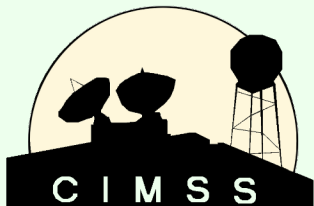


The IR Absolute Radiance Interferometer (ARI) Prototype for CLARREO: Assessing the Ability to Serve as a Satellite Intercalibration Reference (Part-3)

David Tobin, Bob Holz, Robert Knuteson, Fred Nagle,
Michelle Feltz, Bob Knuteson, Fred Best, Joe Taylor, Hank Revercomb
CIMSS/SSEC, UW-Madison

SI- Traceable Space-based Climate Observing System Workshop
NPL, Teddington, UK
9-11 Sep 2019



Topics

- **CrIS Calibration, Uncertainty and Traceability**
- **CrIS Intercalibration examples**
- **CLARREO Intercalibration**

Thank you:

NOAA JPSS Program

NASA JPSS Flight Program

NASA CrIS L1B Project

CLARREO Science Team

CrIS Operational Concept

CrIS on Suomi-NPP,
built by ITT Exelis

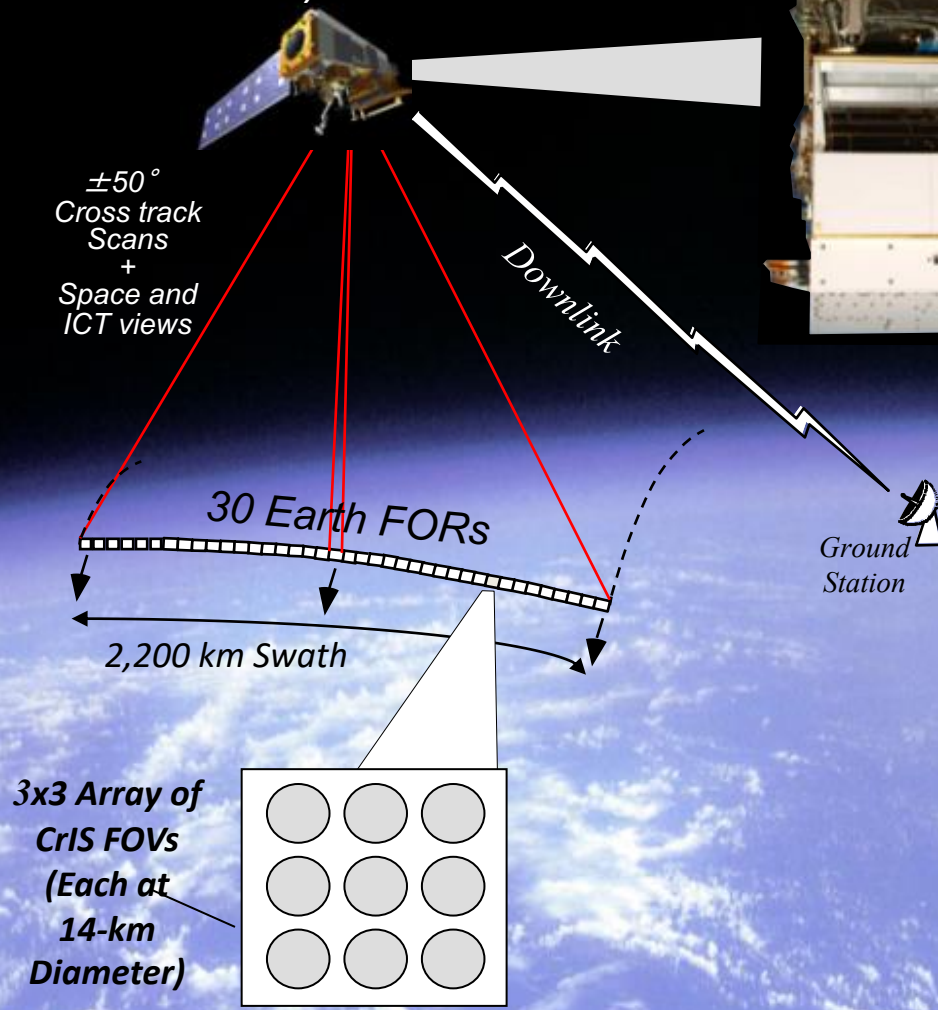


Key Sensor Features

Plane-Mirror Interferometer With DA
Three Spectral Bands
3x3 FOVs at 14 km Diameter
Photovoltaic MCT detectors
4-Stage Passive Detector Cooler
Ambient Internal Calibration Target
and optics/structure
Internal Spectral Calibration
Uncoated Gold SSM

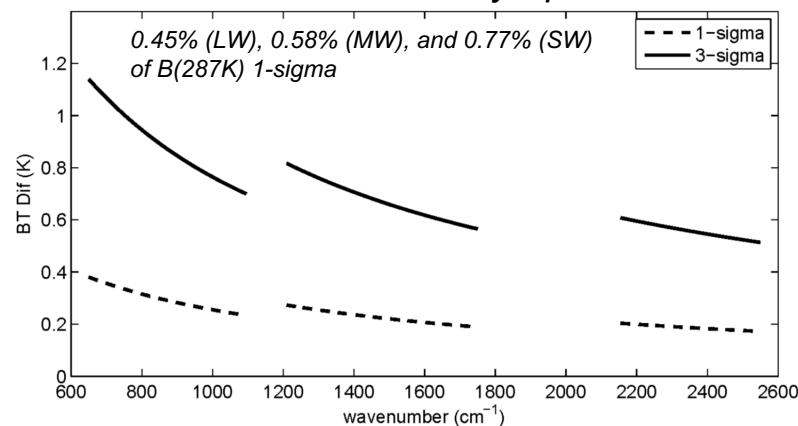
Primary NOAA goals:

EDRs and NWP Radiance DA



Band	Wavelength Range (cm-1) (μm)		Sampling (cm-1)	No. Chan.
SWIR	2155-2550	4.64-3.92	2.5	159
MWIR	1210-1750	8.26-5.71	1.25	433
LWIR	650-1095	15.38-9.14	0.625	713

Radiometric Uncertainty Specification



CrIS Simplified On-Orbit Radiometric Calibration Equation:

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

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

with:

1. ICT Predicted Radiance: $R_{ICT} = \epsilon_{ICT} B(T_{ICT}) + (1 - \epsilon_{ICT}) R_{REFL}$

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

3. Polarization Error (aka Correction): (to be implemented)

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

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

Radiometric Calibration Methodology/Traceability

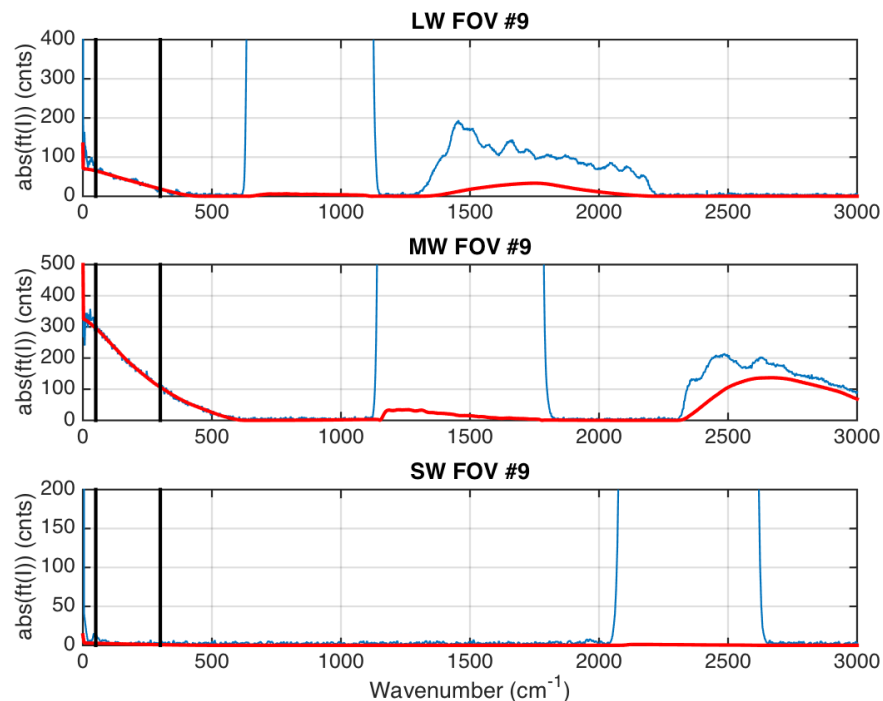
- **ICT (Internal Calibration Target), T_{ICT} and ϵ_{ICT}**
 - Pre-launch PRT calibrations
 - Pre-launch emissivity characterization
 - Pre-launch R_{ICT} verification using ECT at T_{ICT}
- **Nonlinearity, a_2 and V_{DC}**
 - Pre-launch Out-of-band harmonic analyses
 - Pre-launch ECT views at six temperatures
 - Post-launch Out-of-band harmonic analyses
 - Post-launch FOV-2-FOV analyses
- **Polarization, $p_r p_t$**
 - Optical design analyses and post-launch pitch maneuver data

Post-launch Evaluations

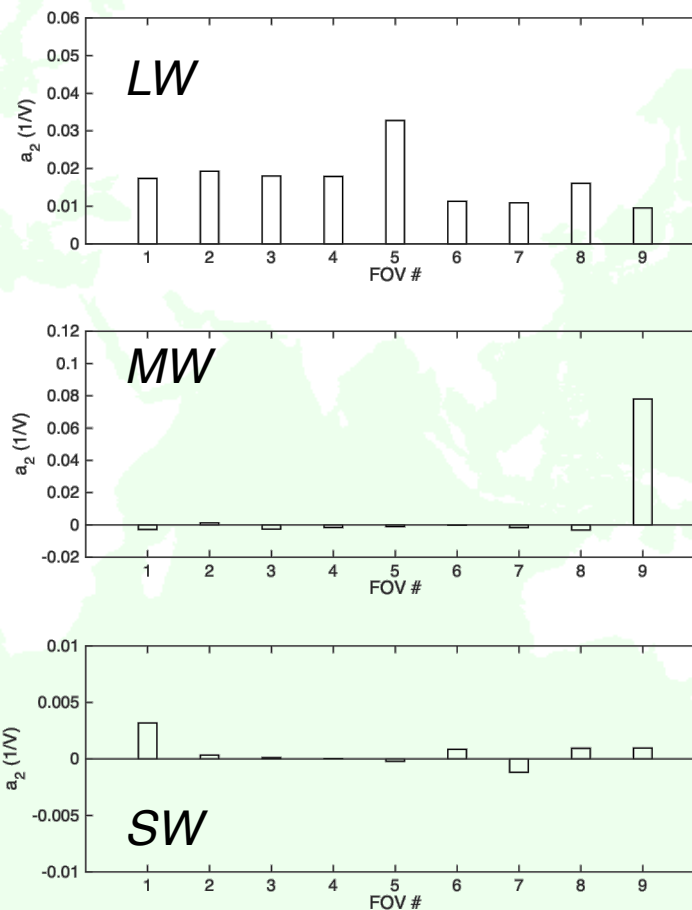
- FOV-2-FOV consistency
- Various comparisons including CrIS/VIIRS, CrIS/AIRS, CrIS/IASI, and associated double differences
- Clear sky Obs-Calc and Obs-Calc double differences

Nonlinearity Characterization, Pre-launch DM data (NOAA20 CrIS example)

$$\frac{FFT\{I_{fg}\}}{a_2 \cdot FFT\{I_{fg}^2\}}$$



Quadratic NL coefficients, a_2

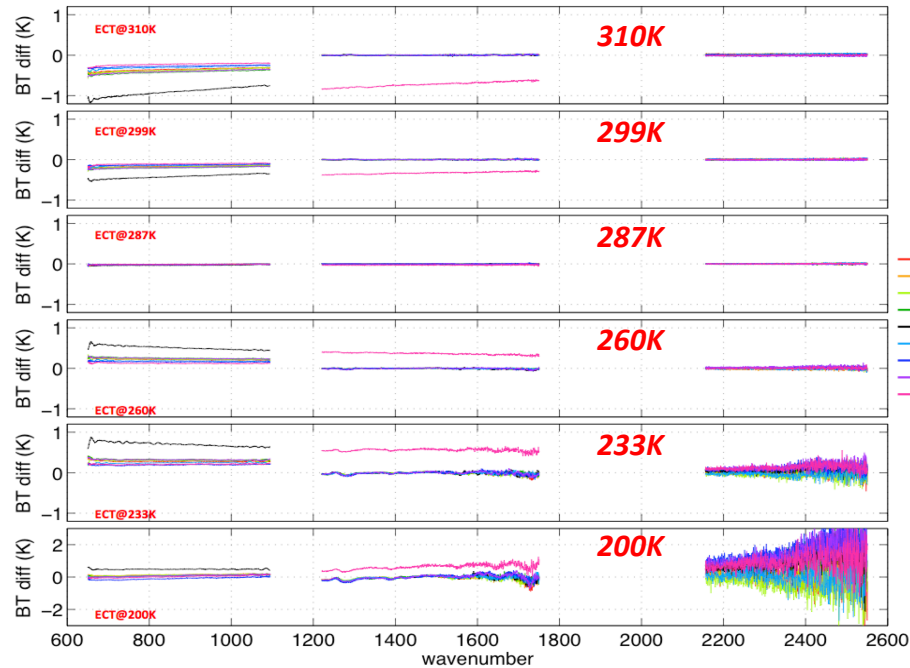


Main Findings:

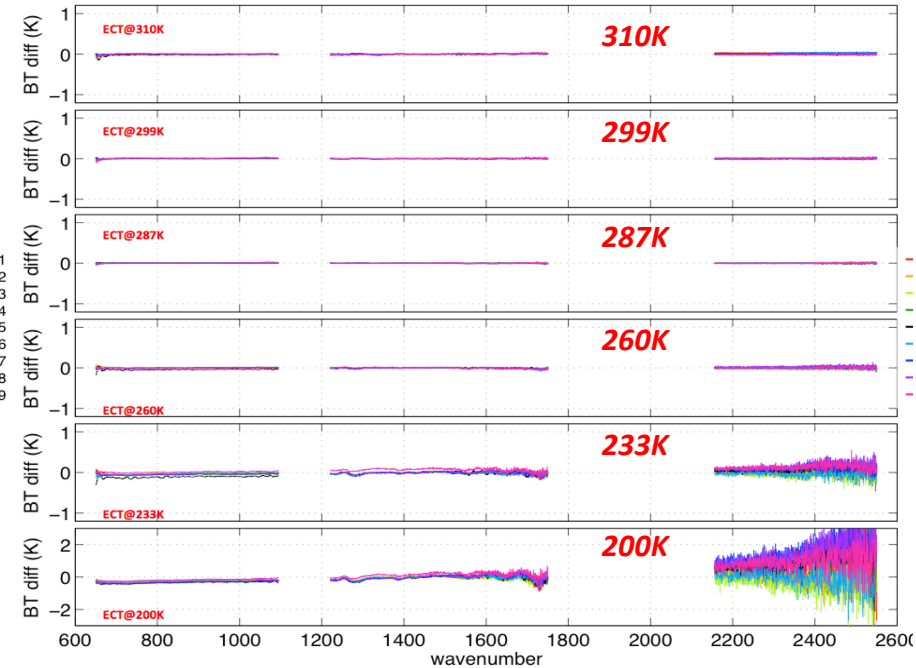
- **SW and MW FOVs 1-8** are very linear
- **LW and MW9** out-of-band signals are consistent with quadratic nonlinearity

Pre-launch External Calibration Target (ECT) view data at six temperatures (Nonlinearity and ICT temperature)

