Characterization of Cross-track Infrared Sounder Calibration Uncertainties and Noise behavior

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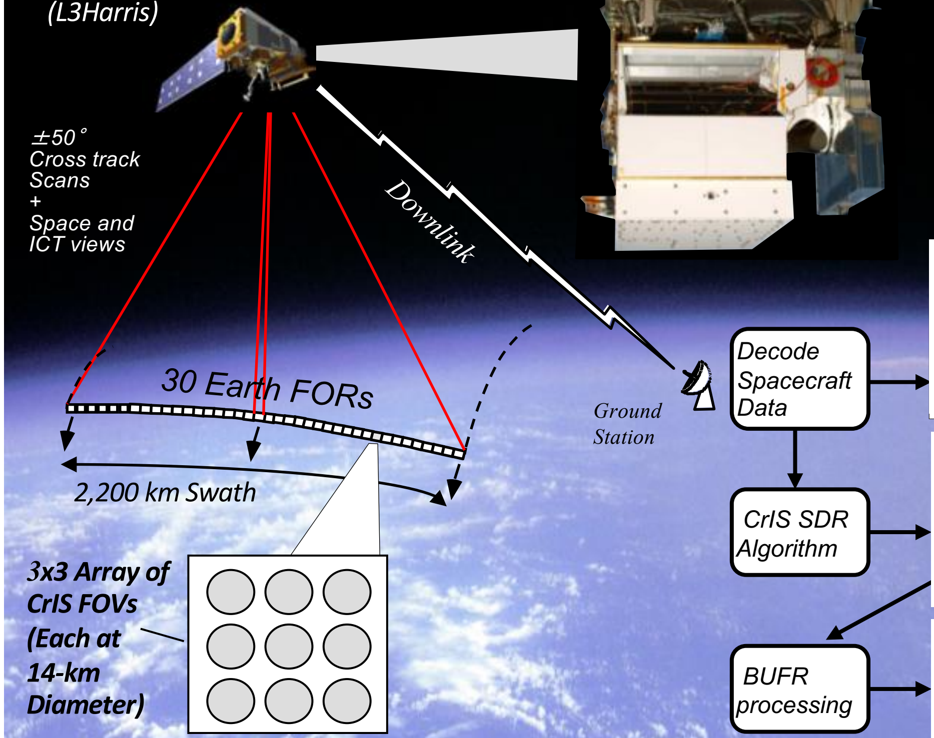
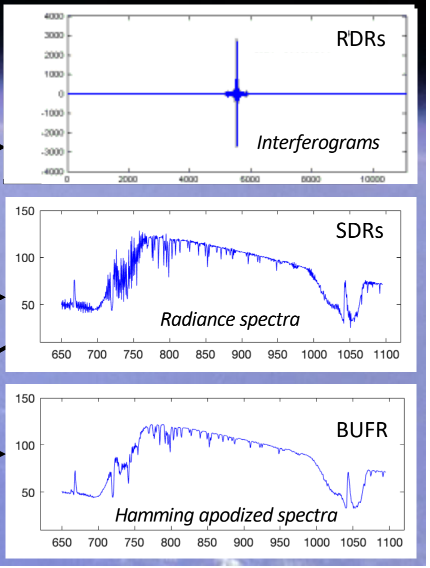
CrIS Overview

CrIS on Suomi-NPP, JPSS built by ITT Exelis (L3Harris)



Key Sensor Features

Large 8 cm Clear Aperture
Three Spectral Bands
3x3 FOVs at 14 km Diameter
Photovoltaic detectors in all 3 bands
4-Stage Passive Detector Cooler
Plane-Mirror Interferometer With DA
Internal Spectral Calibration
Ambient Internal Calibration Target
Modular Construction



Band	Spectral Range	NSR		FSR	
		Sampling,Resolution	# channels	Sampling,Resolution	# channels
LW	650 – 1095 cm^{-1}	0.625 cm^{-1}	717	0.625 cm^{-1}	717
MW	1210 – 1750 cm^{-1}	1.25 cm^{-1}	437	0.625 cm^{-1}	869
SW	2155 – 2550 cm^{-1}	2.5 cm^{-1}	163	0.625 cm^{-1}	637

Outline

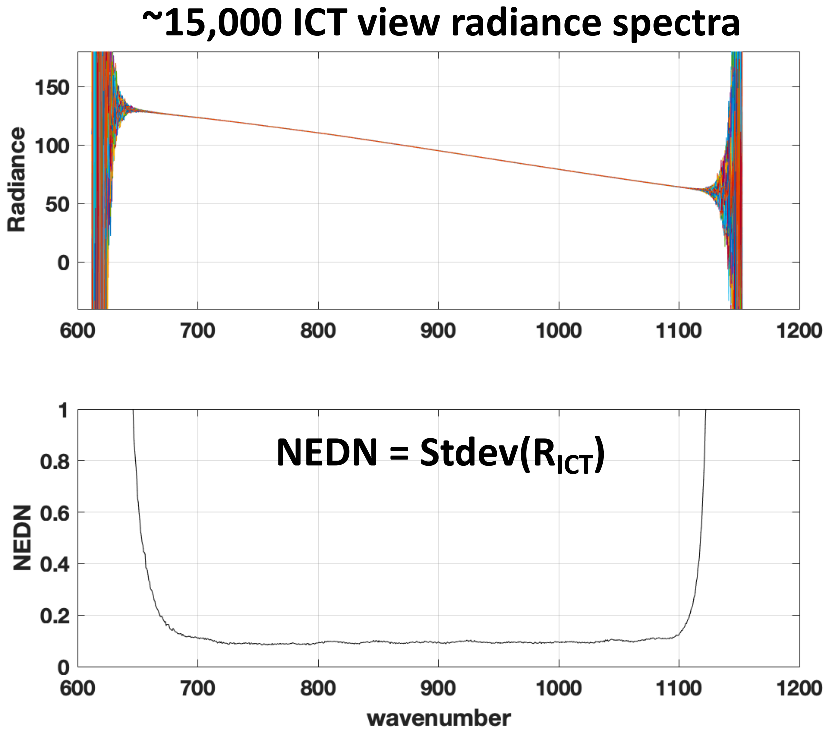
- **CrIS Noise**
  - Gaussian behavior
  - Scene independence of NEDN
  - NEDN variability among FOVs and sensors
  - Spectral correlation
  - Self-apodization corrections and resulting spectral correlations
  - Hamming apodization
  - Example Covariances

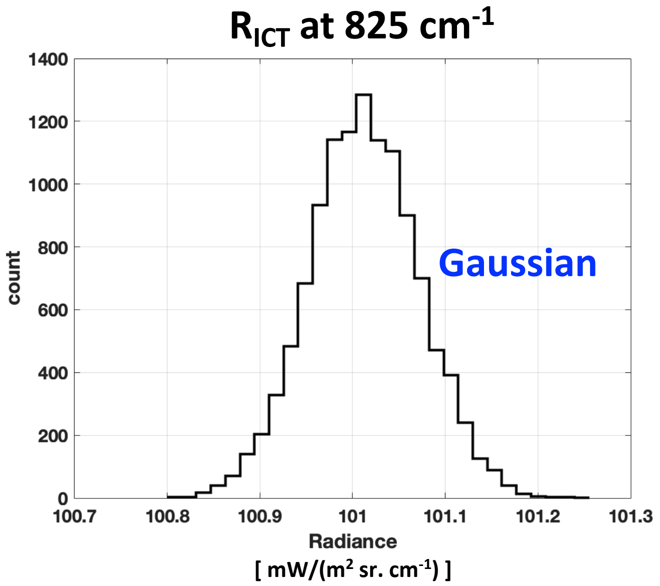
- **CrIS Radiometric Calibration Uncertainties**
  - Calibration Methodology and Uncertainty Contributions
  - Cal/Val assessment examples
  - Warm and cold scene Uncertainty examples

➢ **Main goal is to assess and advertise the CrIS measurement characteristics so the data can be used to its full potential**

one piece of the puzzle

Calibrated ICT (onboard blackbody) spectra ensembles (SNPP CrIS)

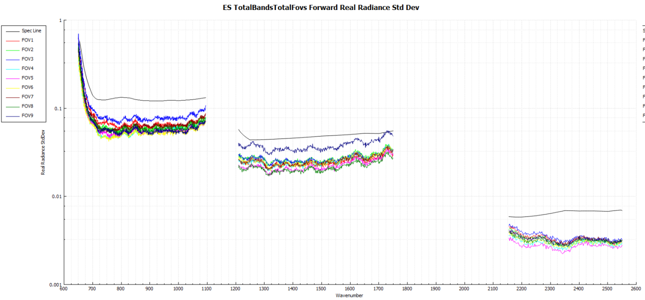




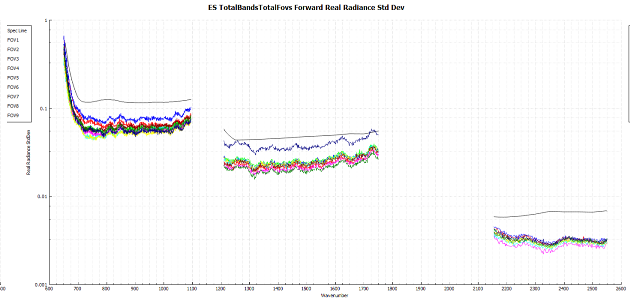
- ➢ CrIS radiance Noise, NEDN, is spectrally smooth
  - One detector for all channels per band, “spectral fidelity”
- ➢ NEDN behavior from one sample to another is highly Gaussian

NEDN for various signal levels (NOAA20 NSR CrIS)

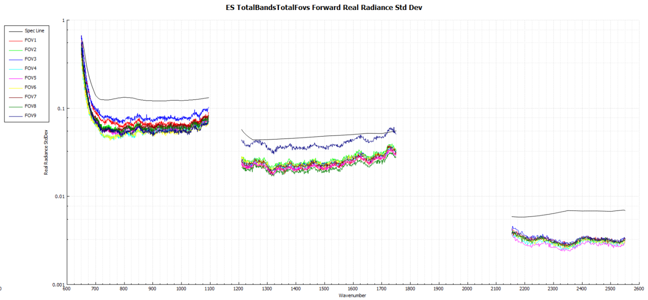
NSR NEDN for 200K scene:



