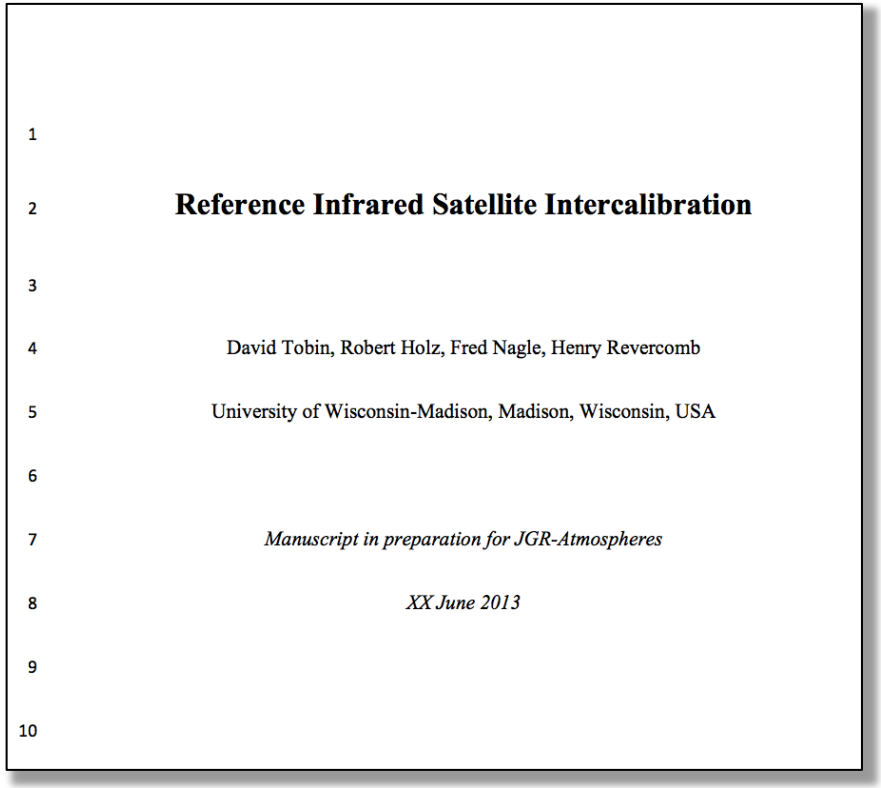
- **My primary remaining SDT task is to finalize and submit this paper …**



1

2 **Reference Infrared Satellite Intercalibration**

3

4 David Tobin, Robert Holz, Fred Nagle, Henry Revercomb

5 University of Wisconsin-Madison, Madison, Wisconsin, USA

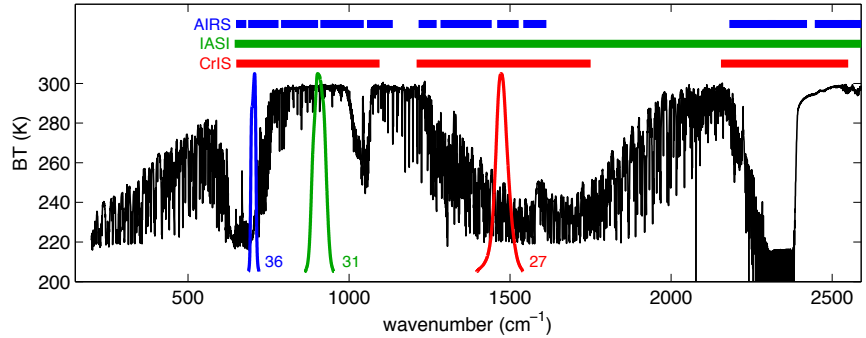
6

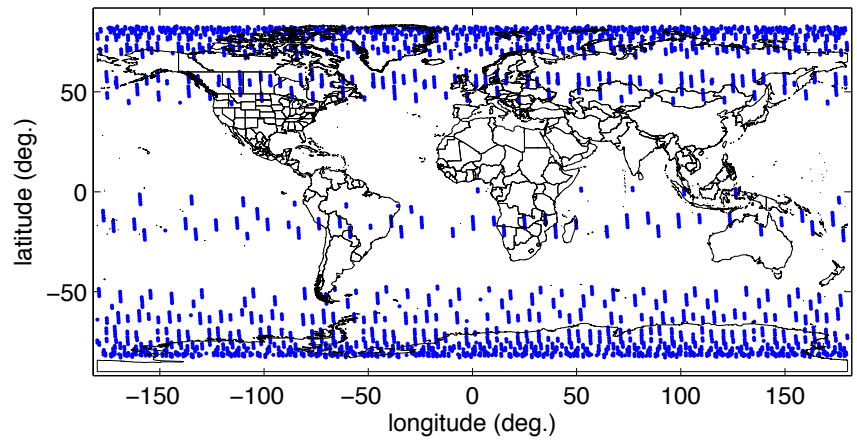
7 *Manuscript in preparation for JGR-Atmospheres*

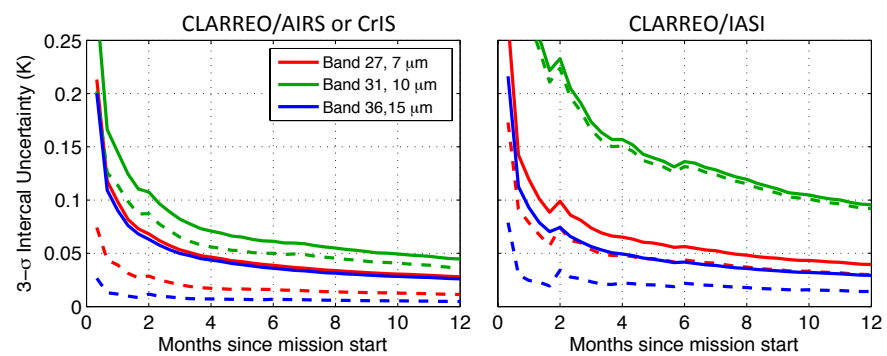
8 *XX June 2013*

9

10







Cross-track Infrared Sounder (CrIS) Radiometric Calibration Uncertainty and Intercalibration Results

Dave Tobin, Hank Revercomb, Joe Taylor, Bob Knuteson, Dan DeSlover, Lori Borg, Graeme Martin
Space Science and Engineering Center, University of Wisconsin-Madison

CLARREO Science Definition Team Meeting
7-9 January 2014

Outline

- CrIS Introduction and Validated Review summary
- Radiometric Uncertainty (RU) Estimates
- Intercalibration Results
- Continuing Work
- JPSS-1 and JPSS-2 CrIS
- Summary and Conclusions

Relevance to CLARREO

1. Similarities, and differences, in the IR sensor design, calibration approach, and resulting performance
2. Accurate characterization of the RU for existing hyperspectral IR data and of inter-sensor differences are required for Climate and CLARREO design studies
3. Demonstrates the IR sensor intercalibration methodology to be used for CLARREO

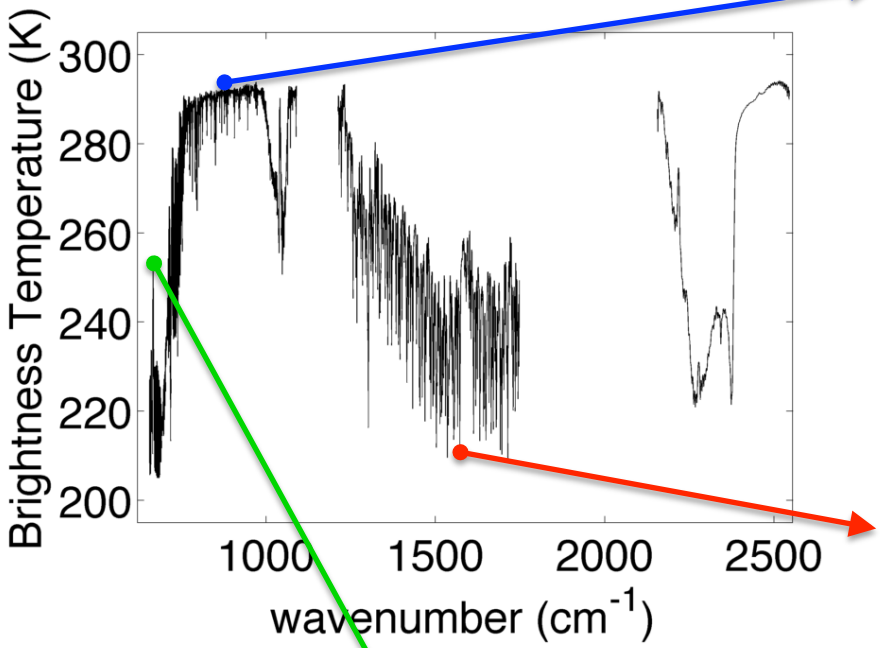
Summary and Conclusions

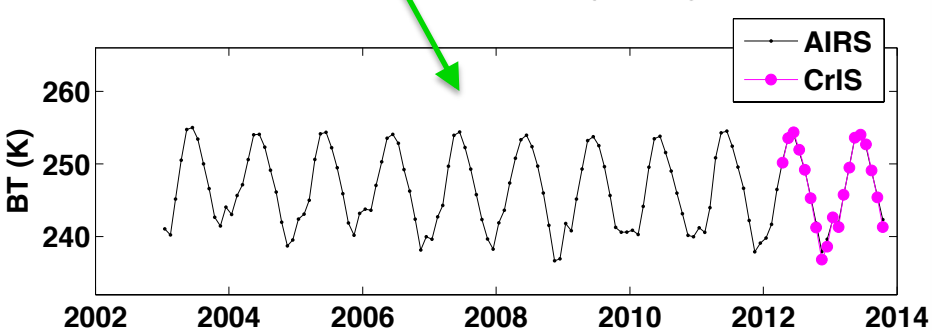
- The CrIS RU is very good, approximately a factor of 3 better than spec. This, along with the excellent spectral calibration performance and robust on-orbit operations, are very positive indications for the technical success of CLARREO and its ability to reach 0.1K 3-sigma on-obit.