*ECT view (NOAA20, Oct 2014) BT residuals,
with linear calibrations:*

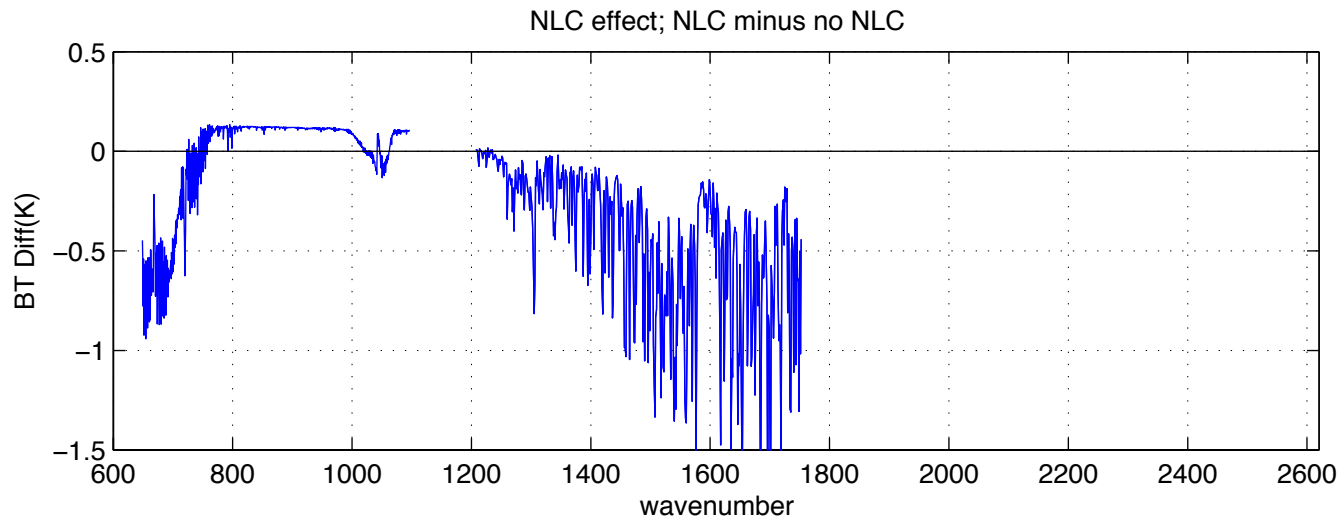
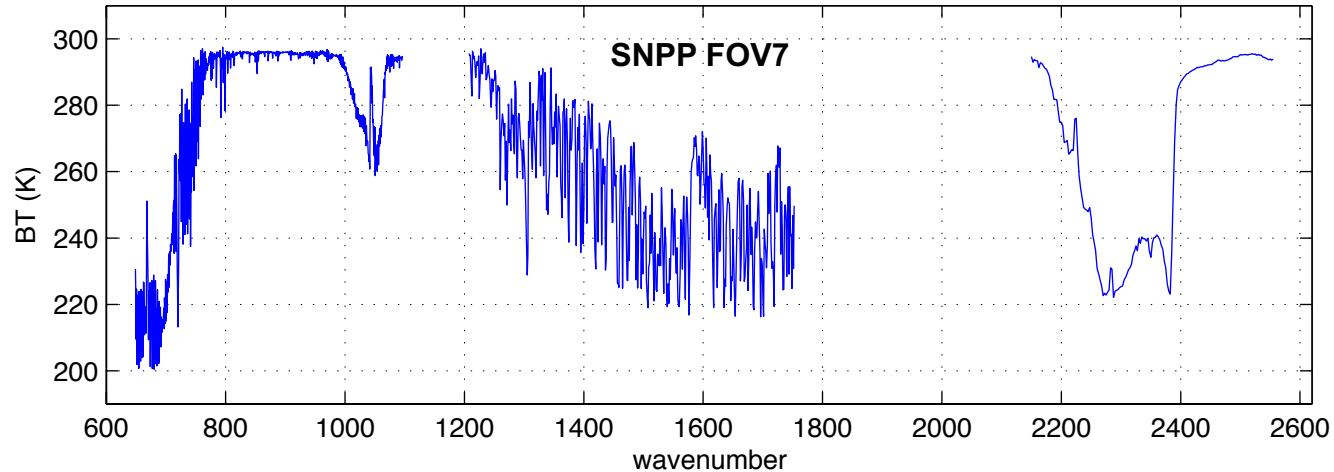


*with quadratic nonlinearity correction
and v113 EP a2 values*



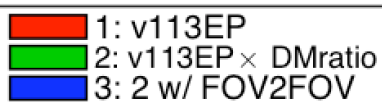
- ECT view data used to assess ICT temperature accuracy and determine a_2 s
- a_2 determinations are needed for overall radiometric accuracy but also for optimal agreement among FOVs
- Cold shortwave evaluations limited by lack of true space view in pre-launch TVAC

Example Quadratic nonlinearity correction for a typical clear sky spectrum

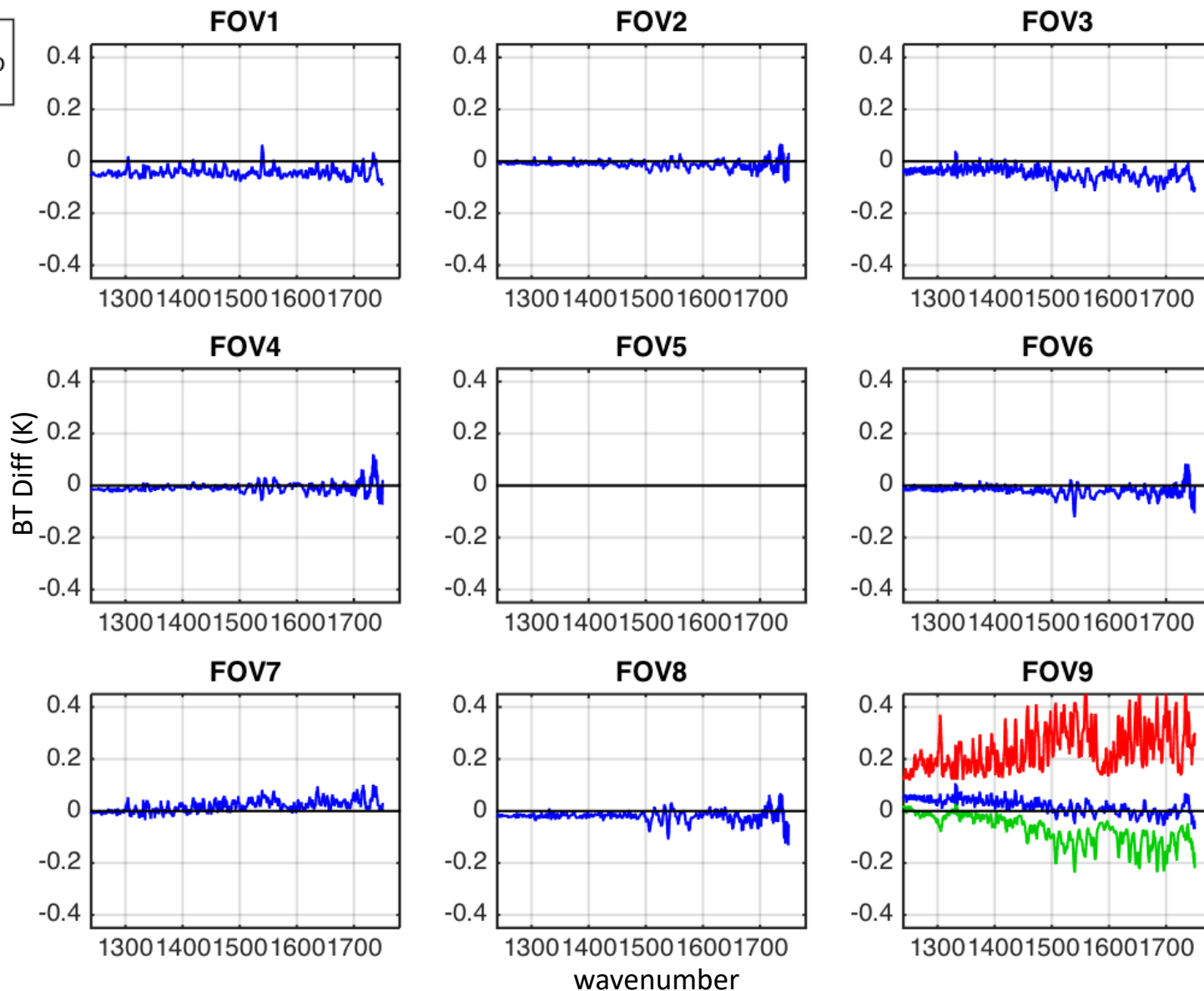


On-Orbit Refinements using Earth view spectra

FOV-to-FOV Brightness Temperature Differences, Midwave band:

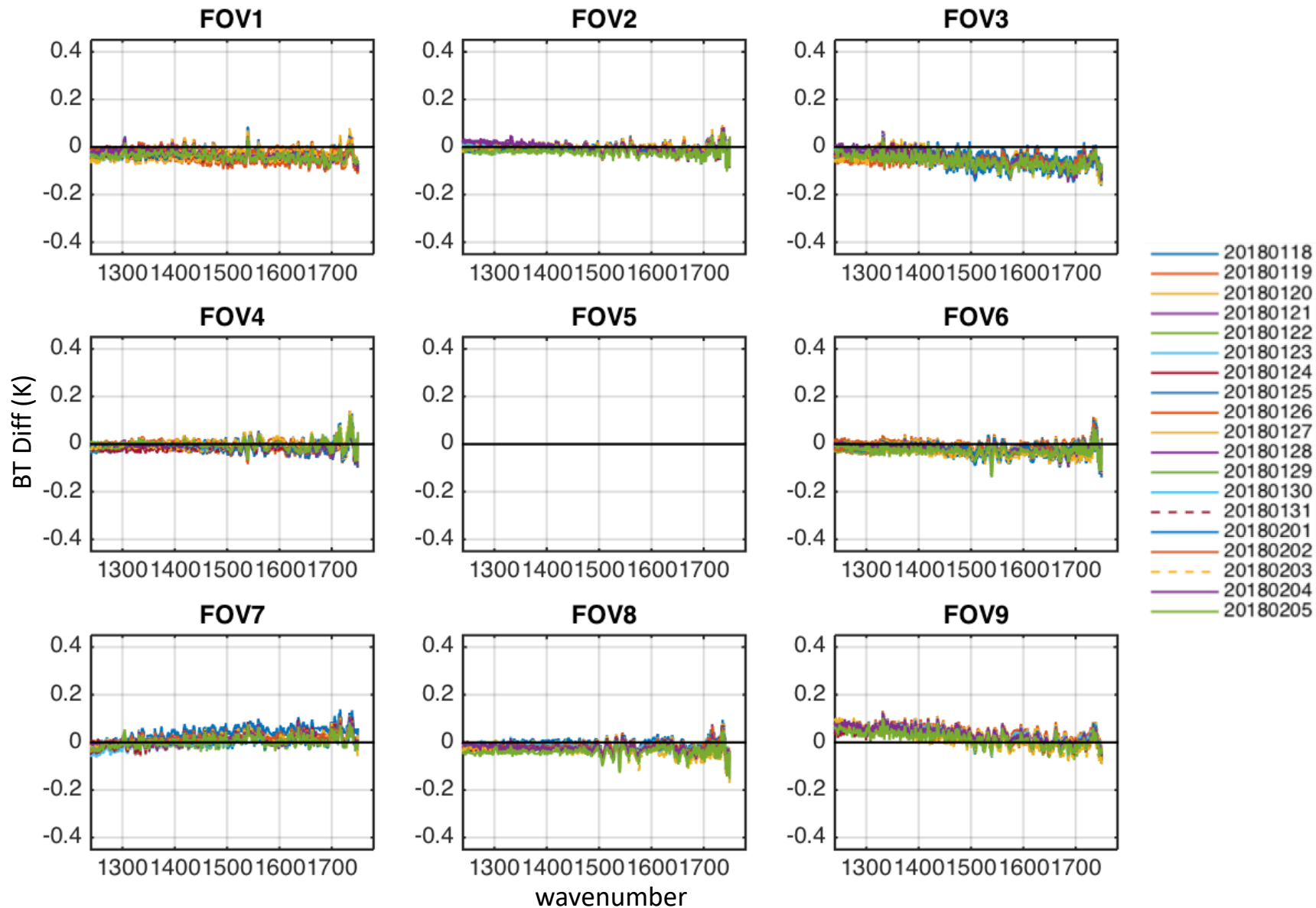


- FOV2FOV differences minimized in 1580-1600 cm^{-1} region
- 21 Jan Golden Day
- Differences from reference FOV 5 for near nadir FORs (13-18)
- Weighted Mean of all granules