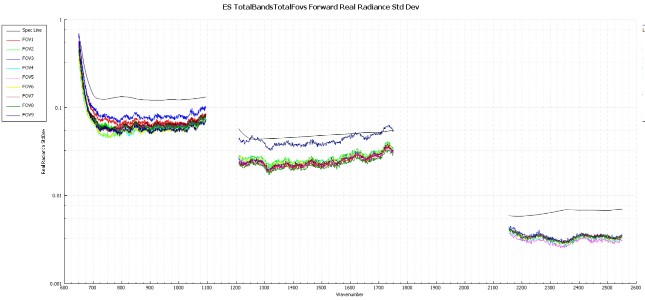
NSR NEDN for 233K scene:



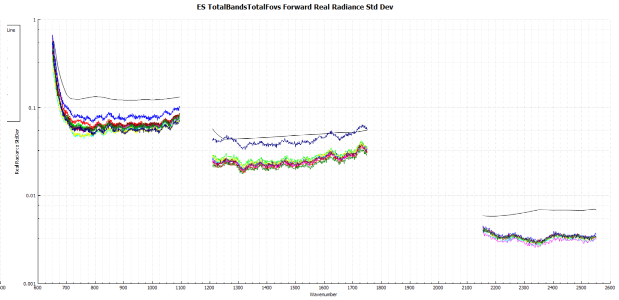
NSR NEDN for 260K scene:



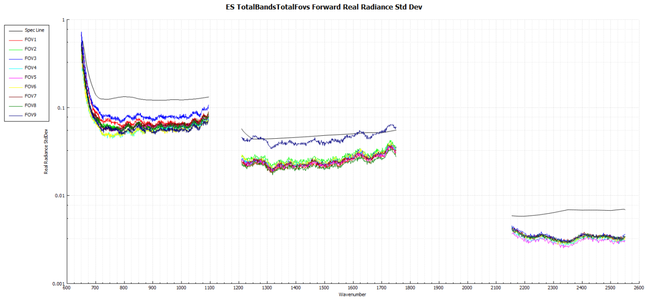
NSR NEDN for 287K scene:



NSR NEDN for 299K scene:



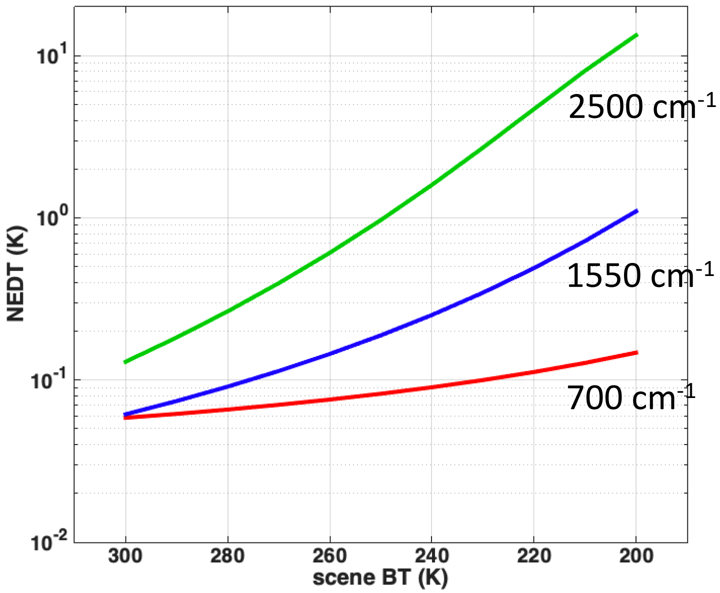
NSR NEDN for 310K scene:



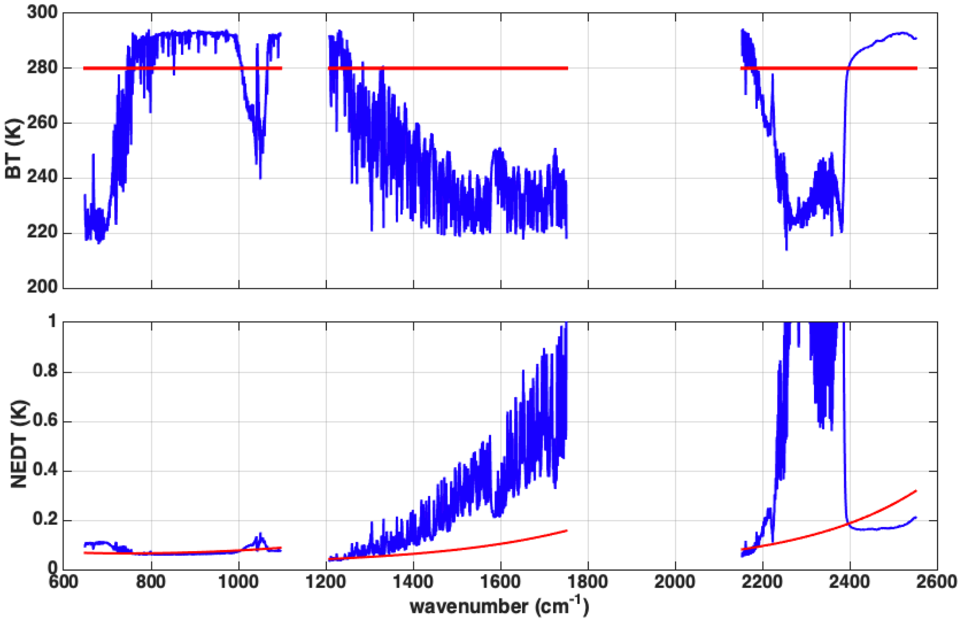
- CrIS Radiance Noise, NEDN in units of mW/(m^2 sr. cm^{-1}), is highly independent of scene, or signal level

NEDN converted to NEDT at various scene temperatures

NEDN [mW/(m^2 sr. cm^{-1})] = 0.1 LW; 0.04 MW; 0.006 SW



NEDN converted to NEDT at 280K (red) and at scene temperature of a typical clear sky spectrum (blue)



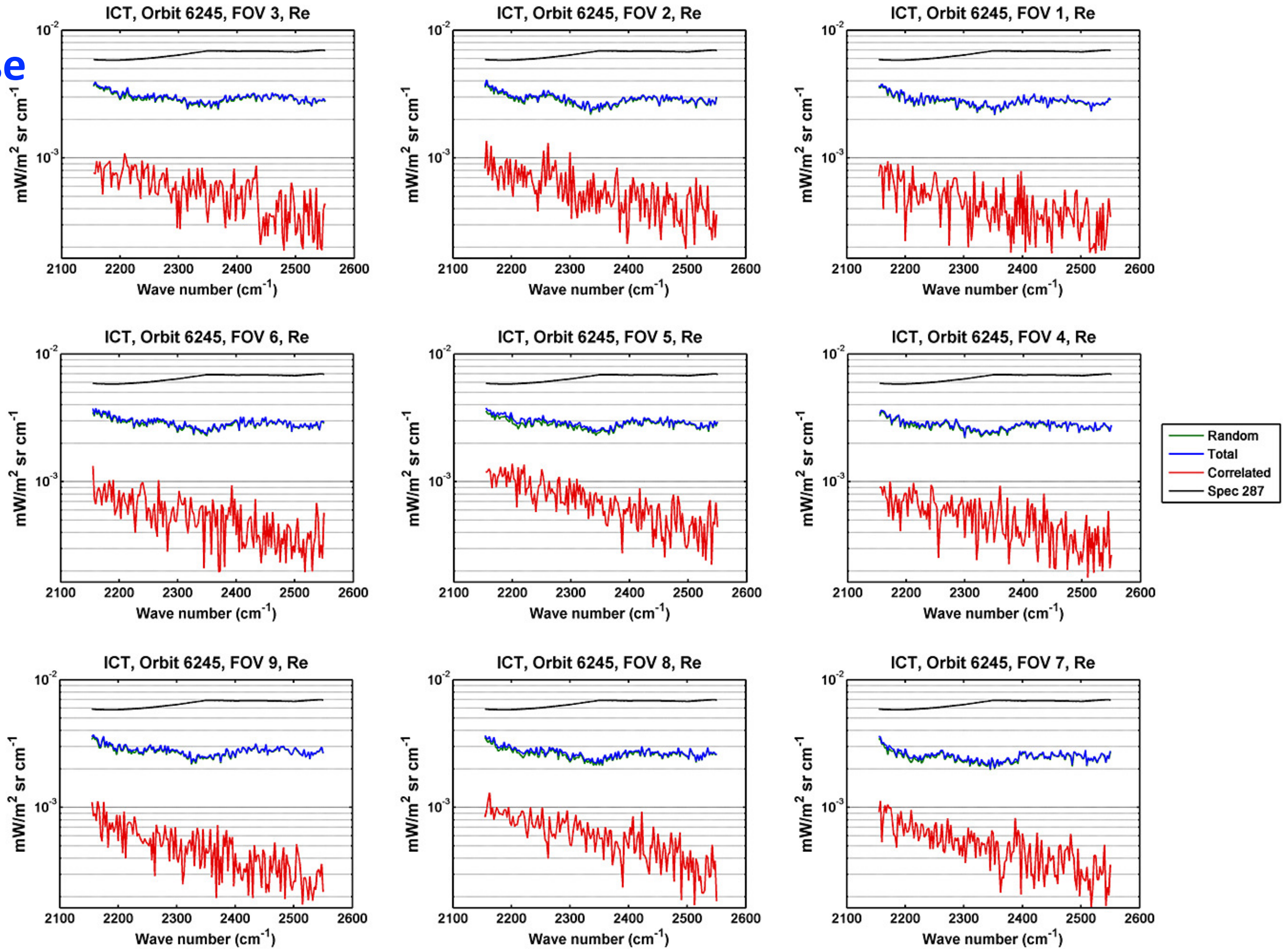
- ➢ **Converting from NEDN to NEDT at a fixed scene T can lead to large errors**
- ➢ **Convert from NEDN to NEDT at scene BT**

SNPP spectrally correlated noise

Shortwave band example from Zavyalov et al., Noise performance of the CrIS instrument

Random/correlated noise contribution to the total NEdN in SWIR spectral band estimated for all nine FOVs from the ICT data acquired on 10 January 2013, Orbit 6245. Note that the blue line (total noise) overlays the green line (random noise).