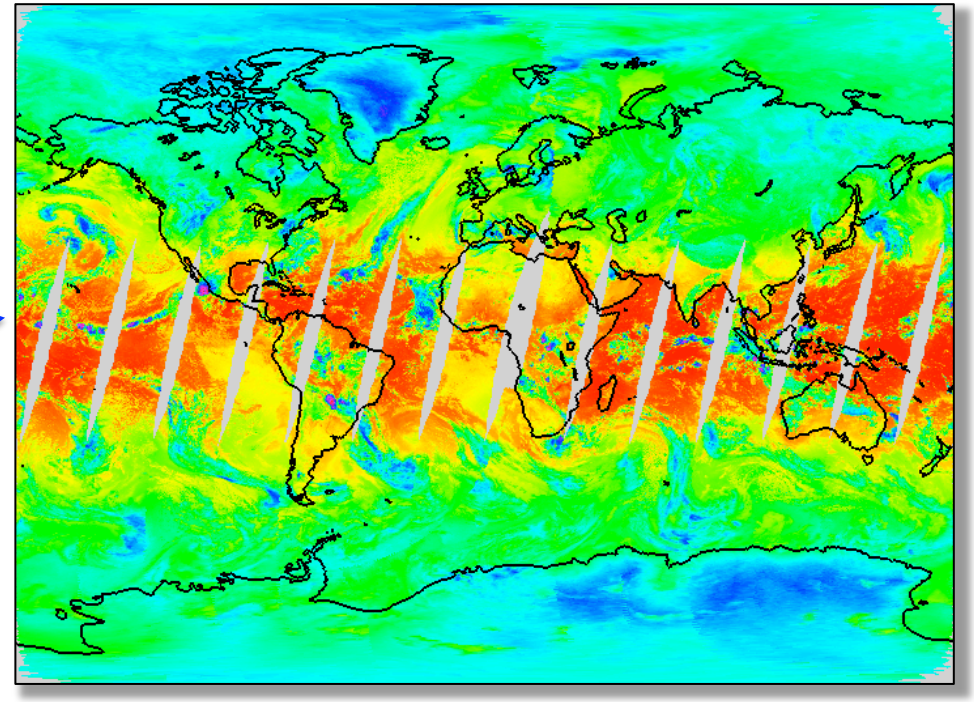
- The CRIS SDRs have undergone extensive on-orbit cal/val, including comparisons with aircraft, VIIRS, AIRS, IASI, and clear sky calculations. Estimated RU and observed differences between the sensors are generally very good, but not insignificant for climate studies in general.

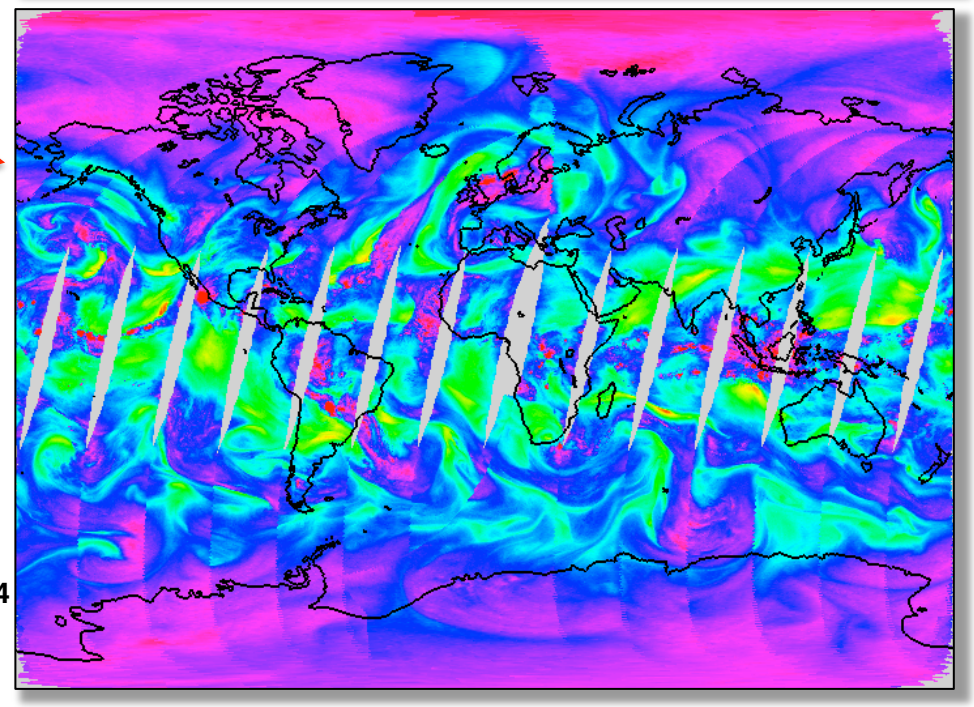
- CrIS post-launch cal/val results provide further demonstration of the same intercalibration methodology which will allow the CLARREO on-orbit 0.1K uncertainty and traceability to be transferred to concurrent operational sounders.

Daily, global high spectral resolution radiance spectra for: NWP, Atmospheric state Retrieval, Regional Forecasting, Climate Process and Trend studies, Intercalibration









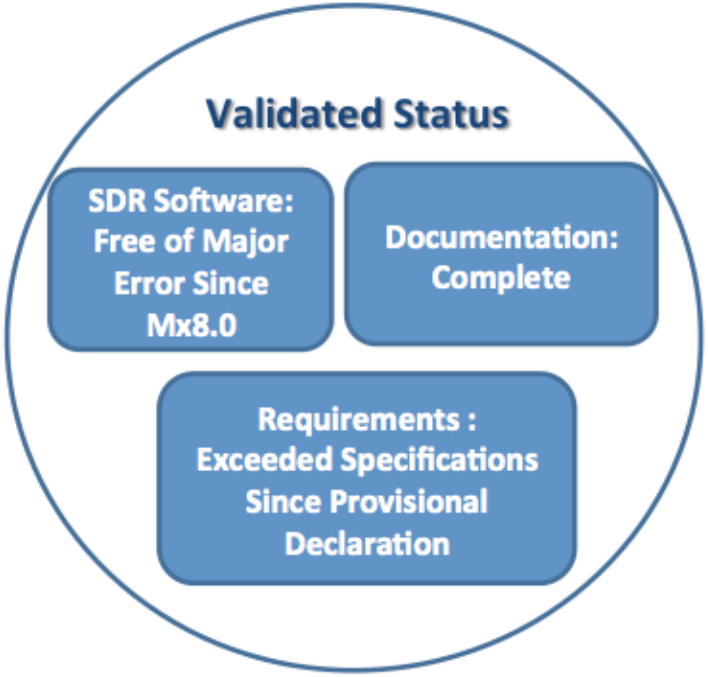
Suomi-NPP SDR Validated Status Review Meeting
(ATMS, CrIS, VIIRS, OMPS)
18-20 December 2013

JPSS Project CrIS SDR Team PIs:

Yong Han, NOAA STAR
Larrabee Strow, UMBC
Dan Mooney, MIT/LL
Mike Cromp, Exelis
Wael Ibrahim, Raytheon
Hank Revercomb, UW
Deron Scott, SDL
Degui Gu, NGAS
Dave Johnson, NASA
Carrie Root, JPSS/DPA

CrIS SDR Reached Validated Maturity Level

- Requirements
  - Instrument & SDR performances exceeded requirements since Provisional status declaration 1/31/2013
- SDR software
  - Stable & free of errors that can impact data quality since 11/14/2013 (Mx8.0)
- Documentation
  - 5 presentations in this meeting
  - 6 Journal papers
  - SDR User's Guide & Revised ATBD
  - Error Budget table



CrIS SDR uncertainties (**blue**) vs. specifications (black)

Band	NEdN @287K BB mW/m²/sr/cm⁻¹	Radiometric Uncertainty @287K BB (%)	Frequency Uncertainty (ppm)	Geolocation Uncertainty (km) *
LW	**0.098** (0.14)	**0.12** (0.45)	**3** (10)	**1.2** (1.5)
MW	**0.036** (0.06)	**0.15**(0.58)	**3** (10)	**1.2** (1.5)
SW	**0.003** (0.007)	**0.2** (0.77)	**3** (10)	**1.2** (1.5)

* Within 30° scan angles

Documentation (1/2)

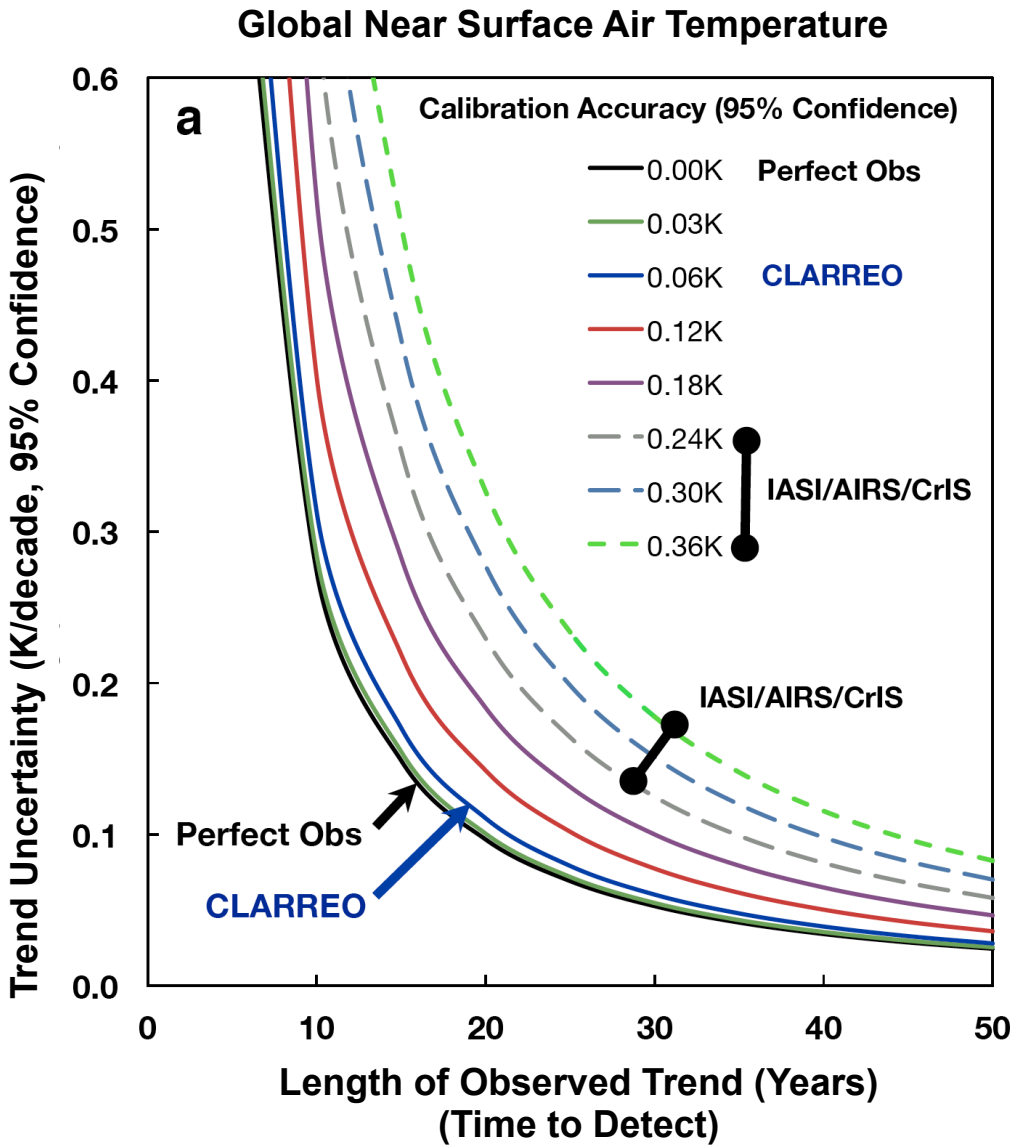
- CalVal results summarized in peer review papers
  - Han et al. (2013): Suomi NPP CrIS Measurements, Sensor Data Record Algorithm, Calibration and Validation Activities, and Record Data Quality, JGR
  - Zavyalov et al. (2013): Noise performance of the CrIS instrument, JGR
  - Tobin et al. (2013): Suomi-NPP CrIS Radiometric Calibration Uncertainty, JGR
  - Strow et al. (2013): Frequency Calibration and Validation of CrIS Satellite Sounder, JGR
  - Wang et al. (2013): Geolocation Assessment for CrIS Sensor Data Records, JGR
  - Chen et al. (2013): Detection of Earth-rotation Doppler Shift from Suomi National Polar-Orbiting Partnership Cross-track Infrared Sounder, Appl. Opt.
- CrIS SDR User's Guide version 1.0 (55 pages)
- Revised CrIS ATBD
- Error Budget (for the review panel)

Radiometric Uncertainty (RU) Estimates

- Perturbation of Calibration Equation and Parameter uncertainties
- On-orbit RU estimates
- Other terms

➢ Required in order to understand the size and dependencies of the primary contributors to the CrIS SDR uncertainties, for calibration improvements, weather, process, trend, and inter-calibration applications.