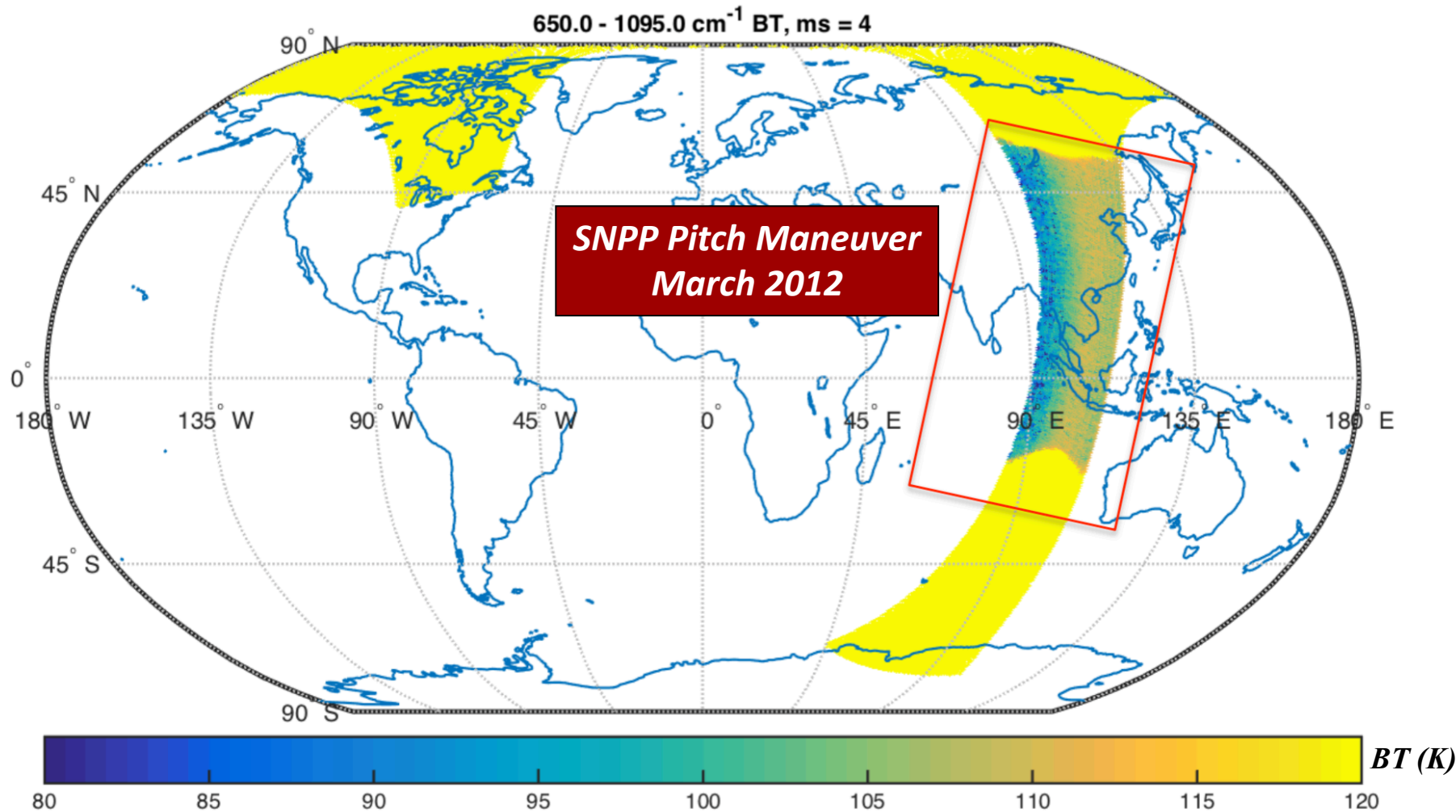


Midwave Band FOV2FOV BT Differences

Daily assessments 18 Jan to 5 Feb 2018

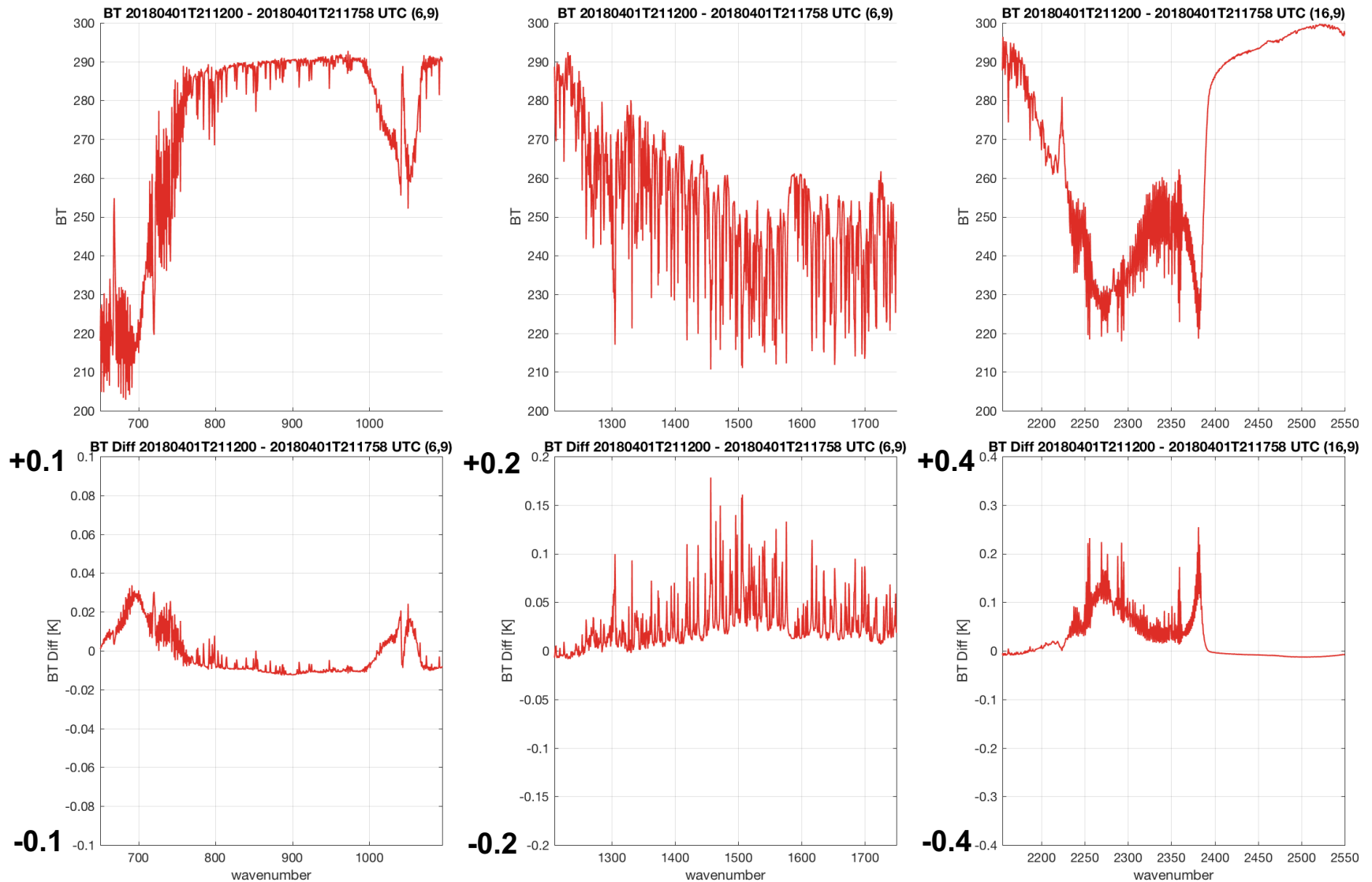


Views of Deep space during the Pitch Maneuvers clearly demonstrate a scan angle dependent calibration effect (without polarization correction)



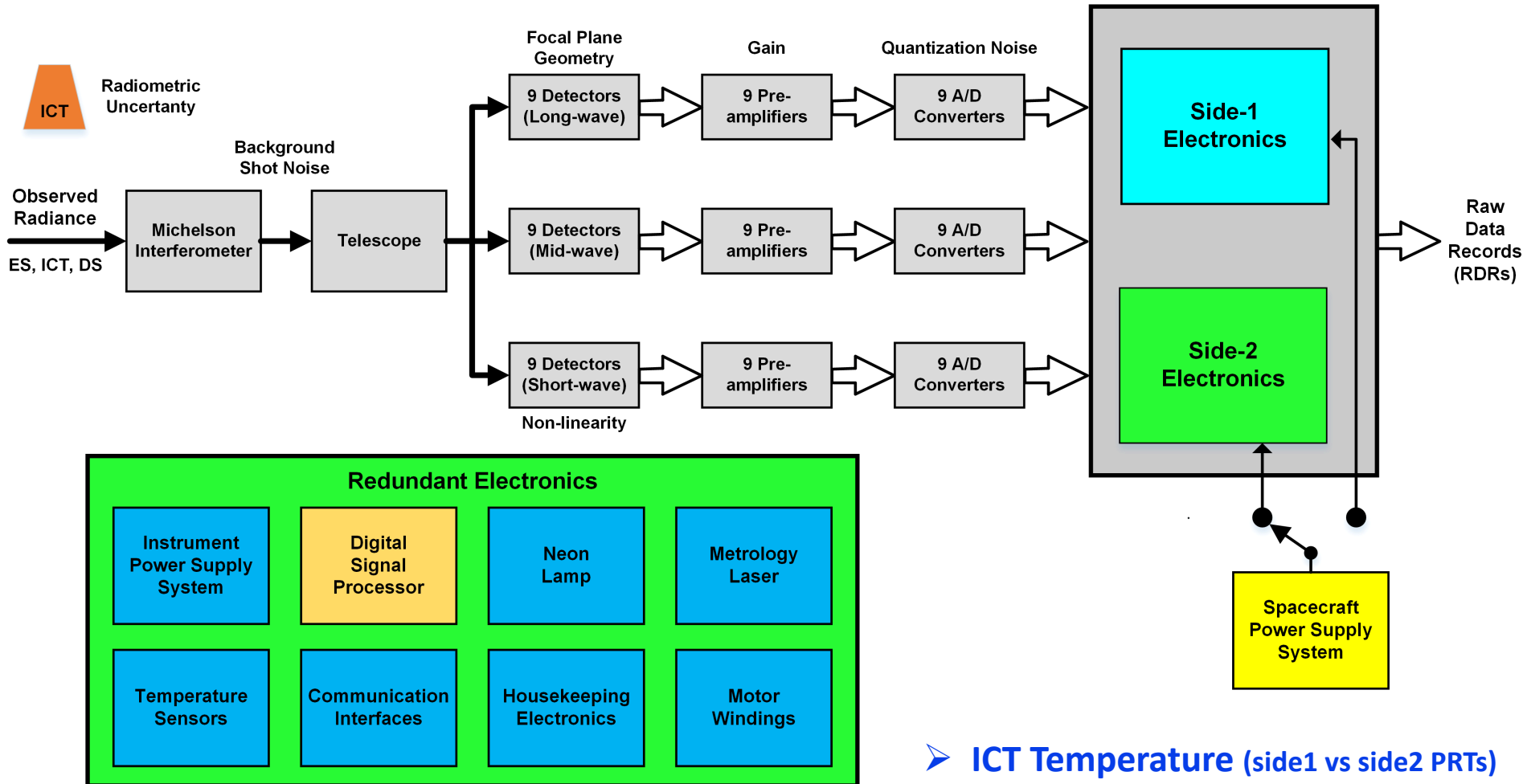
“Earth view” data of deep space at multiple view angles collected during the spacecraft pitch maneuvers has been used to characterize the CrIS polarization effects, and to develop polarization corrections which have been incorporated into calibration software.

Example Polarization Correction for a Tropical clear sky spectrum



2019 SNPP CrIS Electronics Side switch:

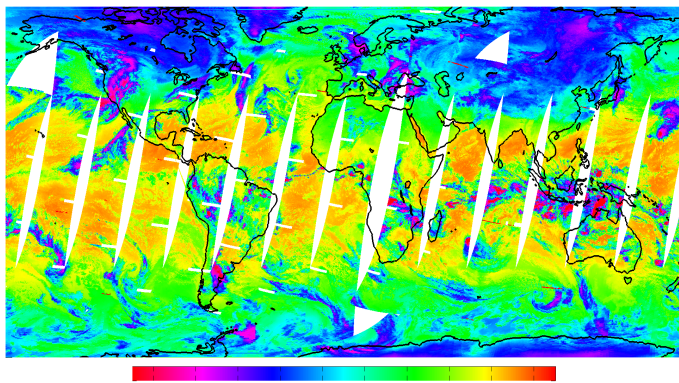
➤ Different ICT PRTs from side1 to side2



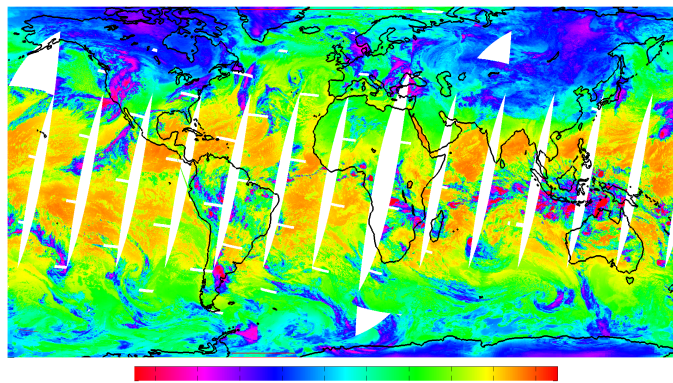
- **ICT Temperature** (side1 vs side2 PRTs)
- **ICT environmental model**
- **Detector Nonlinearity**
- **Polarization**

