Hyperspectral Measurement and Product Validation

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MURI Workshop, 8 June 2005, UW-Madison

Validation of Atmospheric Infrared Sounder (AIRS) Radiance Observations and Retrievals

1. Spectral Radiance Validation using high altitude aircraft observations
2. Noise Characterization using Principle Component Analysis of Earth Scene Spectra
3. Assessment of Aqua MODIS Calibration using AIRS/MODIS comparisons
4. Temperature and Water Vapor Retrieval Validation using ARM site atmospheric state best estimates

Material from papers submitted (1, 3, 4) and in preparation (2) for a JGR special issue on AIRS validation

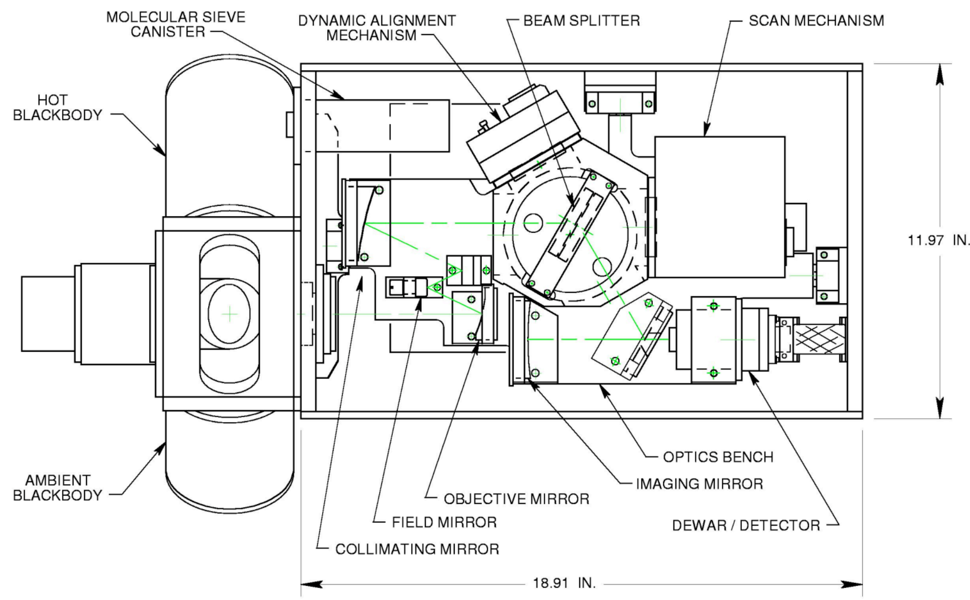
Radiometric and Spectral Validation of AIRS Observations with the aircraft based Scanning High resolution Interferometer Sounder

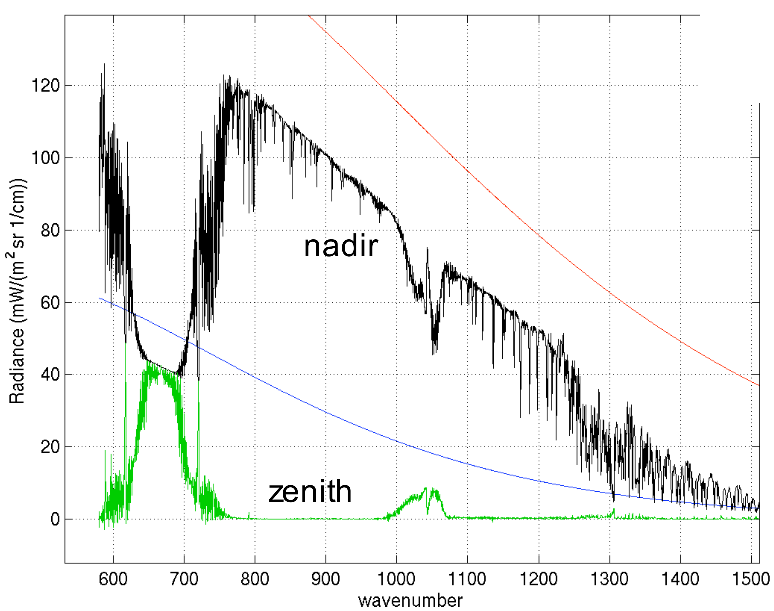
- Paper Outline:
  - Scanning-HIS introduction
  - Comparison approach that accounts for different viewing geometries and spectral characteristics of Scanning-HIS and AIRS
  - Example validation using underflight on 21 November 2002 over the Gulf of Mexico

- Importance:
  - Provides a mechanism for testing the **absolute calibration** of spacecraft instruments with instrumentation for which the calibration can be carefully maintained and verified on the ground.
  - Accurate comparisons made for **nearly all AIRS spectral channels** (except those with significant contribution from above the aircraft altitude, ~20 km)

Scanning-High resolution Interferometer Sounder (S-HIS)

- HIS and AERI heritage
- 0.5 cm^{-1} resolution
- 580-3000 cm^{-1} coverage with three spectral bands
- 100 mrad FOV (~2 km diameter from 20 km)
- programmable cross track downward and zenith viewing
- 1998 to present on NASA ER-2, Proteus, and NASA WB-57
- In-field calibrated spectra





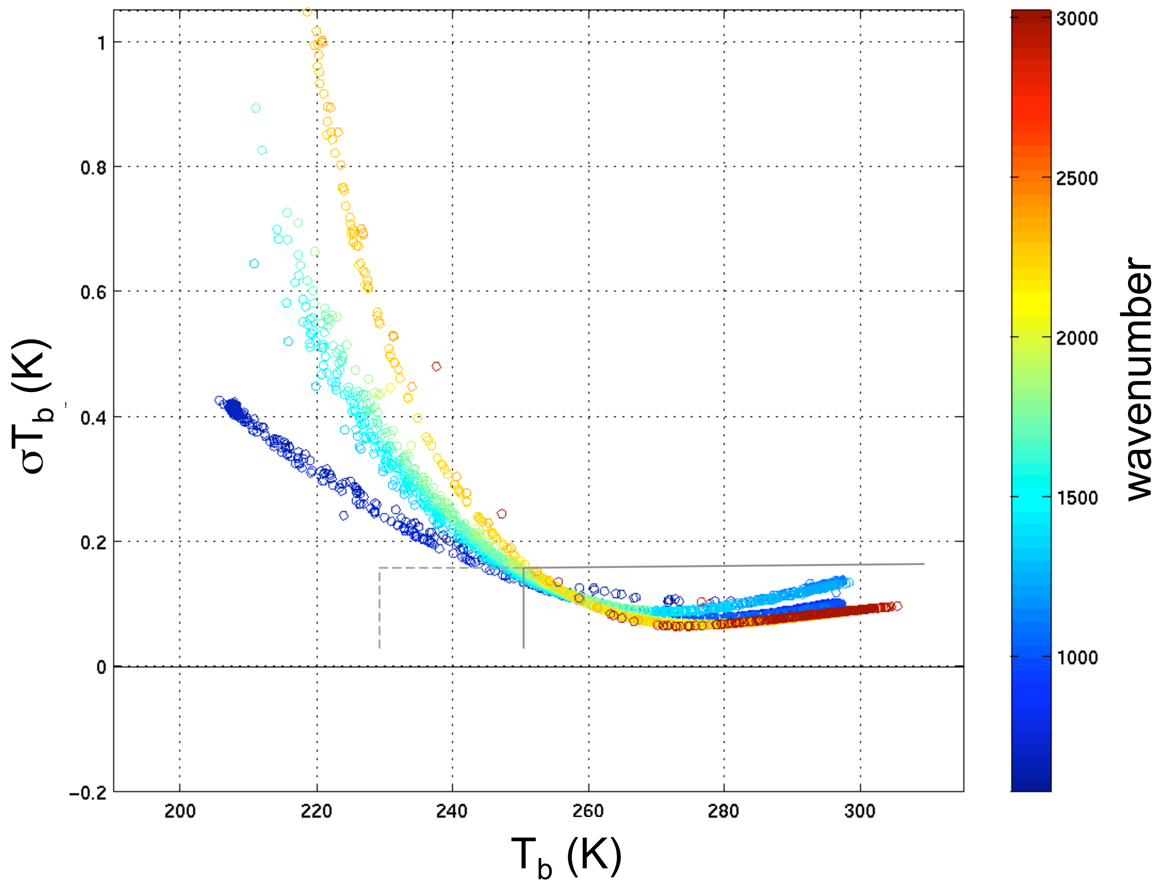
S-HIS on WB-57 wing pod

S-HIS Absolute Radiometric Uncertainty
for 21 Nov 2002 Earth scene spectrum

****Formal 3-sigma absolute uncertainties, similar to that detailed for AERI in Best et al. CALCON 2003**

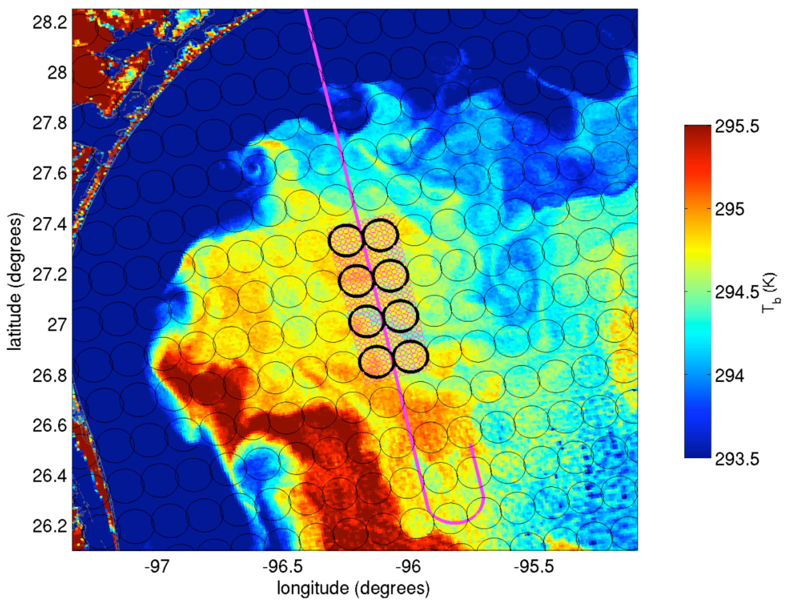
T_{ABB}= 260 K
T_{HBB}= 310 K

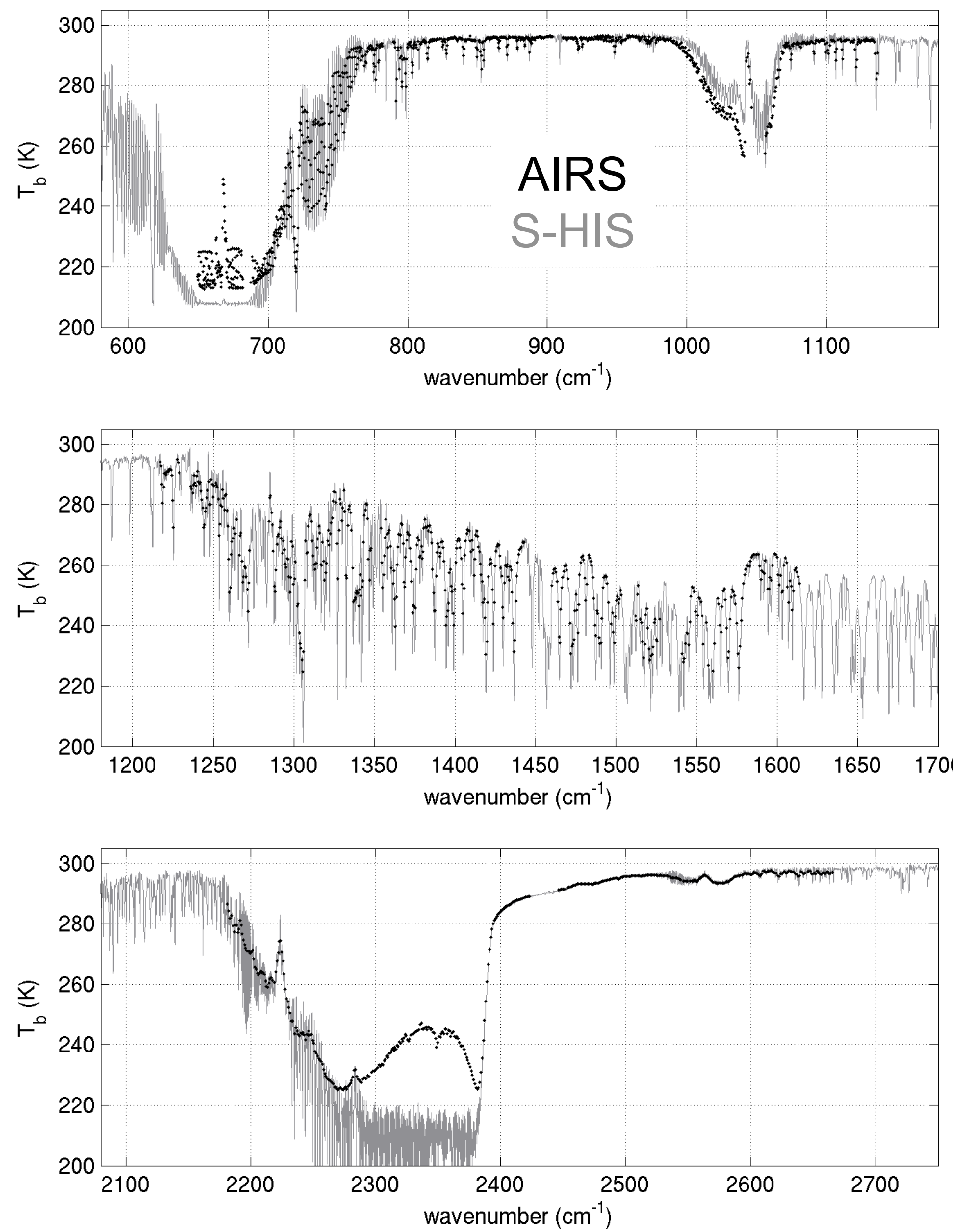
σT_{BB} = 0.10 K
$\sigma \varepsilon_{BB}$ = 0.0010
σT_{refl} = 5 K
10% nonlinearity



AIRS underflight
21 November 2002
Gulf of Mexico
Daytime

AIRS / S-HIS comparison, without accounting for viewing geometry or spectral resolution/sampling differences:



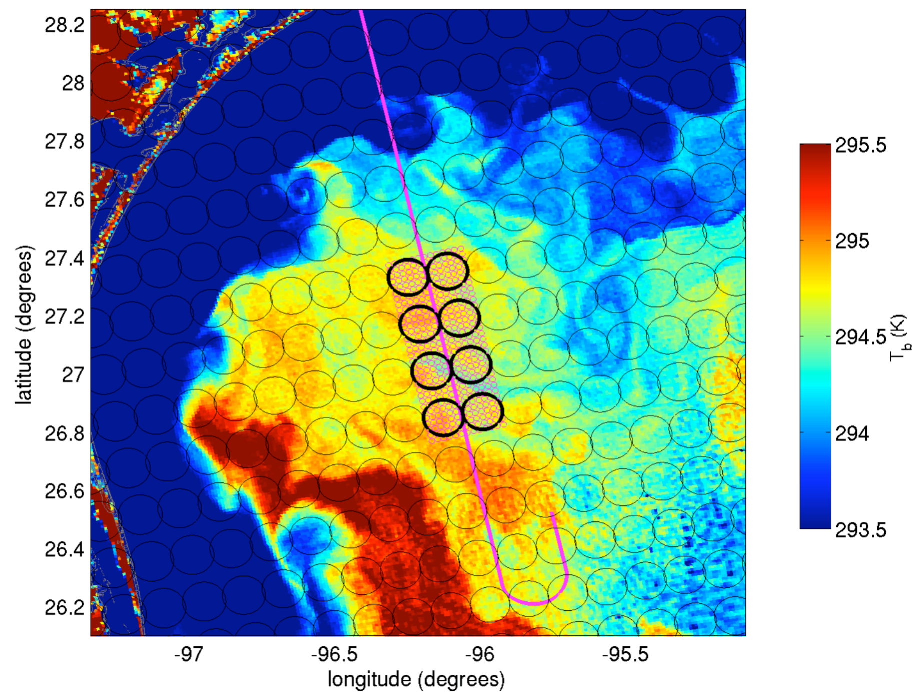


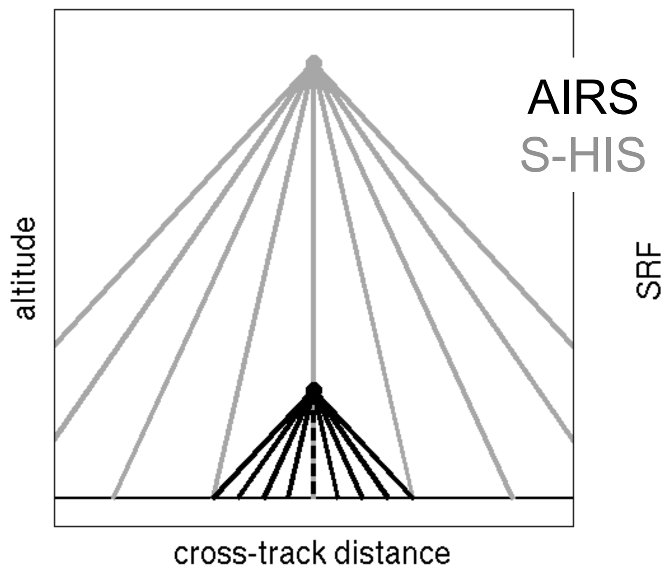
8 AIRS FOVs and 416 collocated S-HIS FOVs selected for comparison.

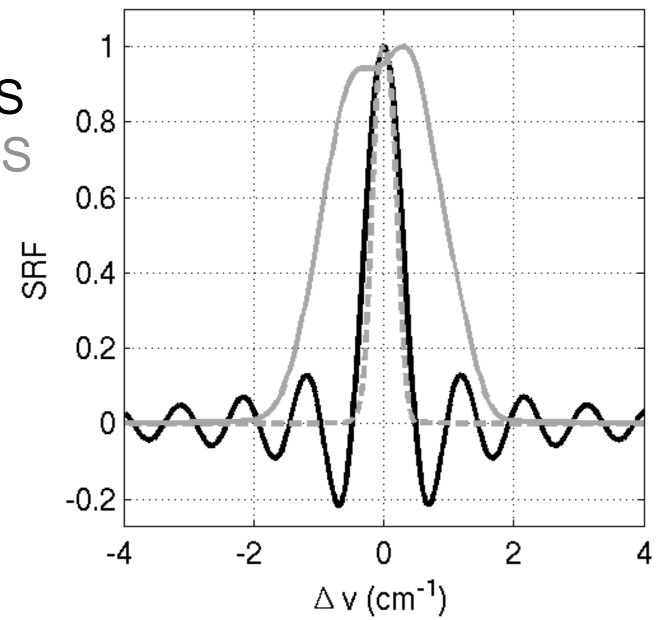
AIRS at 705 km, near nadir

S-HIS at 20.0 km, 13 view angles covering ±30°

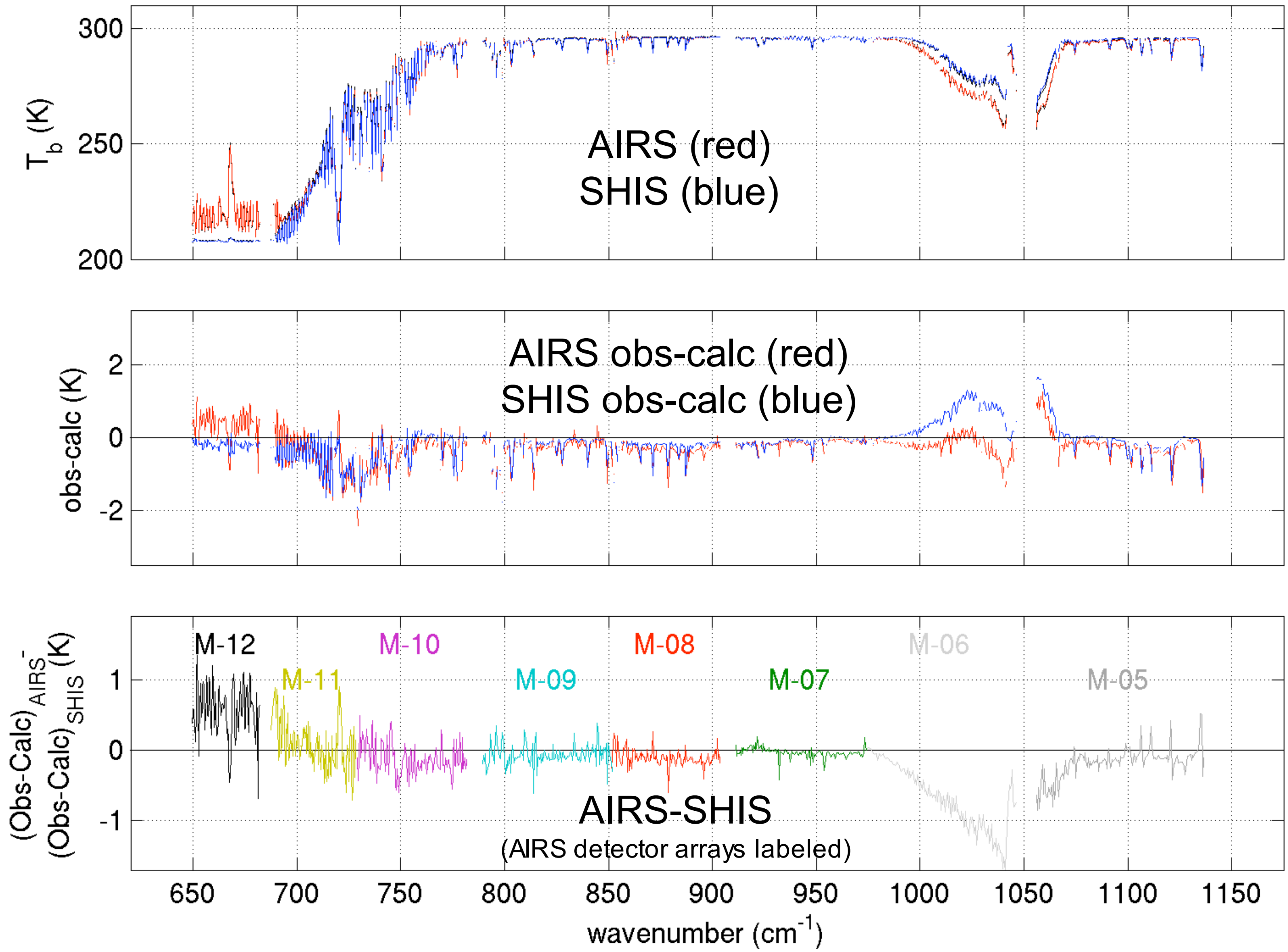
$(Obs_{AIRS}-Calc_{AIRS}) \otimes SRF_{SHIS} - (Obs_{SHIS}-Calc_{SHIS}) \otimes SRF_{AIRS}$