Achieving Climate Change Absolute Accuracy in Orbit,
Wielicki et al., BAMS, 2013



Radiometric Uncertainty Estimates

Simplified On-Orbit Radiometric Calibration Equation:

$$R_{scene} = \mathcal{R}e\{(C'_{scene} - C'_{SP}) / (C'_{ICT} - C'_{SP})\} R_{ICT}$$ with:

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

ICT Predicted Radiance: $R_{ICT} = \varepsilon_{ICT}\, B(T_{ICT}) + (1-\varepsilon_{ICT})\, [\, 0.5\, B(T_{ICT,\, Refl,\, Measured}) + 0.5\, B(T_{ICT,\, Refl,\, Modeled})]$

Parameter Uncertainties:

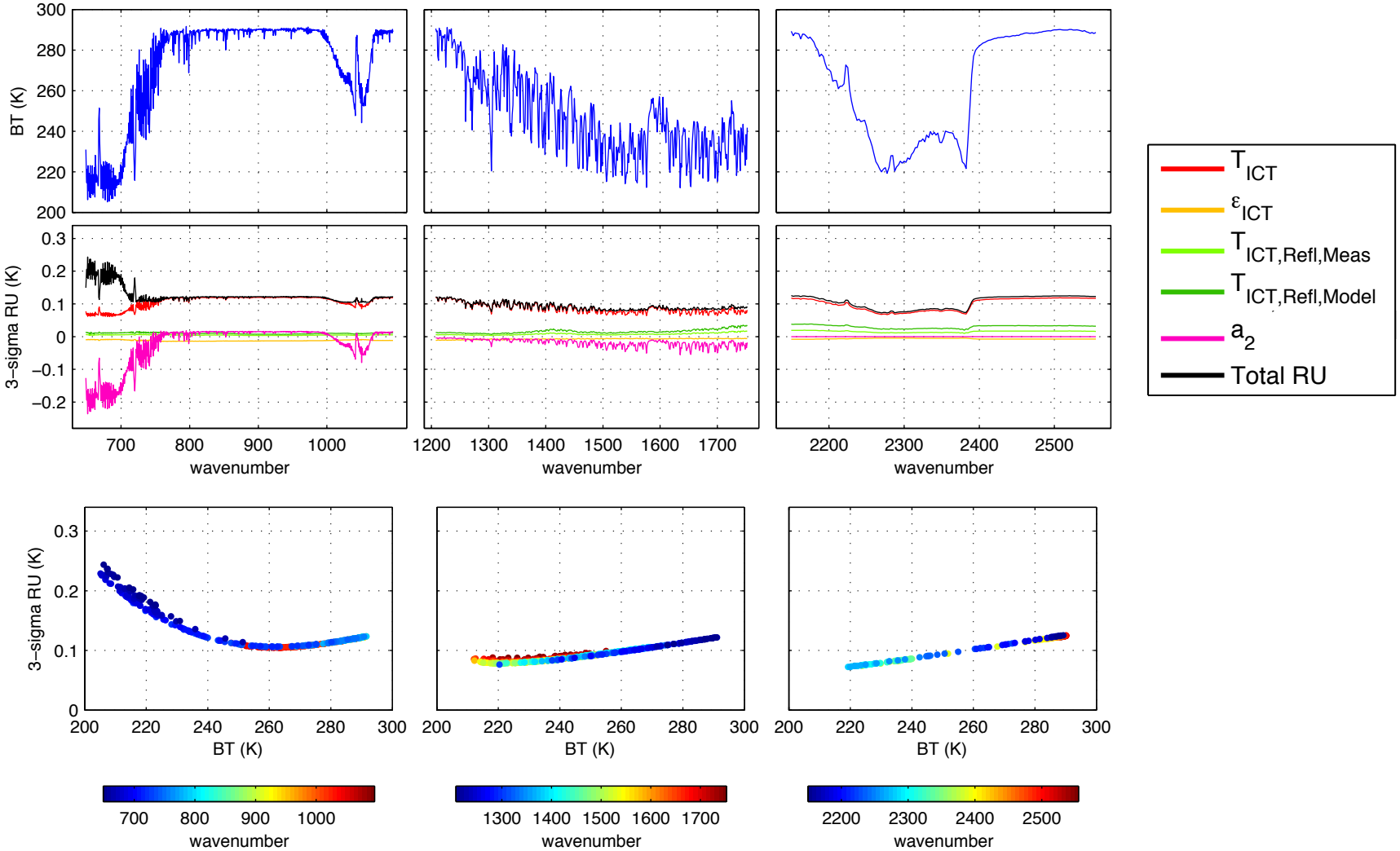
Parameter	Nominal Values	3-σ Uncertainty
T_{ICT}	280K	112.5 mK*
ε_{ICT}	0.974-0.996	0.03
$T_{ICT,\, Refl,\, Measured}$	280K	1.5 K
$T_{ICT,\, Refl,\, Modeled}$	280K	3 K
a_2 LW band	0.01 – 0.03 V^{-1}	0.00403 V^{-1}
a_2 MW band	0.001 – 0.12 V^{-1}	0.00128 – 0.00168 V^{-1}

**Exelis at-launch estimate*

Following *Tobin et al. (2013), Suomi-NPP CrIS radiometric calibration uncertainty, J. Geophys. Res. Atmos., 118, 10,589–10,600, doi:10.1002/jgrd.50809.*