CrIS/VIIRS Comparisons

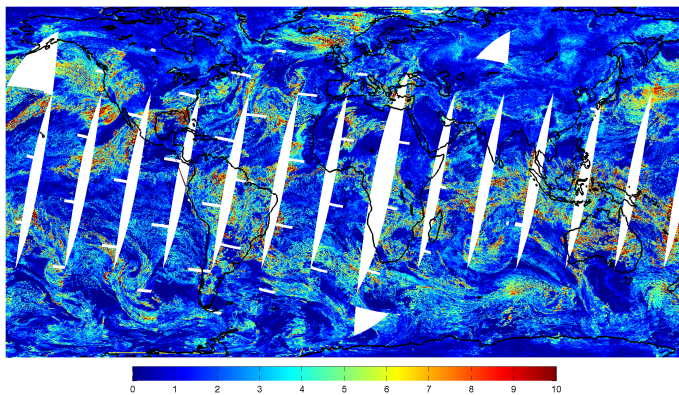
1) CrIS convolved with VIIRS SRF



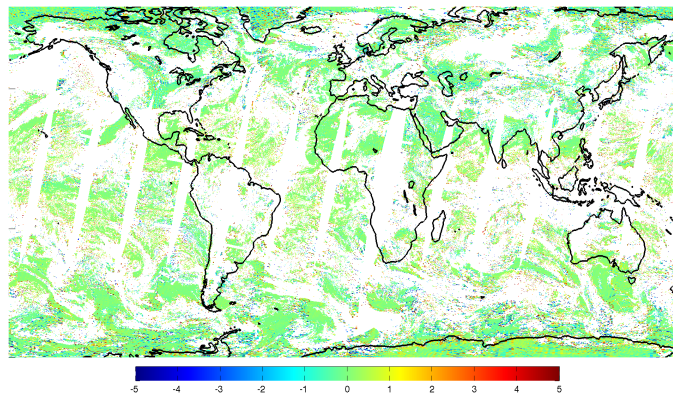
2) VIIRS mean within CrIS footprint



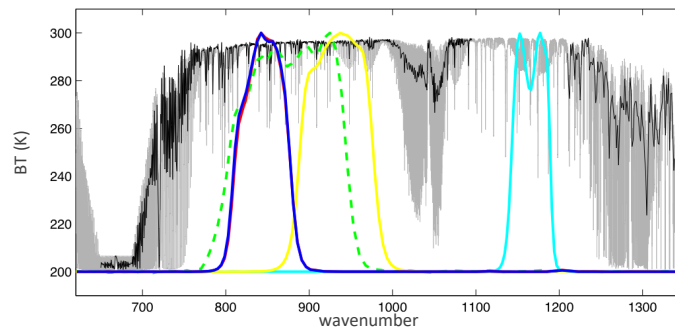
3) VIIRS StdDev within CrIS footprint



4) VIIRS-CrIS differences for homogeneous footprints

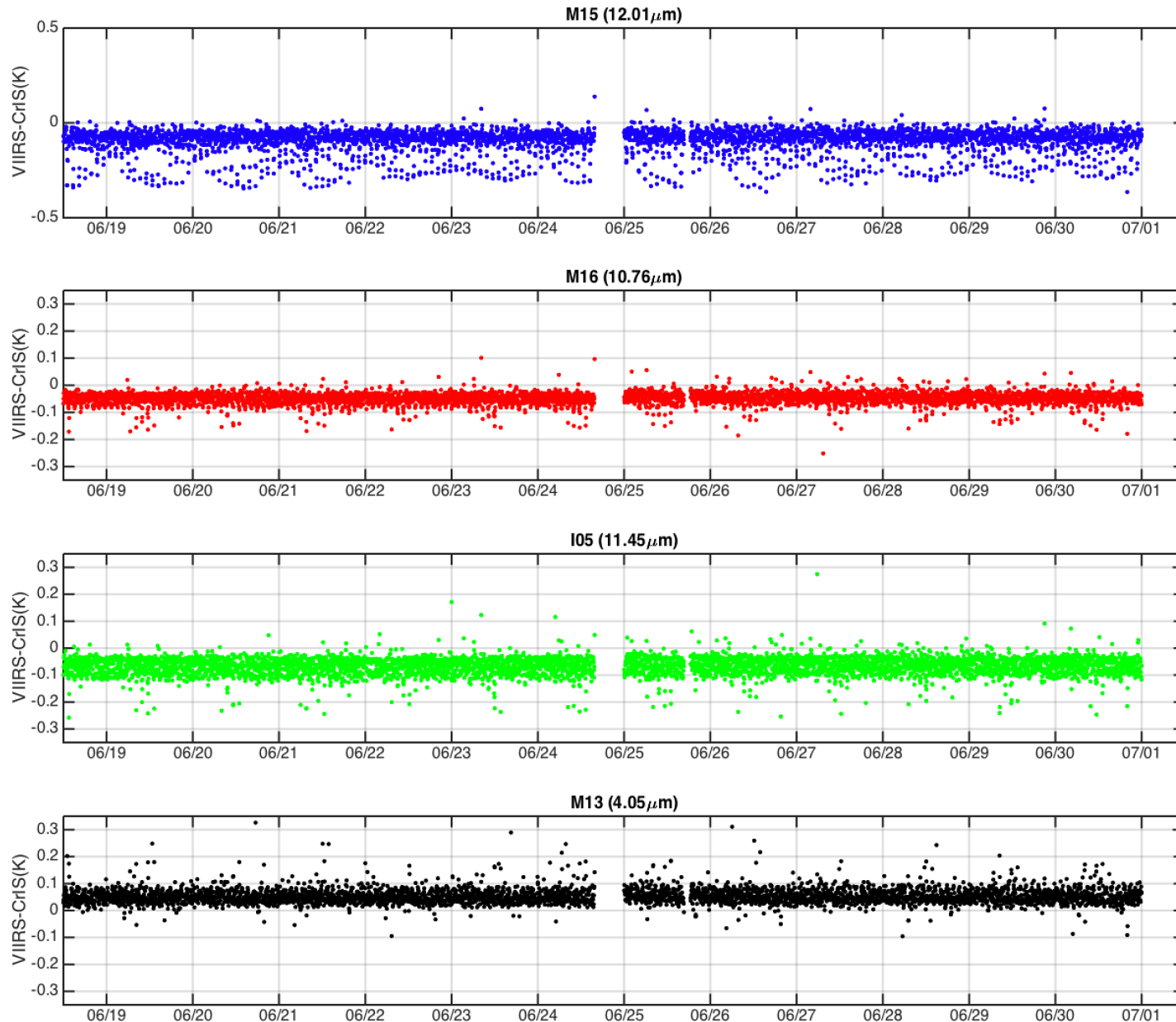


M16 I5 M15

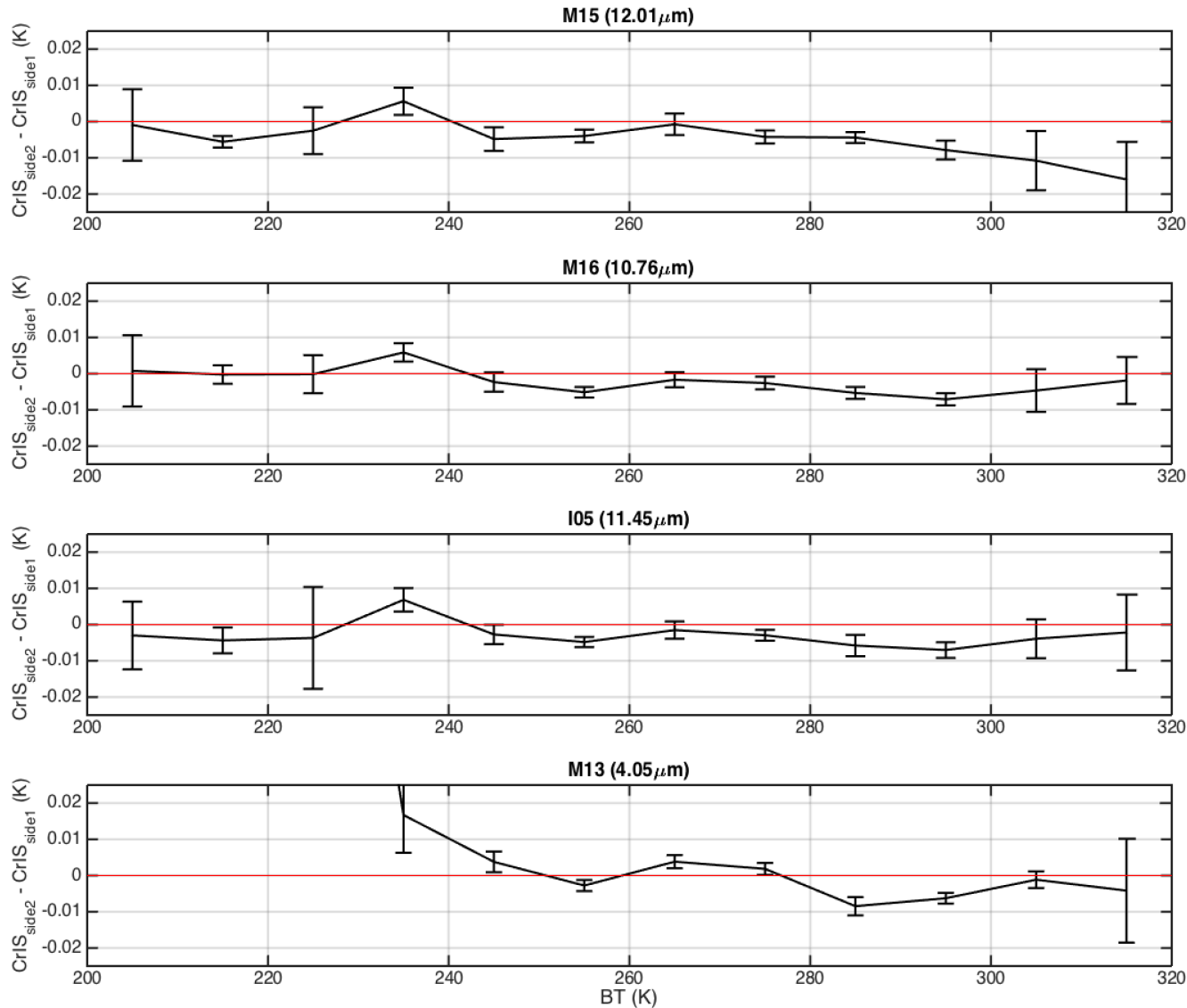


Time-series of differences before and after side switch on 6/24

(average difference for every 4 minutes, all uniform scenes, all FOVs)

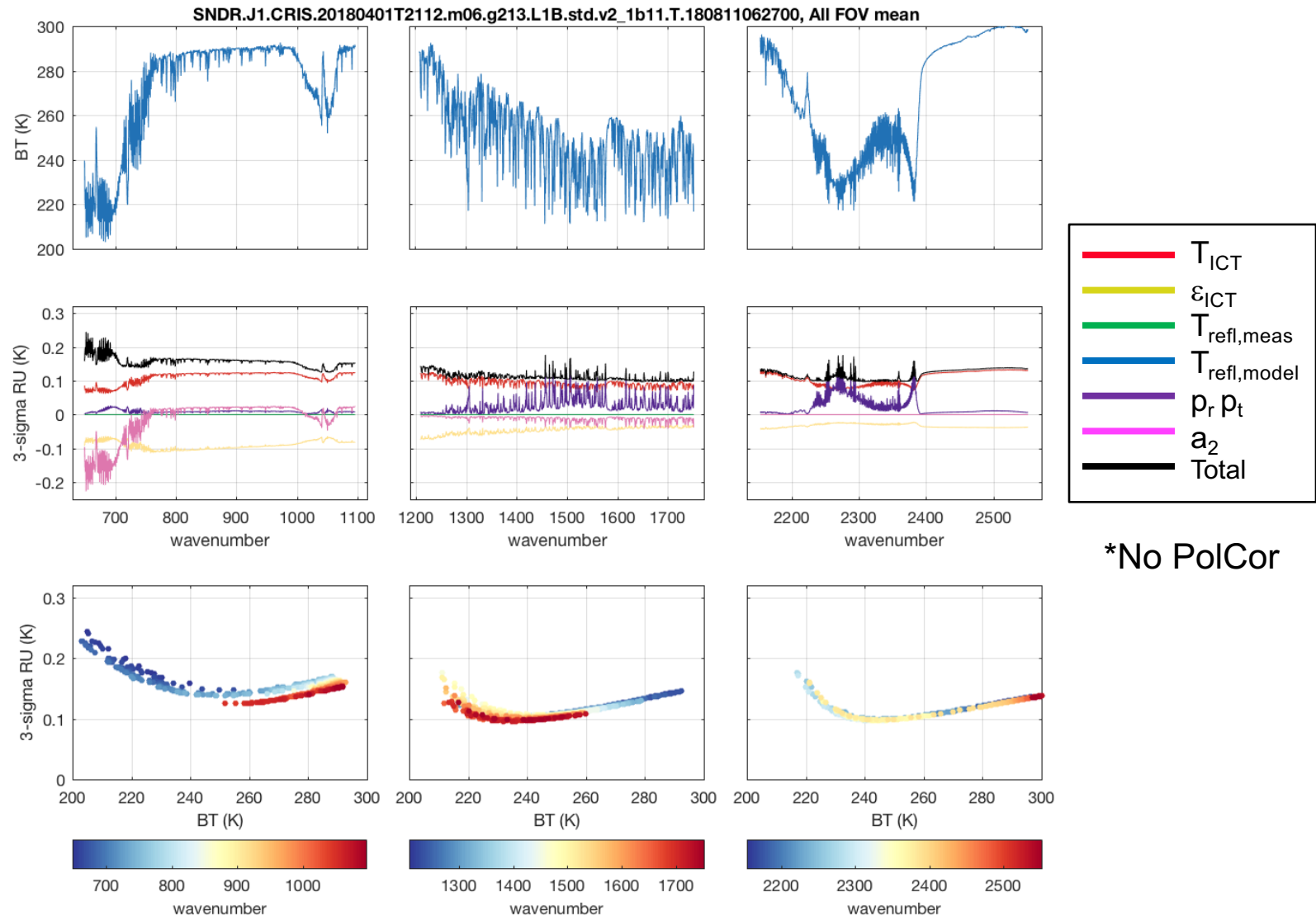


CrIS Side 2 minus CrIS Side 1 as a function of scene BT using CrIS/VIIRS 5 days prior to and 5 days after the side switch (all uniform scenes, all FOVs) k=2 error-bars

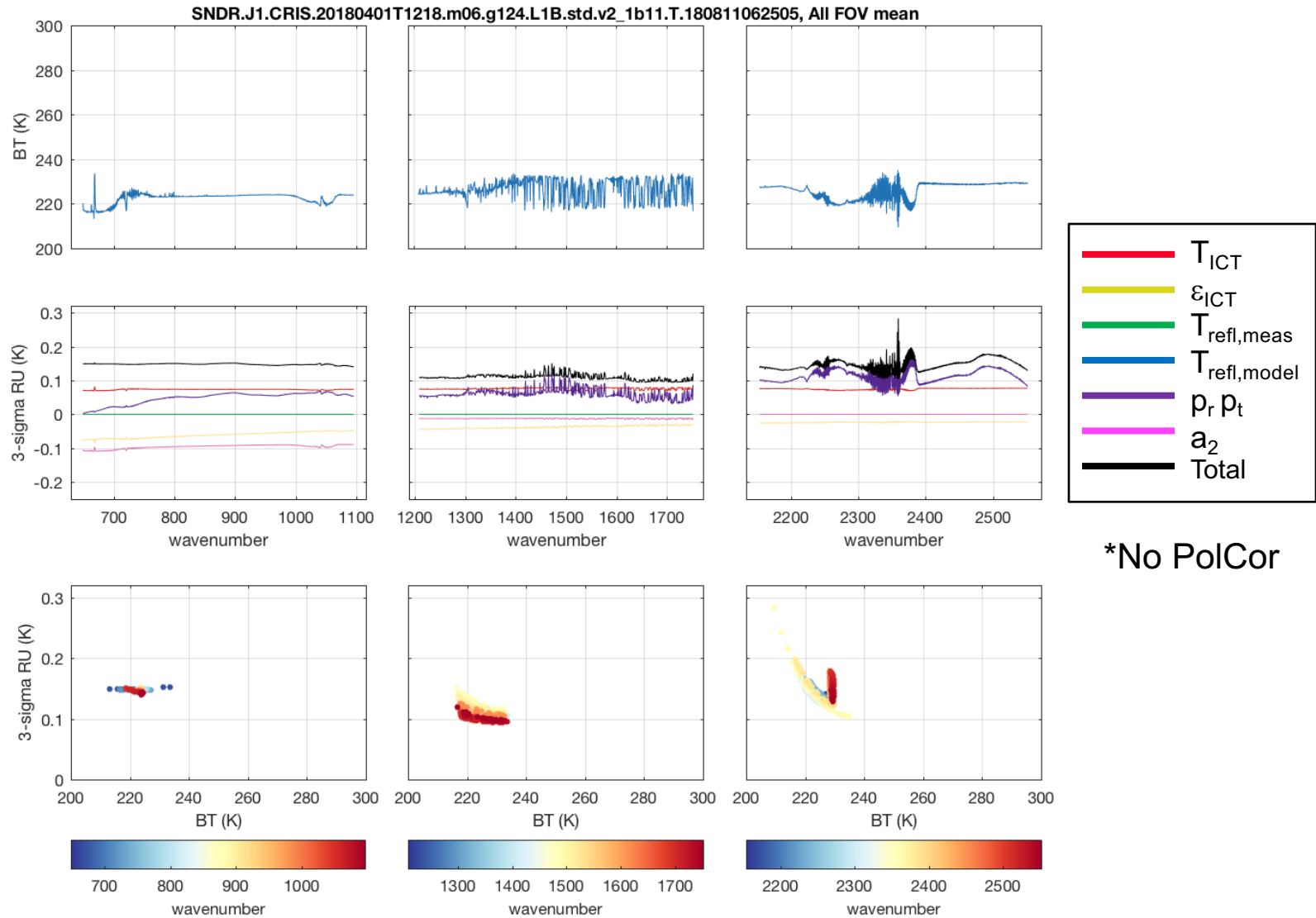


➤ Changes at the ICT temperature ($\sim 280\text{K}$) are consistent and suggest changes in the ICT temperature calibration from side1 to side2 of ~ 5 to 7mK (compared to 37mK 1σ estimated total uncertainty in ICT T, with PRT contribution of 19mK)

For a warm clear sky scene (~worst case)