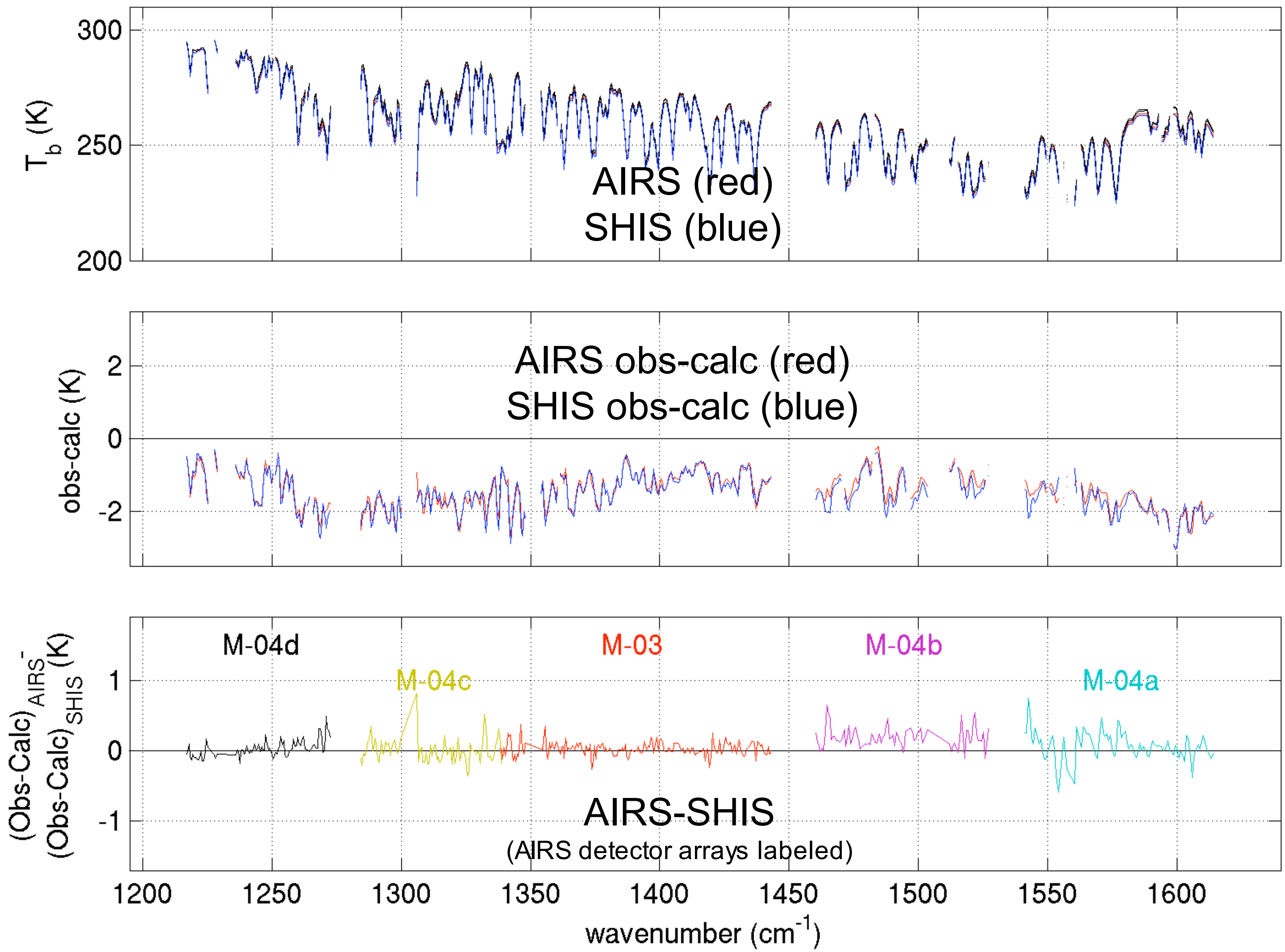




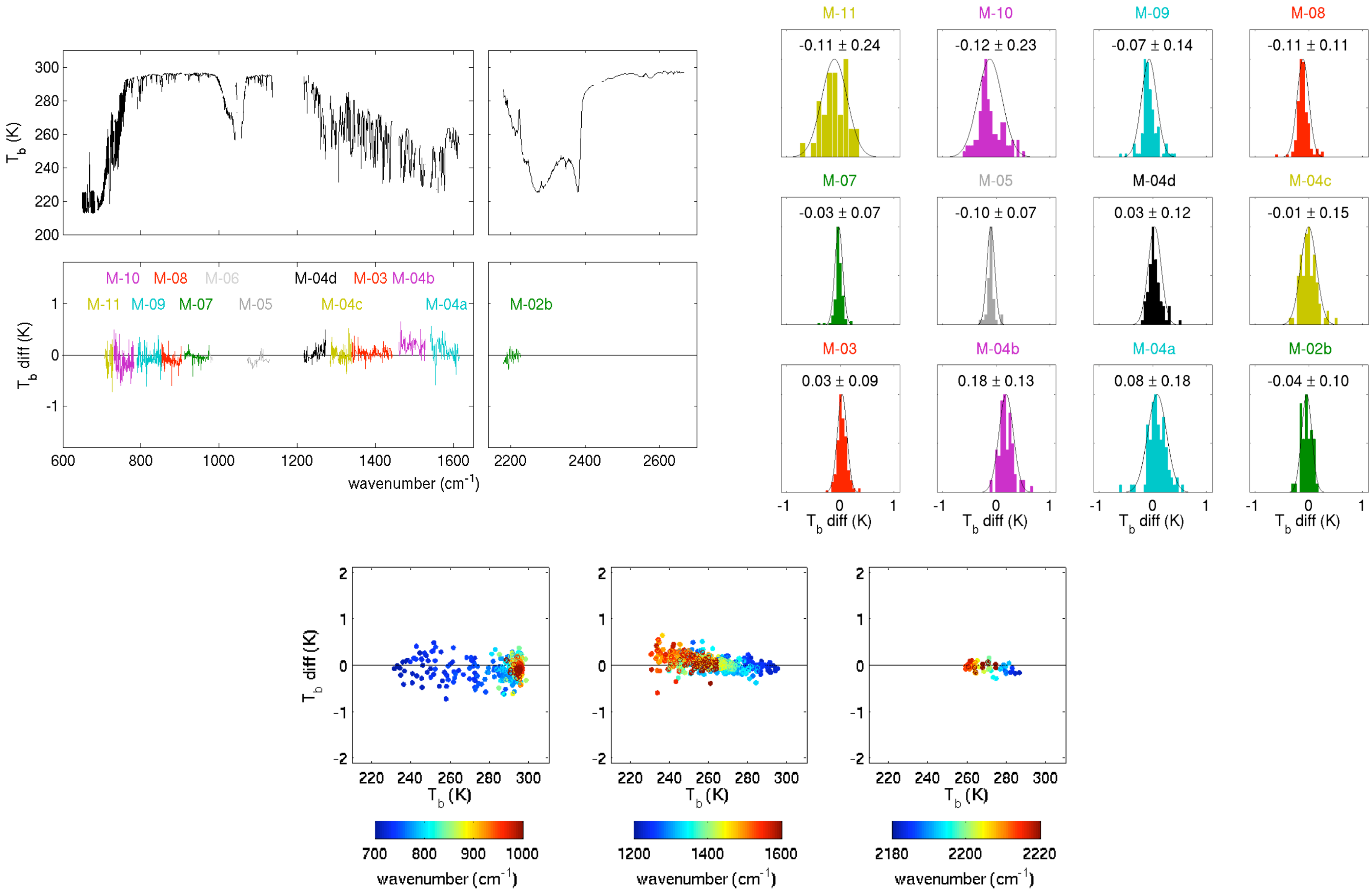
AIRS / S-HIS comparison, accounting for viewing geometry and spectral resolution/sampling differences.



AIRS / S-HIS comparison, accounting for viewing geometry and spectral resolution/sampling differences.



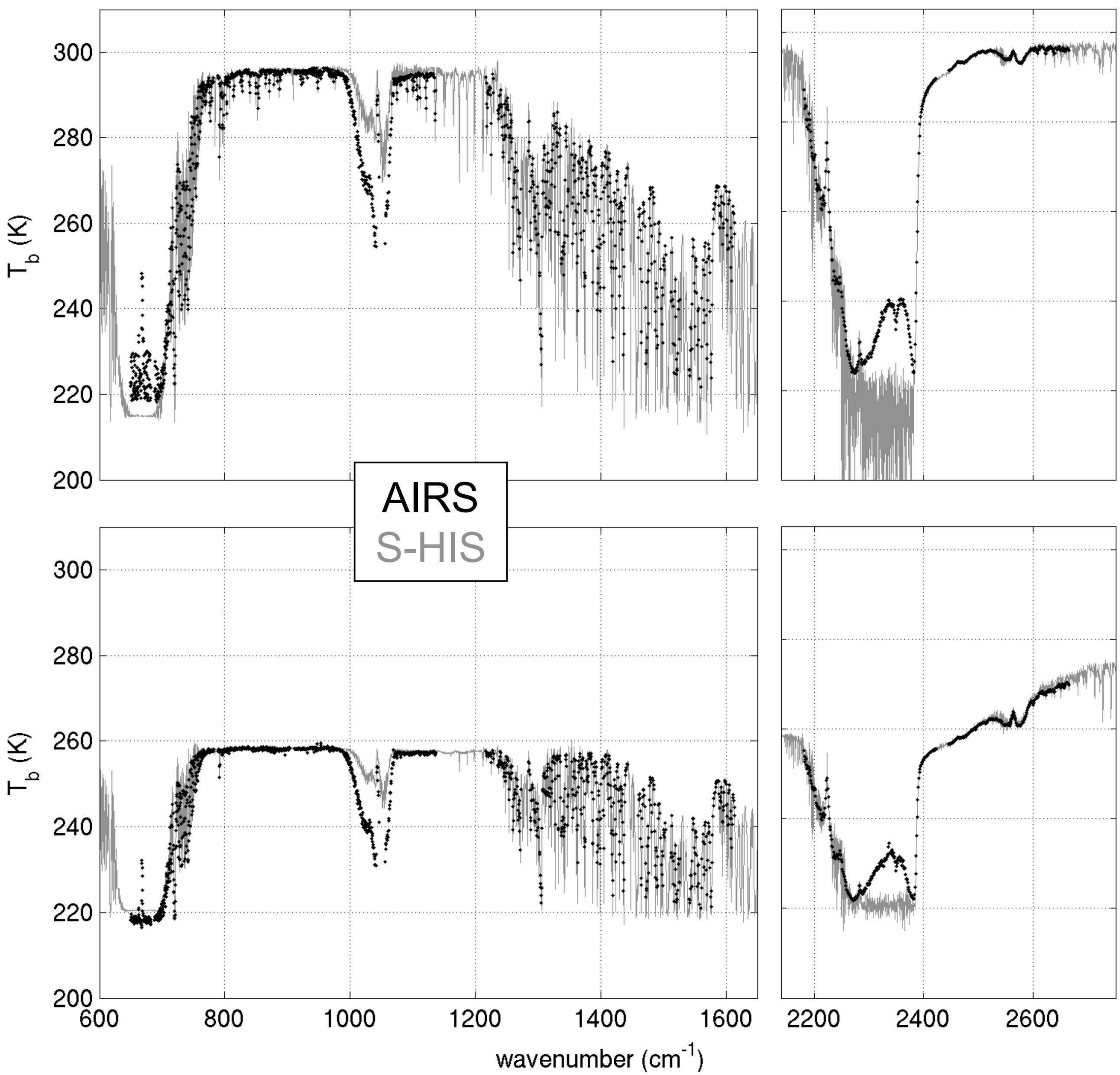
AIRS / S-HIS comparison, accounting for viewing geometry and spectral resolution/sampling differences and excluding channels with 1) significant contribution from above the aircraft altitude and 2) solar contribution.



Quicklooks of more cases:

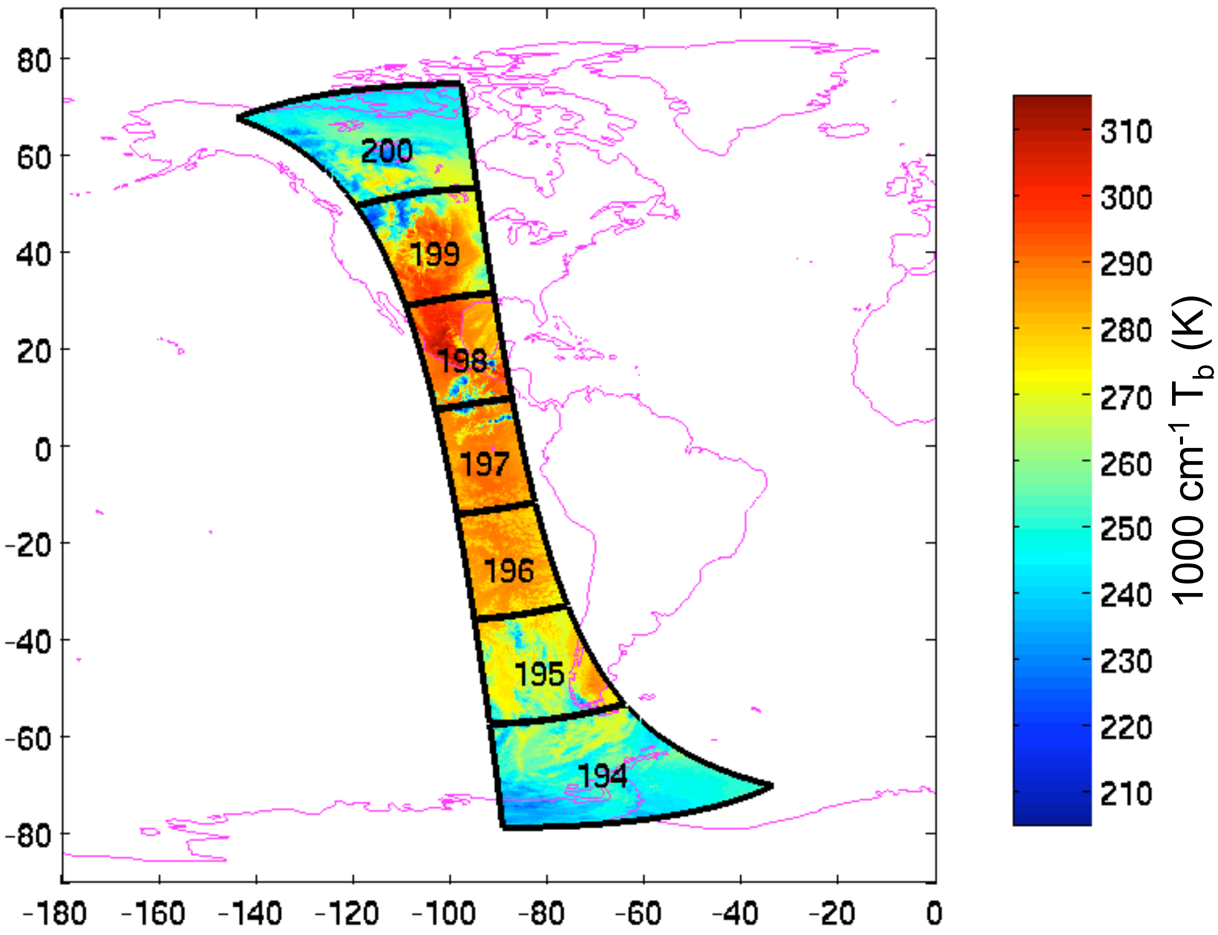
8 September 2004
Clear sky nighttime
over Adriatic Sea:

12 October 2004
Uniform stratus clouds
near Barrow Alaska:



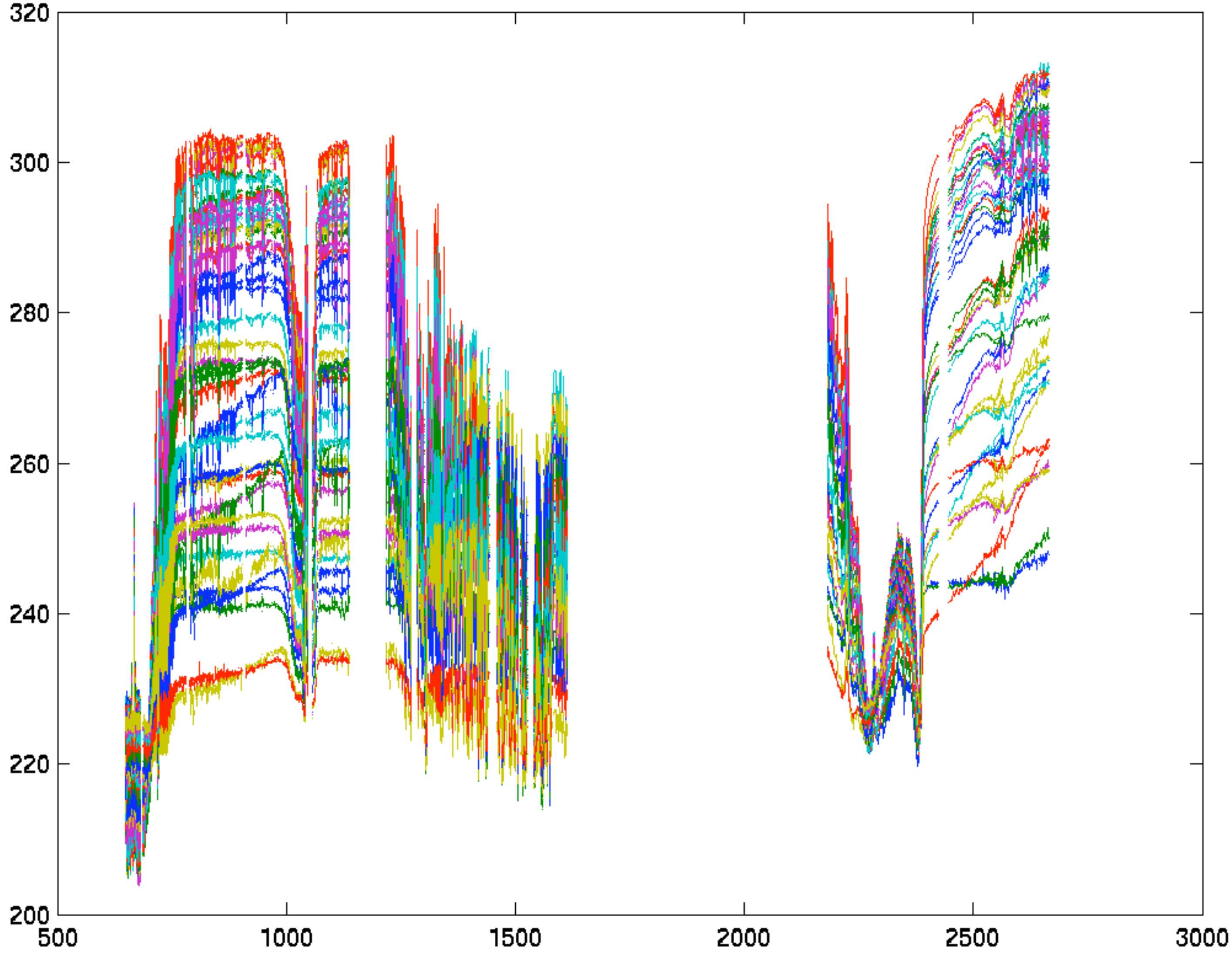
AIRS Noise Characterization using PCA of Earth Scene Spectra