*** Does not include Self-apodization correction effects**



➢ **Spectrally correlated noise due to interferometric effects is very small, negligible**

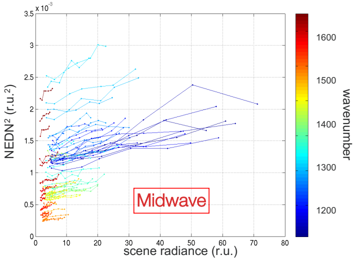
Other examples for EOS-Aqua Atmospheric InfraRed Sounder (AIRS)

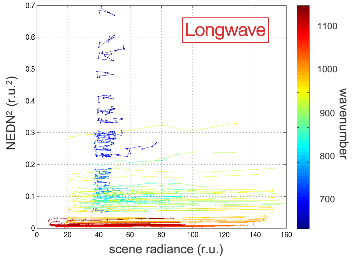
NEDN versus scene radiance

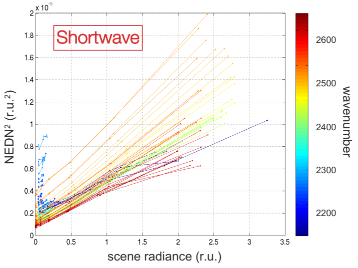
NEDN increases with sqrt{scene radiance}, consistent with photon noise. The total noise at scene temperature T is parameterized as

$$NEDN(T) = [N(T)\ \gamma_{photon} + NEDN_{thermal}^2]^{1/2}$$

where $NEDN_{thermal}^2$ (the y-intercepts) and γ_{photon} (the slopes) are determined for each channel.

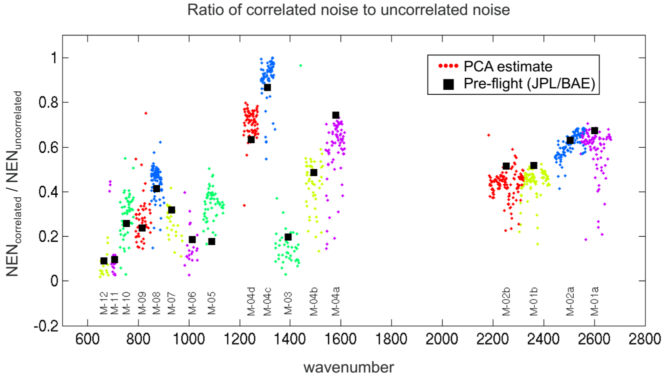






Spectrally Correlated Noise

The PCA estimate is of the spectrally uncorrelated noise; the spectrally correlated noise is computed as $[total\_noise^2 - pca\_noise^2]^{1/2}$ and compared to pre-flight determinations performed by JPL/BAE:



- Very good agreement between two very different and independent analyses.
- The correlated noise is a large fraction of the total noise for several arrays.

NEDN is scene dependent in MW and SW

Large percentage of total noise is spectrally correlated within detector arrays

FOV variability of NEDN (FSR unapodized)

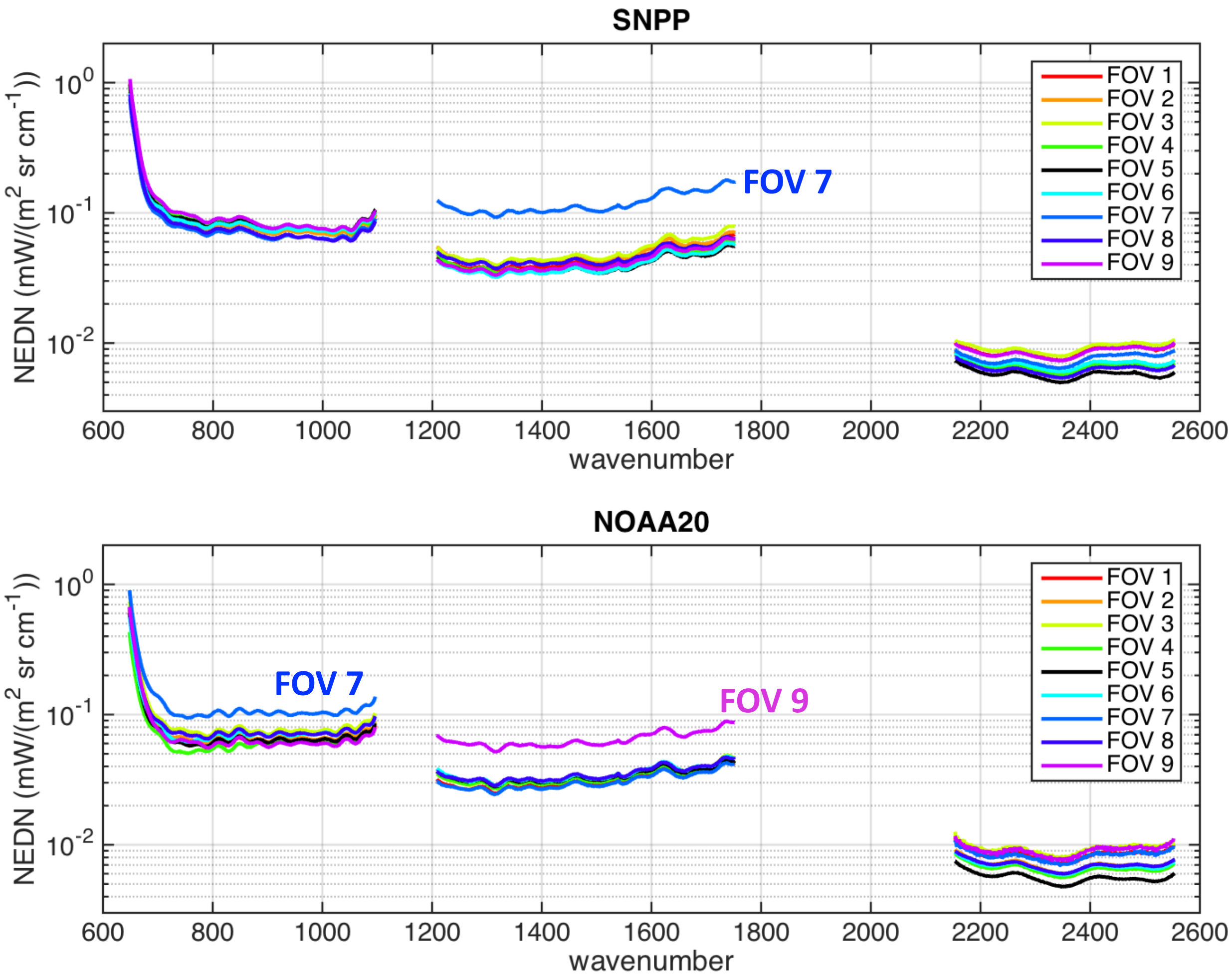
- NEDN estimates provided in every SDR granule

- Most FOVs are in-family. Outliers:

  SNPP: MW FOV7

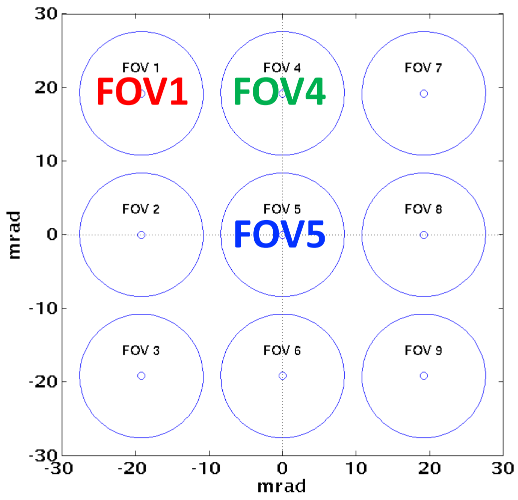
  NOAA20: LW FOV 7, MW FOV 9

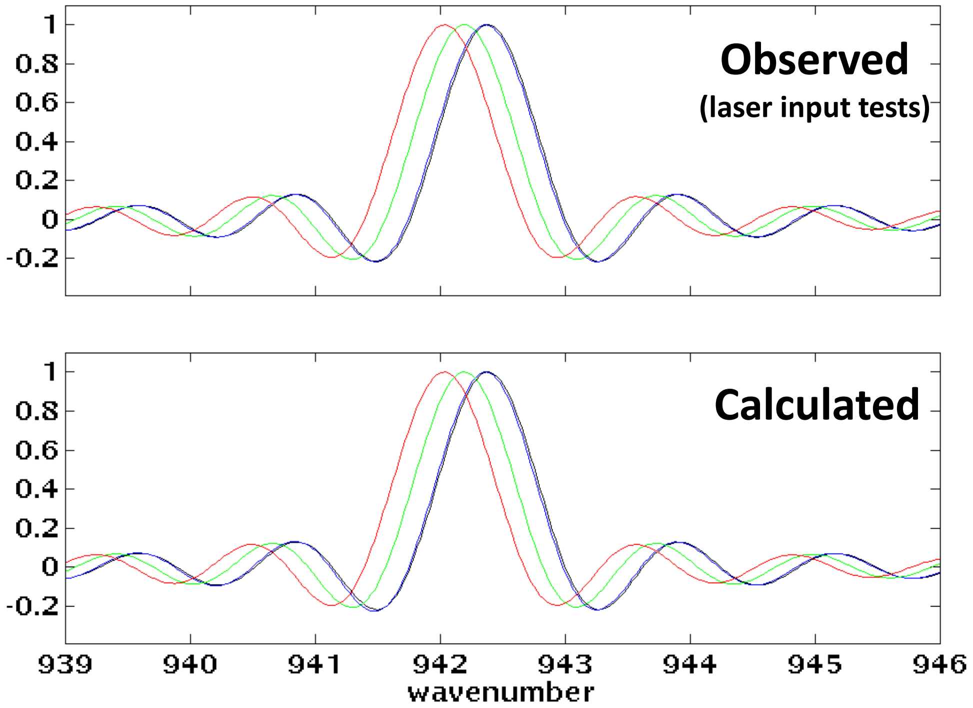
- SW band show self-apodization noise amplification, with values up to 70% greater than on-axis FOV5 at end of SW band



Self-apodization Effects and Corrections

Suomi-NPP CrIS Observed and Calculated Instrument Lineshapes FOVs 5, 4, and 1 before self-apodization correction