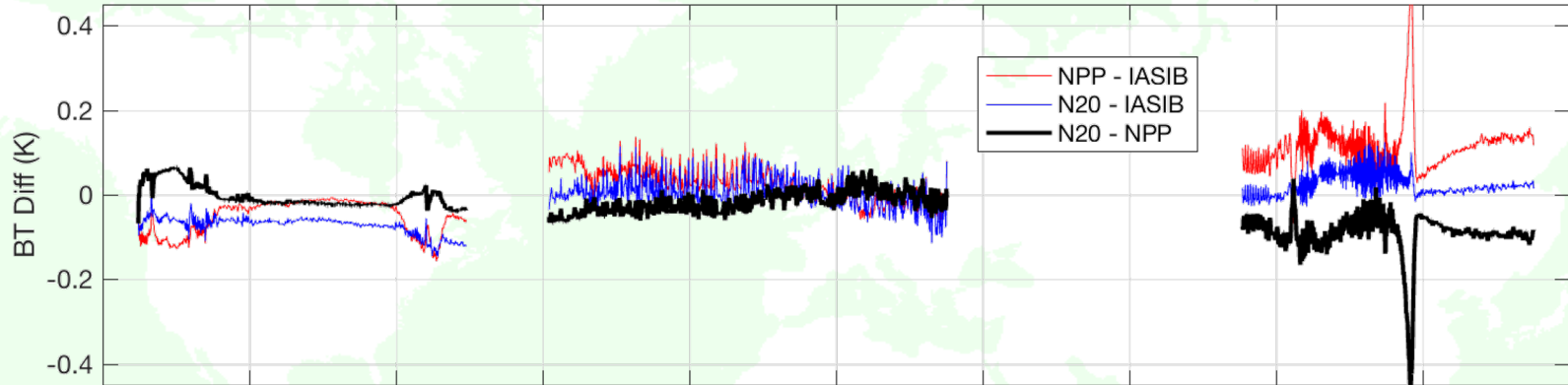


Example 3-sigma RU estimates For Antarctic cloud scene

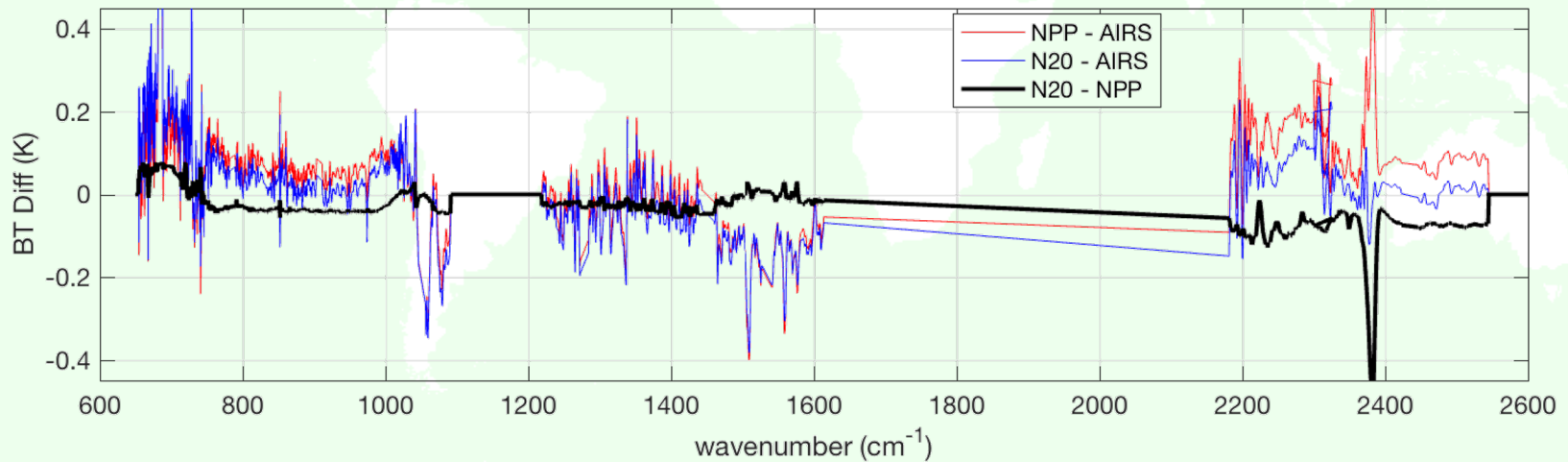


Example Cal/Val Result: SNOs with IASI and AIRS

Differences with IASI-B, and NOAA20/SNPP differences via IASI-B



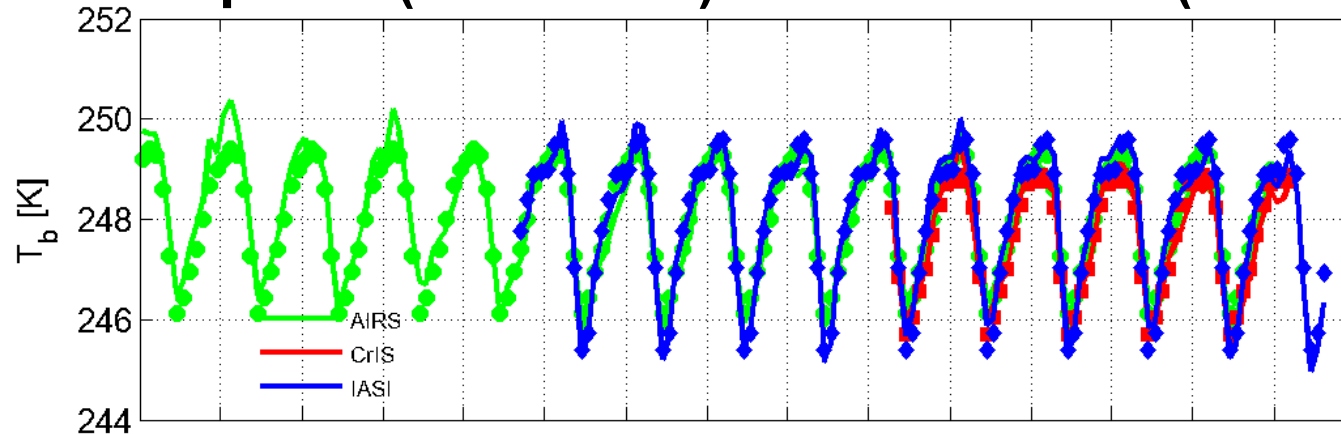
Differences with AIRS, and NOAA20/SNPP differences via AIRS



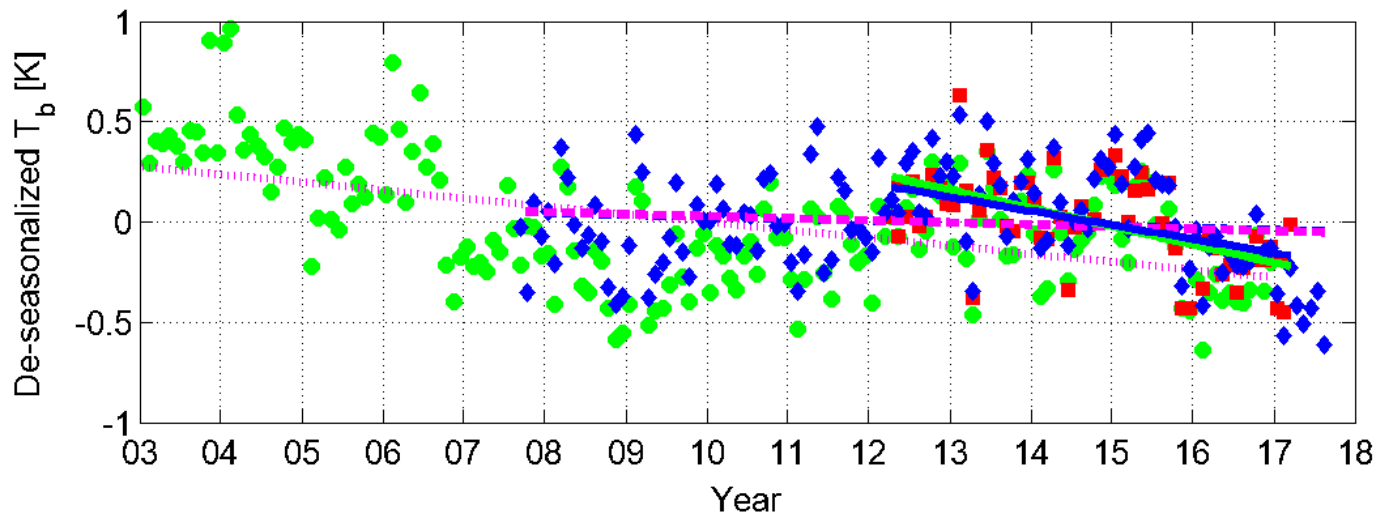
- Differences between NOAA20 CrIS and SNPP CrIS are less than 0.1K
- Differences from IASI-B are less than 0.2K, Differences from AIRS are less than 0.4K
- Larger diffs observed for cold SW scenes; expect improvements with polarization correction

Example Radiance based Climate Product

Upper Stratosphere (667.8 cm^{-1}) BT Time Series (Global, Monthly):



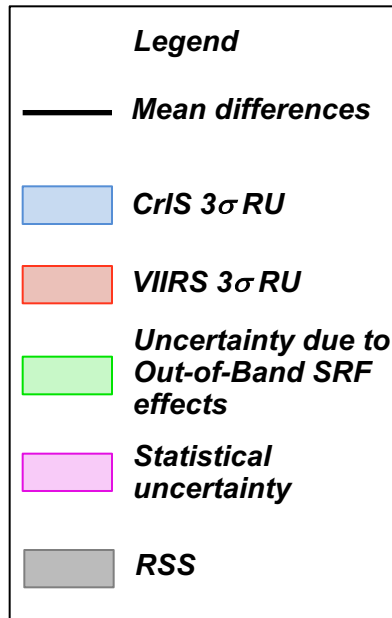
Deseasonalized Trends:



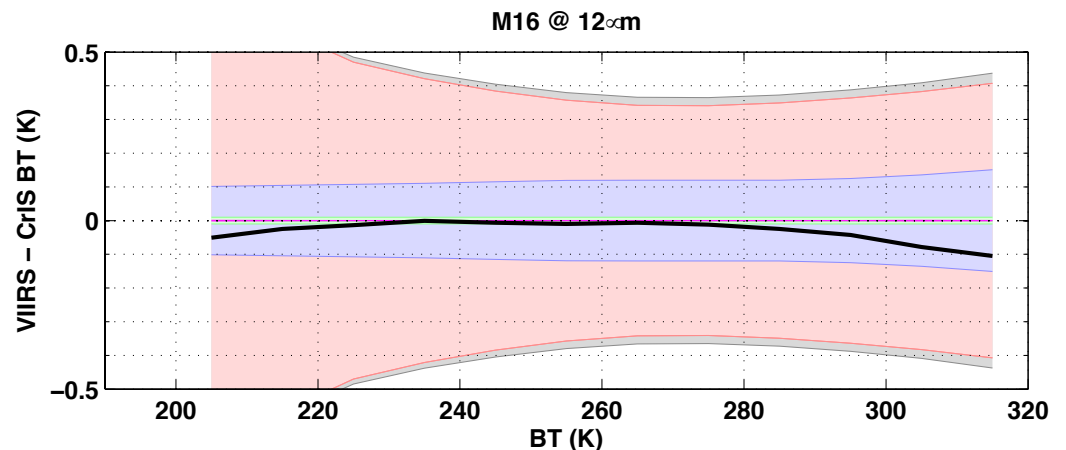
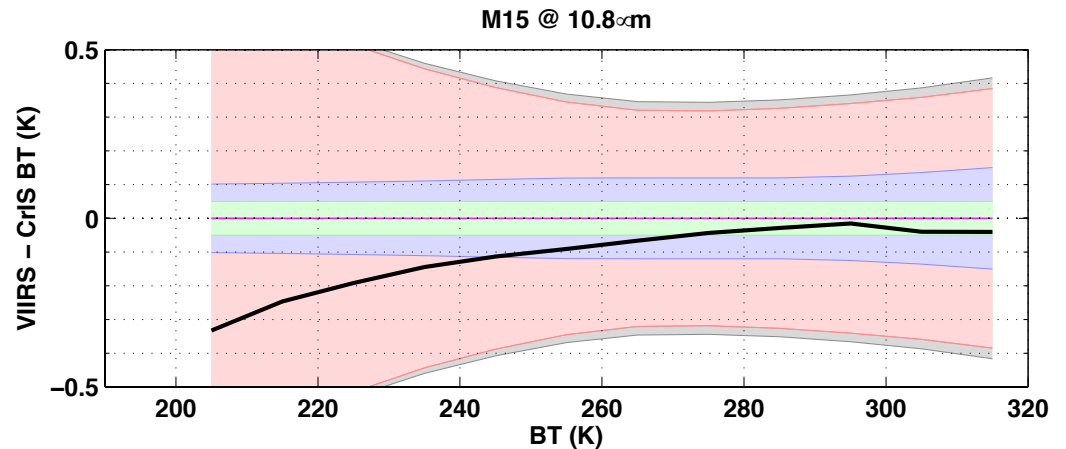
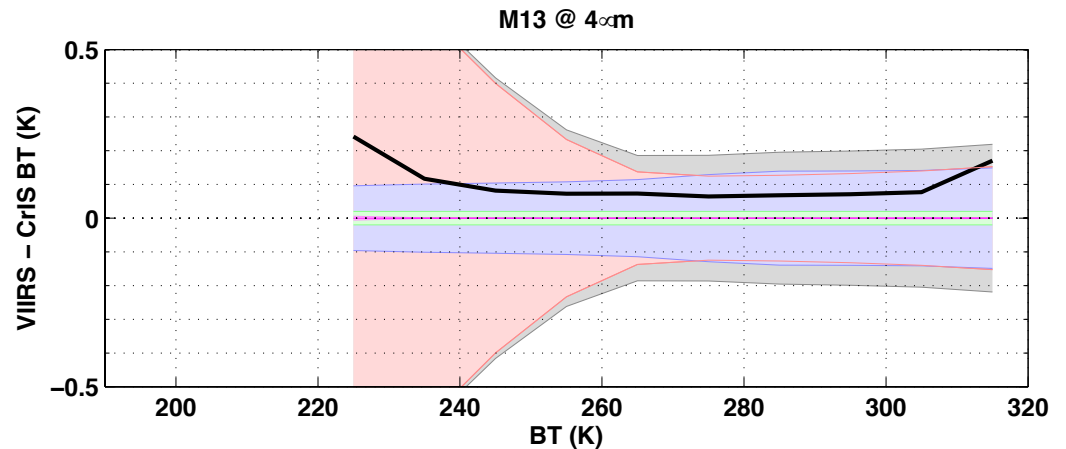
2012-2017 trends:

AIRS	IASI	CrIS
-90 +/- 42 mK/yr	-70 +/- 35 mK/yr	-80 +/- 35 mK/yr

CrIS/VIIRS comparisons versus scene temperature



- VIIRS RU estimates provided by Jeff McIntire et al.
- CrIS uncertainties here do not include polarization contribution
- Scene dependent differences observed for M15, but all differences are bounded by combined RU



SNPP daily mean differences

(All FOV mean, all scene BTs)

M15 (12.01 μ m):

All FOV bias = -99.9 ± 5.3 mK

All FOV trend = -1.25 ± 0.06 mK/yr

M16 (10.76 μ m):

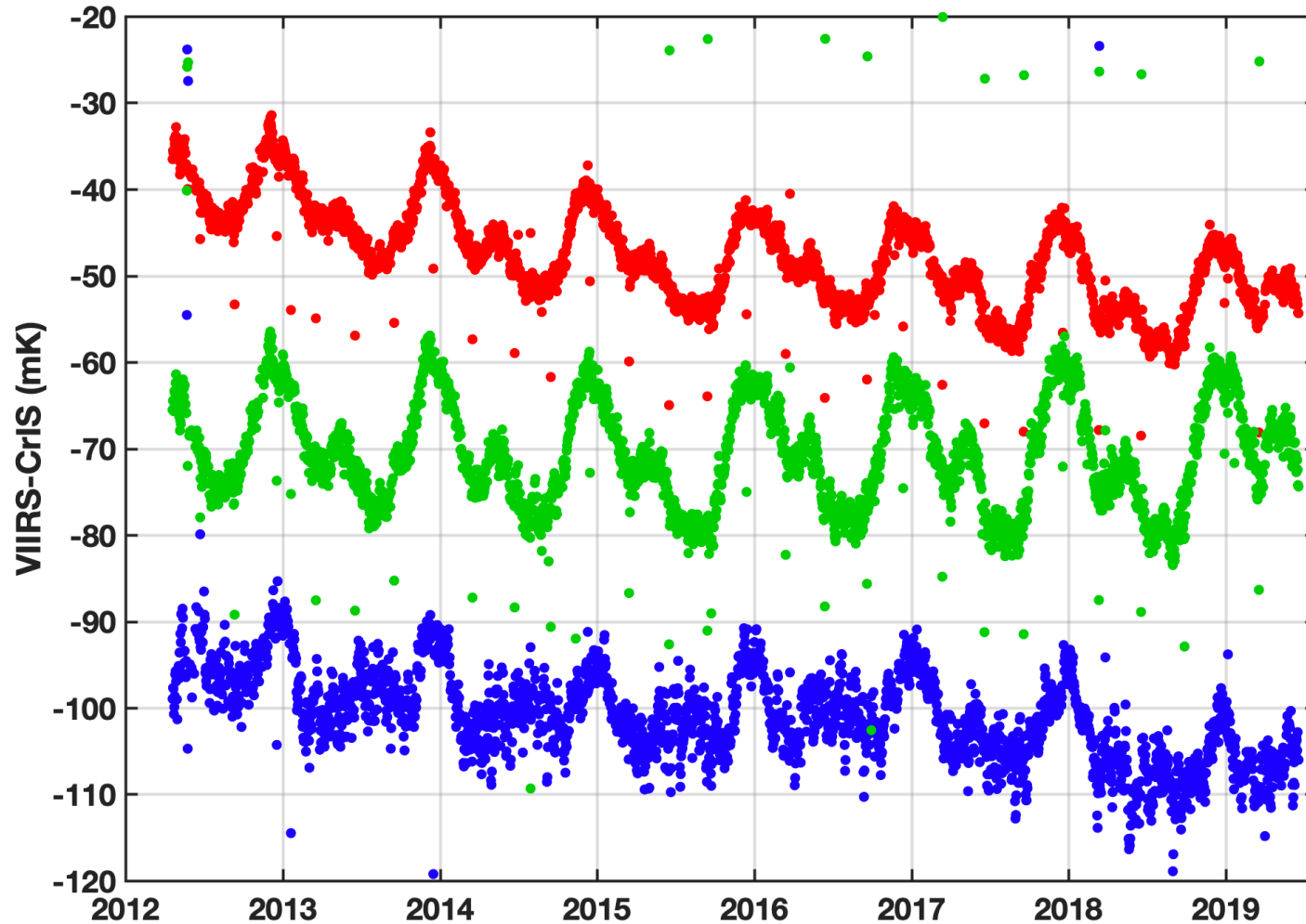
All FOV bias = -46.9 ± 5.5 mK

All FOV trend = -2.02 ± 0.06 mK/yr

I05 (11.45 μ m):