7 ascending (daytime) granules on 1 April 2005

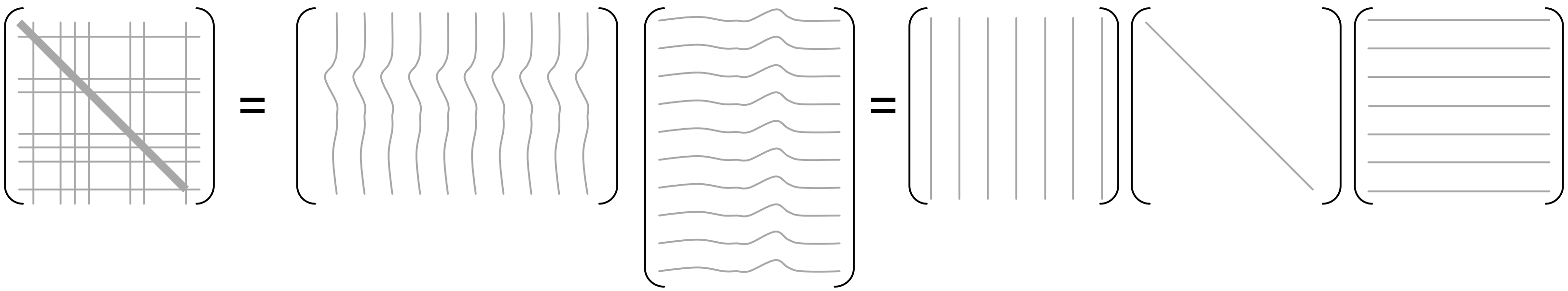


v4.0.9 L1B data

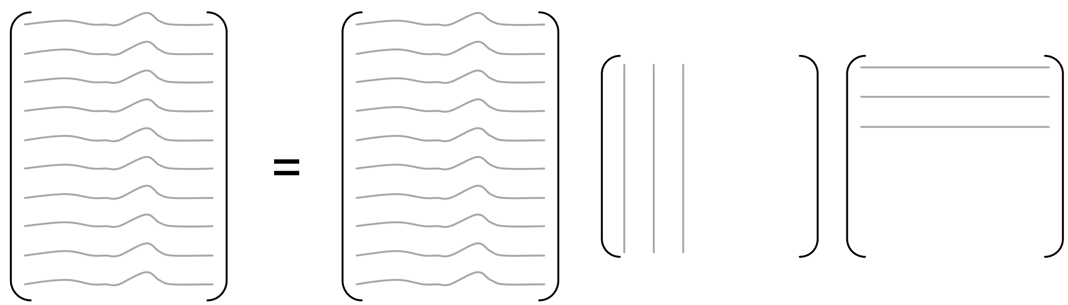
Sample spectra



Dependent Set Principle Component Analysis (PCA)



$$C = S^T S = U D U^T$$



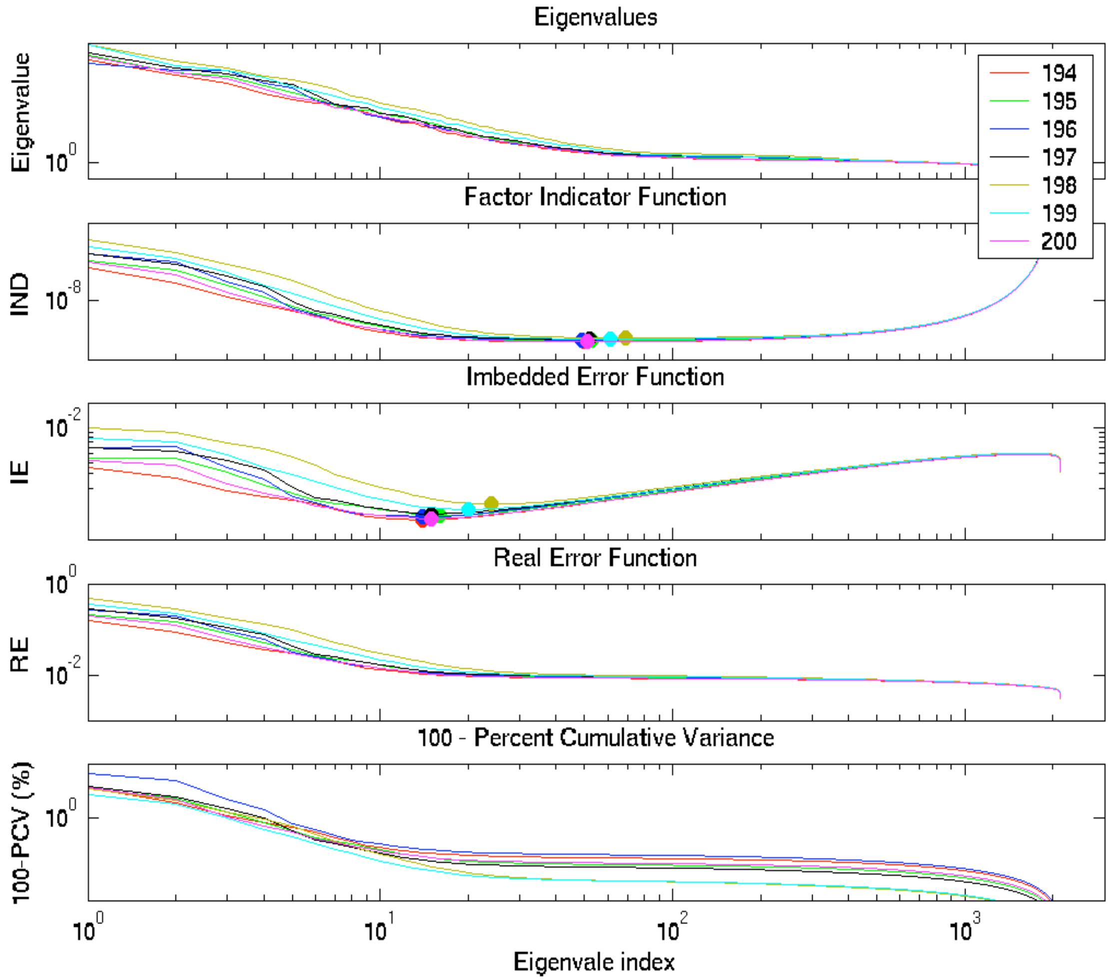
$$\acute{S} = S \acute{U} \acute{U}^T$$

PC Noise Filter (PNF)

Antonelli, P., Revercomb, H. E., Sromovsky, L. A., Smith, W. L., Knuteson, R. O., Tobin, D. C., Garcia, R. K., Howell, H. B., Huang, J.-L., and Best, F. A., A principal component noise filter for high spectral resolution infrared measurements. *Journal of Geophysical Research*, **109**, 2004, pp.22p. Reprint # 3938.

Noise Estimation: noise = $S - \acute{S}$, NEDN = STDEV($S - \acute{S}$)

Variance Metrics for each granule, ala Turner et al.



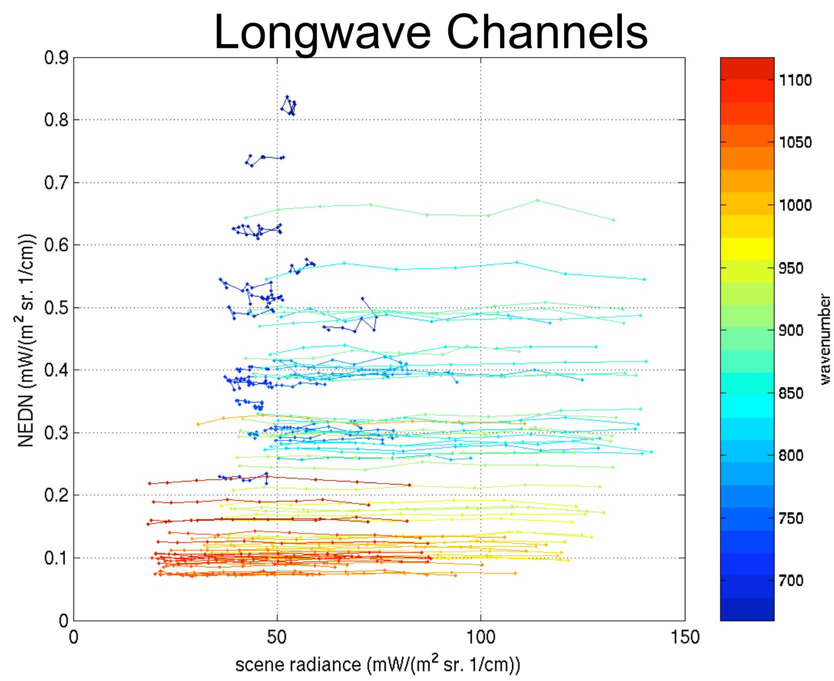
Gran.	IND	IE
194	50	14
195	53	16
196	49	14
197	52	15
198	69	24
199	61	20
200	51	15

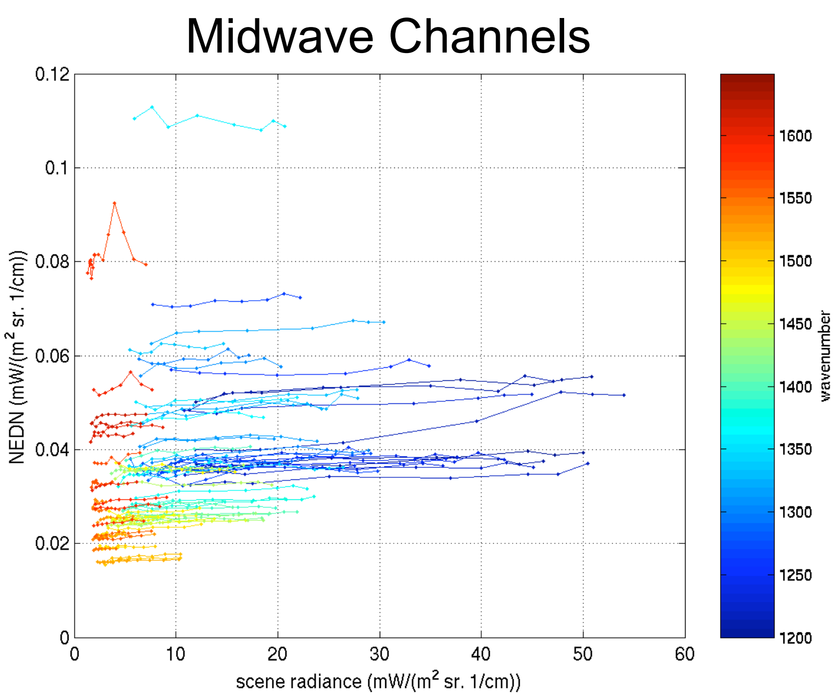
# of PCs used in the reconstructions

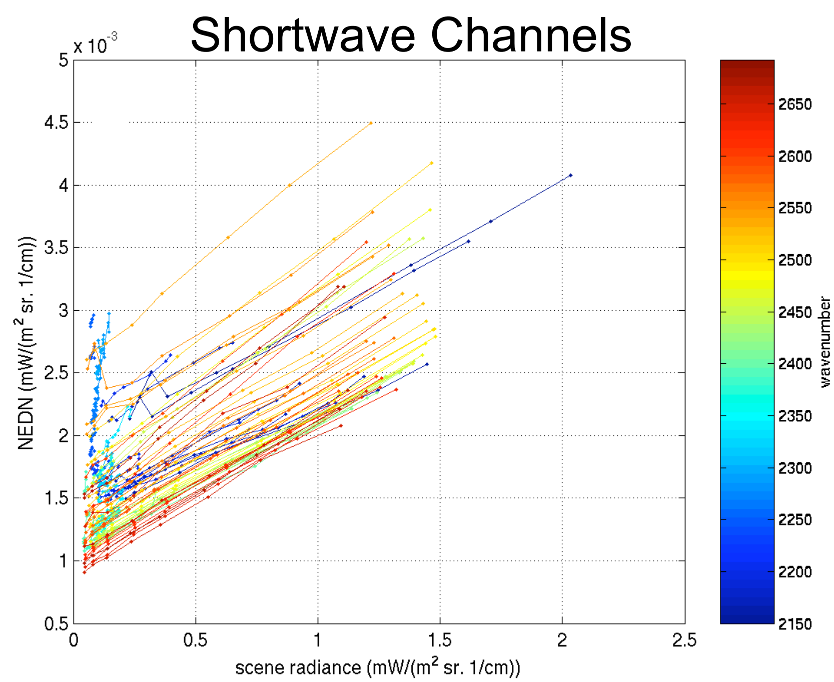
Turner, D. D., C. Lo, R.O. Knuteson, H.E. Revercomb, and R.G. Dedecker Noise Reduction of Atmospheric Emitted Radiance Interferometer (AERI) Observations Using Principal Component Analysis, Journal of Atmospheric and Oceanic Technology, in preparation.

Analysis #1:
NEDN vs. scene radiance

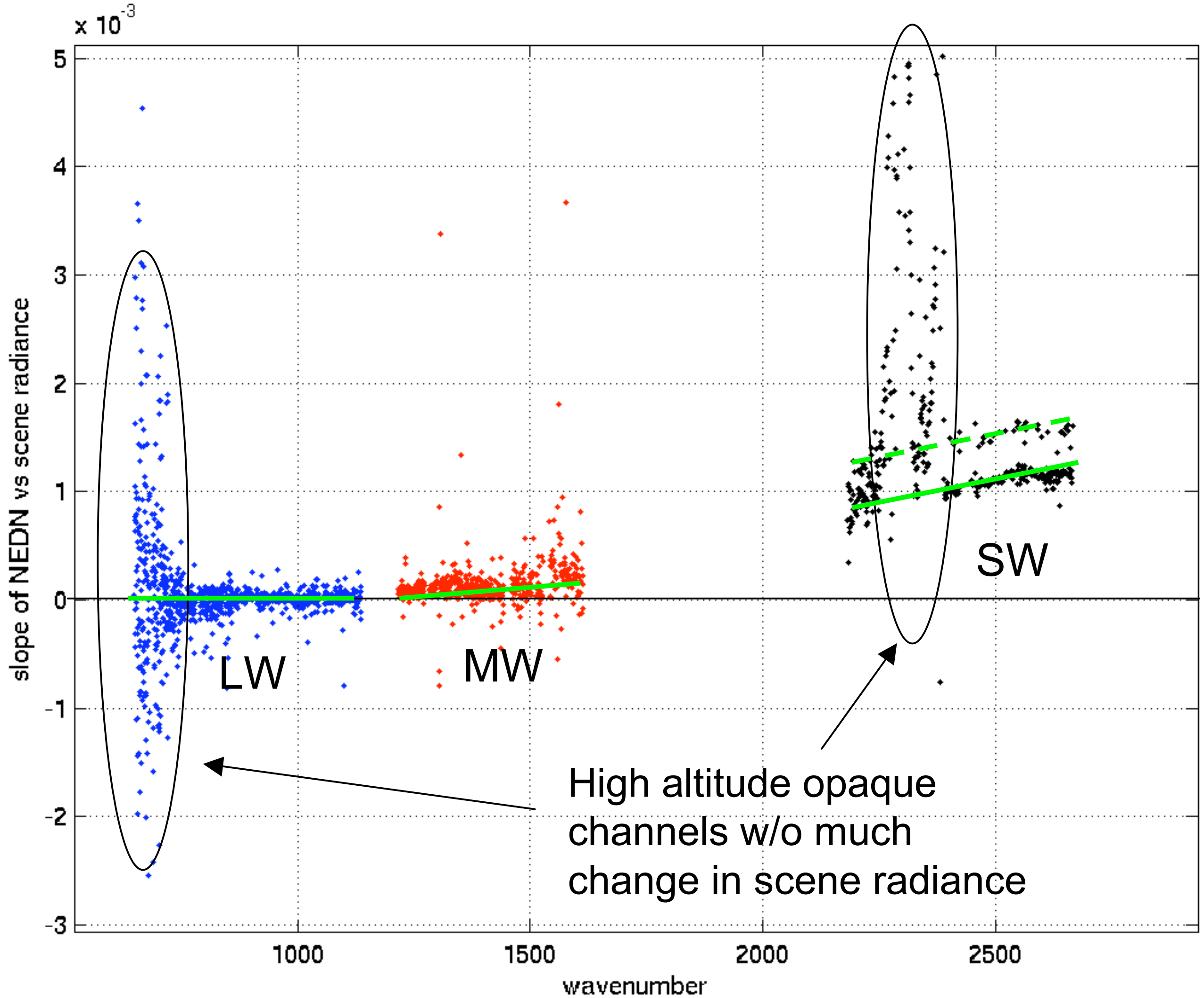
for sample longwave, midwave, and shortwave channels
(Each curve is a different channel)



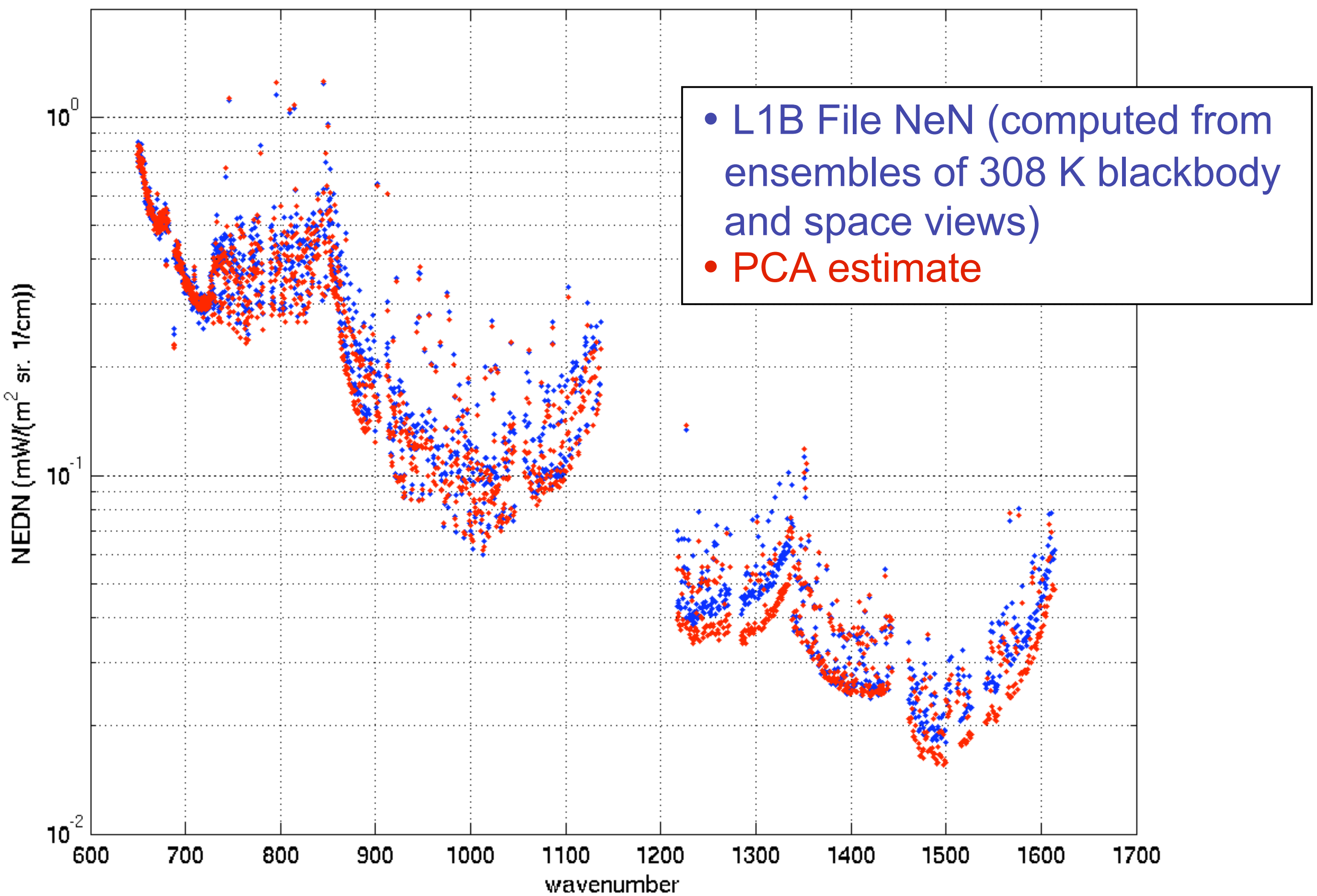




Slope of (NEDN vs. scene radiance) versus wavenumber



Analysis # 2: Comparison of NEN from L1B Granule files and from PCA analysis

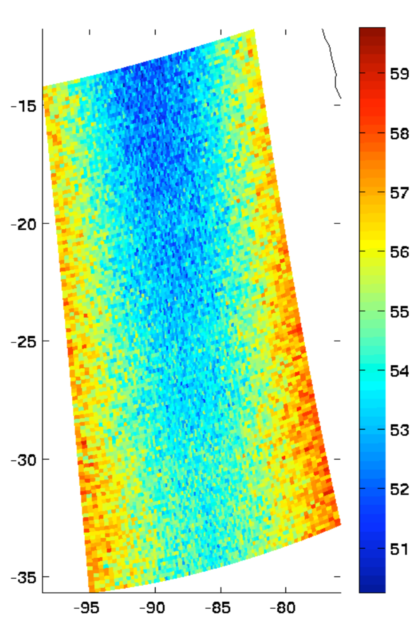


Characterize Extreme events, Popping, and Striping

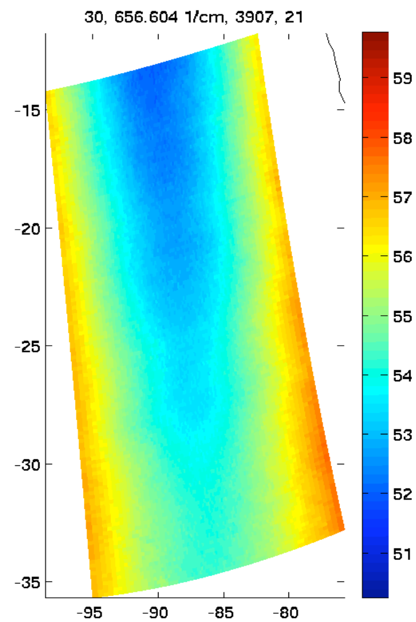
- Count number of 1-sigma, 2-sigma, and 3-sigma events.
- Count 1-sigma, 2-sigma, and 3-sigma “pops” in time series of original minus reconstructed radiances. Pop == 4 or more consecutive N-sigma events of the same sign. (The AIRS Team defines a “pop” as 4 or more consecutive 3-sigma events of the same sign, and identifies 13 channels to exhibit “popping”.)
- Compare to pure Gaussian behavior
- Count number of “stripes” : $>1\sigma$ events extending across a full cross track scan.