CrIS Calibration Equation/Algorithm

$$\tilde{L}^{es} = L^{ict} \cdot \frac{F \cdot f_{ATBD} \cdot \boxed{SA_s^{-1}} \cdot f_{ATBD} \cdot \left[\frac{\Delta S_1}{\Delta S_2} \left| \Delta S_2 \right| \right]}{F \cdot f_{ATBD} \cdot \boxed{SA_s^{-1}} \cdot f_{ATBD} \cdot \left| \Delta S_2 \right|}$$

$\Delta S_1 = S_{ES} - S_{DS}$ $\Delta S_2 = S_{ICT} - S_{DS}$

- Instrument self-apodization (*SA*) correction via inverse self apodization operator (Genest and Tremblay, 1999; Desbiens et al., 2006)

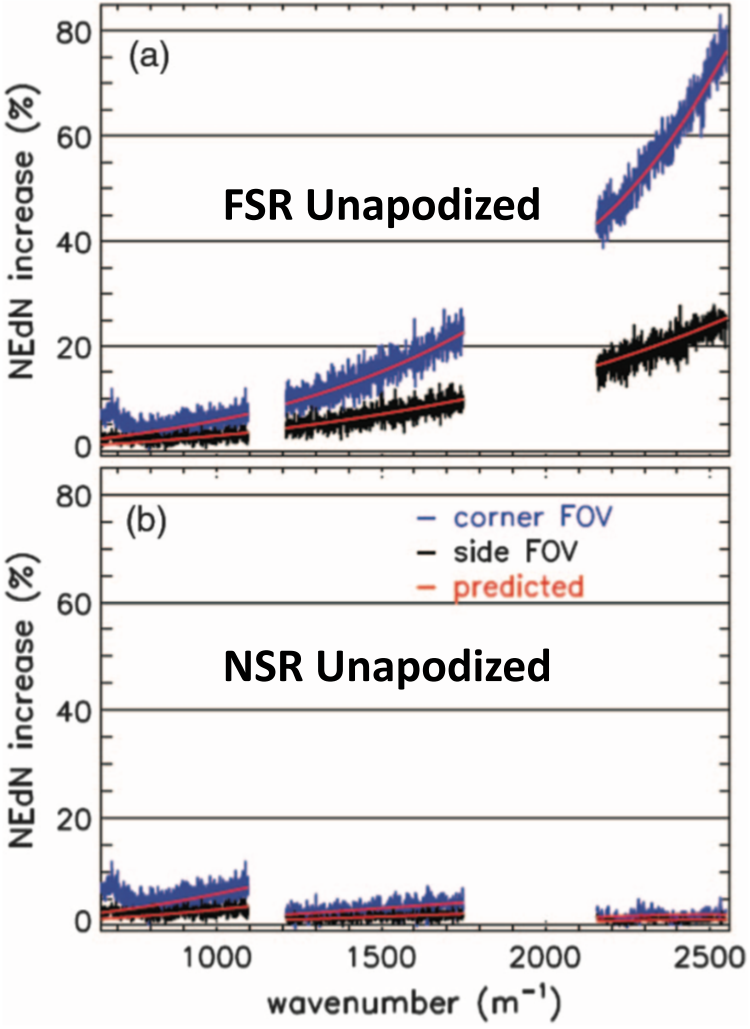
➢ **SA^{-1} is a de-apodization process, amplifying and correlating signal and noise**

➢ Y. Han, L. Suwinski, D. Tobin, and Y. Chen, "Effect of self-apodization correction on Cross-track Infrared Sounder radiance noise," Appl. Opt. 54, 10114-10122 (2015)

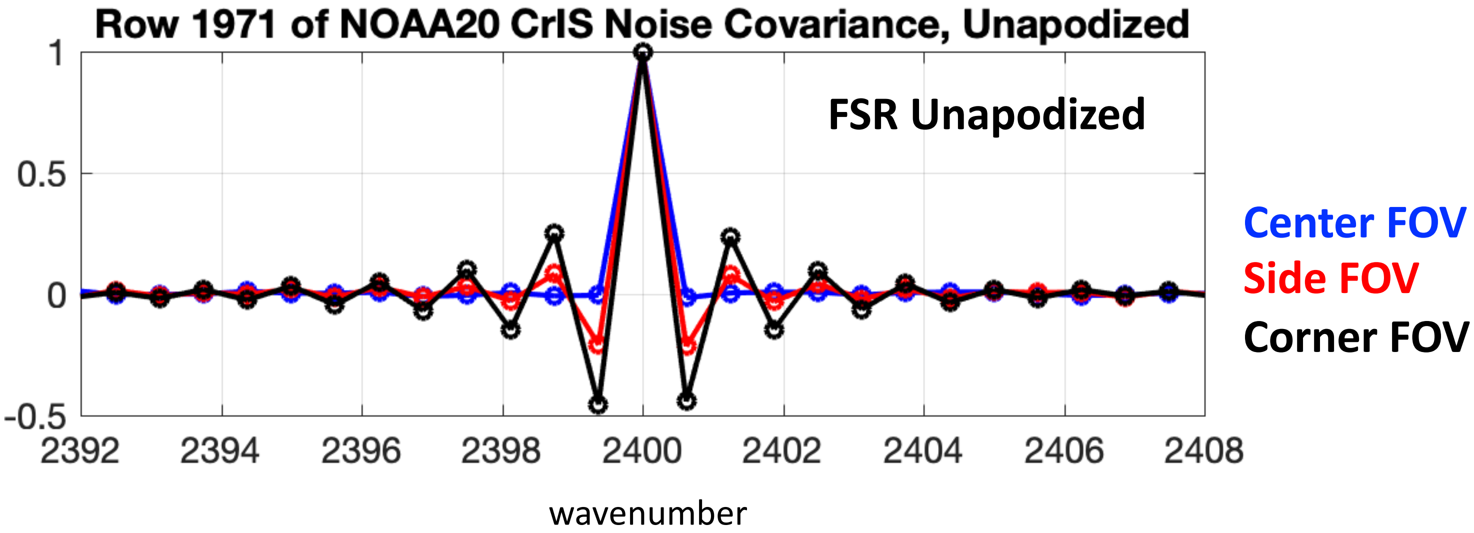
NEDN (diagonal) amplifications due to SA^{-1}

Han et al., "Effect of self-apodization correction on Cross-track Infrared Sounder radiance noise"

- Larger for larger wavenumbers
- Very small effect for NSR, as compared to FSR



CrIS Noise Covariance example



Hamming apodization, Channel selection, Vertical resolution

- Hamming apodization is commonly introduced (e.g. BUFR) to suppress negative side lobes of the unapodized CrIS sinc ILS, to accommodate polychromatic RT models
  - Produces spectral correlation of signal and noise, Reduces diagonal NEDN

- High vertical resolution from CrIS and other advanced sounders is due in part to increased SNR from the signal redundancy and noise advantage of using many spectral channels, not necessarily from sharper weighting functions of individual channels.
  - Channel sub-setting is sometimes performed, in part to avoid the spectral correlation introduced by Hamming

- Full Information Content can be retained if the Hamming function is specified and neighboring channels (±2) are included
  - As demonstrated by ECMWF, for example, by including off-diagonal noise covariance information to remove Hamming
  - Other approaches use the unapodized spectra (e.g. W. Smith et al., X. Liu et al.)

- These considerations are most important for CrIS, as shown on the following slides

Example Longwave Spectra

Monochromatic
AIRS
(near Gaussian SRFs)

Monochromatic
IASI L1C
(± 2cm OPD w/ Gaussian apodization)

Monochromatic
CrIS unapodized (SDRs)
(± 0.8 cm OPD, SDRs)

Monochromatic
- **CrIS with Hamming apodization**

($R'_i = 0.23\ R_{i-1} + 0.54\ R_i + 0.23\ R_{i+1}$, BUFR)