All FOV bias = -70.9 ± 6.2 mK

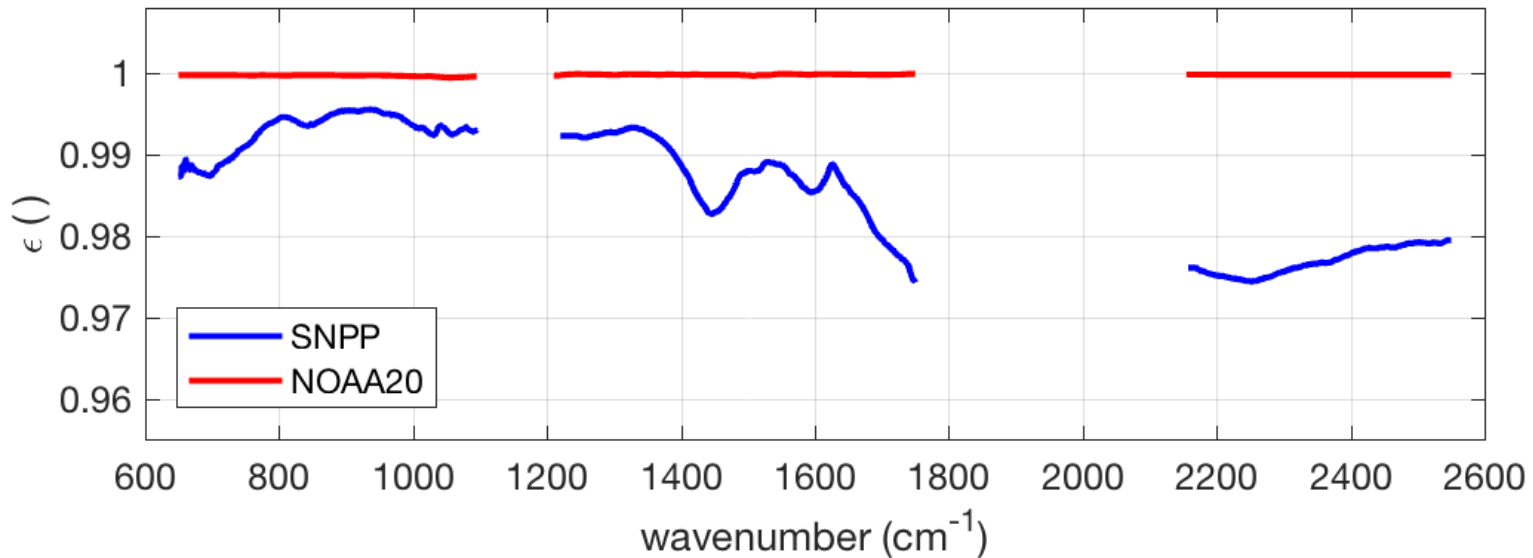
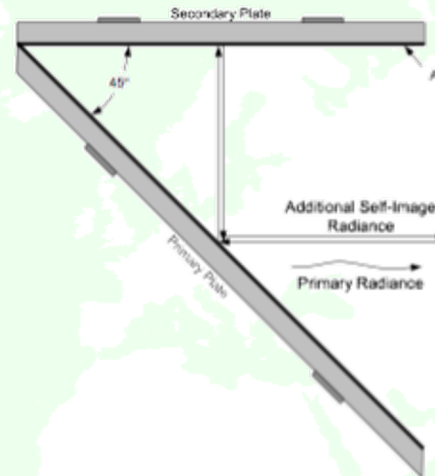
All FOV trend = -0.29 ± 0.09 mK/yr



(Quarterly outliers are VIIRS WUCD events)

Improved ICT for NOAA20 CrIS

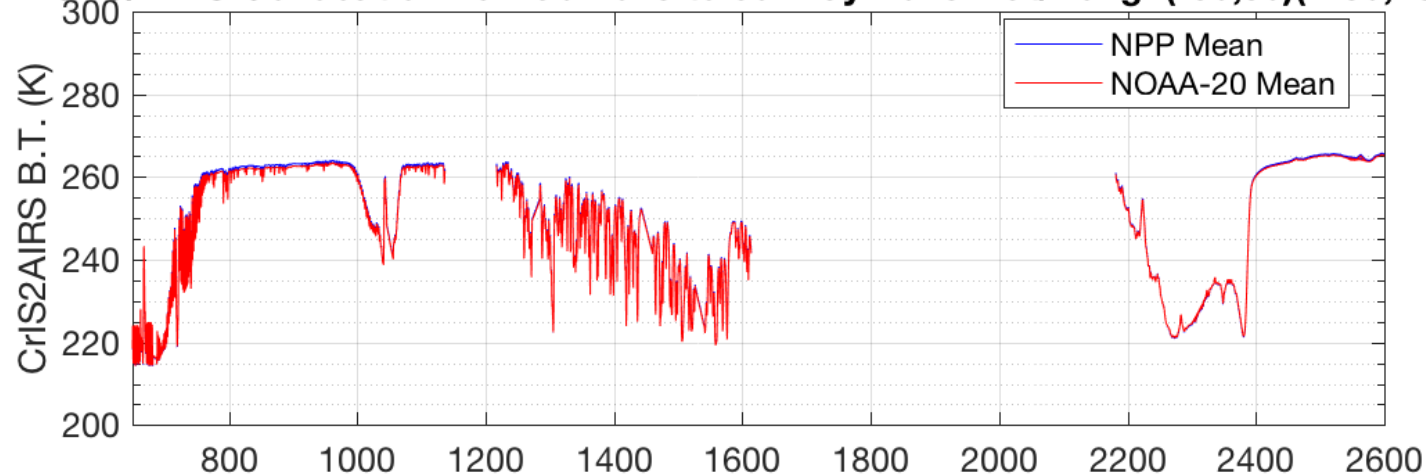
- ◆ Three bounce specular trap design, Z302 paint.
- ◆ Cavity emissivity > 0.9995



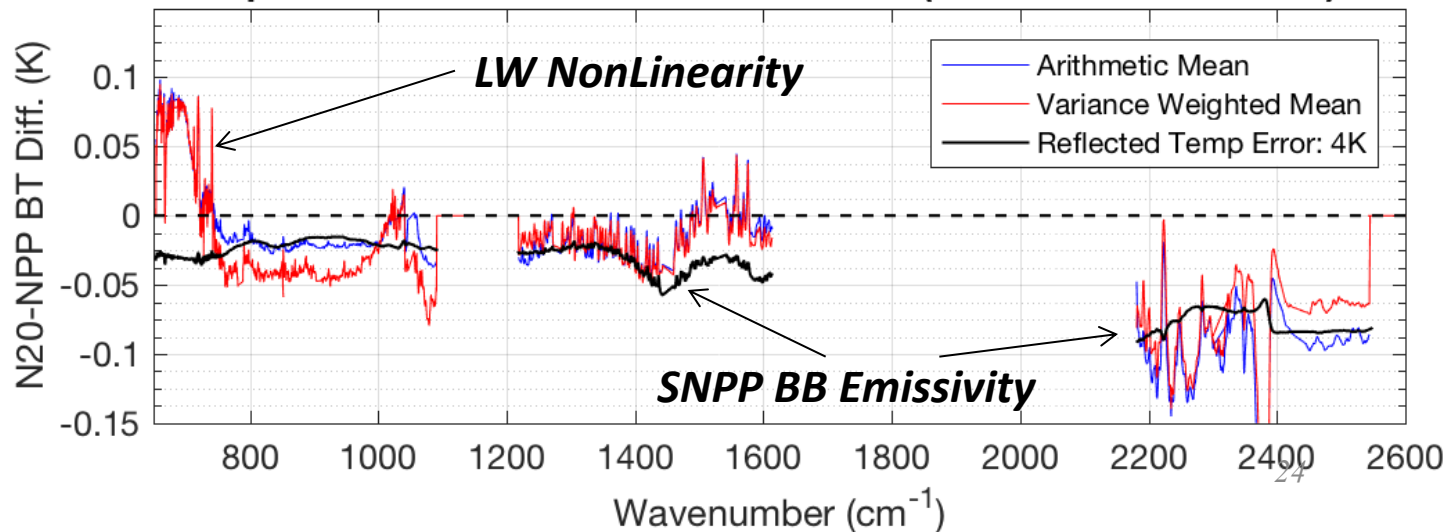
CrIS/AIRS Inter-comparisons accurately characterize SNPP/NOAA20 CrIS differences

- Planning re-calibration to create better *consistency*

CrIS/AIRS Collocation 15-Feb-2018 to 30-May-2018 Lat/Long: (-90,90)(-180,180)



Apodized CrIS/AIRS Double Difference (NOAA-20 minus SNPP)



IR Climate Benchmarking & Intercalibration

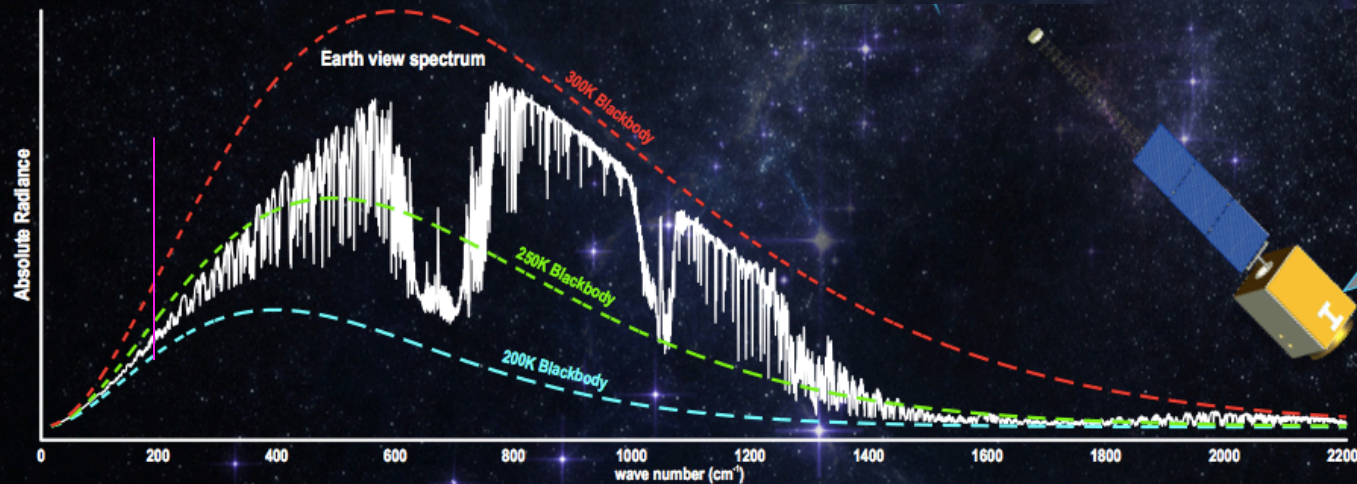
2011 NASA Earth Venture proposal

Benchmarking Radiance for Climate Change:

With the rapid increase in climate forcing through the addition of infrared active molecules to the atmosphere by fossil fuel combustion and the probability of carbon release from expanding melt zones in the Arctic, the need for irrefutable observations to define the current state of the atmosphere is becoming increasingly critical. The first goal of the Zeus mission is to provide a global benchmark climate record for this and future generations that, by virtue of its high accuracy determined against international standards on-orbit, establishes a new foundation for quantitatively defining the rate of climate change. Achieving this goal will provide decision support for a range of societal issues including water resources, human health, natural resources, energy management, insurance infrastructure, and others that are linked to our understanding of how climate is changing. *The first science objective of Zeus is to provide a benchmark of the thermal infrared radiance spectrum against which similar future observations can be compared to establish atmospheric change with credibility.*

Benchmarking Radiance for Climate Forecast Testing:

Significant uncertainties exist in forecasts of our future climate. For example, the differences between the IPCC Fourth Assessment models is significant indeed, ranging from virtually no predicted change to a change of 0.6 K/decade between the Japanese medium resolution model and the GISS-EH model for the North American region. Central to the climate sensitivity discrepancy among different IPCC models, is their different climate feedback strengths. To narrow down the uncertainty of climate projection given by the ensemble of these models, it is imperative to measure and confront these models with the feedback strengths measured from observations. *To address this issue, the second science objective of Zeus is to provide a benchmark of the thermal infrared radiance spectrum to determine longwave forcings and longwave feedbacks for testing climate models.*



Benchmarking Radiance for Reanalysis and Intercalibration:

Weather forecast systems utilize data from a wide range of satellite systems and sensors that are primarily designed for operational weather forecast requirements. Eliminating biases between the various sensors is important for making optimal use of the data, and is a primary goal of the Global Space-based Intercalibration System (GSICS) and data assimilation centers. A spectral radiance dataset with high accuracy and on-orbit traceability is required for both Reanalysis methods employing data assimilation techniques and direct intercalibration techniques such as Simultaneous Nadir Overpass analyses to anchor the calibration of the operational weather sensors. *Addressing this issue, the third science objective of Zeus is to provide a benchmark of the thermal infrared spectrum that can provide reference intercalibration for other sensors and for anchoring reanalysis.*



Characterization of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) ability to serve as an infrared satellite intercalibration reference

Tobin, D., R. Holz, F. Nagle, and H. Revercomb

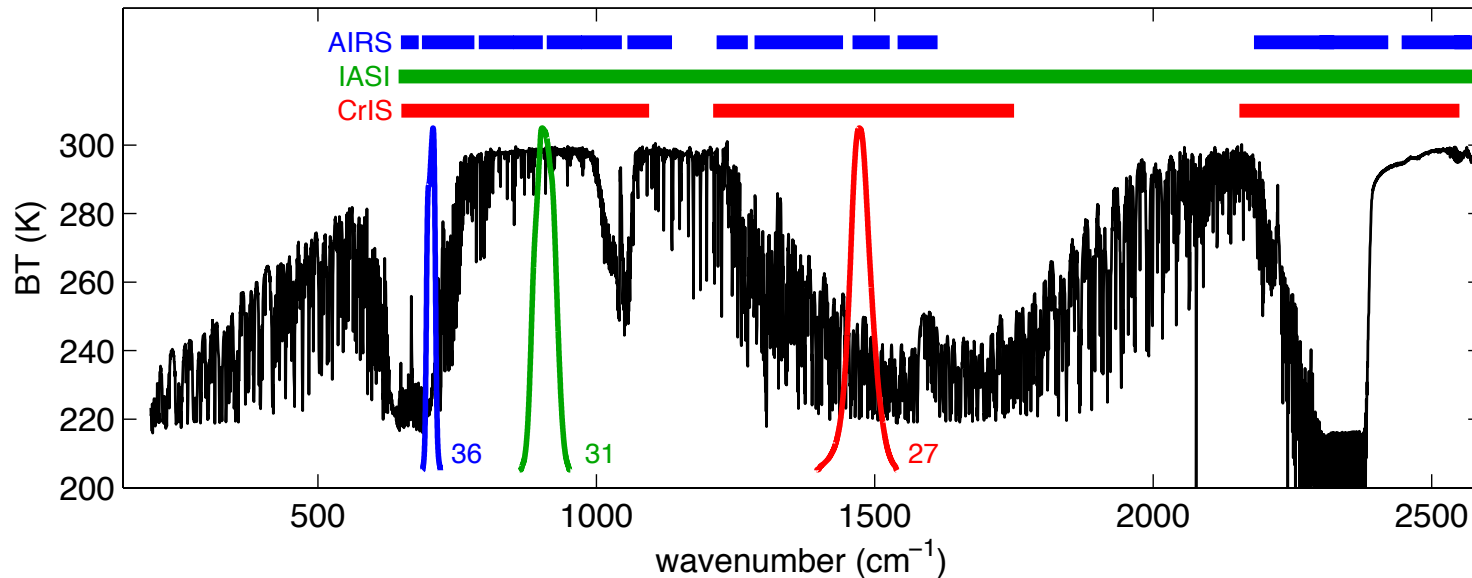
J. Geophys. Res. Atmos., 121, doi:[10.1002/2016JD024770](https://doi.org/10.1002/2016JD024770) (2016).

