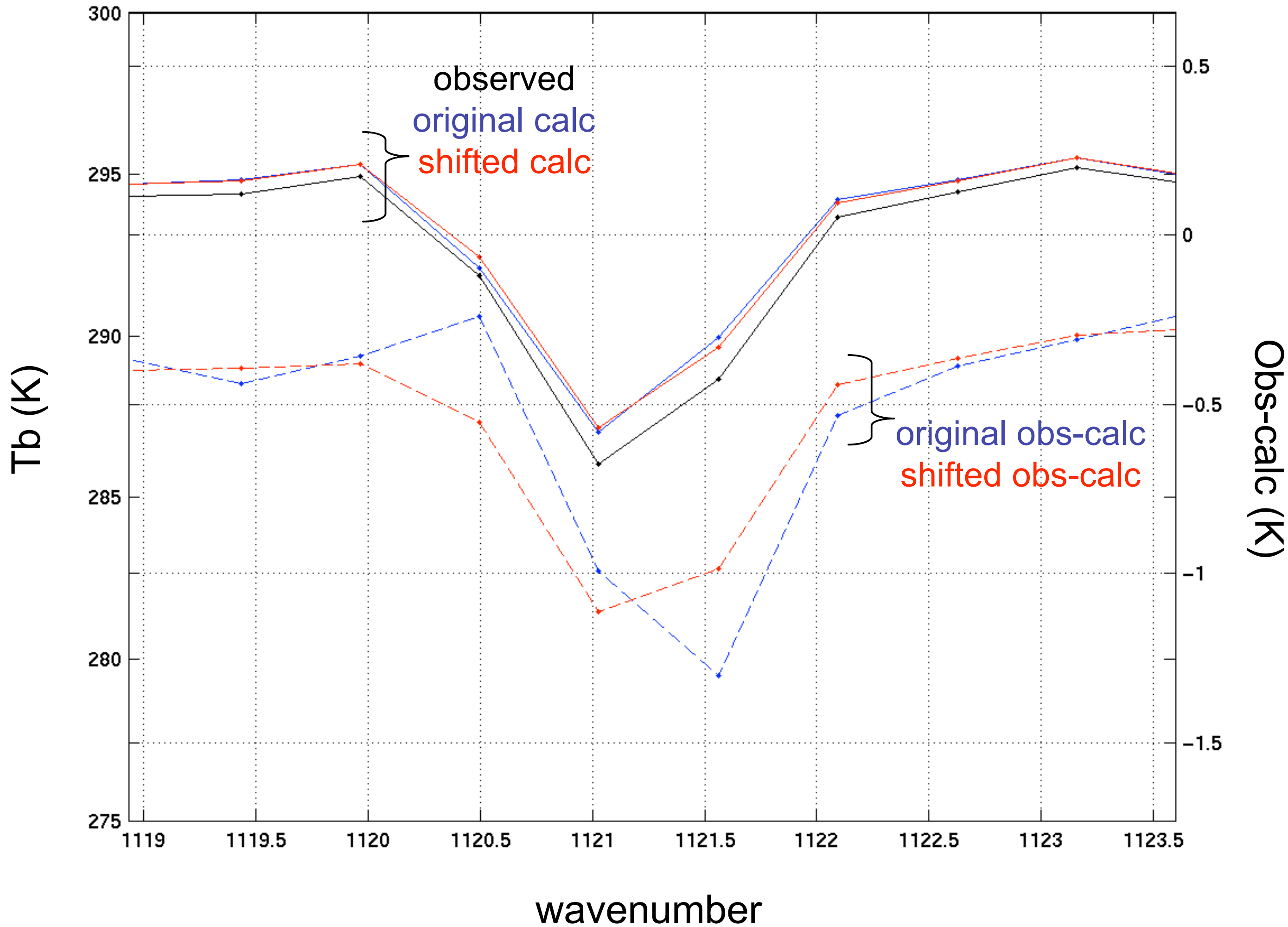


Wavenumber Scale chosen to minimize difference

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

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 $(\pi \nu x b^2/2)$:

$$F(x) = \int d\nu N(\nu) e^{i2\pi\nu x} - \frac{(\pi x b^2/2)^2}{3!} \cdot \int d\nu N(\nu) \nu^2 e^{i2\pi\nu x} + \frac{(\pi x b^2/2)^4}{5!} \cdot \int d\nu N(\nu) \nu^4 e^{i2\pi\nu x} - \ldots$$

- 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)]