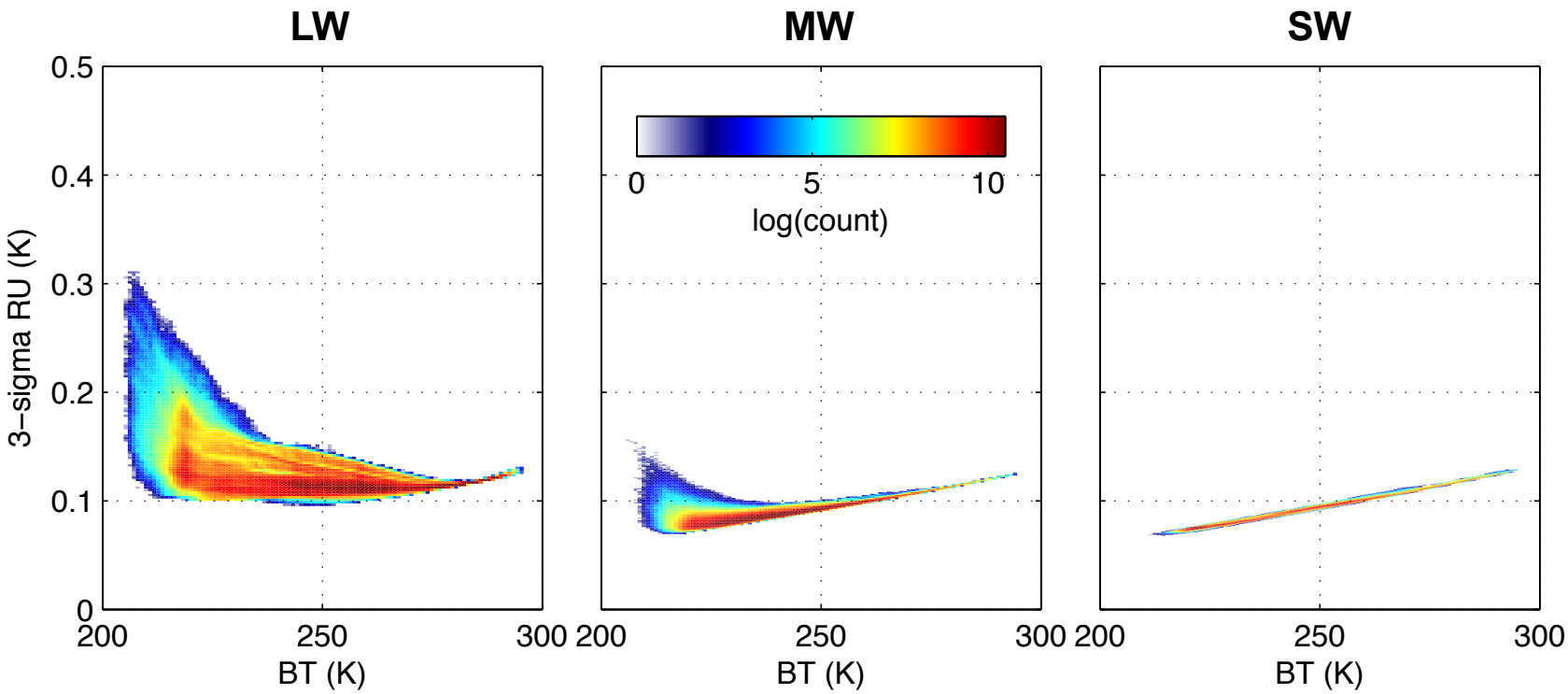
Example 3-sigma RU estimates

For a typical warm, ~clear sky spectrum



Example 3-sigma RU estimates

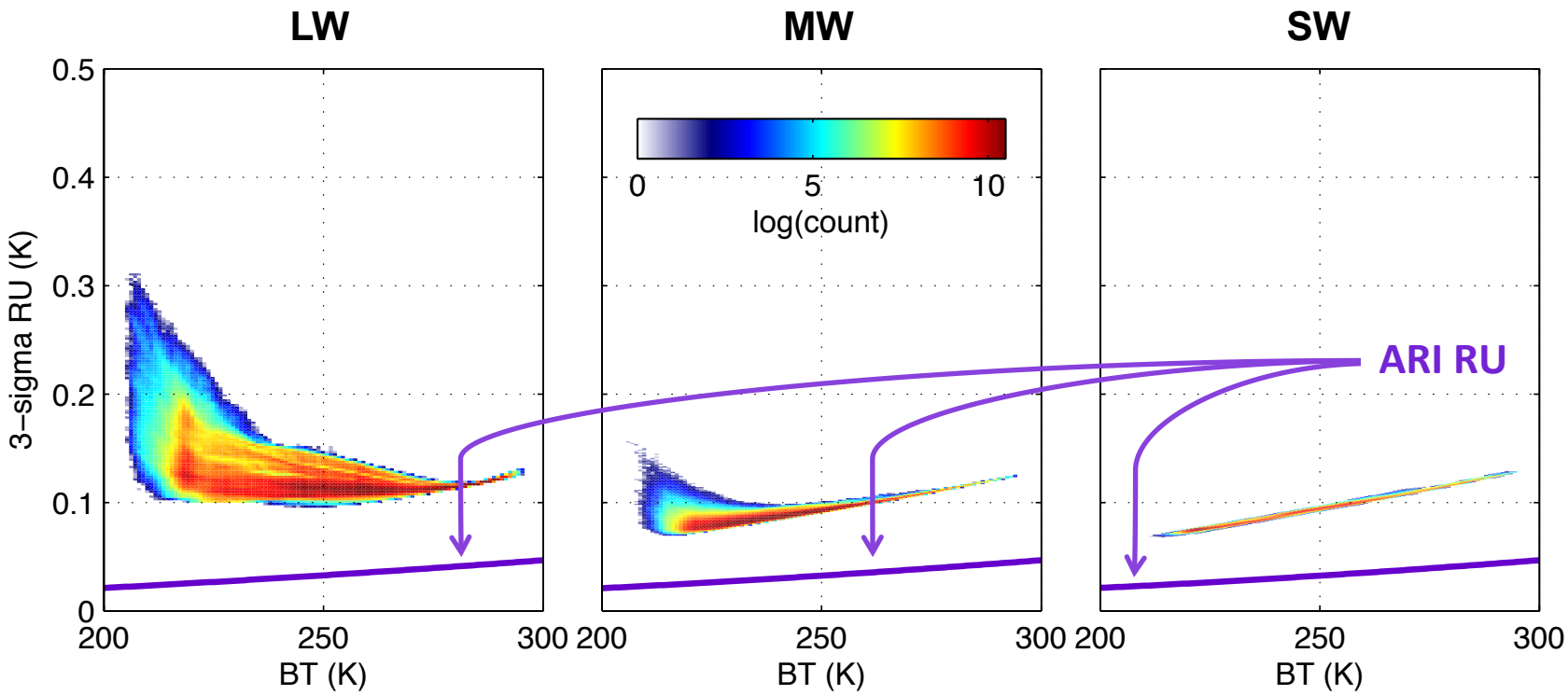
Log scale RU distributions for one orbit of CrIS Earth view data, including all FOVs and spectral channels within the band:



- Uncertainties are greatly reduced due to re-analysis of the TVAC data and on-orbit FOV-2-FOV analysis. In particular, MW band uncertainties are greatly reduced due to the high degree of linearity of MW reference FOV9.
- Overall, RU is <0.3K (LW), <0.15K (MW), <0.15K (SW): Better than spec by approximately a factor of 4.

Example 3-sigma RU estimates

Log scale RU distributions for one orbit of CrIS Earth view data, including all FOVs and spectral channels within the band:



- ARI RU is lower, primarily due to a) blackbody temperature uncertainties ~3x lower, and b) negligible nonlinearity contributions. And oppsed to existing sensors, ARI RU would also be validated routinely on-orbit with the OVTS.
- **CrIS RU is very good, but having CLARREO available for routine intercalibration would greatly benefit weather and climate applications.**

CrIS RU: Other Terms

Contributors not currently accounted for in the calibration algorithm or included in current RU estimates:

- Other smaller/negligible terms:
  - Detector temperature changes, Changes in DA Bias tilt over 4 minutes, Changes in optical flatness, OPD sample rate drift over 4 minutes, Electronic gain drift over 4 minutes, Electronic delay drift over 4 minutes, FOV to FOV crosstalk in same band, FOV to FOV crosstalk between bands, Stray light, Optics temperature change during cal, Changes in channel spectra

- Spectral Ringing
- Polarization
- Possible SW Nonlinearity

} Smaller contributions/artifacts under investigation

Other Performance Notes

- Spectral Calibration, ILS
  - Absolute calibration < 3ppm, Relative calibration (FOV-2-FOV) < 1ppm, and can be improved further with reprocessing.
  - Neon lamp calibration system performance has been excellent
  - Non-uniform scene effects behave as expected
  - Doppler shift effects behave as expected
- Noise performance
  - Excellent
  - Interferometric (spectrally correlated) noise negligible
- Geolocation Accuracy
  - Performance assessed wrt VIIRS @ <1.2km
  - Band to band co-registration is excellent, <100m
- Robust operation
  - Percent valid spectra is > 99.98%
  - No SAO anomolies; Impulse noise very rare
  - No Fringe count errors to date

Reprocessed Dataset

Refined CrIS SDRs for the full mission are available at:

ftp://peate.ssec.wisc.edu/allData/products/results/cris/cspp/SDR_1_4b_ILS_NLC_v33a-04/

Differences with respect to the operational IDPS dataset:

1. Includes Nonlinearity algorithm and coefficient refinements*
2. Includes ILS algorithm and coefficient refinements*
3. Includes consistent SDR algorithm processing for the full mission
4. Processing takes place with ~24 hour latency to avoid missing packet issues

*** The same Nonlinearity and ILS refinements are expected to be implemented in IDPS processing with MX8.1 and EPv36 in February 2014.**

NASA Level 1-B effort

NASA is considering production of new calibration software and independent Level-0, Level 1-A, Level 1-B processing.

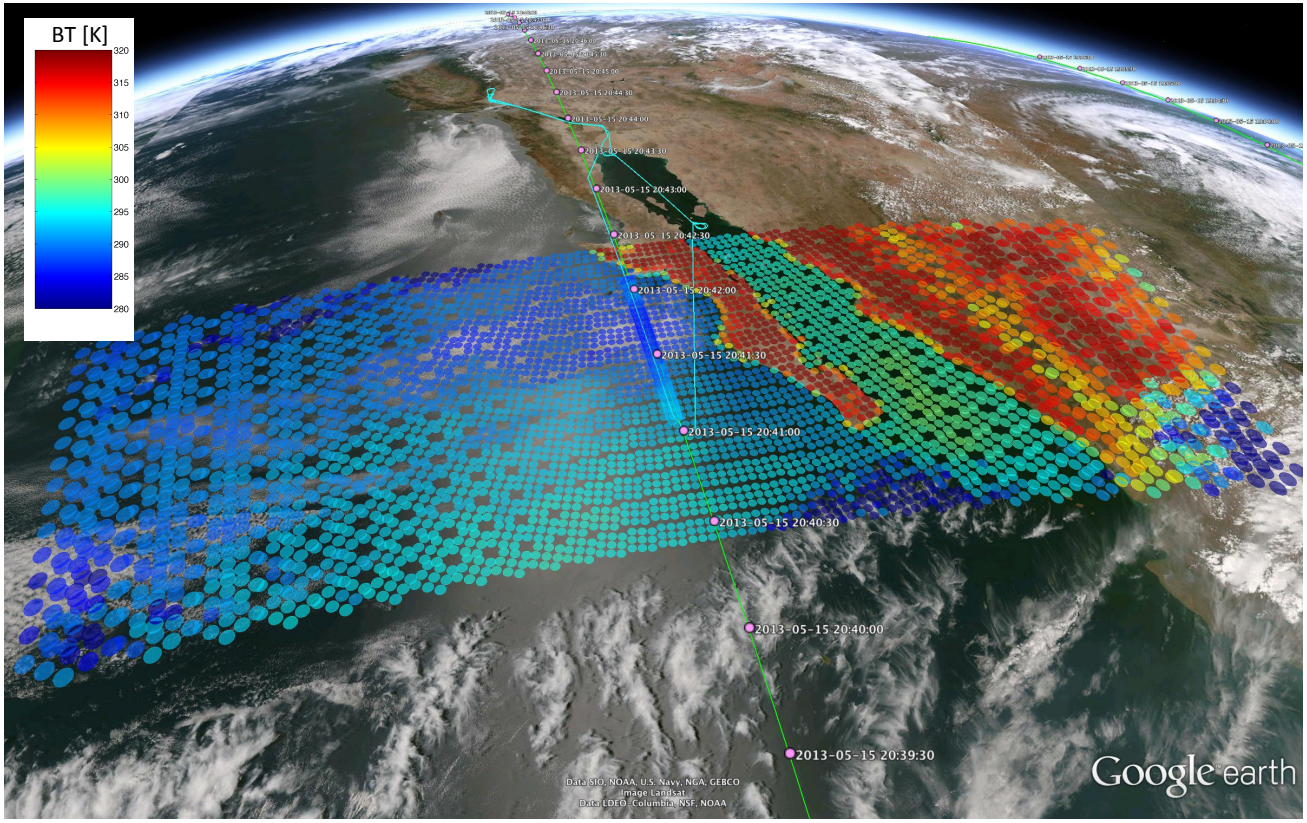
Evaluations of CrIS RU estimates
i.e. post-launch Cal/Val

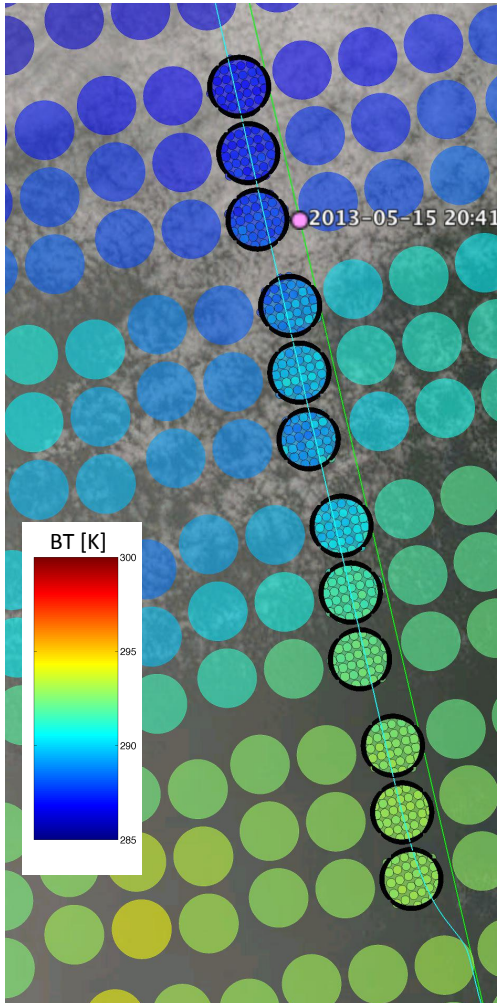
- Aircraft underflights
- CrIS/VIIRS comparisons
- CrIS/IASI comparisons
- CrIS/AIRS comparisons
- Clear sky Obs-Calc

➢ A range of techniques, with various levels of uncertainty/statistics/traceability, to assess the CrIS SDRs and associated RU estimates.