*International
Space Station*

Investigation performed with support from the NASA LaRC CLARREO Project

***Method for minimizing the effects
of space/time sampling differences
and defining associated uncertainty***

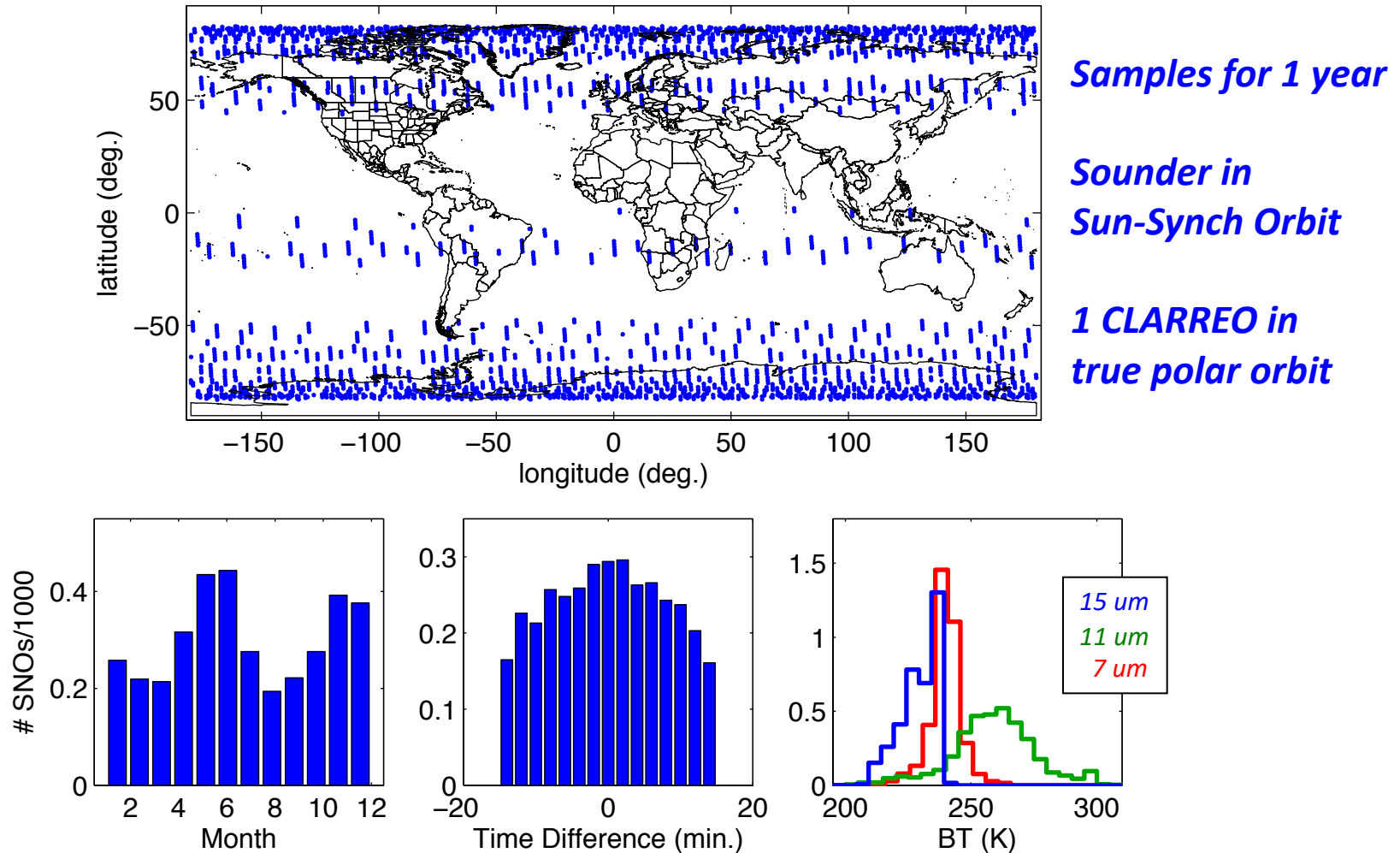
Paper simulates intercalibration sampling errors using MODIS data for bands 36 (14.2 micron CO₂), 31 (11 micron window), 27 (6.7 micron water vapor)



Intercalibration uncertainties investigated as a function of:

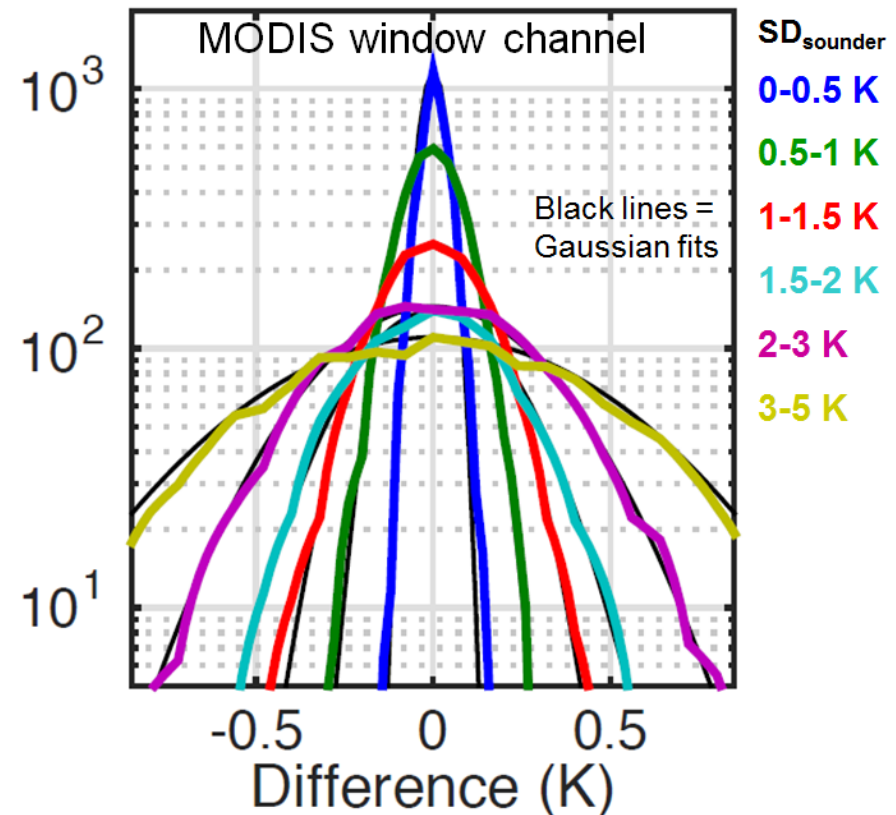
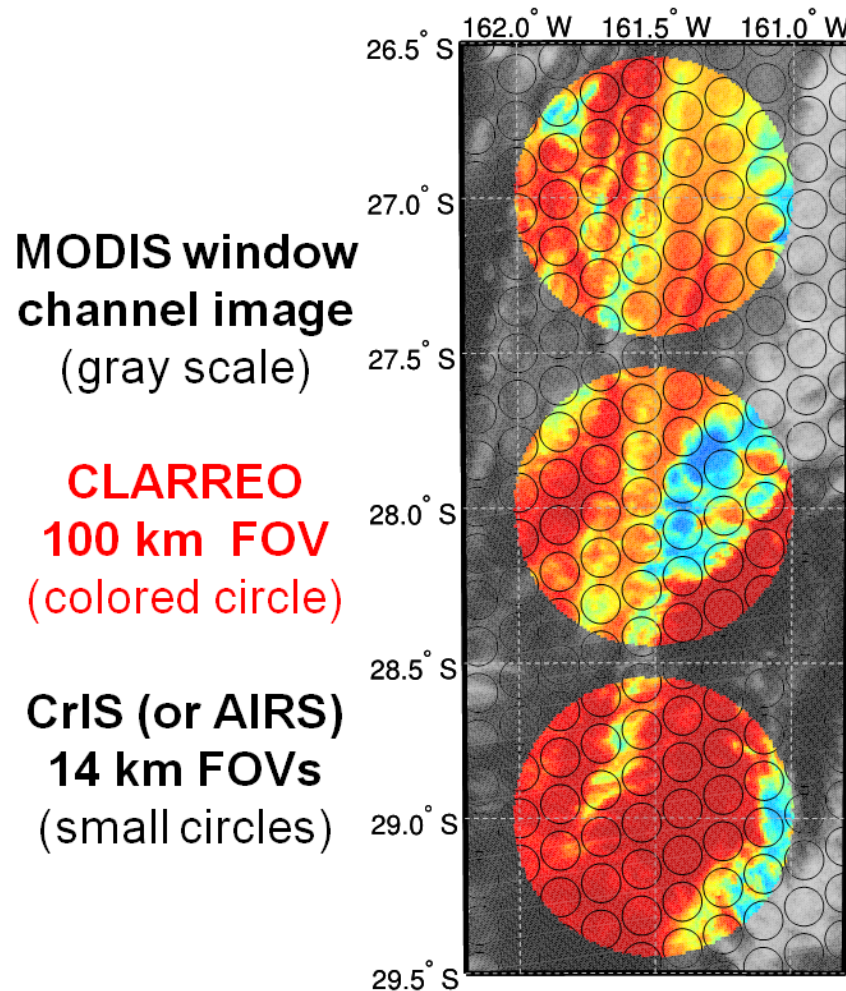
- ***Orbit (90 deg polar orbit and ISS)***
- ***Footprint size***
- ***Radiometric noise level***
- ***Mission length***
- ***Intercalibrated sensor (CrIS, AIRS, or IASI)***

Characteristics of CLARREO to Sounder Simultaneous Nadir Overpasses



- **General approach is to transfer CLARREO cal to CrIS/IASI/AIRS, and then CrIS/IASI/AIRS used as reference sensors in on-going intercalibration efforts**
- **Provides SNOs with good seasonal, time-of-day, and signal level coverage**
- **Time differences are symmetric about zero**

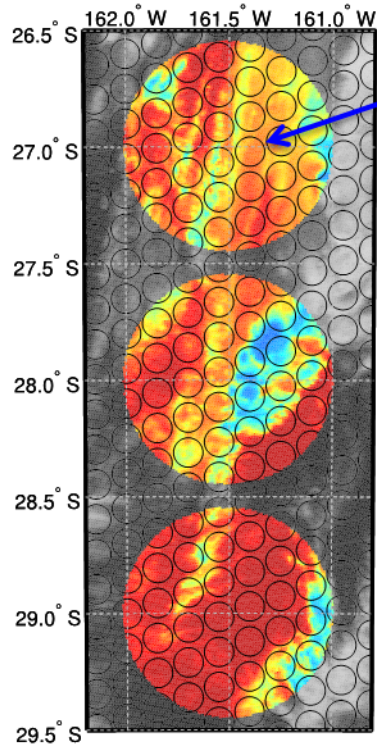
Simulation study used MODIS temporal & spatial variability to evaluate sampling collocation errors



CrIS-CLARREO T_b Distribution for SNOs
separated by standard deviation
of sounder sub-samples

Shows that the limited space/time coverage of each SNO leads to sampling difference residuals with Gaussian PDFs characterized by the Standard Deviation of sounder samples

Mathematics of sampling collocation errors



M = # sounder footprints overlapping the CLARREO footprint

N = # sounder footprints that would fill the CLARREO footprint
[by area, i.e. $N = (\text{diam CLARREO} / \text{diam Sounder})^2$]

$\sigma_{i \text{ sounder}}$ = Standard Deviation of sounder footprints for i^{th} SNO

(Sounder – CLARREO) sampling error for SNO_i

$$\sigma_{SNOi} = \underbrace{(M/N)}_{\text{Overlap area fraction}} \bullet \text{zero} + \underbrace{((N-M)/N)}_{\text{Non-Overlap fraction}} \bullet \underbrace{[\sigma_{i \text{ sounder}} / (N-M)^{1/2}]}_{\text{Error of mean for non-overlapping samples}}$$