Granule 196, Channel # 1000 @ 1000.098 cm^{-1}
(Gaussian channel example)

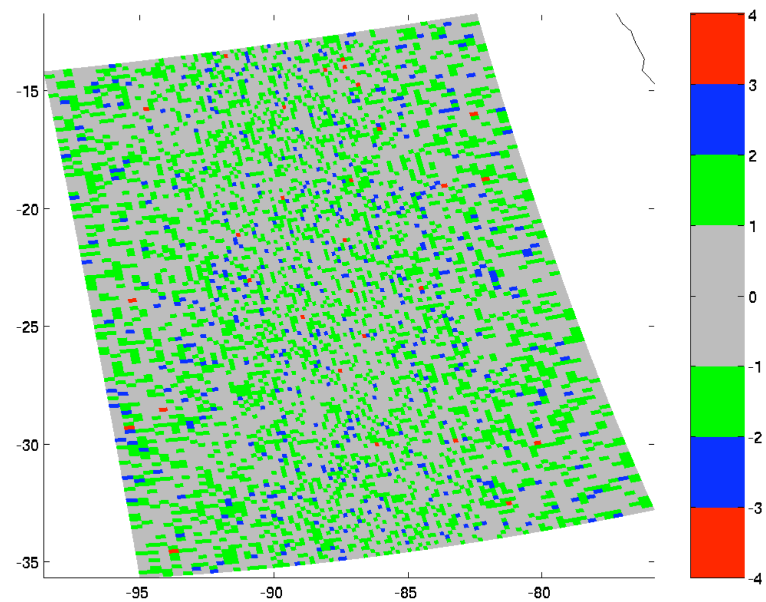
Original rad

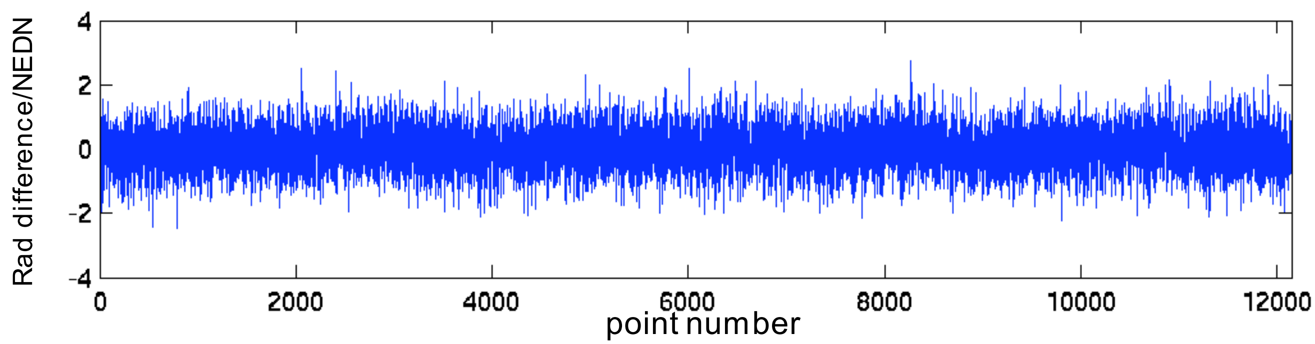


Reconstructed rad



Rad difference/NEDN

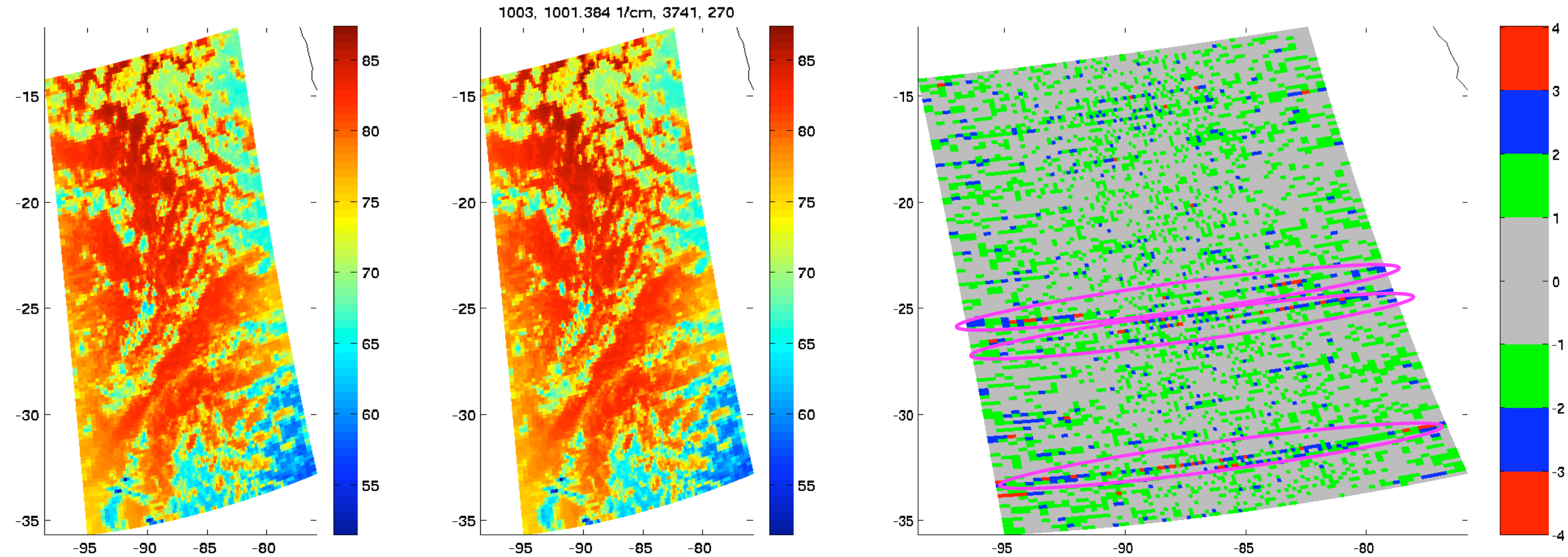


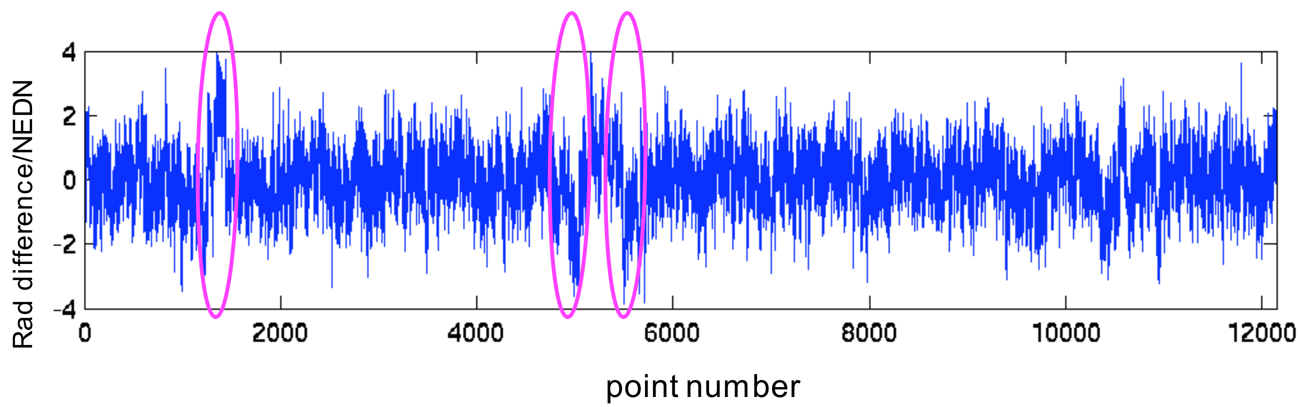


1σ events = 3907
2σ events = 511
3σ events = 30
1σ pops = 21
2σ pops = 0
3σ pops = 0

Granule 196, Channel # 1003 @ 1001.384 cm^{-1} (“Striping” example)

Original rad | Reconstructed rad | Rad difference/NEDN

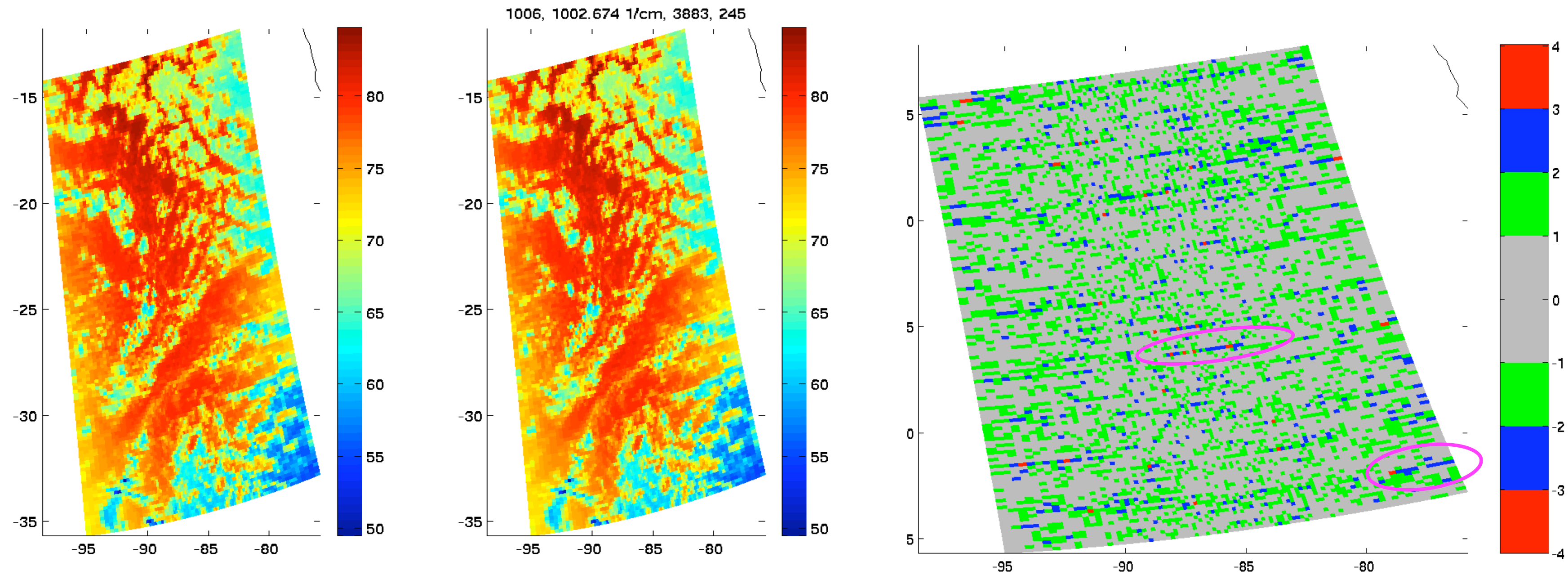


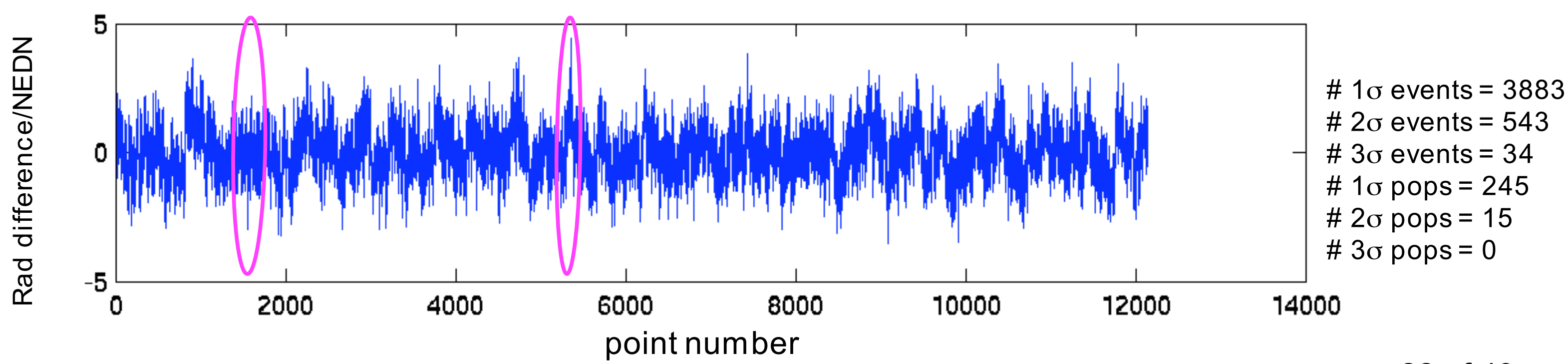


1σ events = 3741
2σ events = 556
3σ events = 64
1σ pops = 270
2σ pops = 22
3σ pops = 0

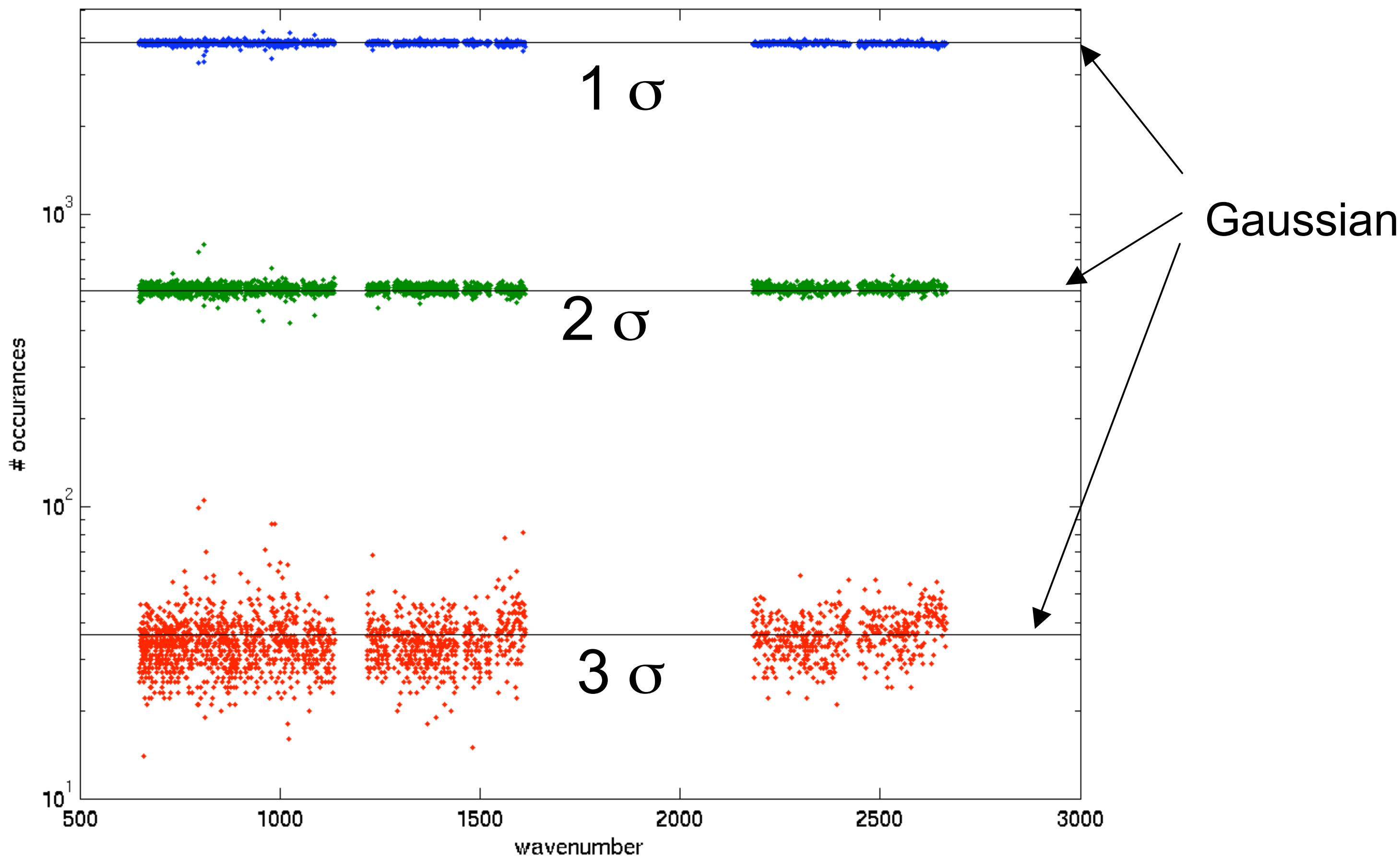
Granule 196, Channel # 1006 @ 1002.674 cm^{-1} ("Popping" example)

Original rad | Reconstructed rad | Rad difference/NEDN





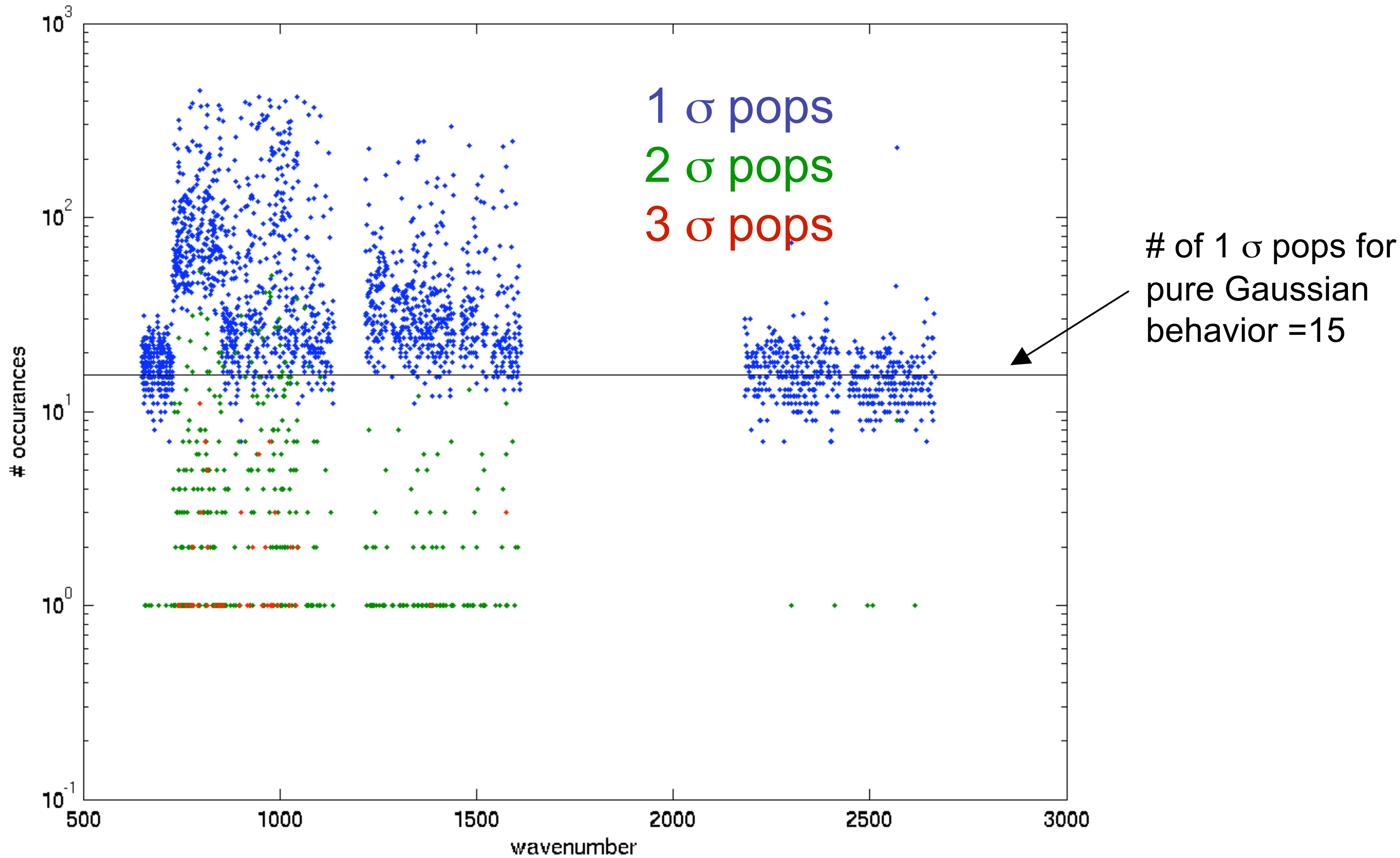
Granule 196. Number of N-σ events detected



pure Gaussian behavior:

- # 1σ events per granule = 90*135*(1-0.683) = 3852
- # 2σ events per granule = 90*135*(1-0.955) = 547
- # 3σ events per granule = 90*135*(1-0.997) = 36

Granule 196. Number of N-σ pops detected



pure Gaussian behavior:

– # 1σ pops per granule = 2*90*135*(0.5*(1-0.683))^4 = 15
– # 2σ pops per granule = 2*90*135*(0.5*(1-0.955))^4 = 0
– # 3σ pops per granule = 2*90*135*(0.5*(1-0.997))^4 = 0

Summary

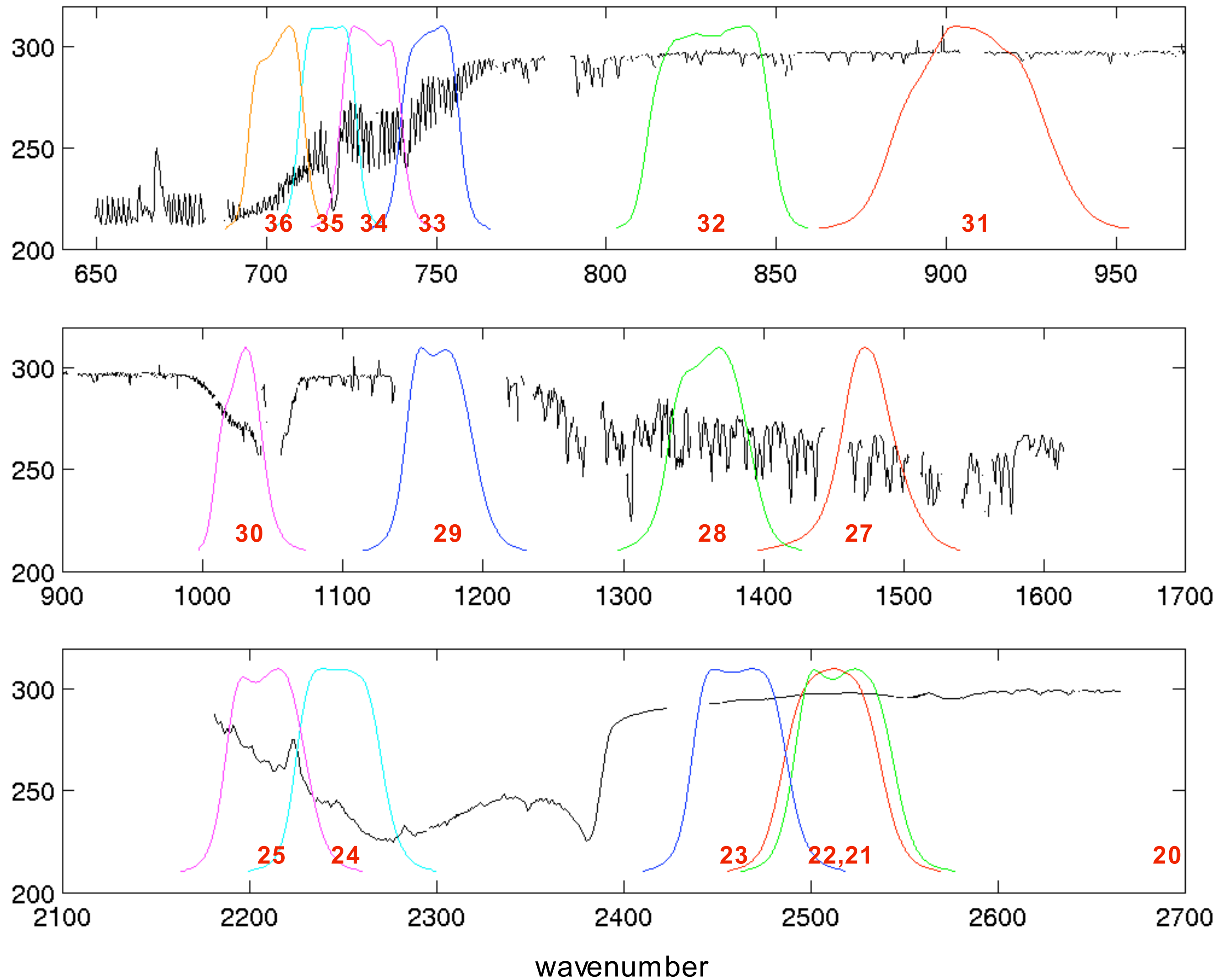
- Spectral redundancy of high spectral resolution observations allows effective noise filtering (and noise characterization) via PCA.
- PCA estimates of NEDN compare well with estimates computed from the on-board blackbody views and provided in the L1B granule files.
- The signal dependence of NEDN is accurately parameterized as a slope (NEDN/Radiance) versus wavenumber.
- Nearly all longwave and midwave PV detectors exhibit “popping” behavior above that expected from pure Gaussian behavior.
- A smaller percentage (14 out of 2378) of channels exhibit “striping”.

Use of AIRS high spectral resolution spectra to assess the calibration of MODIS on EOS Aqua

- Paper Outline:
  - Comparison Approach
    - Match spectral resolutions
    - Match spatial resolution and sampling and select uniform fields of view
  - Differences characterized as a function of scene temperature, scan angle, and solar zenith angle for global data collected on 6 Sept 2002 and 18 Feb 2004

- Important for:
  - Understanding differences between AIRS products and MODIS products
  - Diagnosing the calibration of both sensor
  - Development of applications utilizing data from both sensors
    (e.g. AIRS cloud-clearing using MODIS, synergistic use
    of AIRS and MODIS for cloud property retrievals)

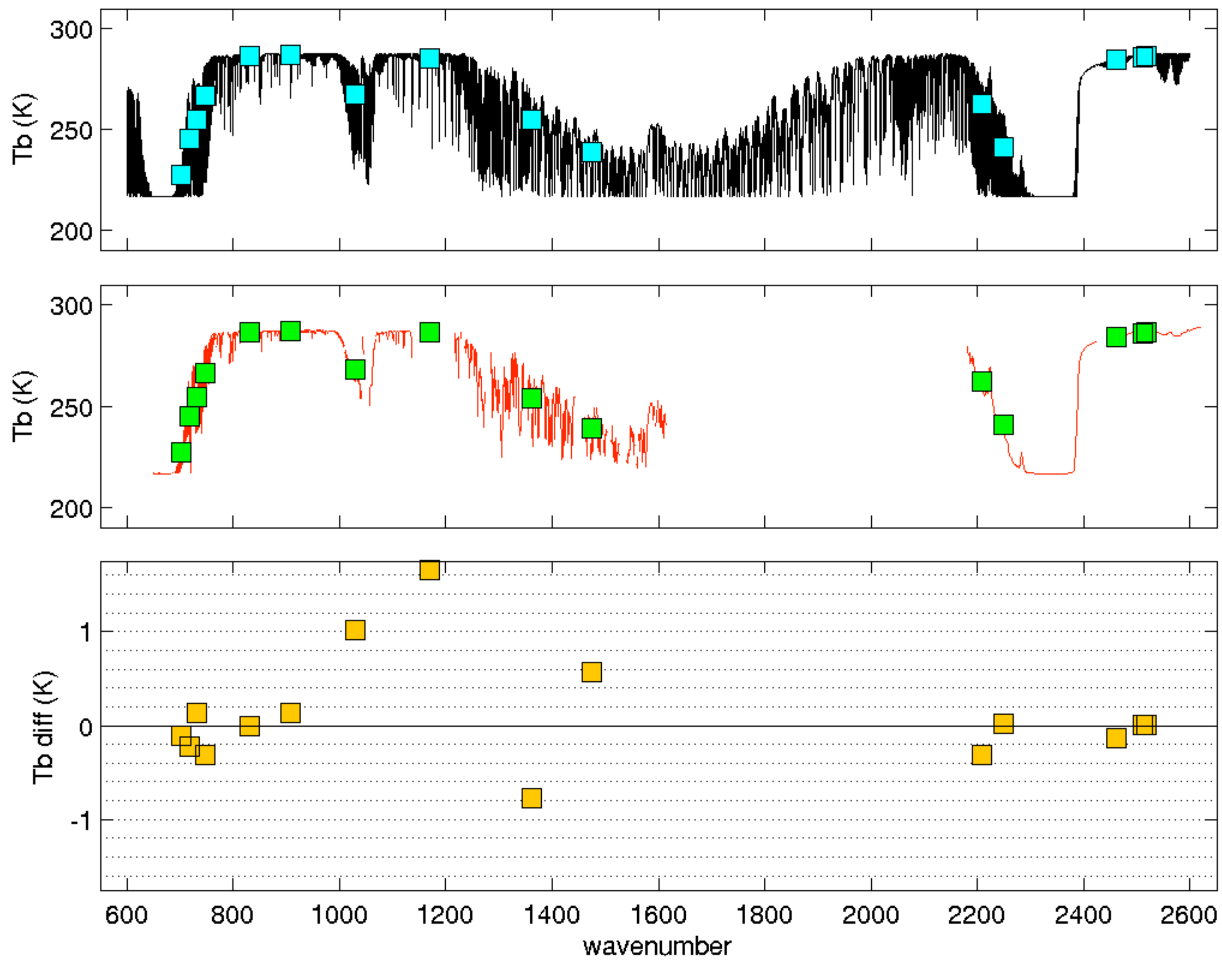
A sample AIRS brightness temperature spectrum overlaid with the Aqua MODIS Spectral Response Functions



To match the MODIS spectral resolution, the AIRS spectra are convolved with the MODIS SRFs

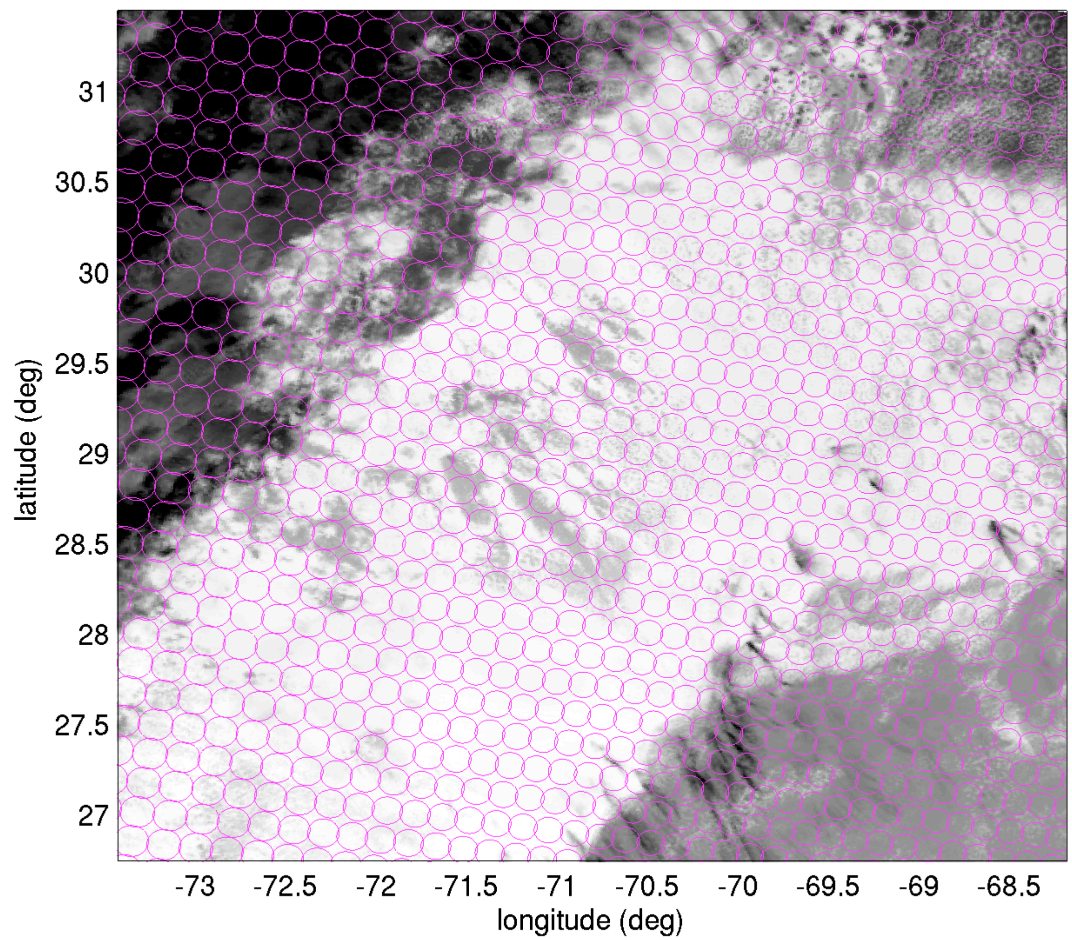
$$R_{MONO} \otimes SRF_{MODIS} - (R_{MONO} \otimes SRF_{AIRS}) \otimes SRF_{MODIS}$$

Convolution Correction: factor that accounts for small gaps in AIRS spectra when convolving AIRS radiance spectra with the MODIS SRFs.

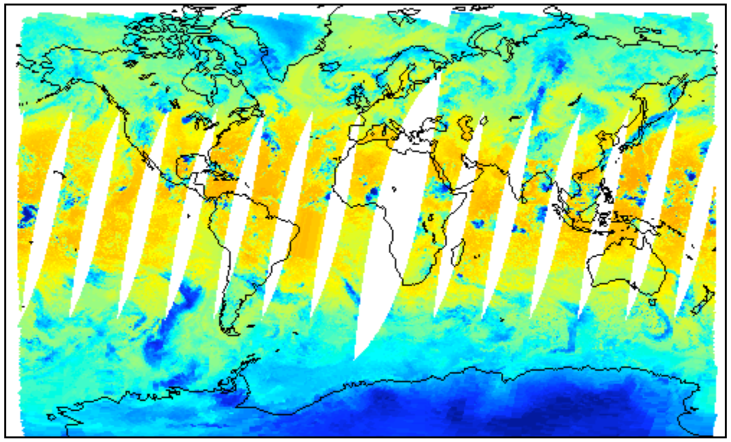


The 1 km MODIS data is collocated with AIRS by representing the AIRS FOVs as slightly oversized circular footprints, and computing the mean MODIS value within those footprints for each band.

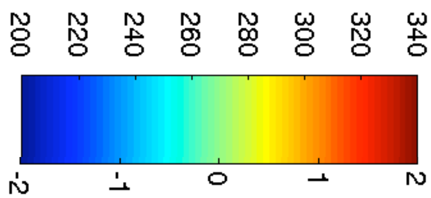
Spatially uniform scenes are selected by requiring the standard deviation of the MODIS data within each AIRS footprint to be 0.2K or less.



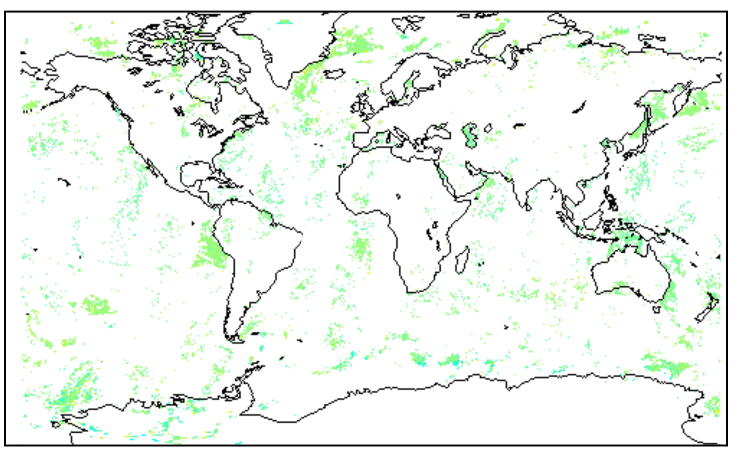
Example comparisons for band 22 (4.0 μm) on 6 Sept 2002.

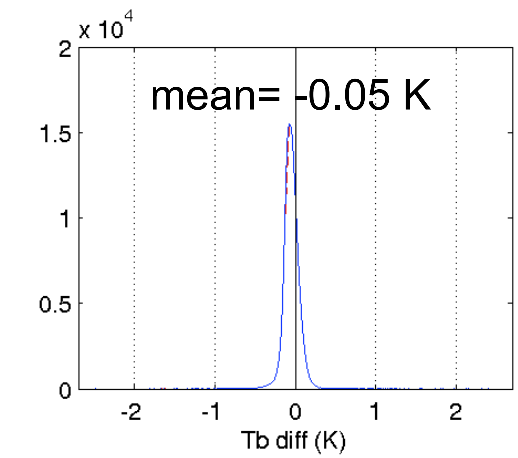


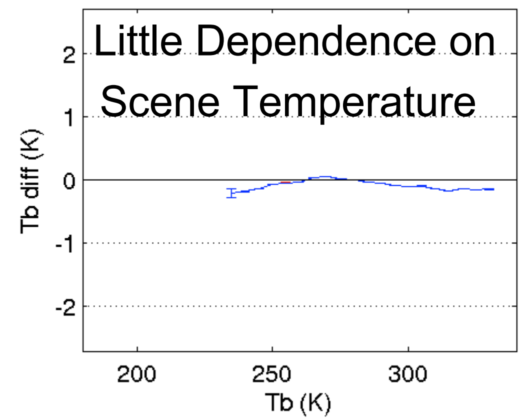
AIRS BT (K)

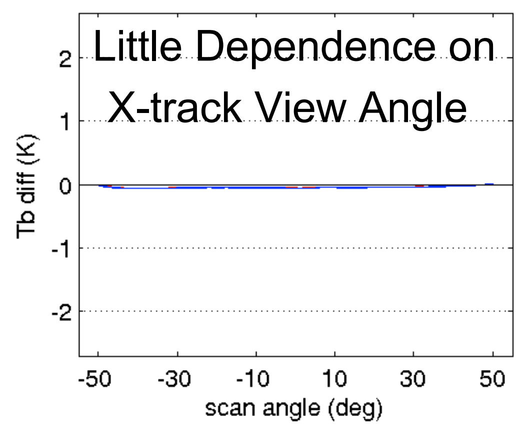


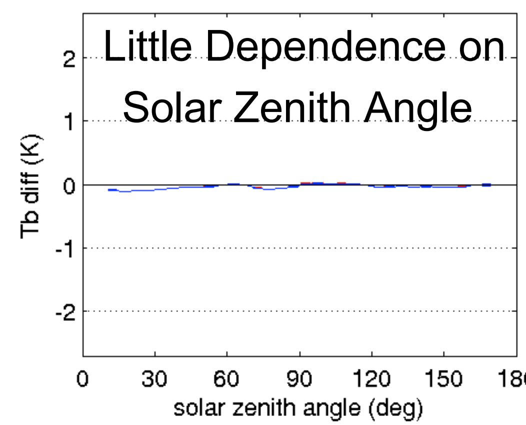
AIRS minus MODIS (K)