May 2013 Suomi-NPP JPSS Aircraft Campaign

Scanning-HIS evaluations of CrIS Calibration

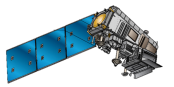


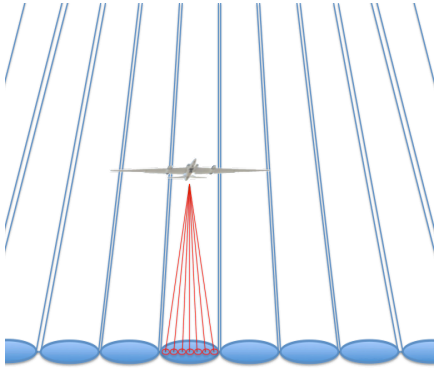


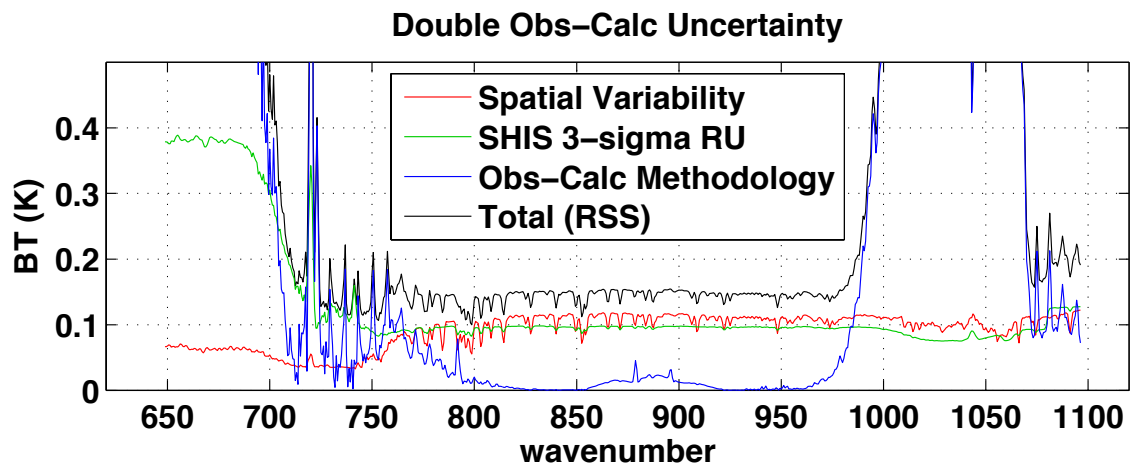
May 15 Underflight example:
S-HIS and CrIS 895–900 cm^{-1} BTs overlaid on VIIRS true color image

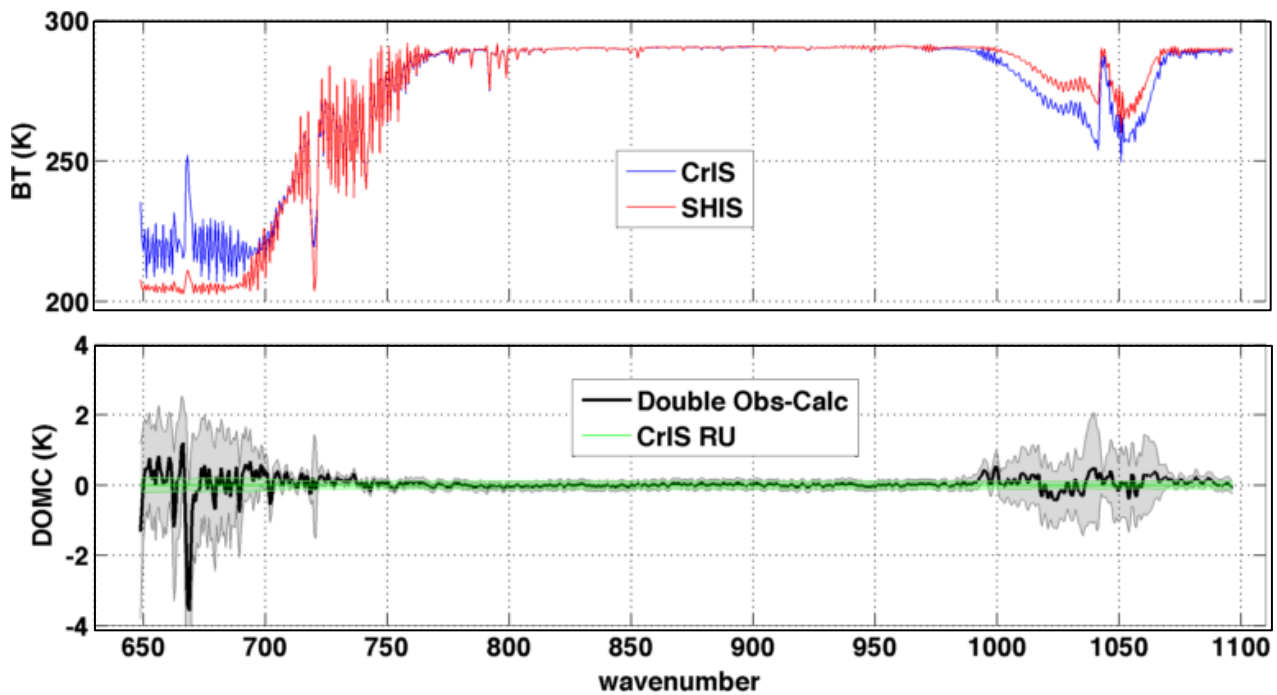
Double Obs-Calc Comparison Methodology and Uncertainty

$(CrIS_{obs}-CrIS_{calc})-(SHIS_{obs}-SHIS_{calc})$





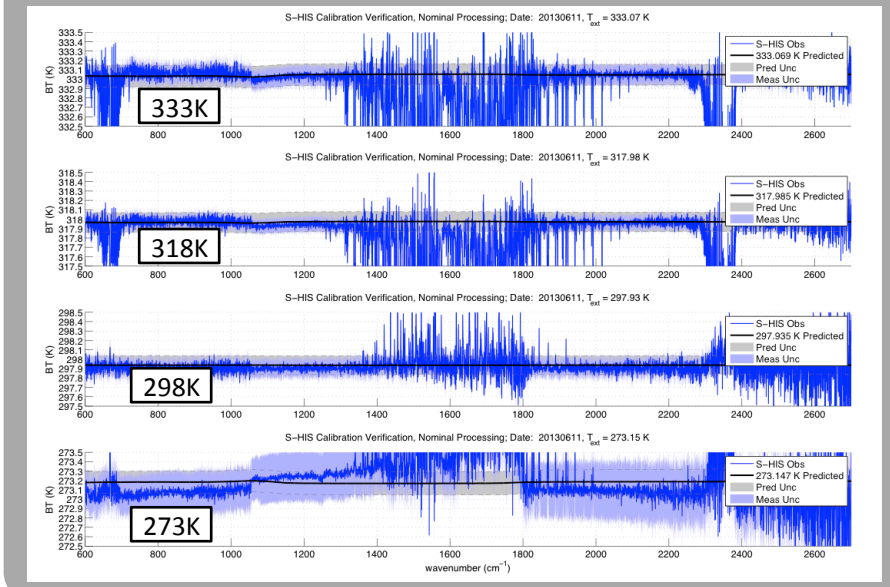




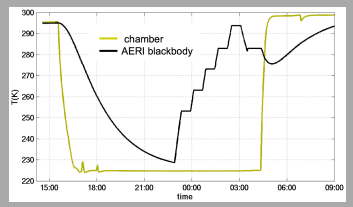
S-HIS Calibration, Calibration Verification, and Traceability

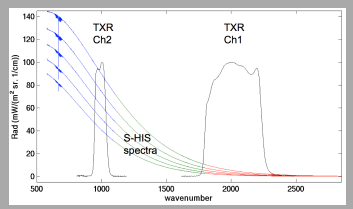
- Pre and post deployment end-to-end calibration verification
- Instrument calibration during flight using on-board calibration blackbodies
- Periodic end-to-end radiance evaluations under flight-like conditions with NIST transfer sensors

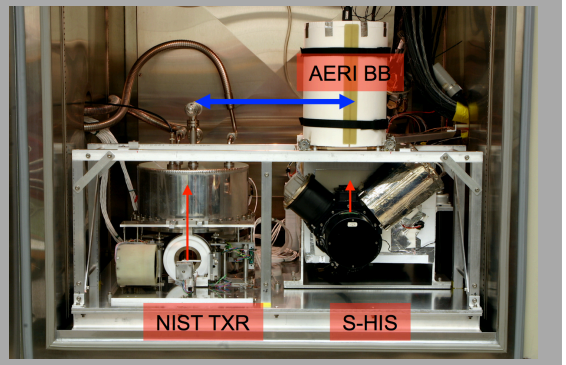
Post SNPP End-to-End Calibration Verification