Overlap area fraction

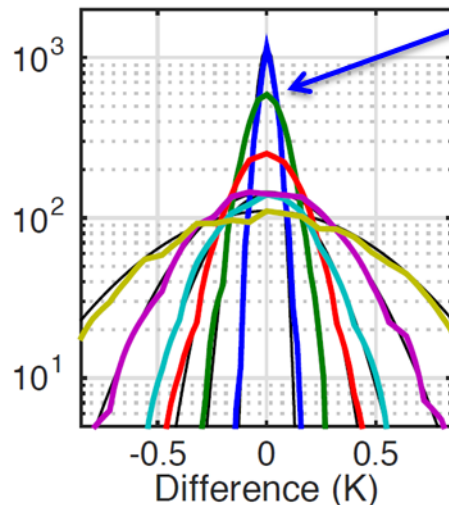
Non-Overlap fraction

Error of mean for non-overlapping samples

$$\sigma_{SNOi} = (1 - M / N)^{1/2} \sigma_{i \text{ sounder}} / N^{1/2}$$



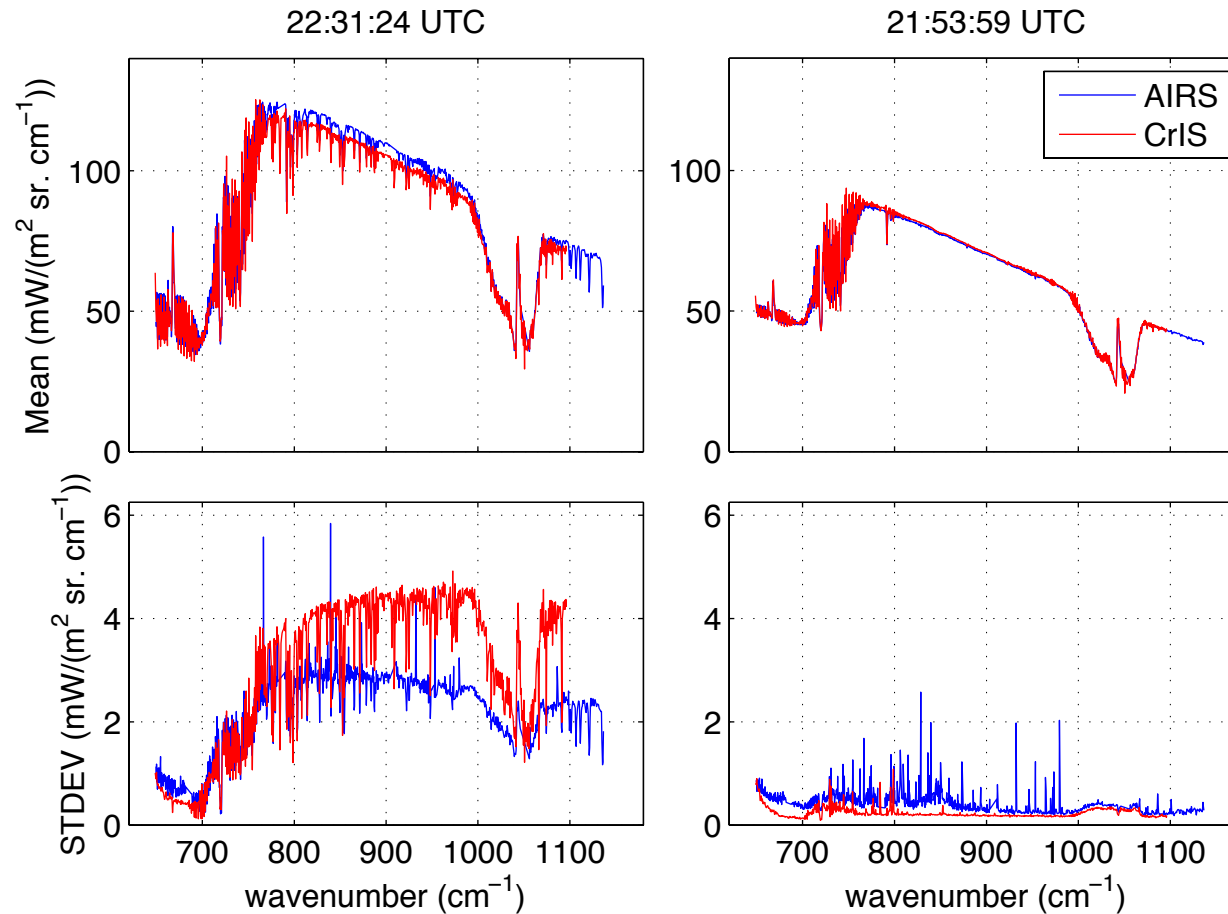
$N^{1/2} \rightarrow M^{1/2}$



This spatial sampling error formalism can be used
[combined with noise and temporal sampling errors]
to optimally weight mean SNO differences
[weights $w_i = 1/(\text{total error variance for SNO}_i)$]
and yield a rigorous uncertainty estimate [= $1/\sum w_i^{1/2}$]

This approach results in a rigorous mean difference and uncertainty, with no clear sky selection or other SNO filtering!

Examples with real data: AIRS/CrIS SNOs

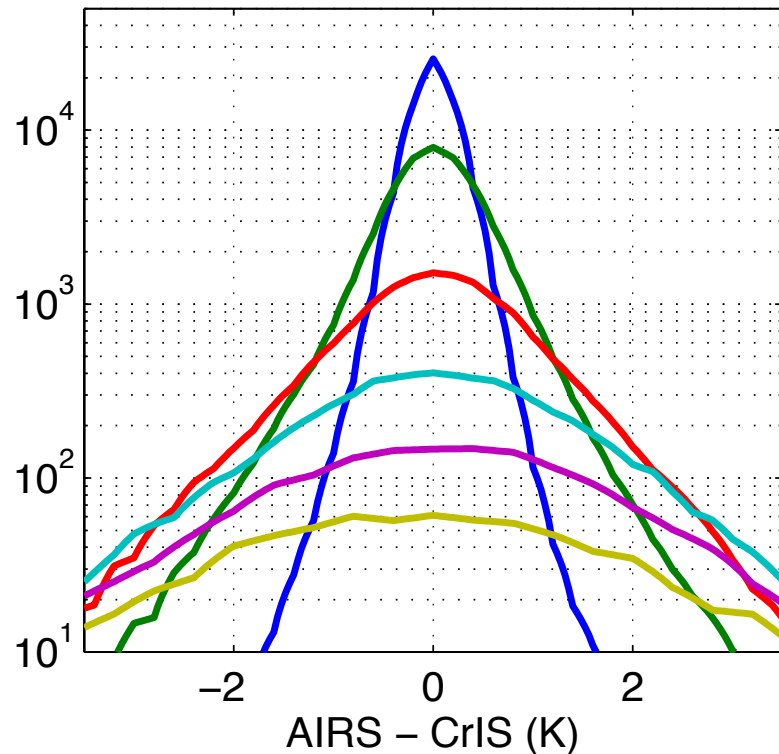


50 km radius “big circle” SNOs

Observed spatial variability is a very good indicator of the quality of the SNO

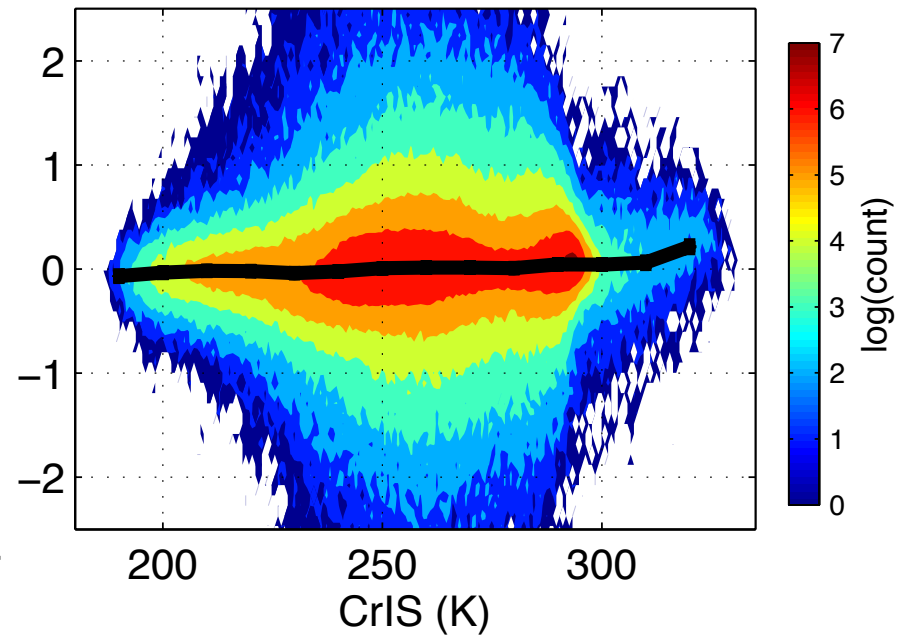
Examples with real data: AIRS/CrIS SNOs @ 900 cm⁻¹

*SNO differences (AIRS-CrIS)
for 6 spatial variability bins*



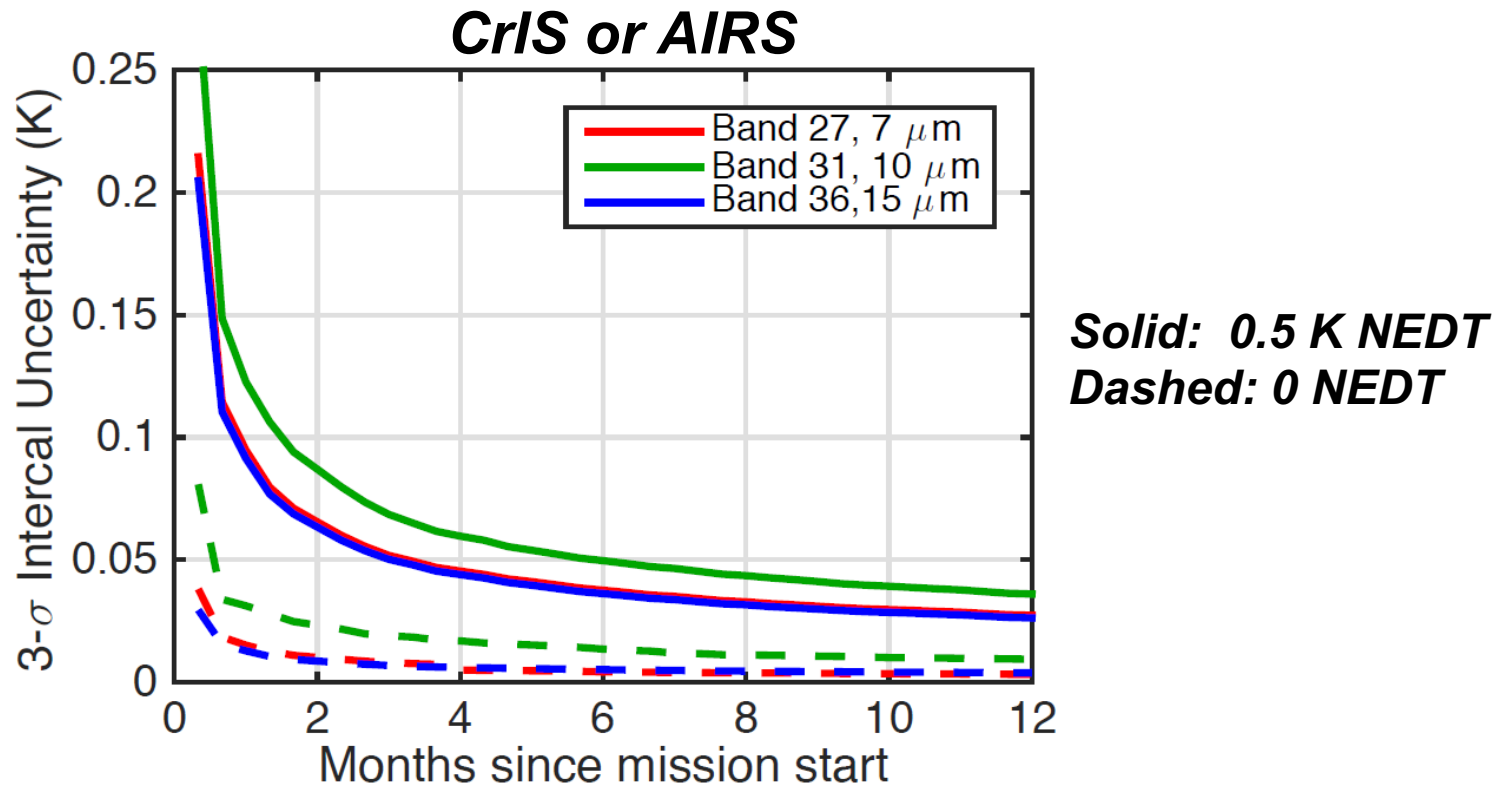
*Observed behavior is very similar
to model results*

*AIRS-CrIS (K) differences as
a function of scene temperature*



Intercalibration Uncertainty (IU)

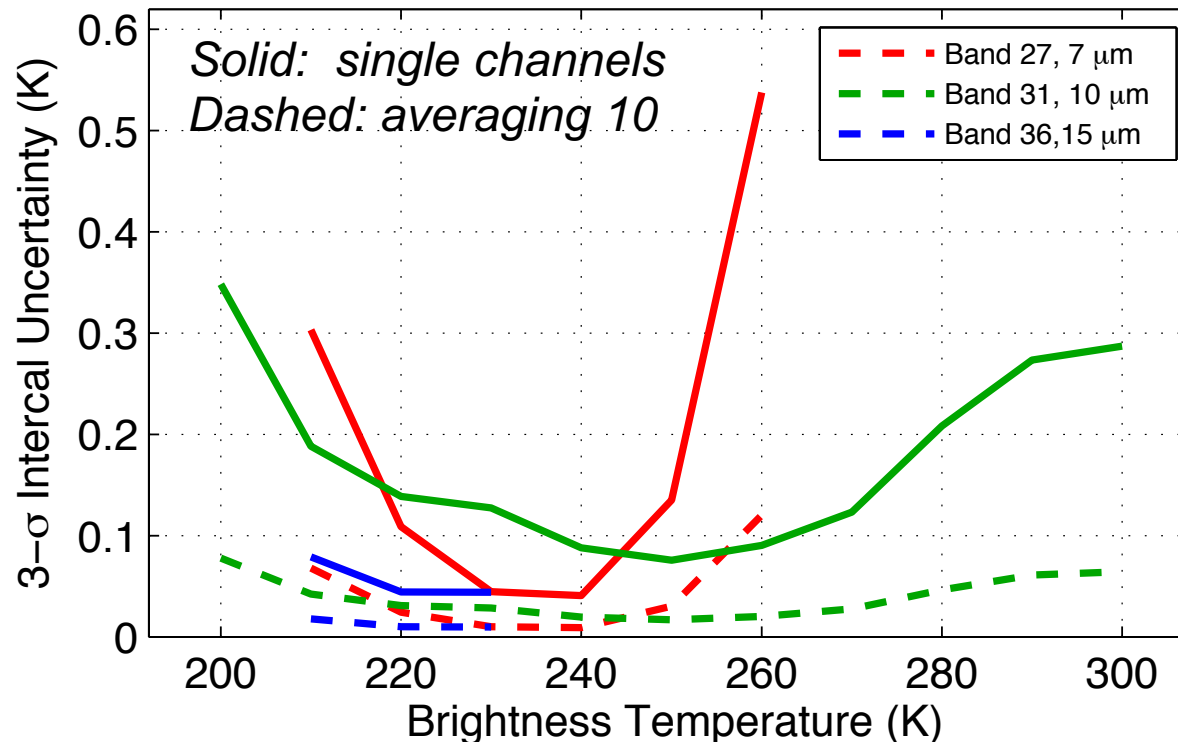
as a function of time since mission start, for a single spectral channel



Simulations include CLARREO in 90 degree polar orbit, CLARREO FOV diameter of 50 km, and 20 seconds between adjacent CLARREO FOVs.

Single Channel Intercalibration Uncertainty is less than 0.05 K 3-sigma in 6 months, even assuming a reasonably large CLARREO noise and for a window channel where spatial non-uniformity is largest

Intercalibration Uncertainty for 10K scene temperature bins (e.g. nonlinearity assessment) CrIS or AIRS



CLARREO/AIRS/CrIS Intercalibration uncertainty as a function of scene brightness using one year of SNOs. Simulations include CLARREO in 90 degree polar orbit, CLARREO FOV diameter of 50 km, and 20 seconds between adjacent CLARREO FOVs.

Results demonstrate the practicality of identifying mechanisms for intercalibration biases from which corrections can be based.

Conclusions from the paper

- ◆ **Biases between CLARREO and sounder observations can be determined with low rigorously defined uncertainty and with high time frequency during a CLARREO mission**
- ◆ A CLARREO footprint of 50 to 100 km in diameter is optimal for intercalibration
- ◆ Intercalibration uncertainty will be less than 0.1 K for channels at infrared window wavelengths using 2 months of SNOs (and even lower uncertainty with more time averaging)
- ◆ For more absorbing channels with less scene variability the uncertainties are less than 50 mK in 2 months
- ◆ **Also, experience with current advanced sounders (CrIS/AIRS/IASI) confirm this approach and level of evaluations possible with in-orbit inter-comparisons**