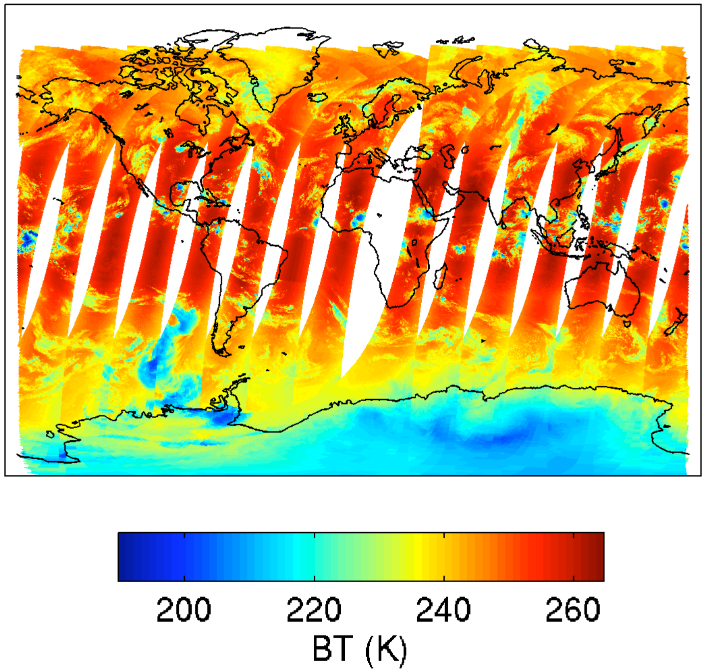


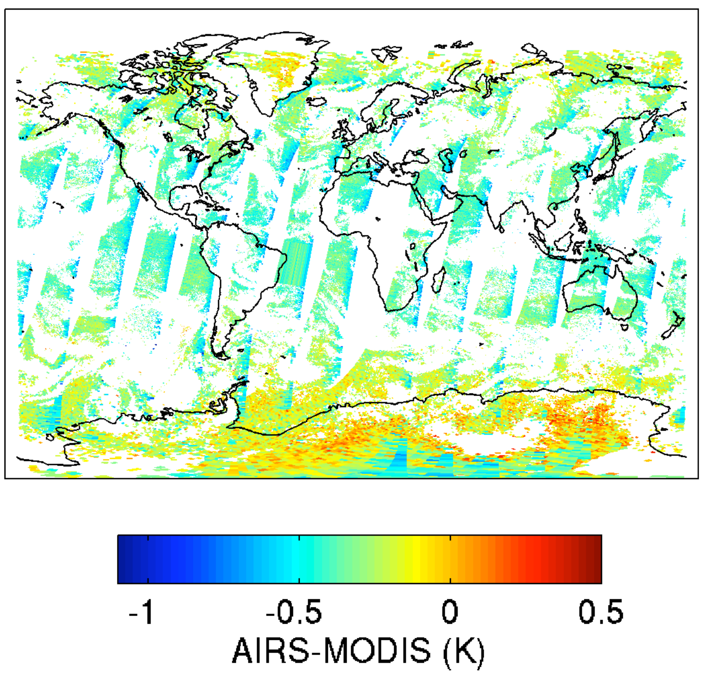


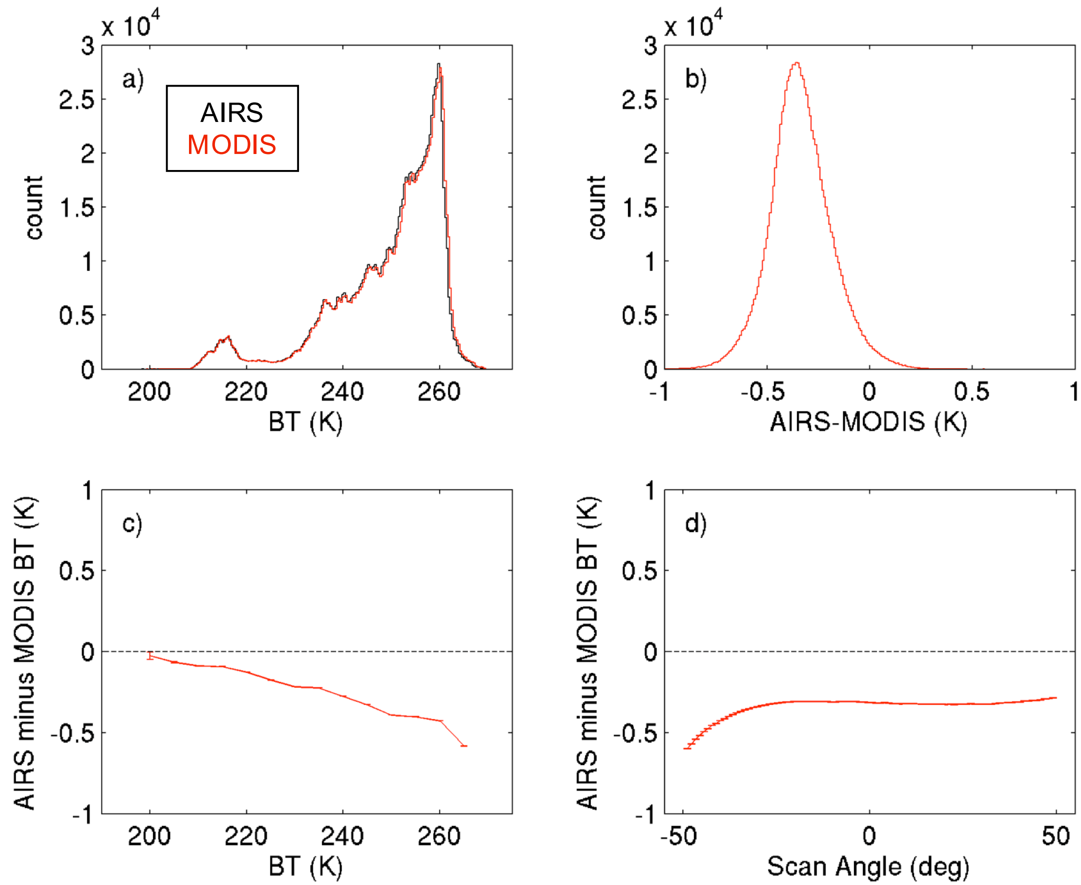




Example comparisons for band 34 (13.7 μm) on 6 Sept 2002.

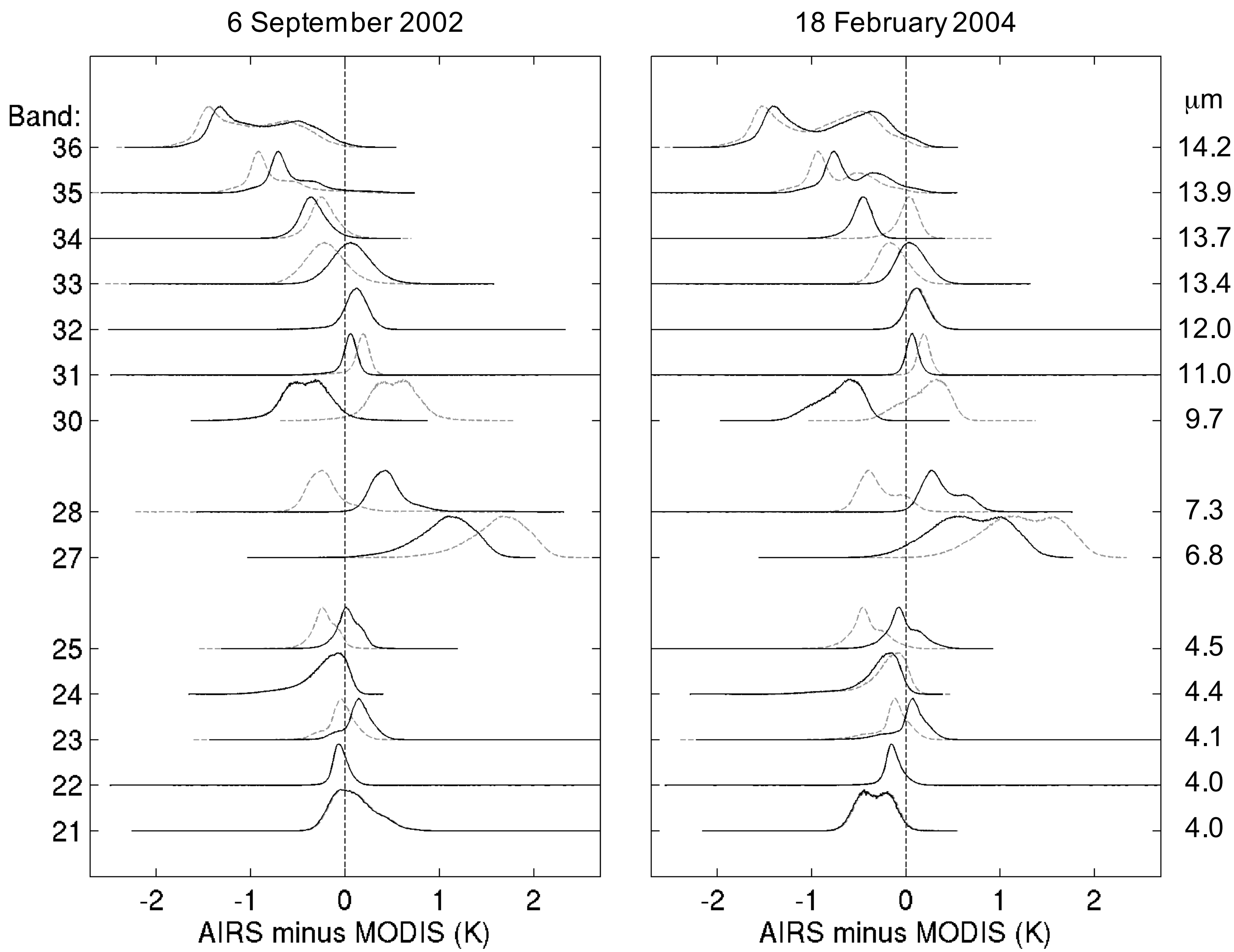




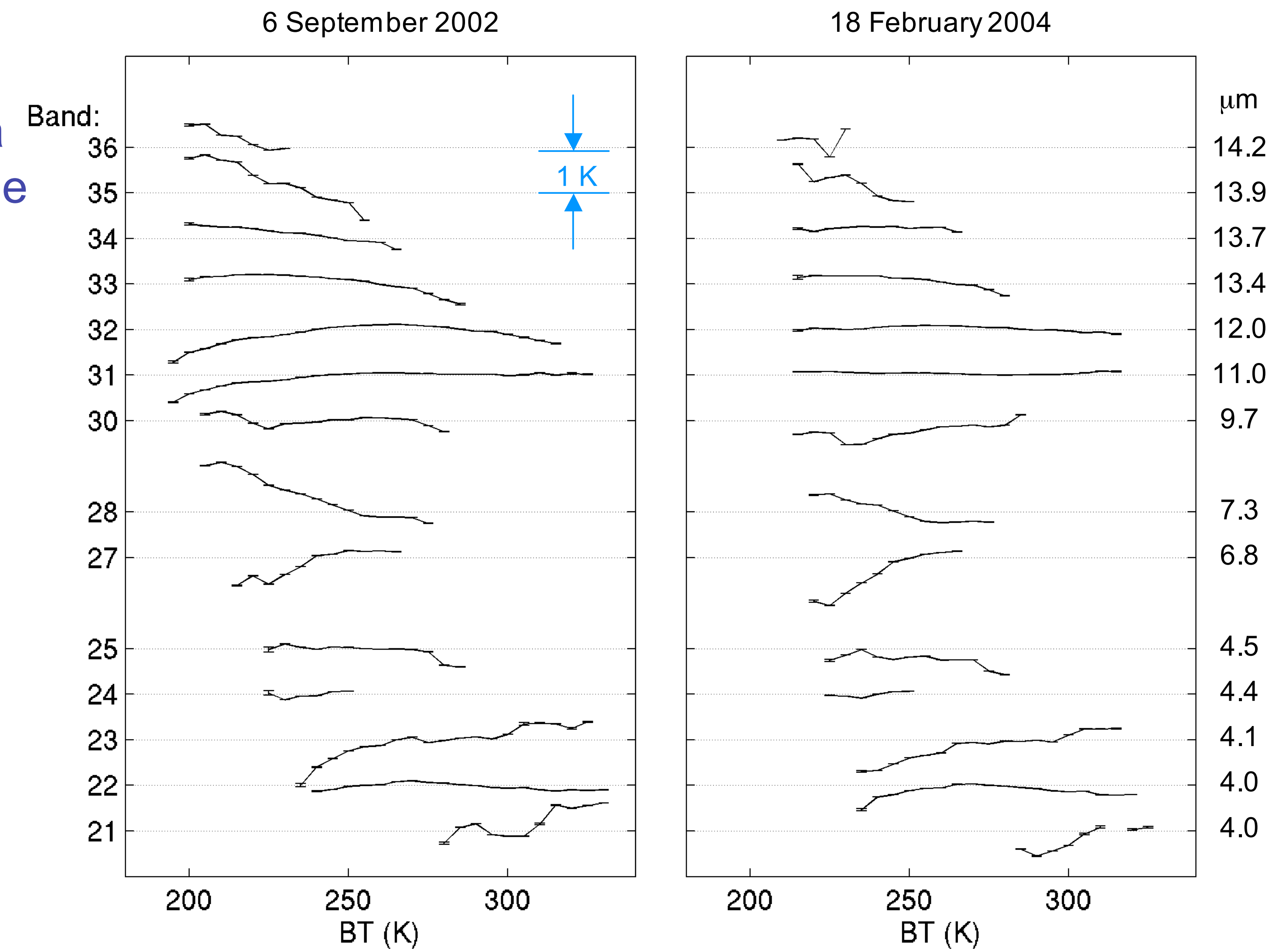


Histograms of brightness temperature differences.

(Light gray curves are distributions without the convolution corrections)

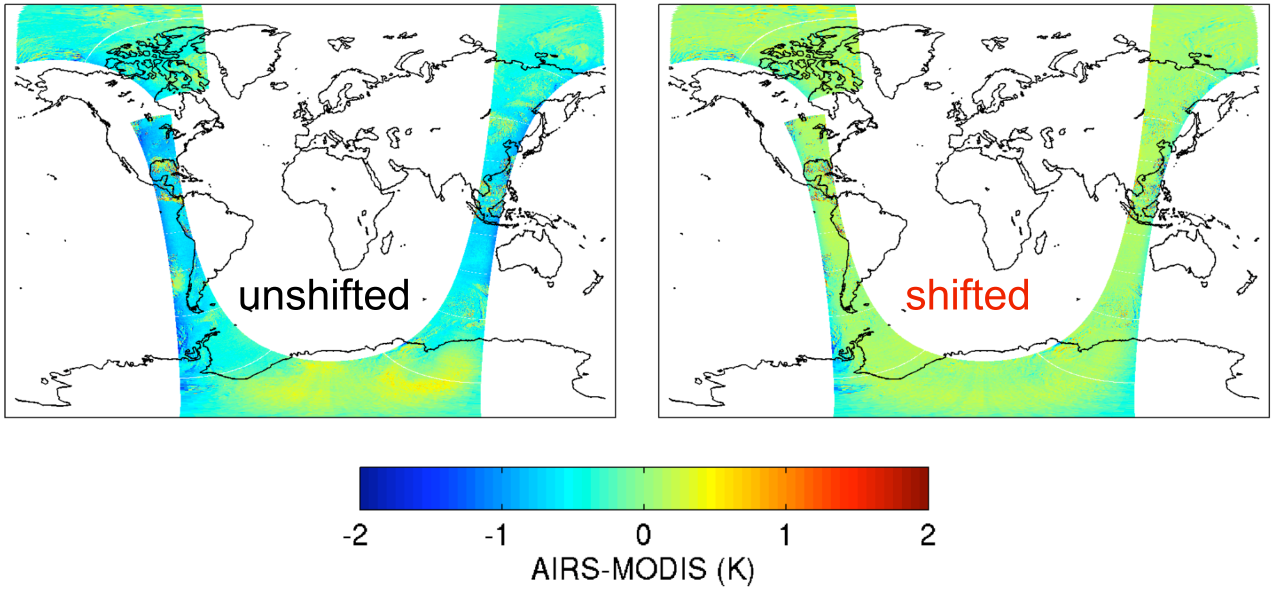


Brightness temperature differences as a function of scene temperature.

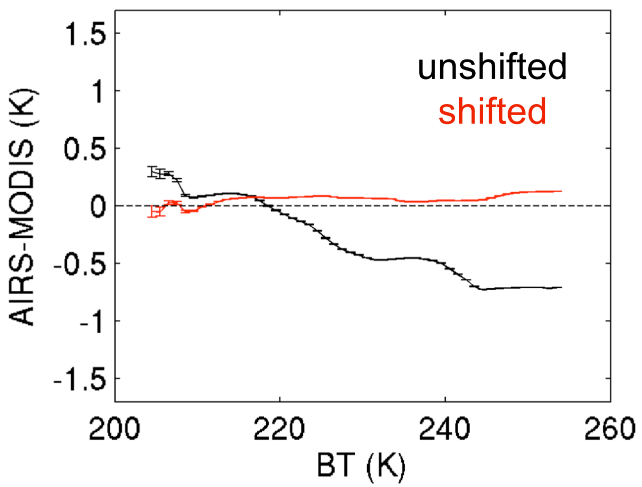


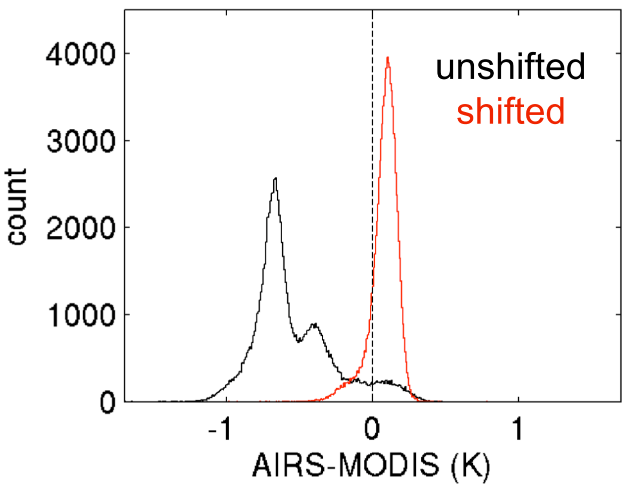
Band 35 (13.9 μm)

brightness temperature differences for one orbit of data on 6 Sept 2002 using (1) the nominal MODIS SRF and (2) the MODIS SRF shifted by $+0.8\ cm^{-1}$.

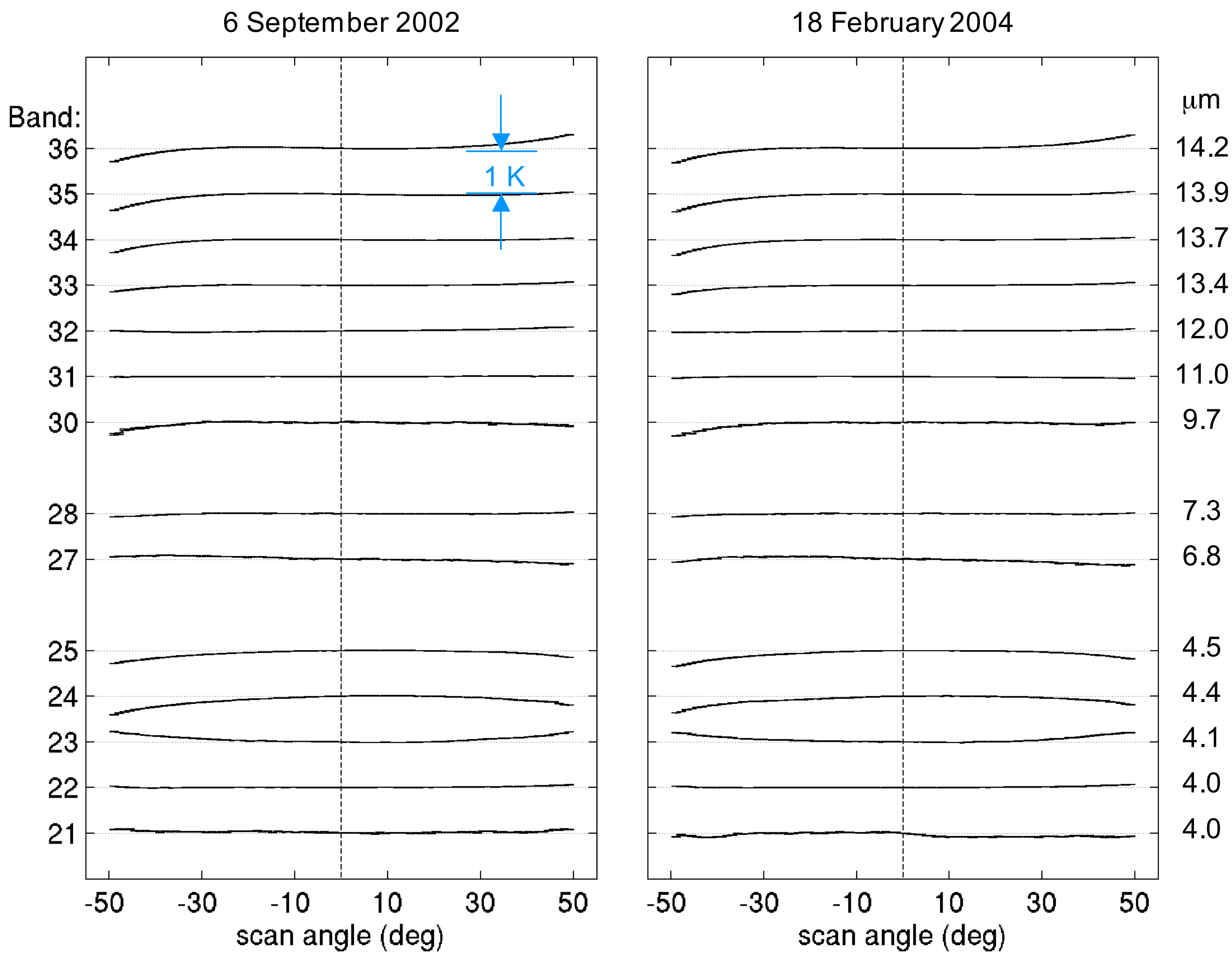


MODIS SRF out-of-band response also currently being investigated.





Brightness temperature differences as a function of scan angle.



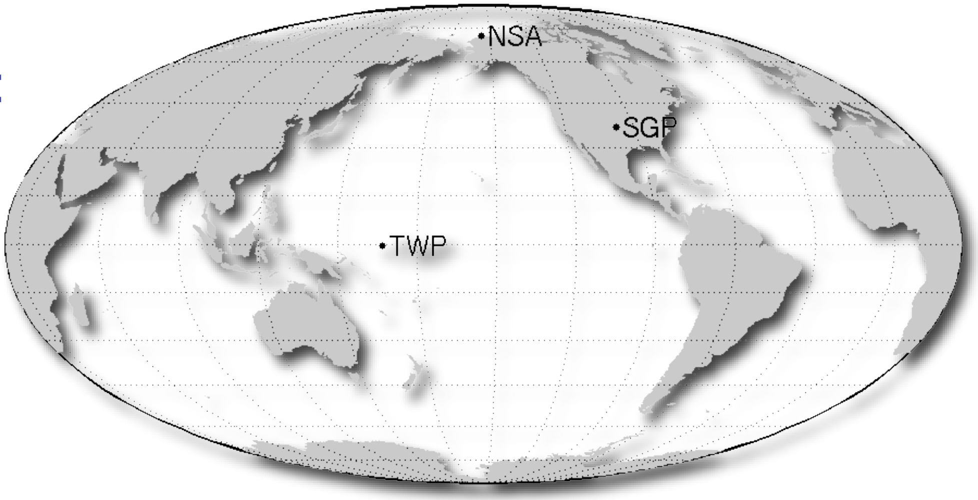
Summary

- A detailed comparison of EOS Aqua AIRS and MODIS infrared radiances for spatially uniform scenes collected on 6 September 2002 and 18 February 2004 has been presented.
- An approach to account for spectral gaps in the AIRS spectra when convolving with the MODIS SRFs has been introduced.
- Estimates of the absolute uncertainty of the comparisons are 0.1 K or less for the majority of the MODIS bands.
- Mean differences between AIRS and MODIS are ~1 K or less for all bands and many bands show agreement of 0.1 K or better. But at the same time, only band 22 (3.9 μm) shows good absolute agreement and no significant dependence on scene temperature, scan angle, or solar zenith angle.
- Differences for MODIS bands 27 (6.8 μm), 28 (7.3 μm), 34 (13.7 μm), 35 (13.9 μm), and 36 (14.2 μm) display clear and significant dependencies on scene temperature.
- Results for the two days are very similar with changes in mean differences of 0.1 K or less for most bands.