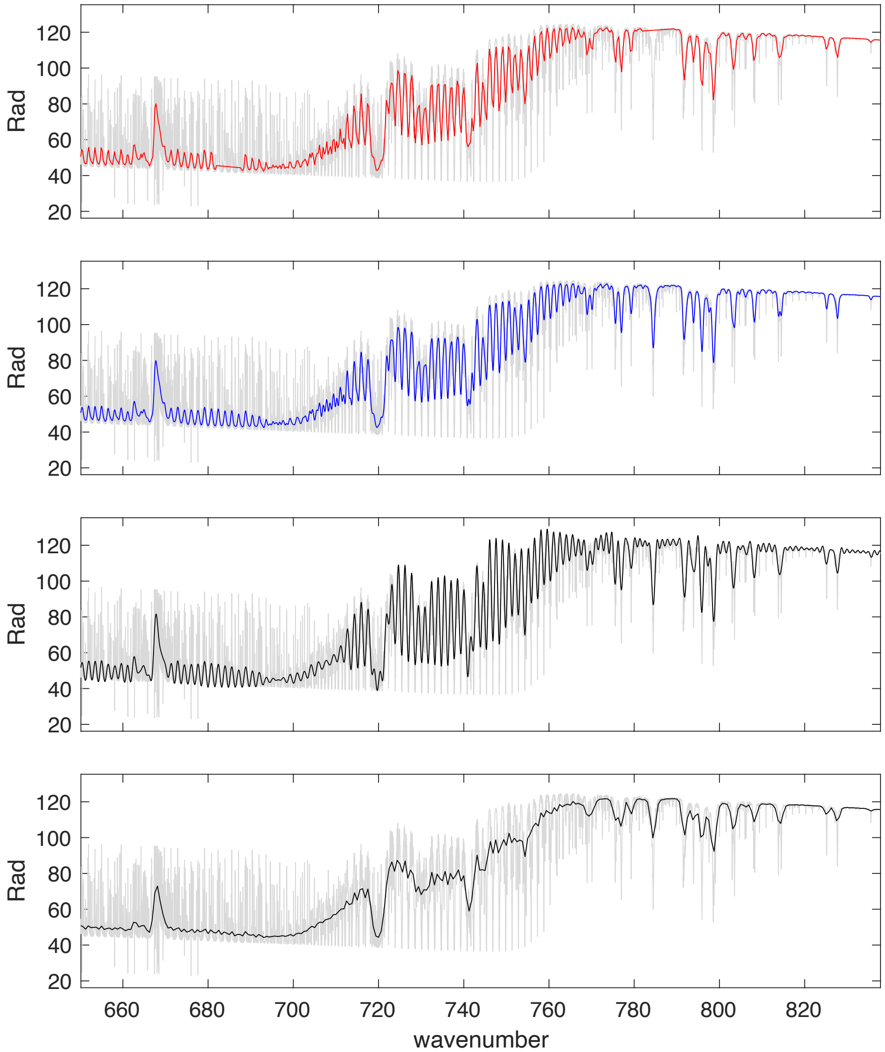
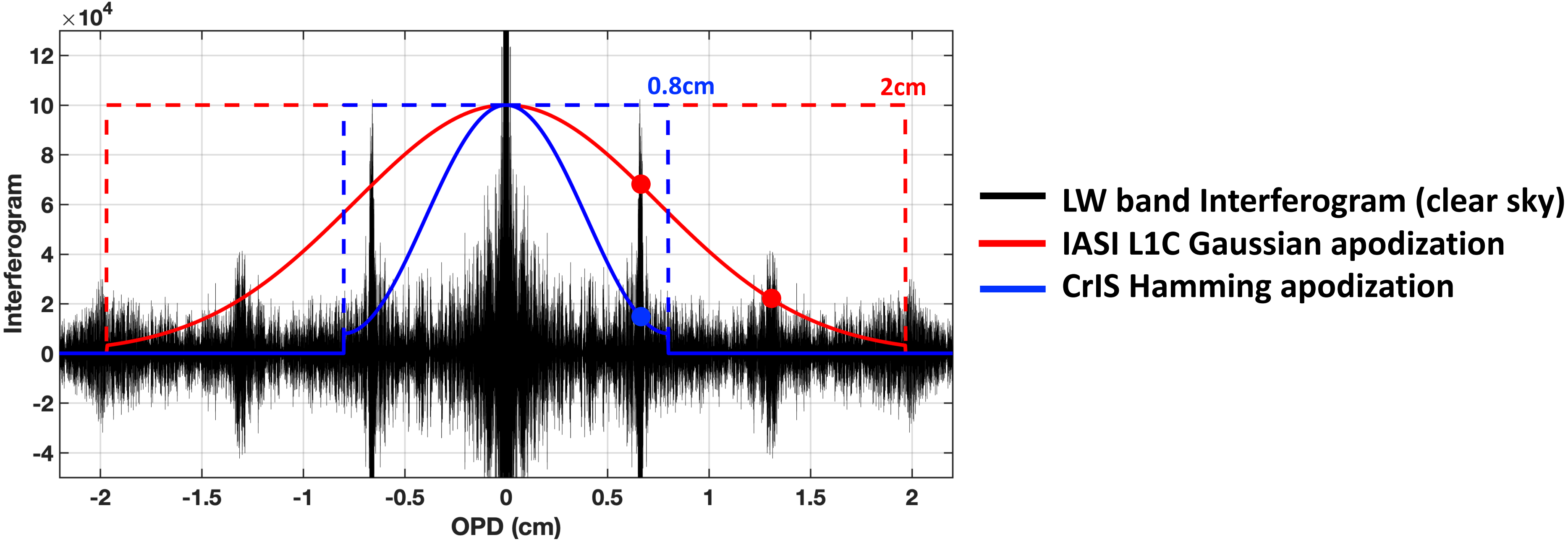
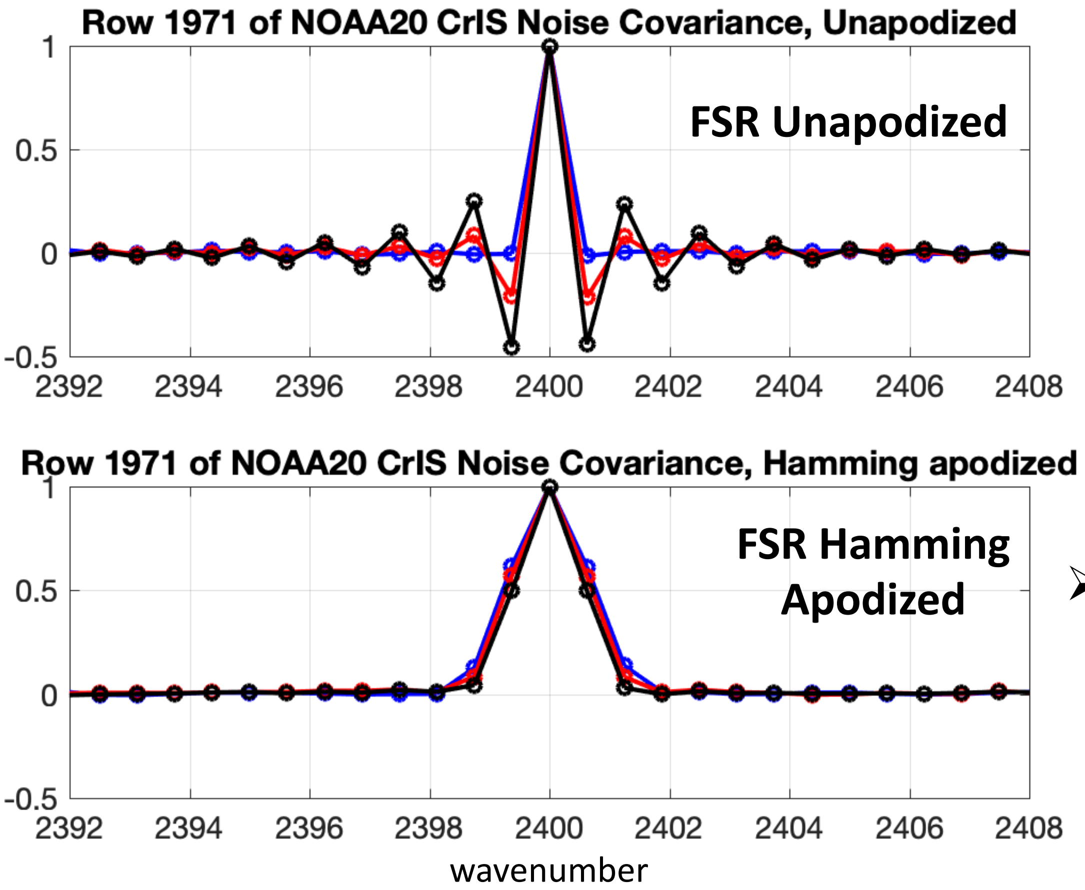


Illustration in the Interferogram Domain



- Resonances at 0.65 and 1.3 cm capture vertical sounding information from the 15μm CO_2 band
- IASI L1C Gaussian apodization retains 70% of the first resonance and 20% of the second resonance
- ➢ CrIS Hamming apodization retains only 10% of the first resonance
- ➢ Important to effectively remove the apodization, especially for CrIS
- Potential similar situation for MTG-IRS (maxOPD ~0.82 cm)