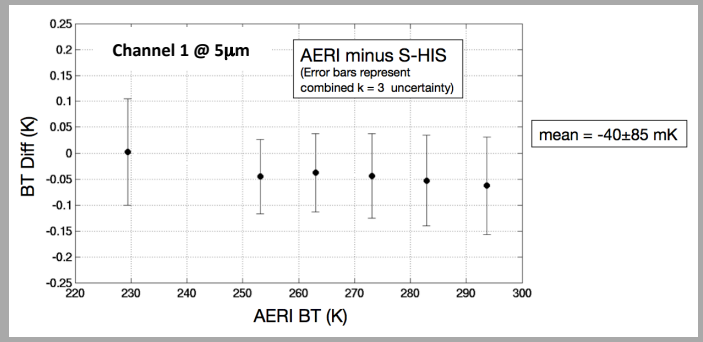


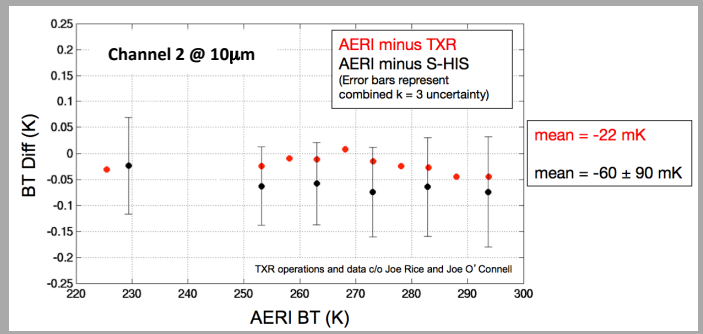
NIST TXR Validation of S-HIS Radiances





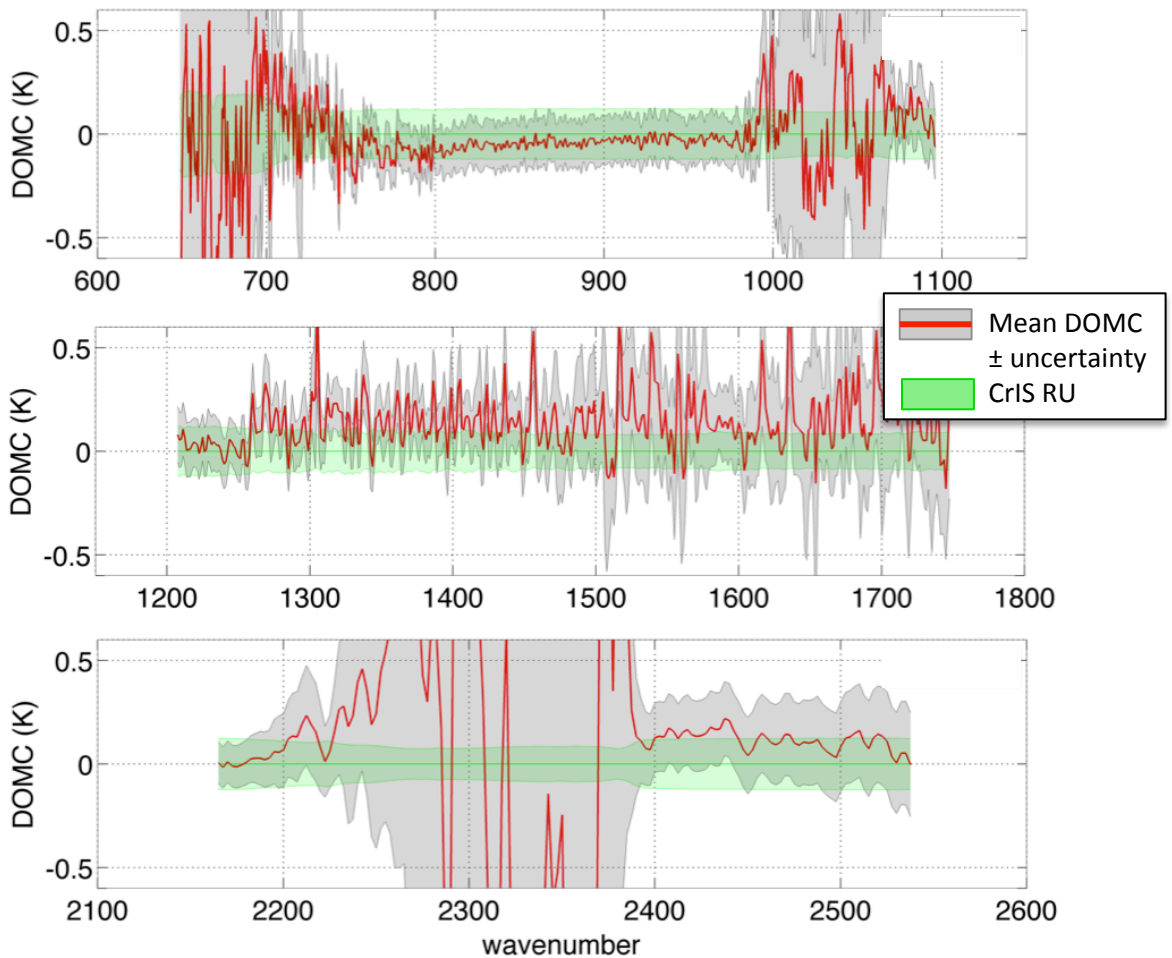






CrIS/S-HIS Underflight Results

Hamming apodization

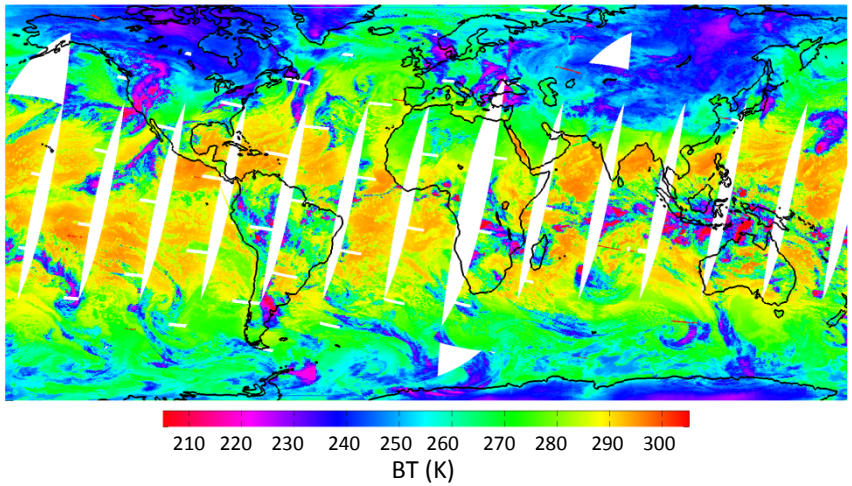


- Aircraft underflights provide periodic end-to-end verification of CrIS RU estimates with 0.1-0.2K uncertainty over most of the spectrum.
- **CLARREO in-orbit would provide this type of traceable, end-to-end evaluation on a routine, on-going basis.**

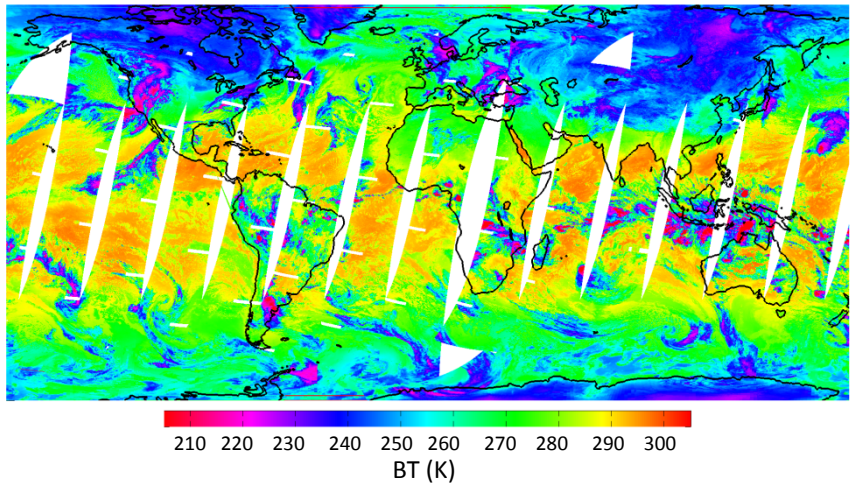
CrIS/VIIRS comparisons

Example Daily Comparisons, M15 band @ 10.8μm, Descending

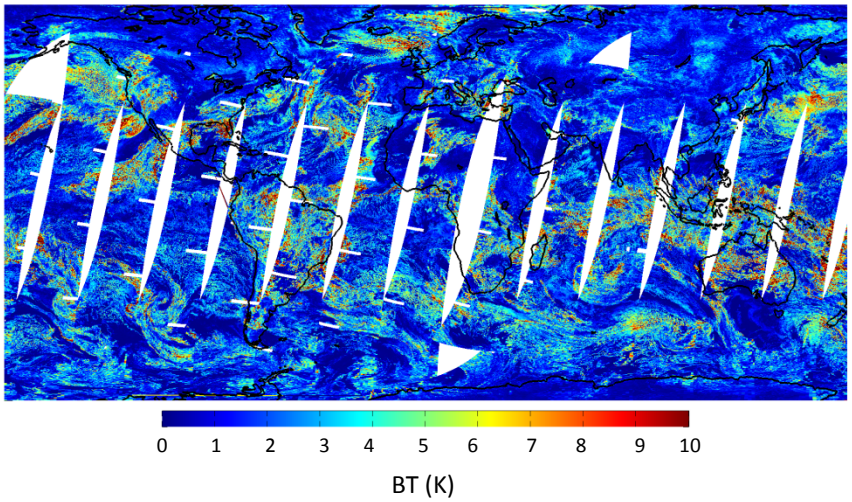
CrIS convolved with VIIRS SRF



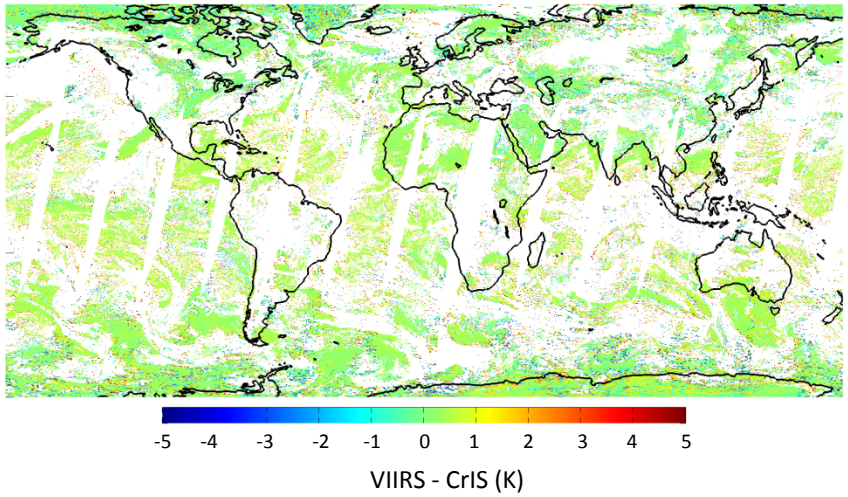
VIIRS mean within CrIS FOVs



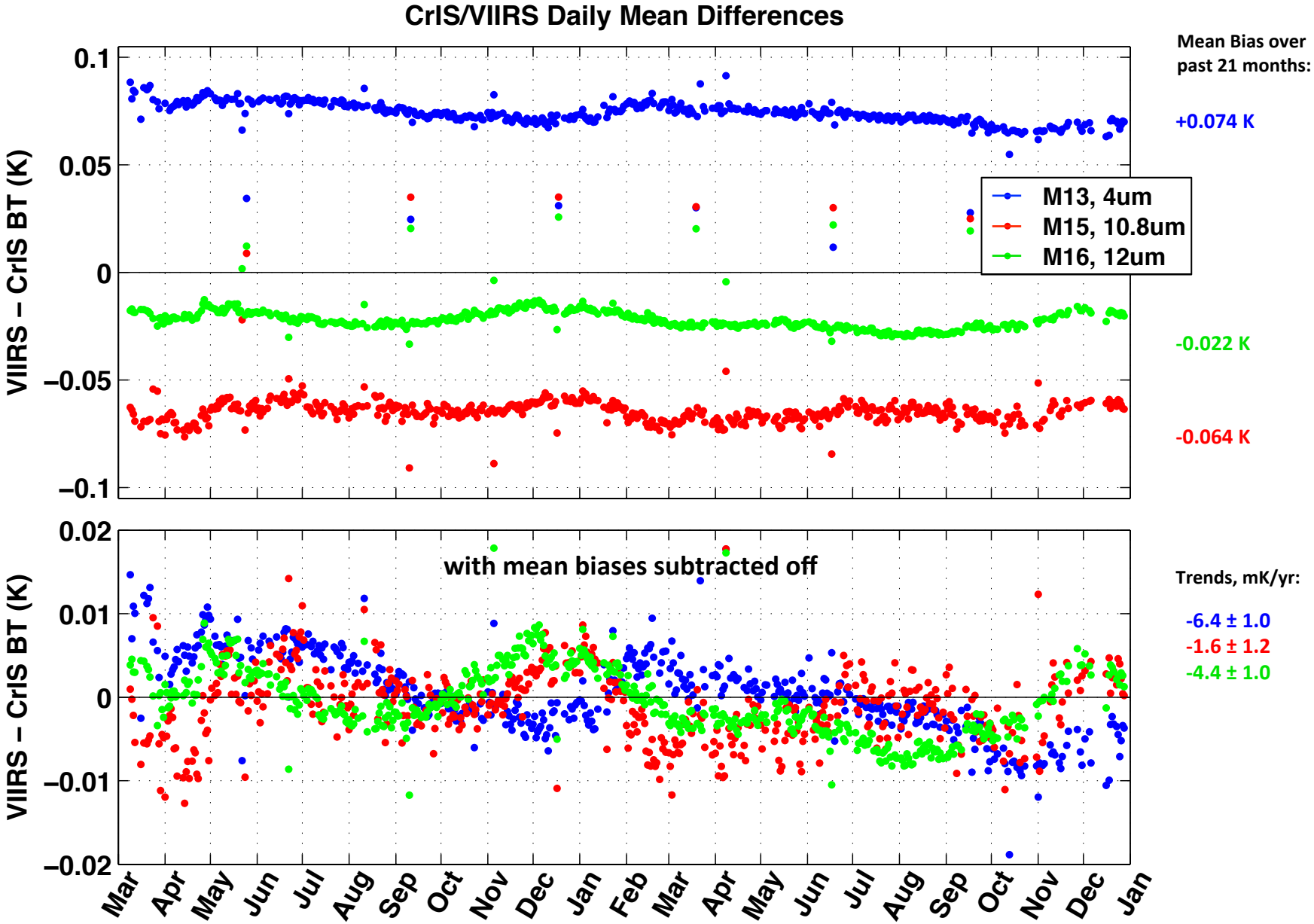
VIIRS standard deviation within CrIS FOVs