ARM site atmospheric state best estimates for AIRS temperature and water vapor retrieval validation

Locations of the three ARM sites:

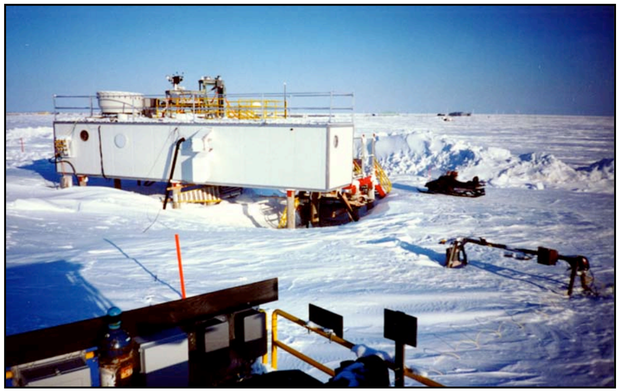
Tropical Western Pacific (TWP)
Southern Great Plains (SGP)
North Slope of Alaska



TWP

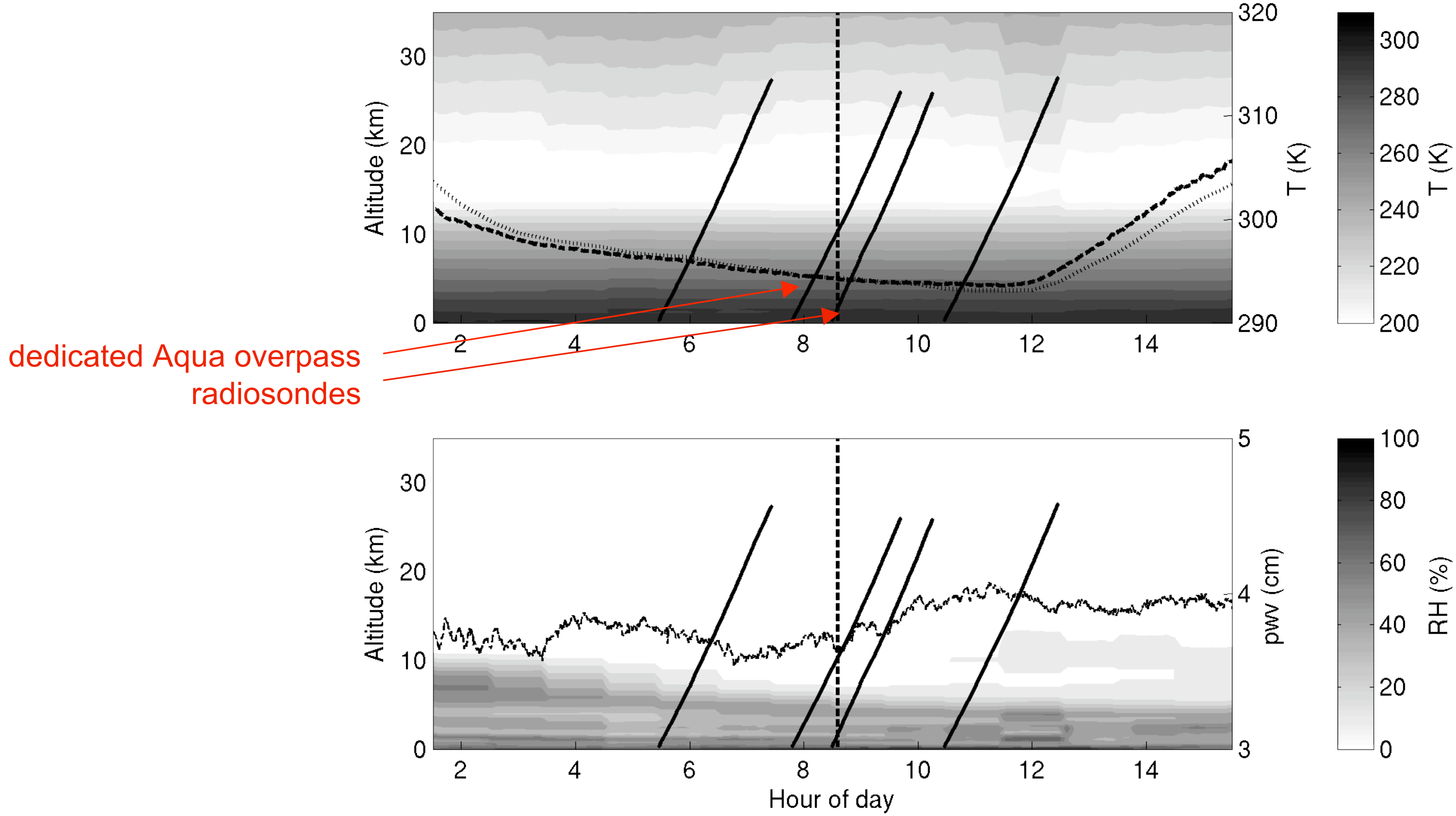
SGP

NSA



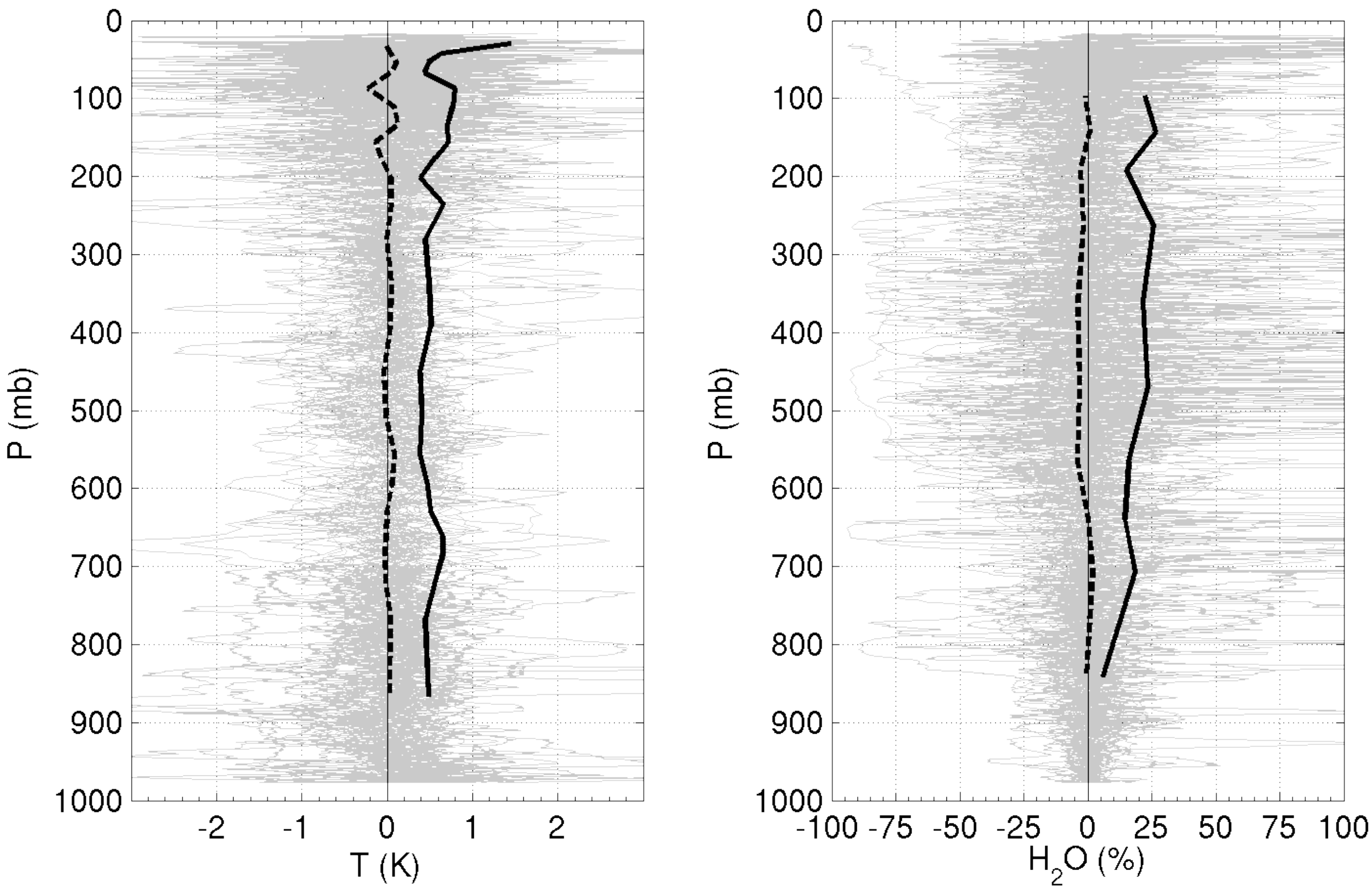
Time series of various SGP ARM data on 25 July 2002

Top panel: cross section of AERI+ temperature retrievals (with colorbar and left hand altitude scale) and time series of the near surface air temperature measured with a surface met station (dotted gray curve) and the surface temperature measured with a down-looking broadband IRT (dashed black curve), both with the right hand y-axis scale. Bottom panel: cross section of AERI+ relative humidity retrievals (with colorbar and left hand altitude scale) and time series of total column precipitable water vapor measured by the MWR (dashed black curve with right hand y-axis scale). In both panels the Aqua overpass time (black vertical dashed line) and radiosonde trajectories (solid black curves) are overlaid.



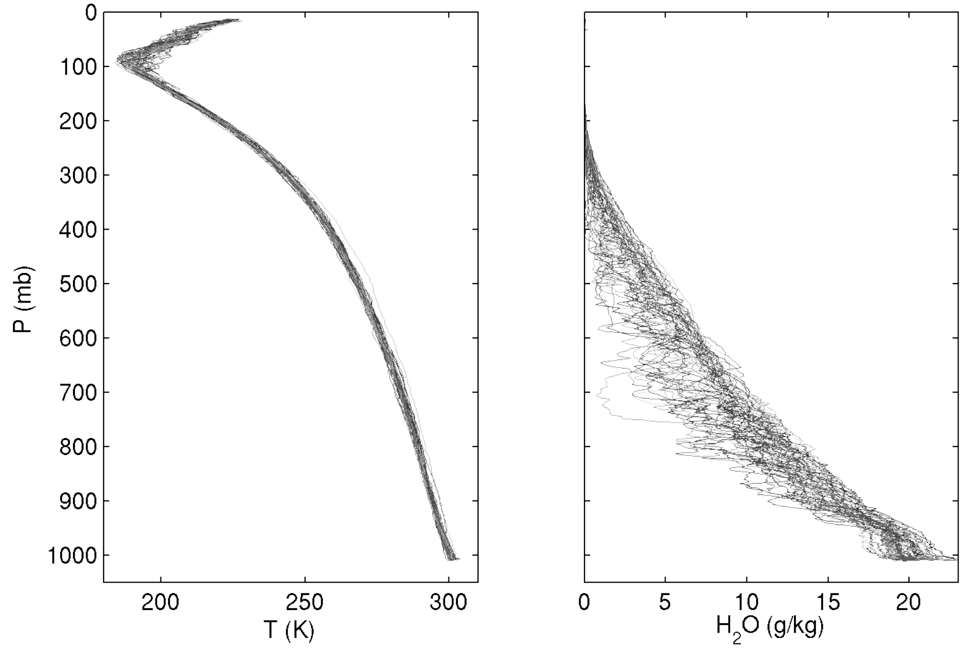
Short term temporal variability at the SGP site

Differences between pairs of dedicated nighttime radiosonde profiles, one launched ~45 minutes before the Aqua overpass and one at the overpass time. The left hand panel shows temperature differences and the right hand panel shows percent difference in water vapor amounts. In each panel, the light grey curves are differences for individual profiles, and the dashed black and solid black curves are the mean and RMS differences, respectively, for 1 km (temperature) and 2 km (water vapor) thick layers. MWR total column water vapor scaling has been applied to each radiosonde water vapor profile as discussed in the text.

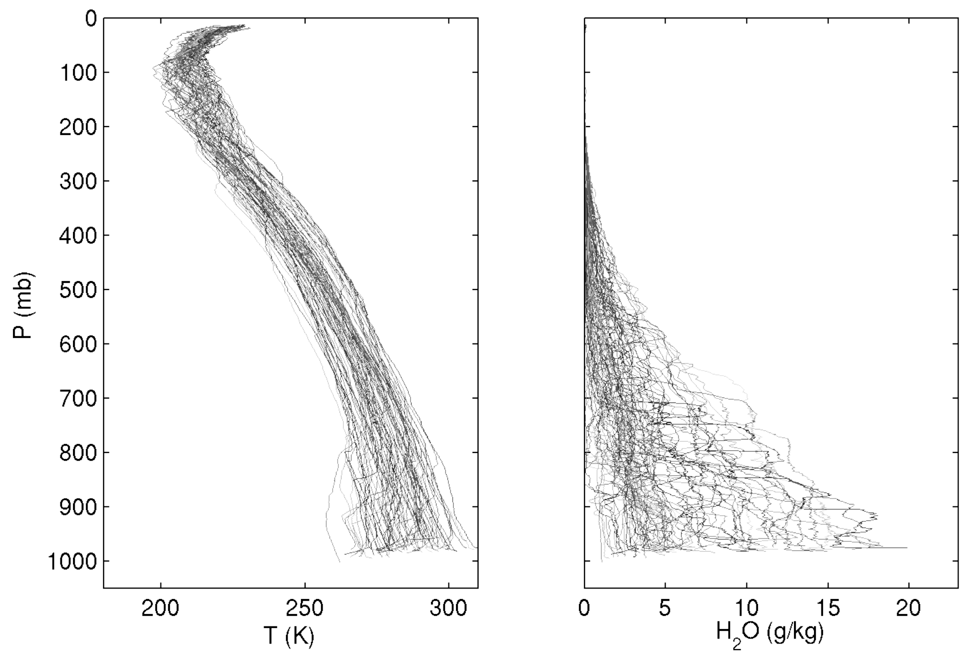


Sample profiles:

TWP



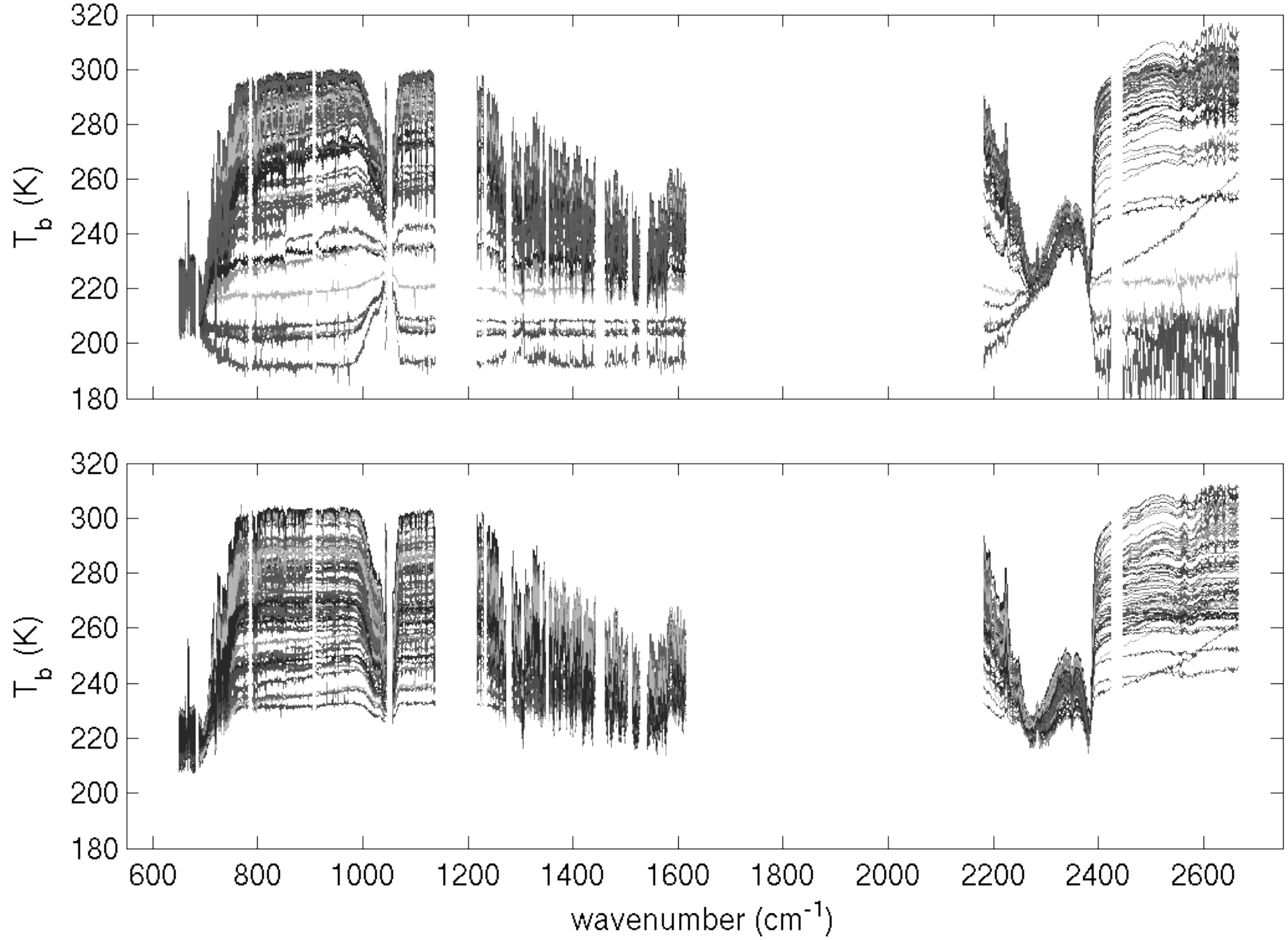
SGP



Sample spectra:

TWP

SGP

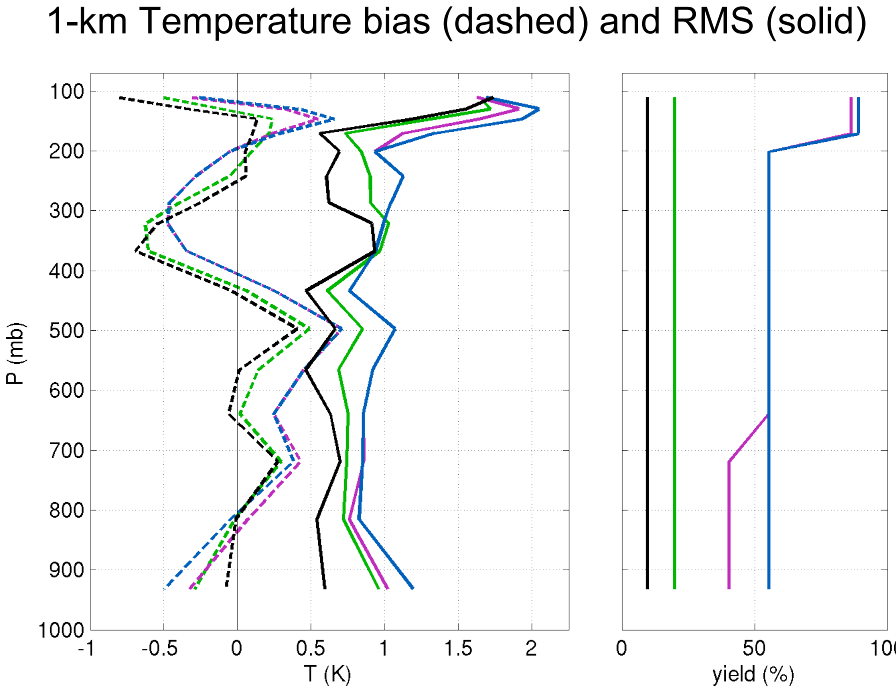


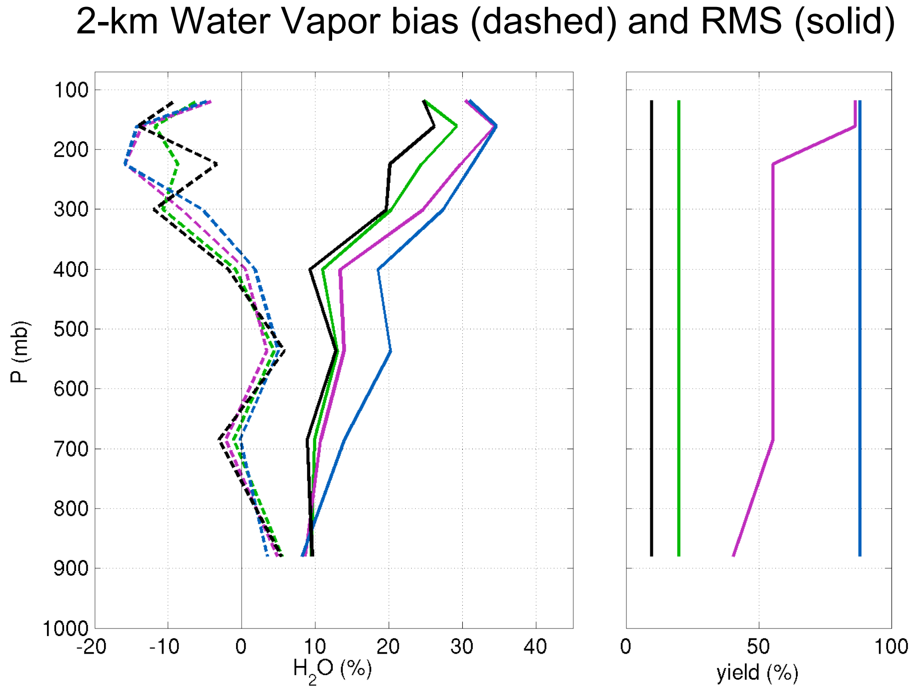
AIRS version 4 retrieval validation

using four v4 QA selections, ranging from tightest to loosest QC

1. BLACK (QC1)
   - Qual_H2O=0 and Qual_Temp_Profile_Top=0 and Qual_Temp_Profile_Mid=0 and Qual_Temp_Profile_Bot=0
   - And, Qual_Surf=0 for TWP (but not SGP)
2. GREEN (QC2)
   - Qual_H2O≠2 and Qual_Temp_Profile_Top≠2 and Qual_Temp_Profile_Mid≠2 and Qual_Temp_Profile_Bot≠2
   - And, Qual_Surf≠2 for TWP (but not SGP)
3. PURPLE (QC3)
   - Qual_Temp_Profile_Top=0 and Qual_H2O=0
   - Qual_Temp_Profile_Mid=0 and Qual_H2O=0
   - Qual_Temp_Profile_Bot=0 and Qual_H2O=0
4. BLUE (QC4)
   - For temperature:
     - Qual_Temp_Profile_Top≠2
     - Qual_Temp_Profile_Mid≠2
     - Qual_Temp_Profile_Bot≠2
   - For water vapor:
     - Qual_H2O≠2