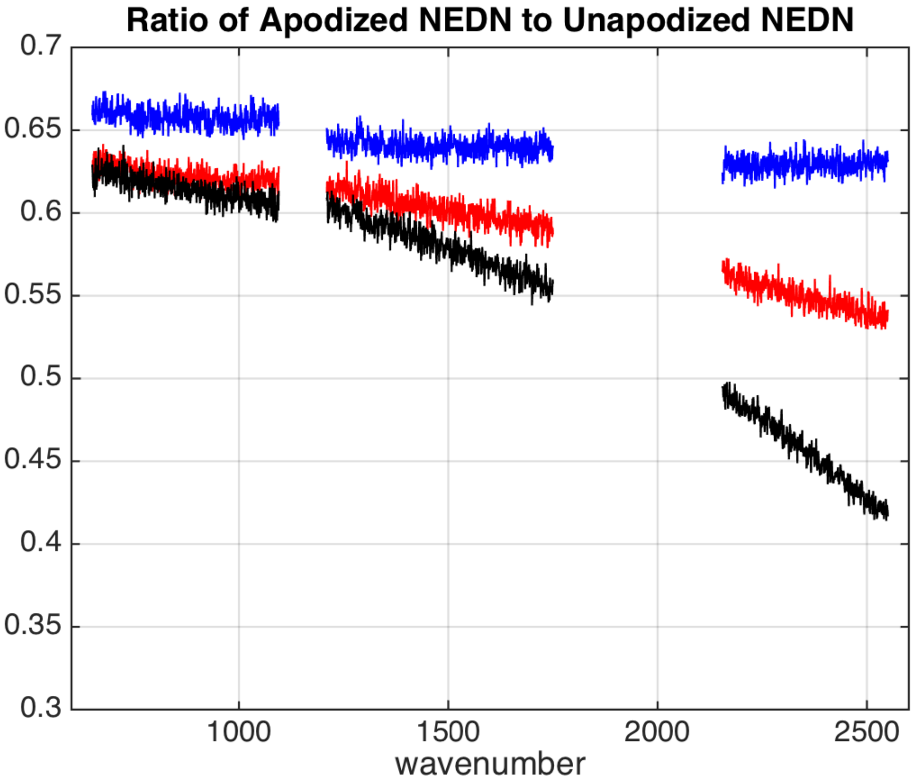
CrIS Noise Covariance example



Center FOV
Side FOV
Corner FOV

- ➢ **Hamming is very strong and mostly overwhelms the SA correlation effects**

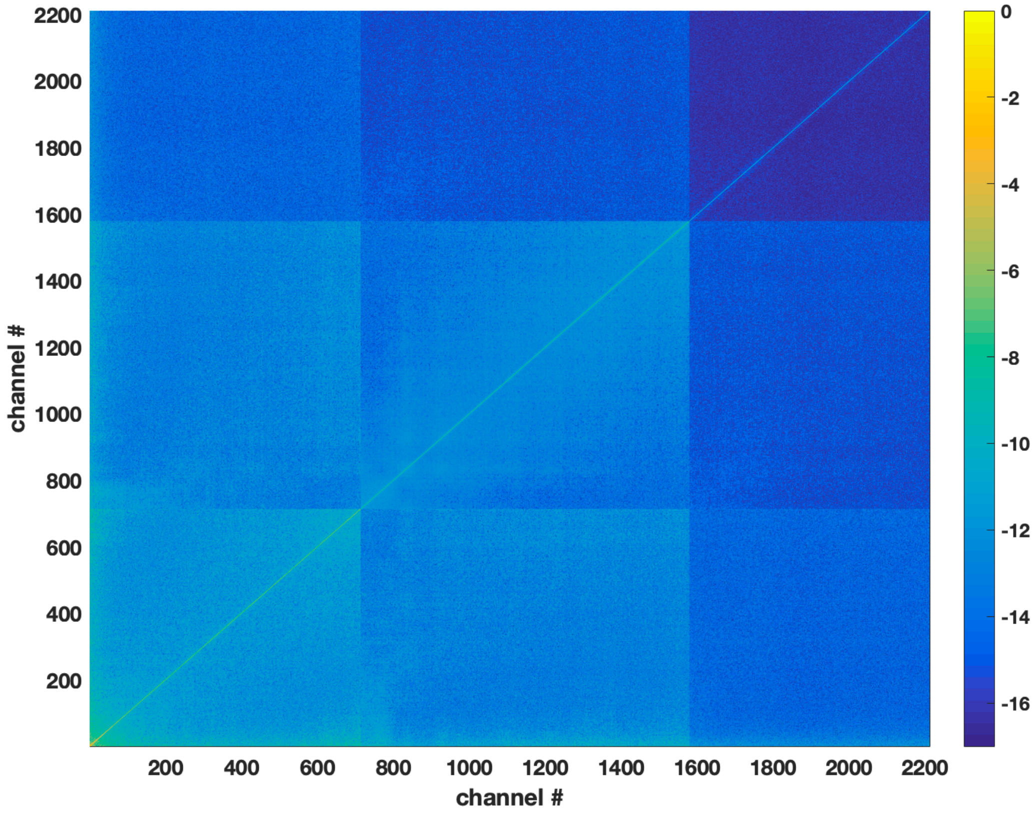
Effects of SA^{-1} and Hamming Apodization on NEDN



Center FOV
Side FOV
Corner FOV

CrIS Noise Covariance example

FOV1 noise covariance, FSR Hamming apodized, log scale



Noise Summary

Summary:

- Original measurement noise, NEDN, is highly random
- NEDN is highly scene independent (vs NeDT)
- Self-apodization corrections produce spectral correlations which are FOV and wavelength dependent
- Hamming apodization introduces additional spectral correlation

Next Steps:

- Distribute draft covariances and get feedback
- PCA Representation/Distribution of CrIS spectra and corresponding Noise characterization

CrIS On-Orbit Radiometric Calibration Equation:

$$L_S = \mathit{Re}\,\{(C'_{ES} - C'_{DS}) / (C'_{ICT} - C'_{DS})\}\, R_{ICT}$$

for observed complex spectra, C, of the Earth scene (**ES**), Internal Calibration Target (**ICT**), and Deep Space (**DS**) views.

with:

1. ICT Predicted Radiance: $R_{ICT} = \varepsilon_{ICT}\, B(T_{ICT}) + (1-\varepsilon_{ICT})\, R_{reflected}$

2. Quadratic Nonlinearity Correction: $C' = C \cdot (1 + 2\, a_2\, V_{DC})$

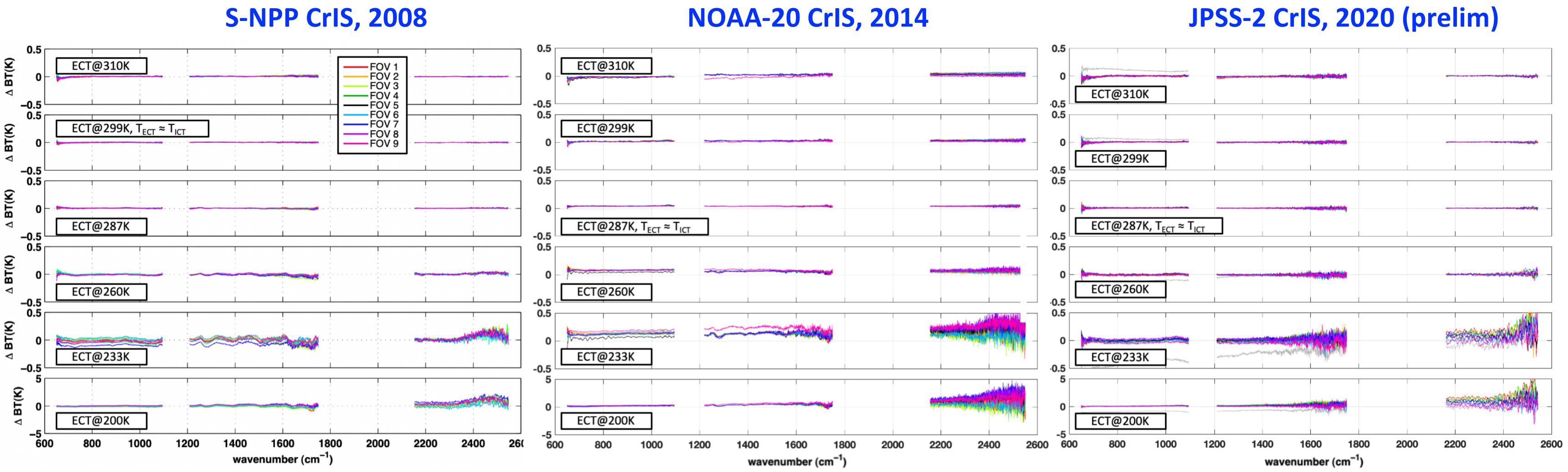
2. Polarization Correction/Error:

$$E_p \cong p_r p_t \left\{ \begin{array}{l} L_S \cos 2(\delta_S - \alpha) - L_H \dfrac{L_S - L_C}{L_H - L_C} \cos 2(\delta_H - \alpha) - L_C \dfrac{L_H - L_S}{L_H - L_C} \cos 2(\delta_C - \alpha) \\ -B_{SSM} \left[\cos 2(\delta_S - \alpha) - \dfrac{L_S - L_C}{L_H - L_C} \cos 2(\delta_H - \alpha) - \dfrac{L_H - L_S}{L_H - L_C} \cos 2(\delta_C - \alpha) \right] \end{array} \right\}$$

with polarization coefficients $p_r p_t$, scene selection mirror polarization angle δ, sensor polarizer angle α, and emission from the scene mirror B_{SSM}. *(H==ICT, C==DS).*

Pre-launch CrIS calibration assessment using SI-traceable External Calibration Target (ECT)

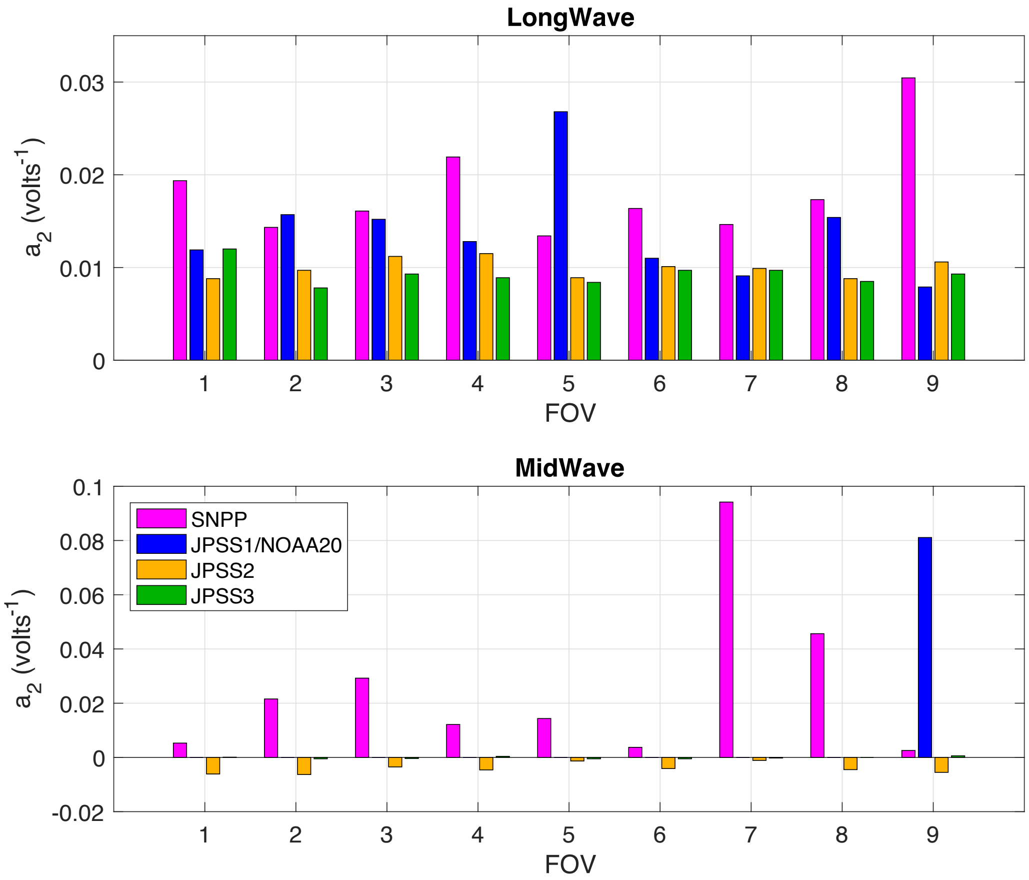
ECT view calibrated BT spectra minus ECT predicted BT, for ECT at 200K, 233K, 260K, 287K, 299K, 310K



(JPSS-3 CrIS testing on-going now)

- ECT view data used to characterize the sensor radiometric nonlinearity and provide end-to-end calibration traceability to NIST via temperature sensor calibrations and NIST TXR measurements
- BT residuals are sub 0.1K for ECT temperatures of >260K, and larger as expected for 233 and 200K plateaus due to TVAC Space Target uncertainties; residuals are well within pre-launch RU

Quadratic Nonlinearity Coefficients, a_2



- Midwave Band Nonlinearity is greatly reduced for JPSS-2 (and subsequent) CrISes
- NEDN is also more consistent among FOVs