Differences for uniform scenes



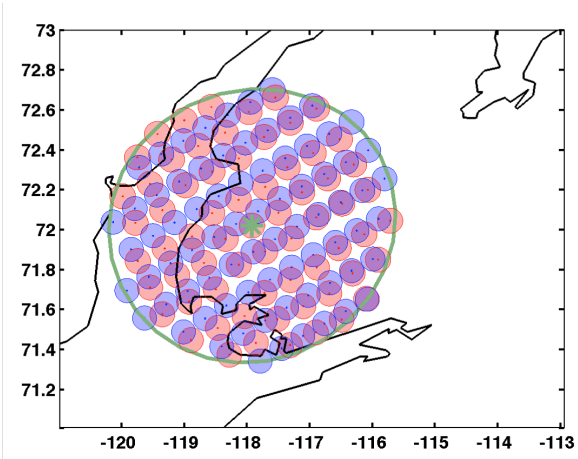
- Each day includes ~500,000 colocations which pass a spatial uniformity test



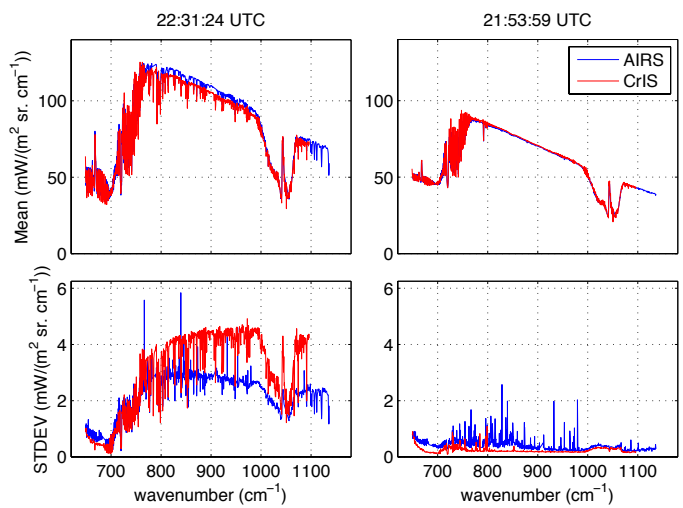
- CrIS/VIIRS daily mean differences are < 0.1K and trends are < 10 mK/yr.
- Small, but not insignificant for climate trend evaluations.

SNO Comparison Methodology

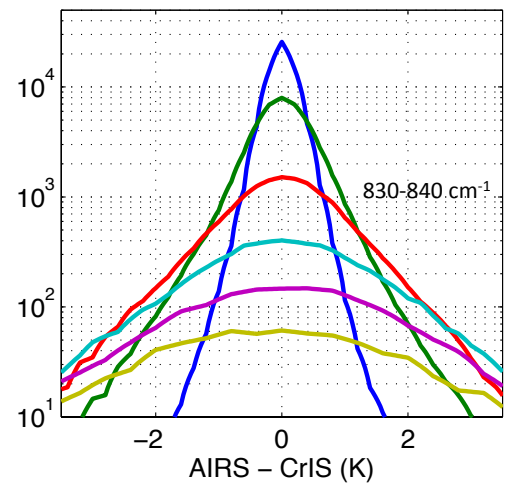
The SNO comparison technique is aimed at minimizing differences in the spatial/temporal collocation process and providing well understood uncertainties to identify persistent biases between two sensors.



A sample SNO showing CrIS and AIRS footprints within 100 km of the SNO location.



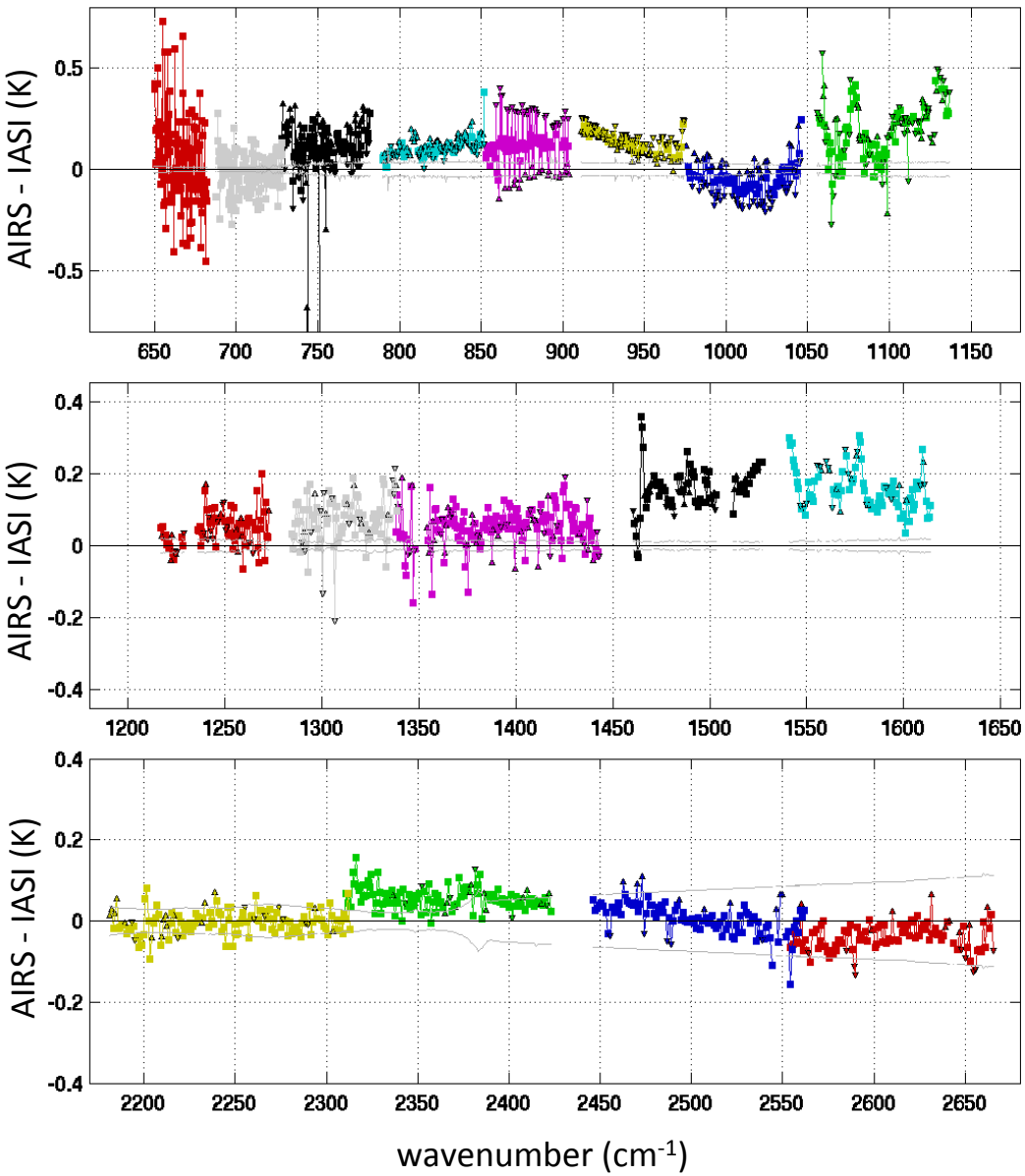
LW mean and standard deviation spectra for two example SNOs collected on 20120816.



Collocation difference distributions for a large ensemble of SNOs for various ranges of spatial variability.

➢ **Same IR intercalibration methodology intended for CLARREO**

Example SNO comparisons: AIRS/IASI Mean Differences 2007-2010

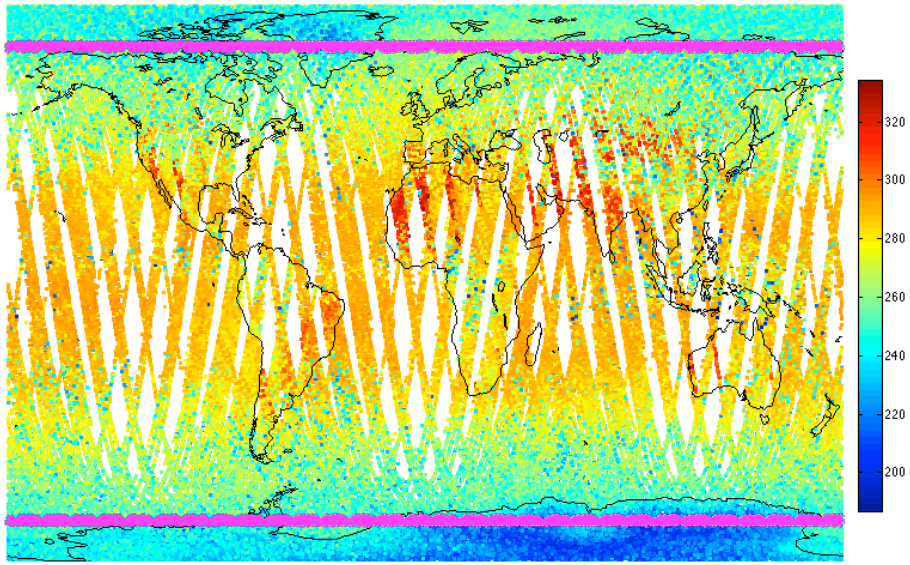


- **Calibration of both AIRS and IASI is very good but observed differences are not insignificant for retrieval/climate studies**
- **Highlights the need for an on-obit reference**

SNO Datasets

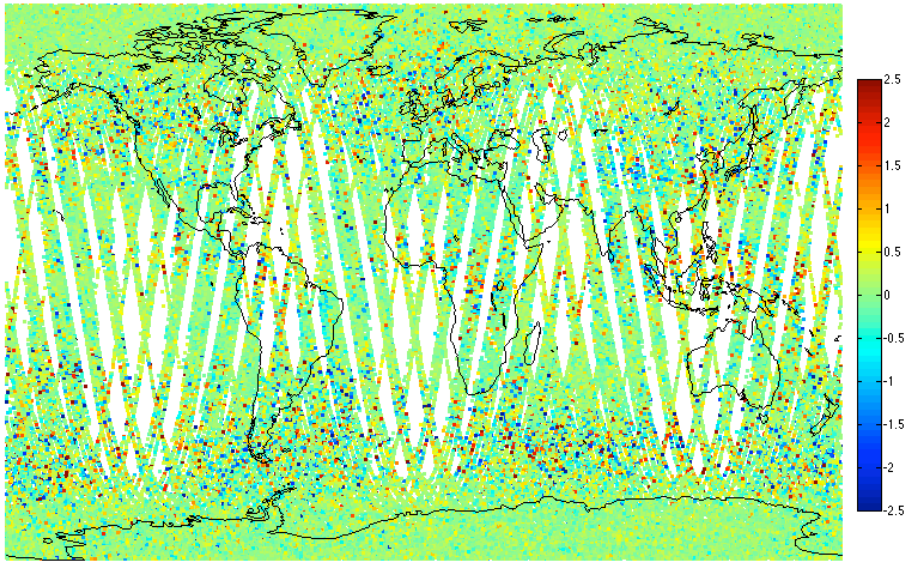
CrIS/AIRS: 1.2M "Big Circle" SNOs collected to date (March 2012 to Nov 2013);
20 minute window; -30 to 30 deg scan angle, <=2 deg scan angle diff.
AIRS V5 L1B; CrIS ADL/CSPP SDR_1.4b_NLC_ILS