TWP



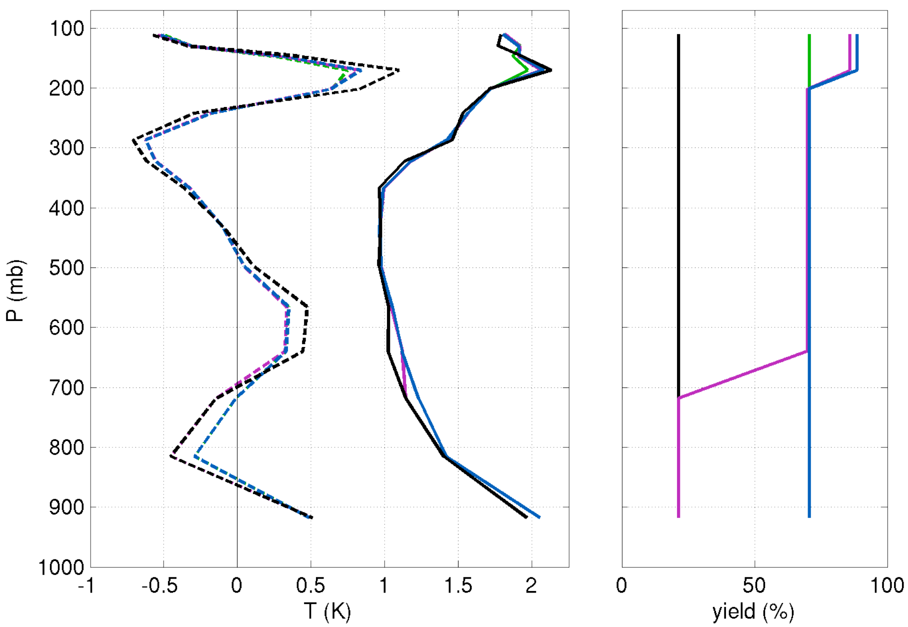


Note: H_2O weighting approach used for H_2O stats shown here.

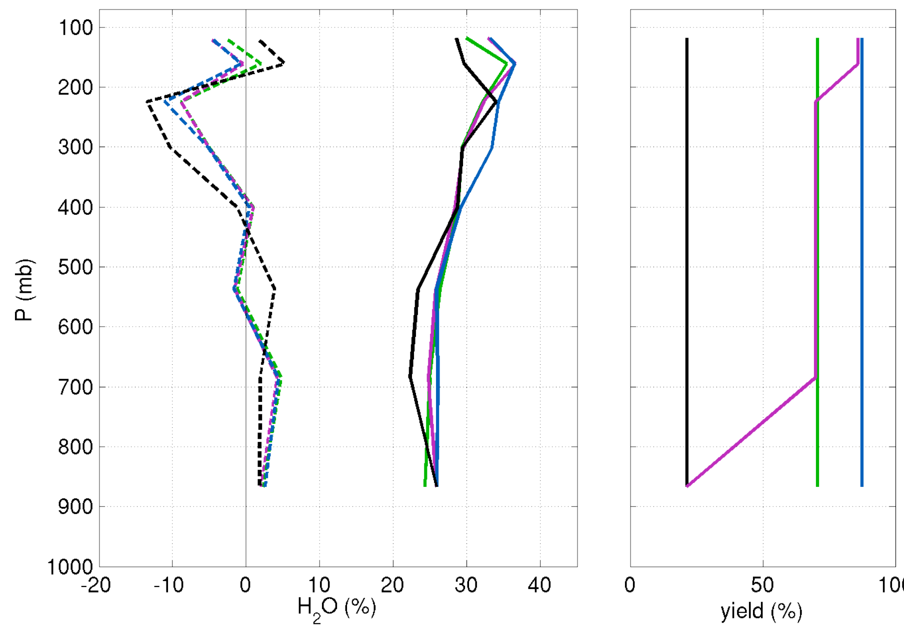
$$\text{Mean \% error} = 100\ \Sigma_i(q_{ret,i}-q_{tru,i}) \ / \ \Sigma_i\ q_{tru,i}$$
$$\text{RMS \% error} = 100\ [\ \Sigma_i(q_{ret,i}-q_{tru,i})^2 \ / \ \Sigma_i\ q_{tru,i}^2\ ]^{1/2}$$

SGP

1-km Temperature bias (dashed) and RMS (solid)



2-km Water Vapor bias (dashed) and RMS (solid)



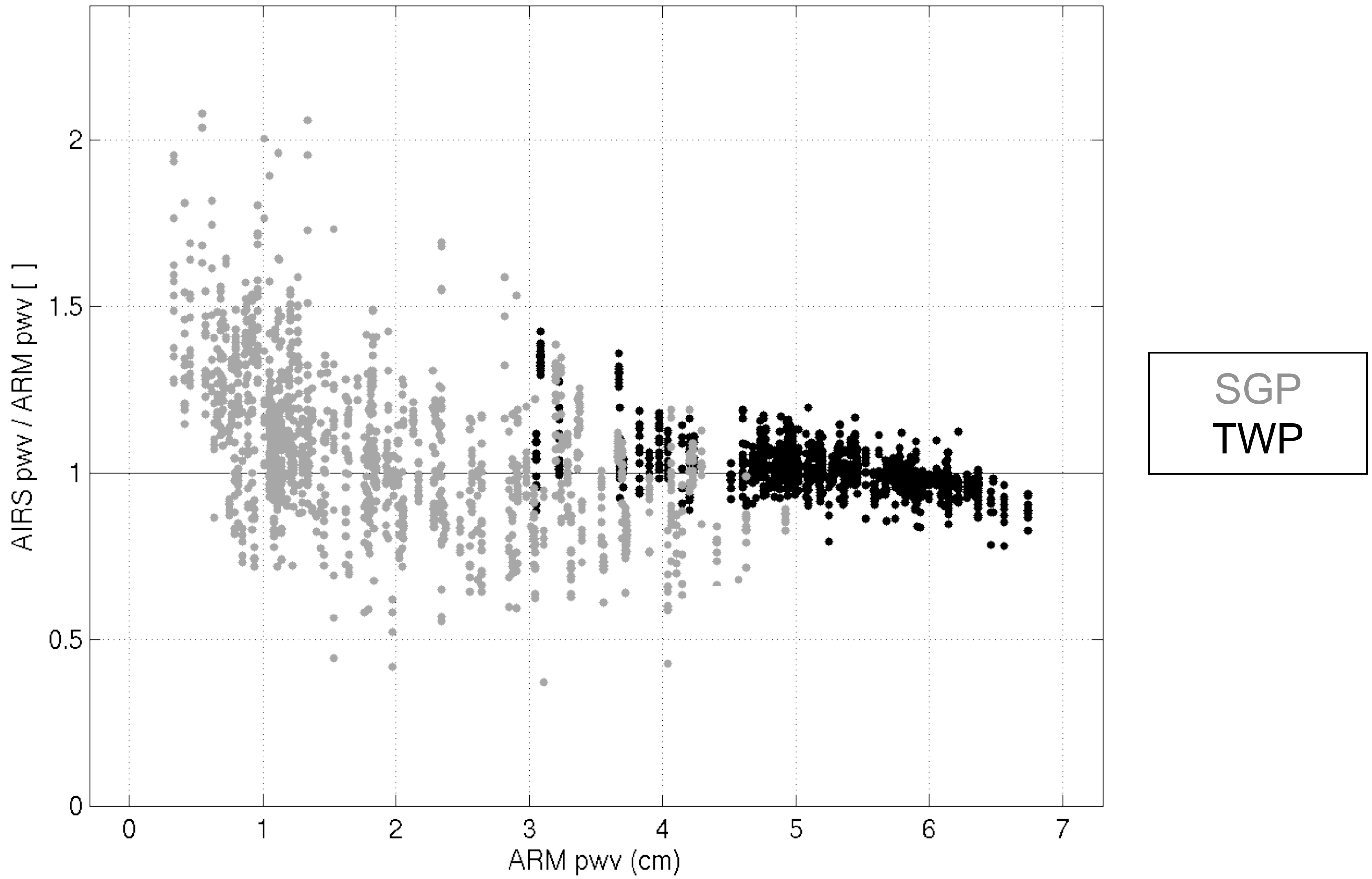
QC1 QC2
QC3 QC4

Note: H_2O weighting approach used for H_2O stats shown here.

$$\text{Mean \% error} = 100\ \Sigma_i(q_{ret,i}-q_{tru,i}) / \Sigma_i\ q_{tru,i}$$

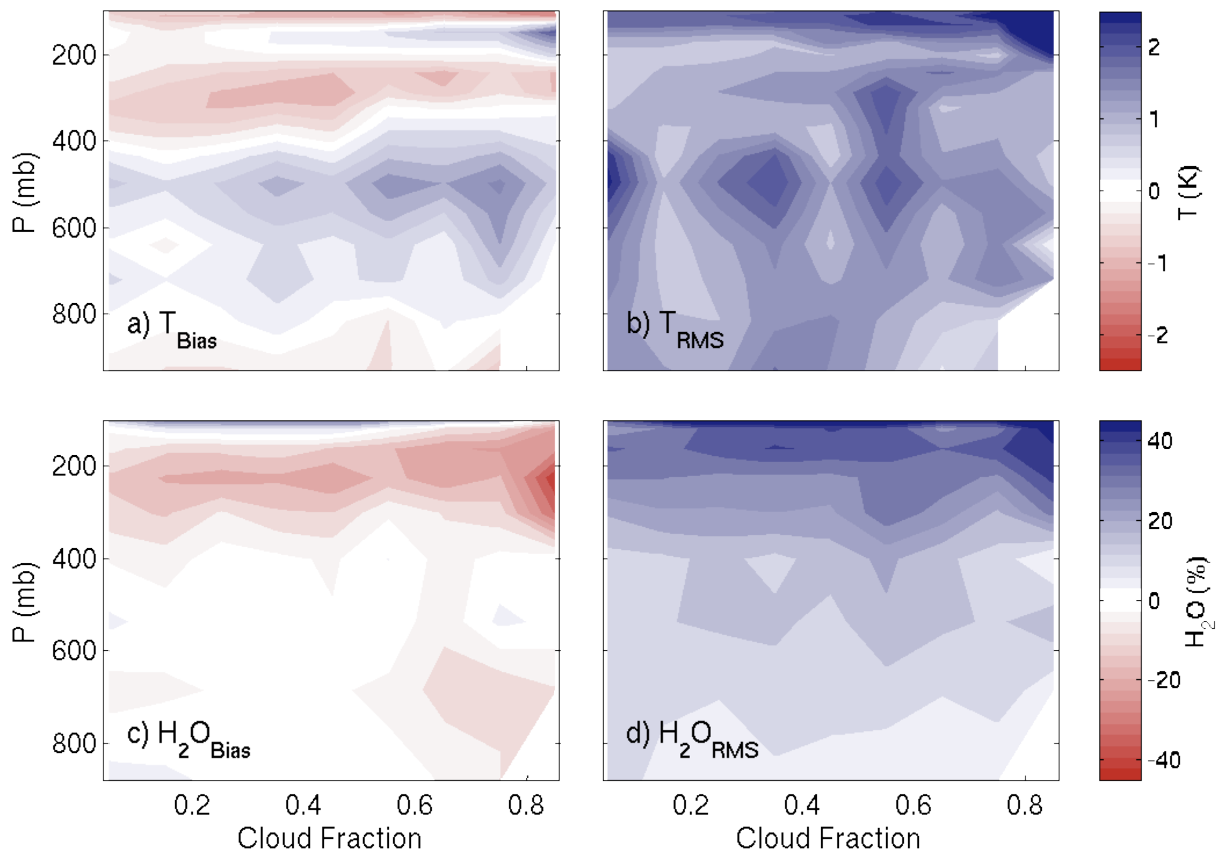
$$\text{RMS \% error} = 100\ [\ \Sigma_i(q_{ret,i}-q_{tru,i})^2 / \Sigma_i\ q_{tru,i}^2\ ]^{1/2}$$

Total column precipitable water vapor (pwv) fractional error versus pwv

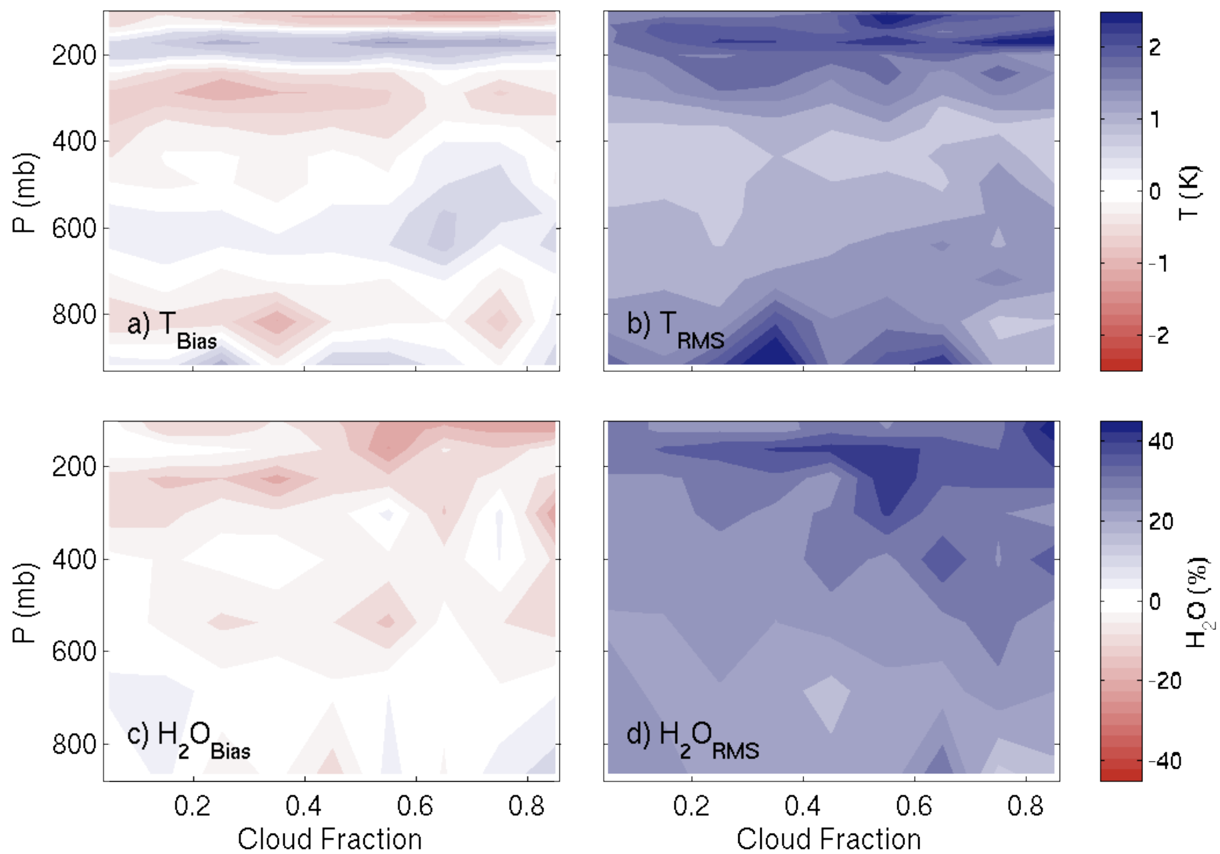


Without the H_2O weighting approach, the SGP mean bias and RMS in the lower troposphere are ~20% and ~55%, respectively (opposed to values of ~5% and 25% shown on the previous slide)

TWP site retrieval bias and RMS as a function of AIRS retrieved cloud fraction:
a) Temperature bias, b) temperature RMS, c) water vapor bias, d) water vapor RMS.
(QC4 ensemble).



Same as previous slide but for the SGP site.



Summary:

• Short term and small scale **variability of the atmosphere is significant** and should be taken into account when validating large area footprint retrievals from polar orbiting satellites. This is particularly important for assessing RMS errors of the retrievals, opposed to the mean differences (biases) for which the random variability cancels for a large ensemble of cases. RMS errors computed using validation profiles that do not fully account for the variability should be interpreted as upper bounds of the true errors.

• The conventional approach used to report AIRS water vapor retrieval statistics (and used in this paper) of weighting the observed percent errors by water vapor concentration can produce significant differences from the traditional, un-weighted, calculations. This is particularly true for ensembles with high water vapor variability, such as the SGP site lower troposphere.

• The **yields** of AIRS retrievals with temperature, water vapor and surface products flagged with highest quality (i.e. the QC1 ensembles) are 10 and 21 percent for the TWP and SGP sites, respectively. Considering all accepted products (i.e. the QC4 ensemble) at the TWP site, the mid and bottom level (below 200 mbar) temperature yield is 55 percent, the top level (above 200 mbar) temperature yield is 89 percent, and the water vapor yield is 88 percent. Analogous yields for the SGP site are 71, 89, and 87 percent, respectively.

• **AIRS retrievals for the tropical ocean TWP site have very good performance**, with RMS errors approaching the theoretical limit predicted by retrieval simulation studies performed with no errors in the truth data or radiative transfer algorithms. Retrievals for which the temperature, water vapor, and surface products are flagged as highest quality (QC1) have the best performance, and the performance degrades gradually as retrievals flagged with lower quality (and more cloudy scenes) are included. For all accepted temperature and water vapor products (QC4), **1 km layer temperature RMS errors are ~1 K or less below 200 mbar and 2 km layer water vapor RMS errors are 20 percent or less below 400 mbar**.

Summary (cont.)

• **AIRS retrievals for the mid-latitude land SGP site have poorer RMS performance with respect to the TWP site results for both temperature and water vapor.** 1 km layer temperature RMS errors range from 1 to 2 K and 2 km layer water vapor RMS errors range from 25 to 35 percent. This performance is largely independent of the retrieval quality flags, yield, and cloud fraction. AIRS total column **precipitable water vapor (pwv) fractional errors are higher for lower pwv** conditions encountered at the SGP site, with mean fractional errors of ~25 percent (AIRS wetter than ARM) at 1 cm pwv. These larger percent errors observed for lower water vapor amounts are suppressed when the water vapor weighting approach is used to report the AIRS water vapor mean and RMS differences.

• For both the TWP and SGP ensembles, **small scale (~0.5 K) vertical oscillations are present in the AIRS temperature retrievals** (AIRS retrievals are too warm at ~600 mbar, too cold at ~300 mbar, too warm at ~150 mbar). The magnitude of the oscillations are largely independent of retrieved cloud fraction.

• For both the TWP and SGP sites, **water vapor biases are ~5 percent or less below 400 mbar and increase to minus ~10 percent (AIRS drier than ARM) at 200 mbar**. The biases are largely independent of retrieved cloud fraction. The significance of the reported upper troposphere bias is questionable given the estimated absolute accuracy of the ARM profiles (~10 percent) at these levels.

• Diurnal biases in the ARM upper level water profiles are not evident in the AIRS retrieval comparisons.