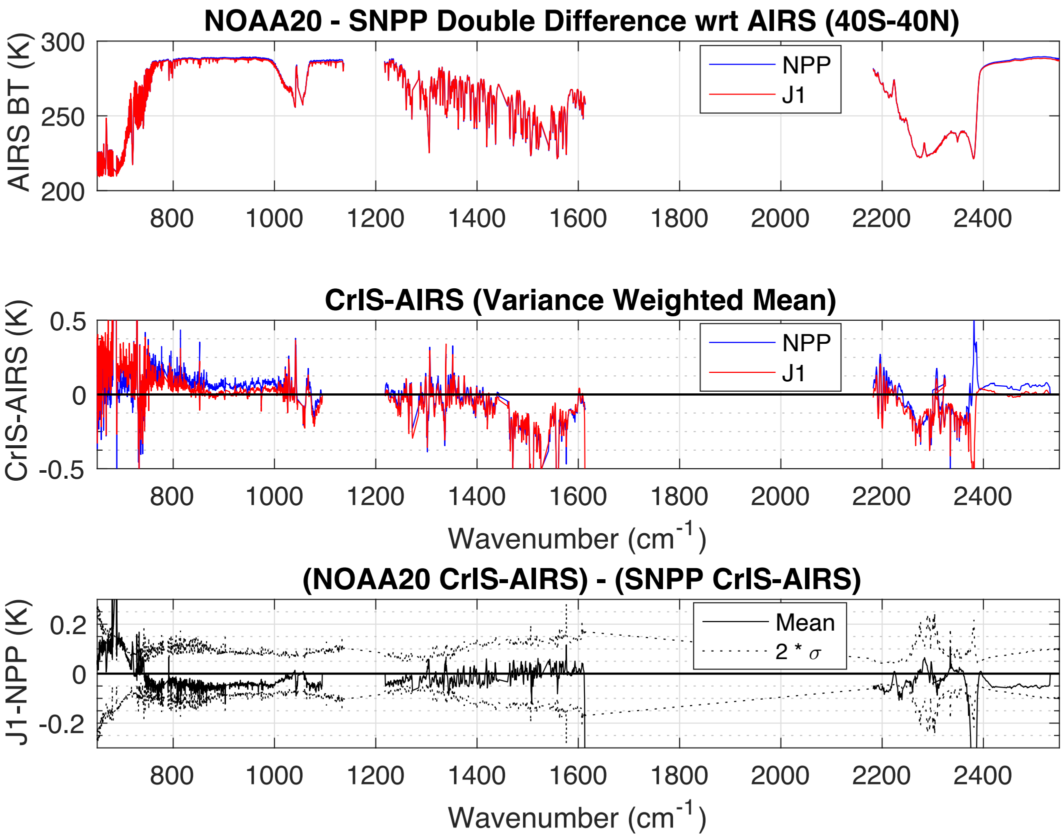
Post-Launch Calibration Assessment example

SNOs of CrIS and AIRS (Jul – Dec 2019)

AIRS Mean BT

CrIS BT – AIRS BT
(smoothed)

NOAA20 CrIS
minus
SNPP CrIS



+/- 0.5K Differences between AIRS and CrIS

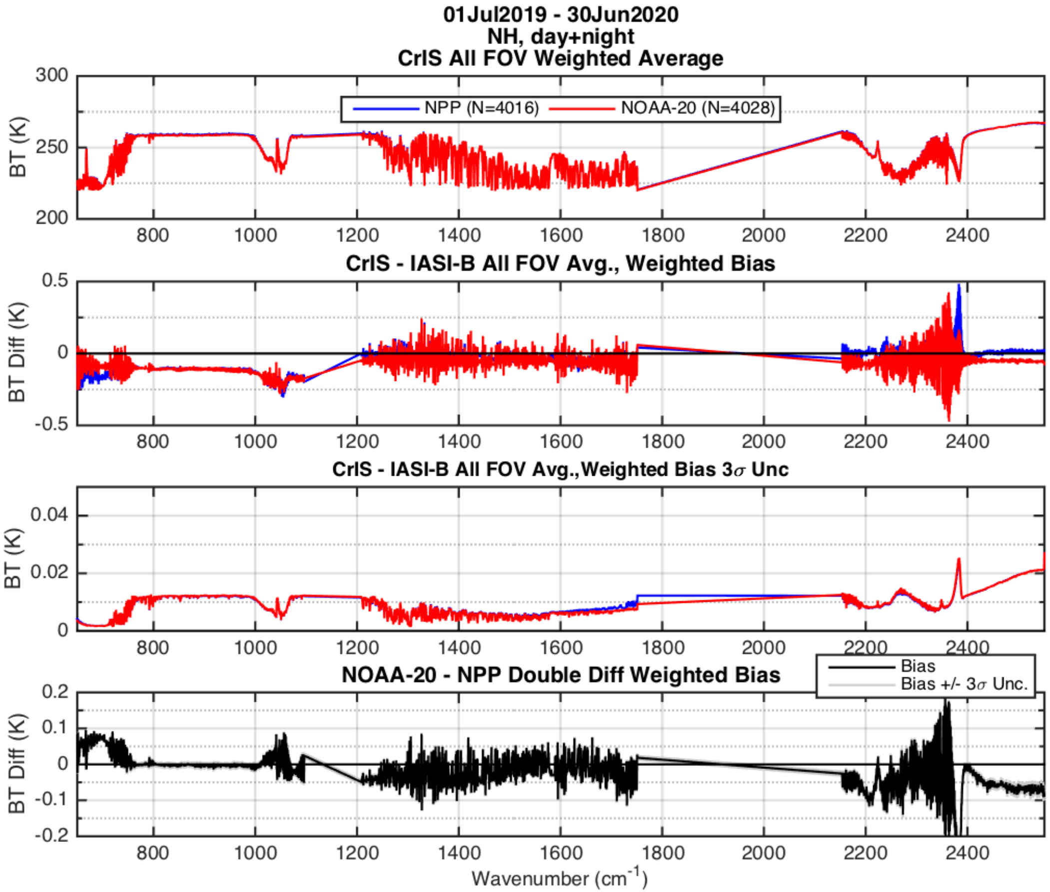
~0.1K level agreement between NOAA20 and SNPP CrIS

Post-Launch Calibration Assessment example

SNOs of CrIS and METOP-B IASI (Jul 2019-Jun 2020)

NOAA-20 - IASI-B
SNPP – IASI-B

NOAA-20 – NPP Double Diff

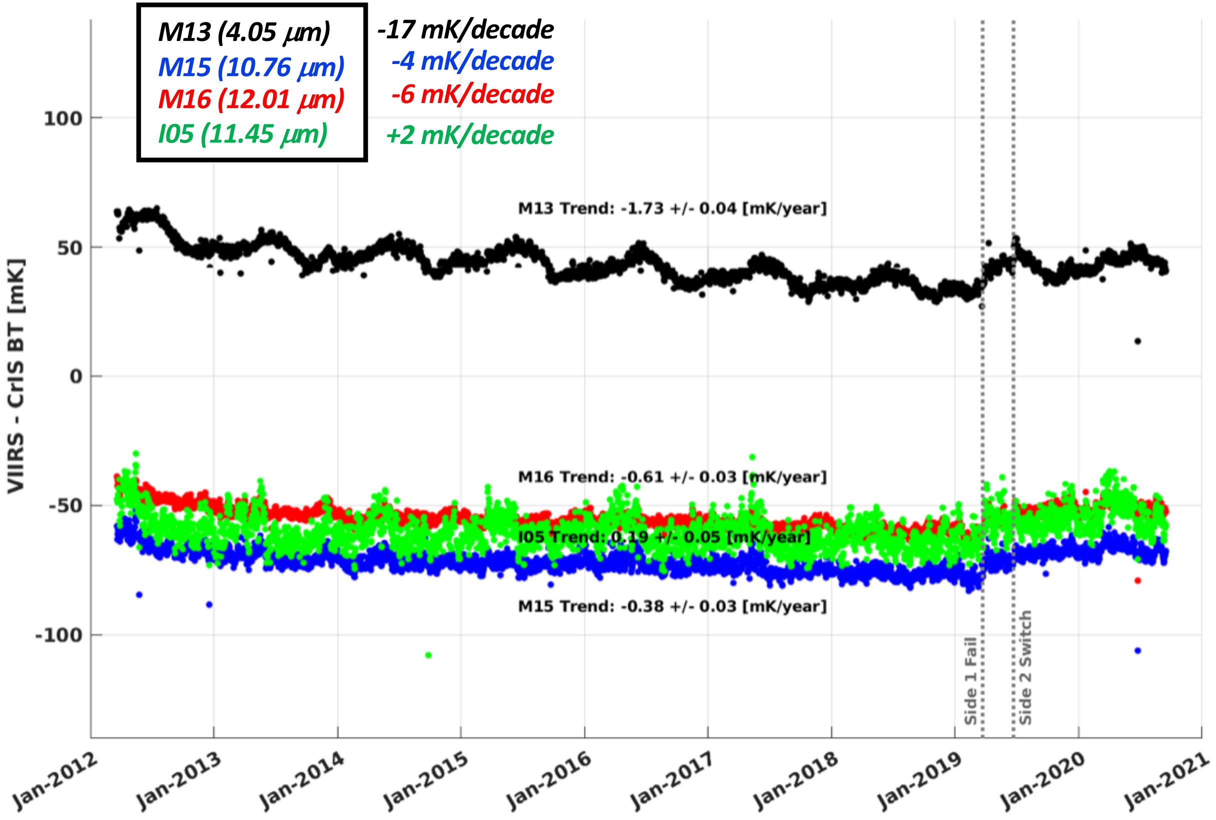


Similar results for IASI-A and IASI-C

- **~0.1K level agreement between two CrISes and three IASIs**

Post-Launch Calibration Stability Assessment example

S-NPP CrIS/VIIRS Differences, Global Daily Means for 280-290K Scenes



- ***Trends of +2, -4, -6, and -17 mK per decade***
- ***Small discontinuities associated with 2019 CrIS electronics side switch***

Radiometric Calibration: Coefficient Traceability and On-Orbit Uncertainty

- A critical aspect of a reference sensor and quality measurement record is the documentation of and ability to calculate the uncertainty in the sensor measurements
- The radiometric uncertainty (RU) in the calibrated radiance can be determined via a perturbation analysis of the calibration equation
  - Equivalent to a differential error analysis described in the GUM (Guide to Uncertainty in Measurements)
- SNPP CrIS: Tobin, D., et al. (2013), Suomi-NPP CrIS radiometric calibration uncertainty, *J. Geophys. Res. Atmos.*, 118, 10,589–10,600, doi: 10.1002/jgrd.50809.

CrIS Calibration Parameters:

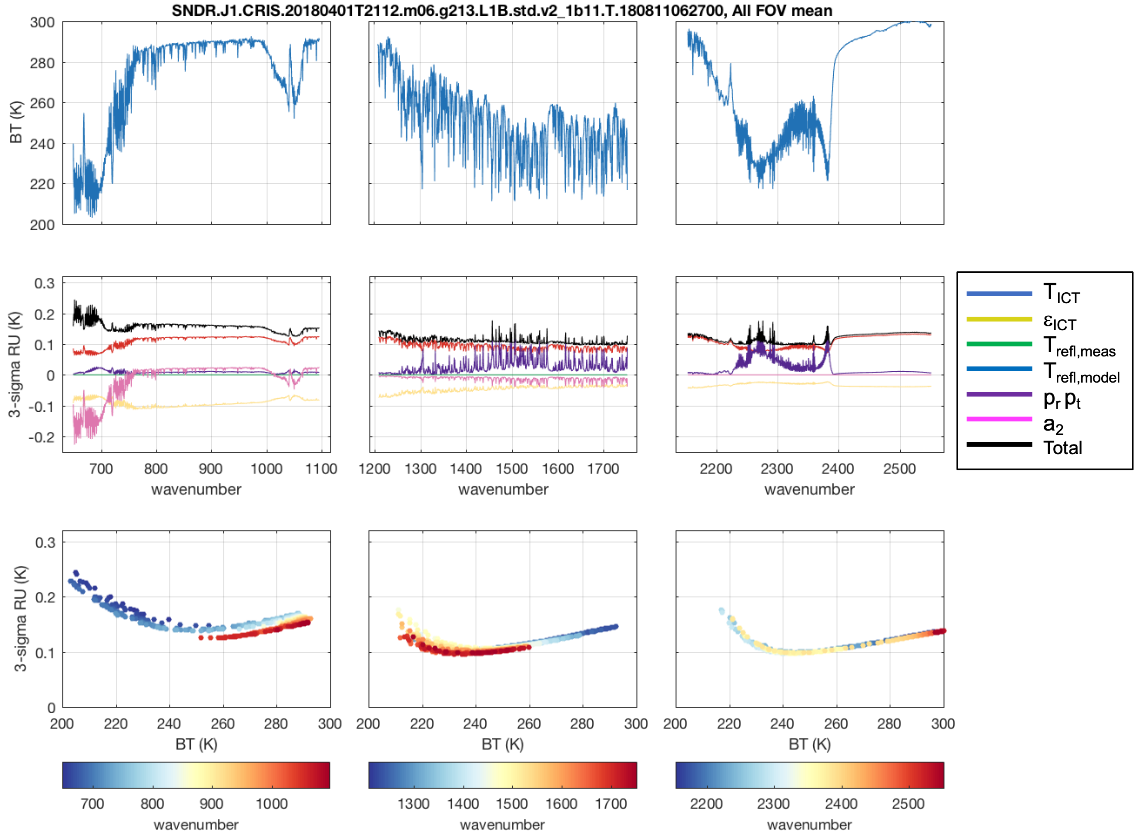
- ICT (Internal Calibration Target), T_{ICT} and e_{ICT}
  - Pre-launch PRT calibrations
  - Pre-launch emissivity characterization
  - Pre-launch L_{ICT} verification using ECT at T_{ICT}

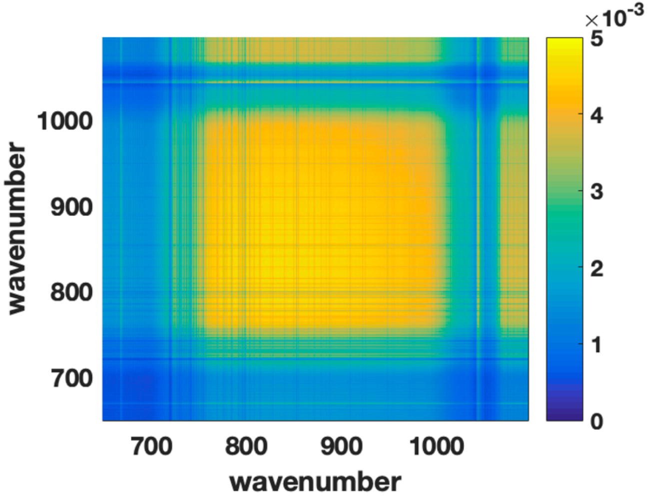
- Nonlinearity, a_2 and V_{DC}
  - Pre-launch Out-of-band harmonic analyses
  - Pre-launch ECT views at six temperatures
  - Post-launch Out-of-band harmonic analyses
  - Post-launch FOV-2-FOV analyses

- Polarization, $p_r p_t$ and α
  - Optical design analyses
  - post-launch pitch maneuver data

Example Radiometric Uncertainty estimates

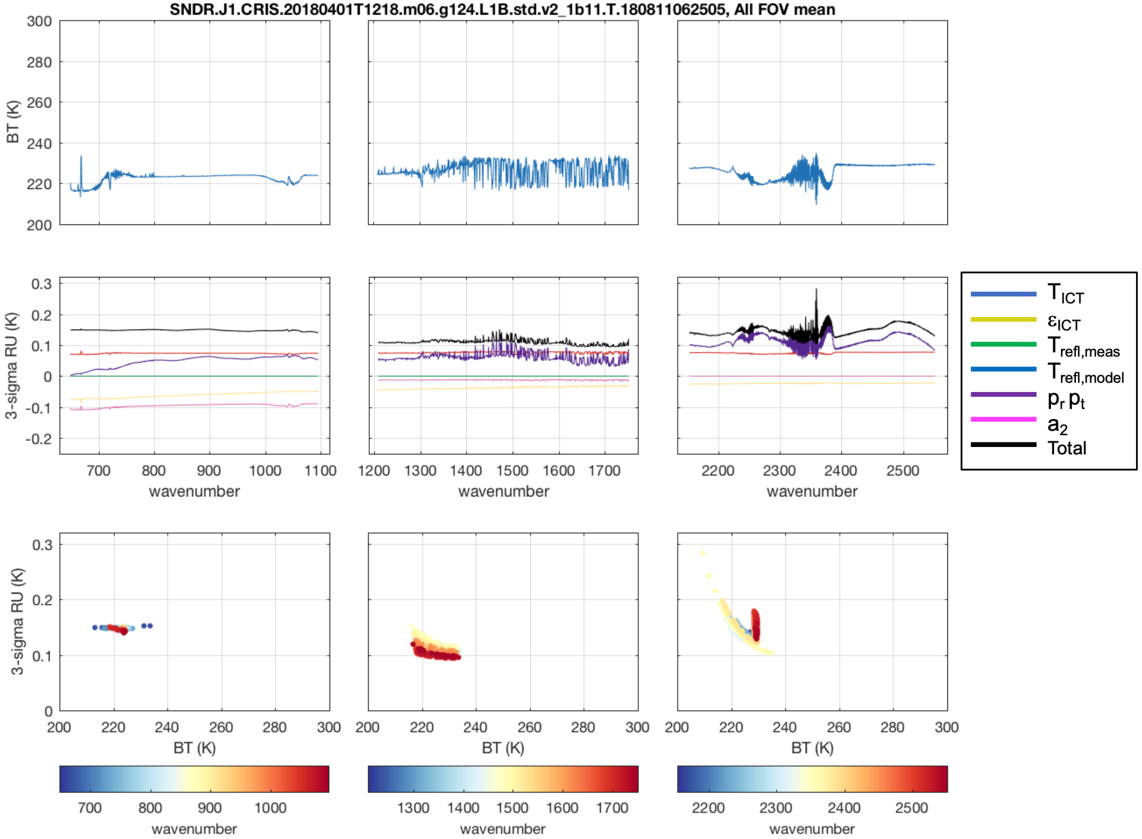
For a warm clear sky scene (~worst case)

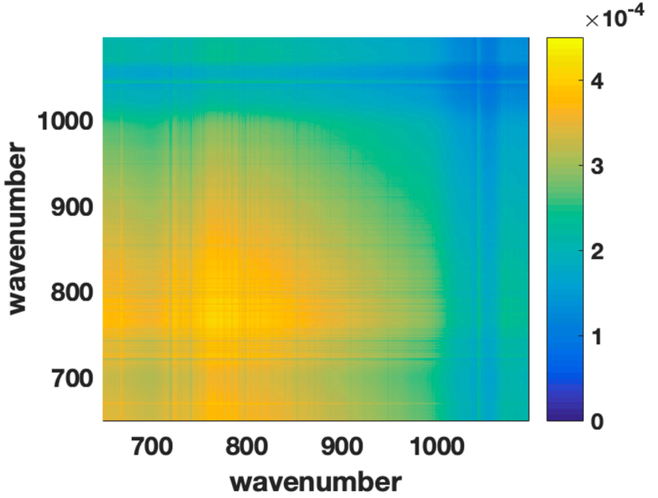




Example Radiometric Uncertainty estimates

For a cold cloud





Radiometric Uncertainty Tools

- Radiometric Uncertainty estimates for CrIS are available via a NASA L1b product, which contains the information needed to accurately calculate the radiometric uncertainty for any calibrated radiance spectrum
  - (Including RU spectral estimates for each observation would double the file sizes)
  - The Radiometric Uncertainty Tool documentation, sample code, and static RU parameters are available for the Version 3 release
- Based on the above tool, a separate tool/function is also under recent development and assessment for potentially wider use
  - A statistical representation of Earth spectra and matching RU estimates, for each CrIS sensor and FOV
  - Can compute RU in a few milli-seconds per spectrum

Calibration Summary

Summary:

- The CrIS Radiometric Calibration Uncertainty is less than a few tenths K 3σ
- Resulting potential calibration biases are therefore small but
  - Highly spectrally correlated
  - Different for different Earth scenes
  - Slightly different for different FOVs and sensors
- Pre- and Post-launch assessments support these findings
- To the extent that these Uncertainties are small, and understood, in relation to other sources of error, allows the CrIS observations to be used as “reference” or “anchor” observations

Next Steps:

- Refine and then distribute the statistical CrIS RU tool/function, and get feedback

The End. Thank you