2510 cm^{-1} CrIS/AIRS SNO BTs



CrIS/IASI SNO locations

835 cm^{-1} CrIS/AIRS SNO BT Diffs

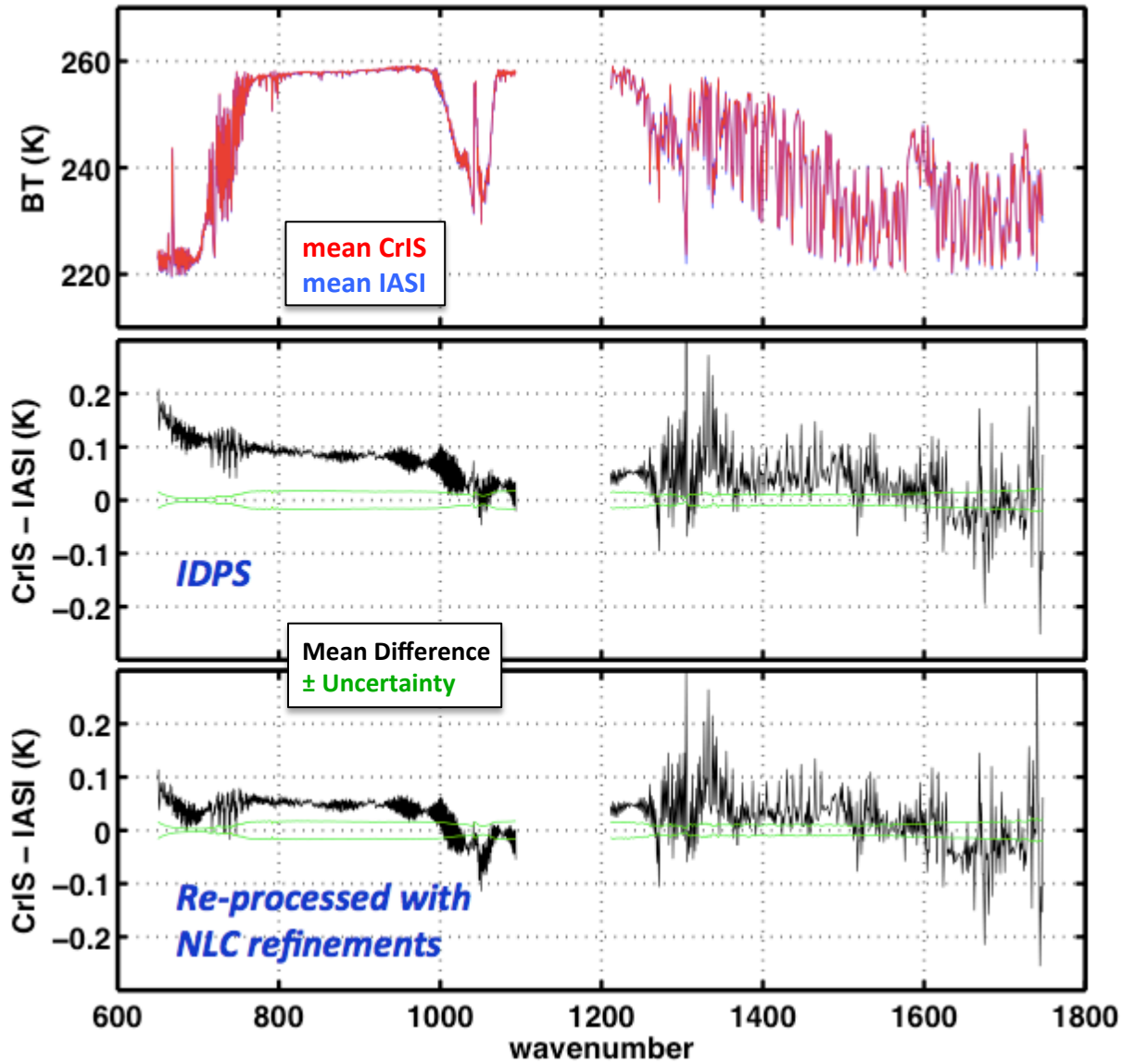


CrIS/IASI-A: 5270 "Big Circle" SNOs collected to date (March 2012 to Nov 2013);
20 minute window; nadir. ~20 days of coincidences, ~30 day gaps,
~half at +72.4 deg, ~half at -72.4 deg.
IASI_xxx_1C_M02; CrIS ADL/CSPP SDR_1.4b_NLC_ILS

CrIS/IASI Northern SNOs

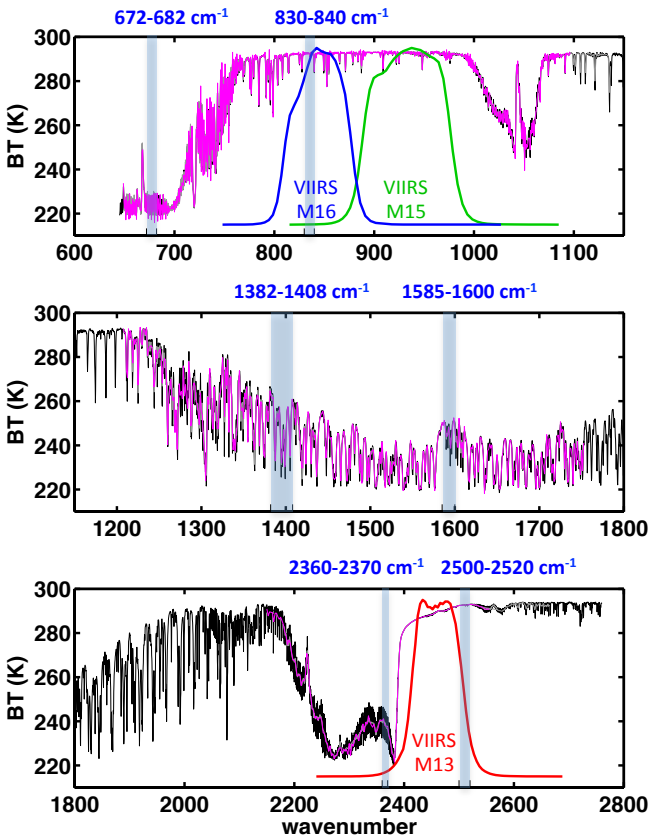
Hamming apodization

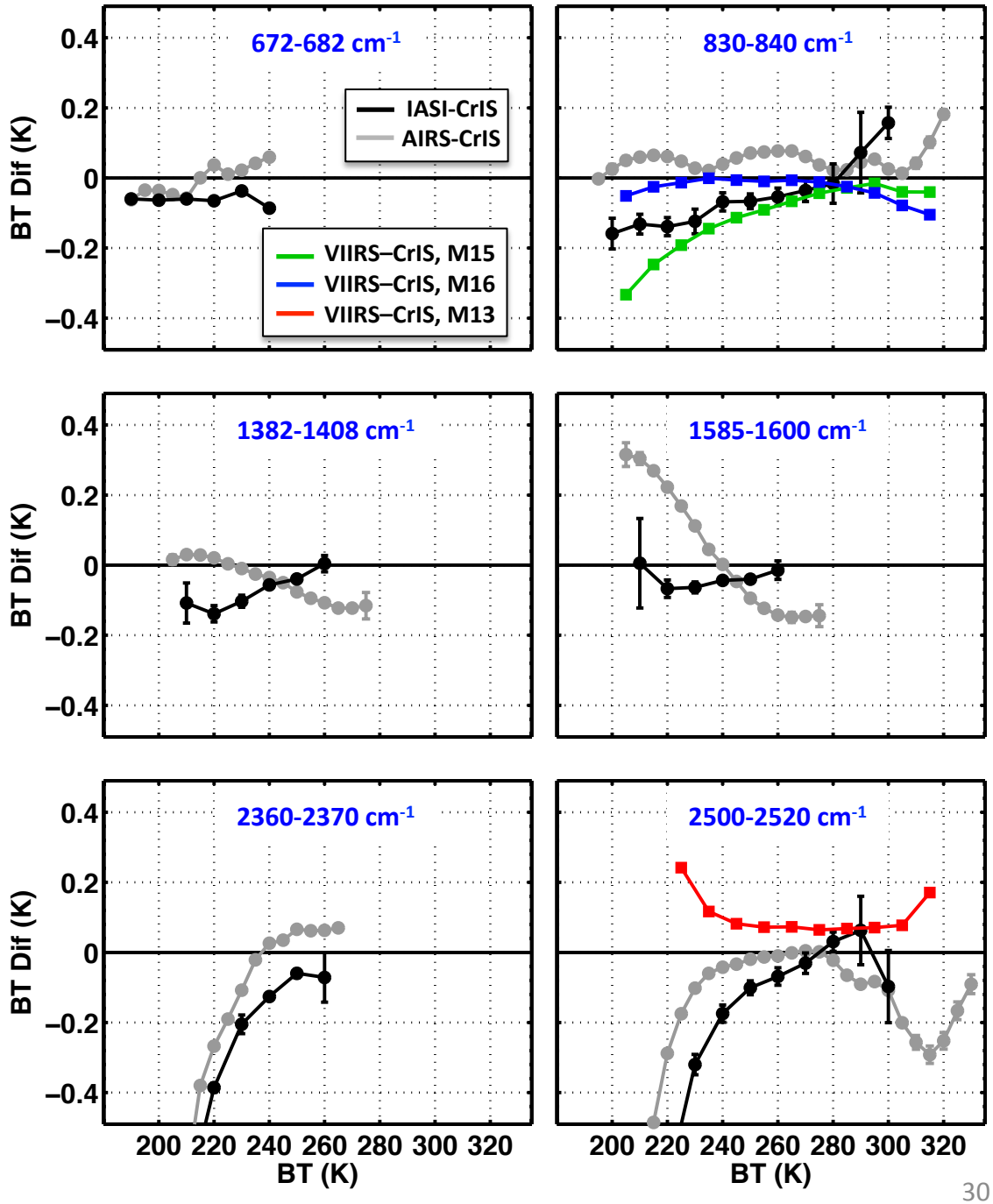
- Results shown for IDPS processing and with the reprocessed dataset including NLC and ILS refinements.
- Differences of ~0.2K or less
- NLC refinements:
  - Improved agreement in the LW band.
  - Negligible changes in the the MW band (as expected).



Summary of SNO results

for 6 representative spectral regions, and VIIRS/CrIS comparisons:

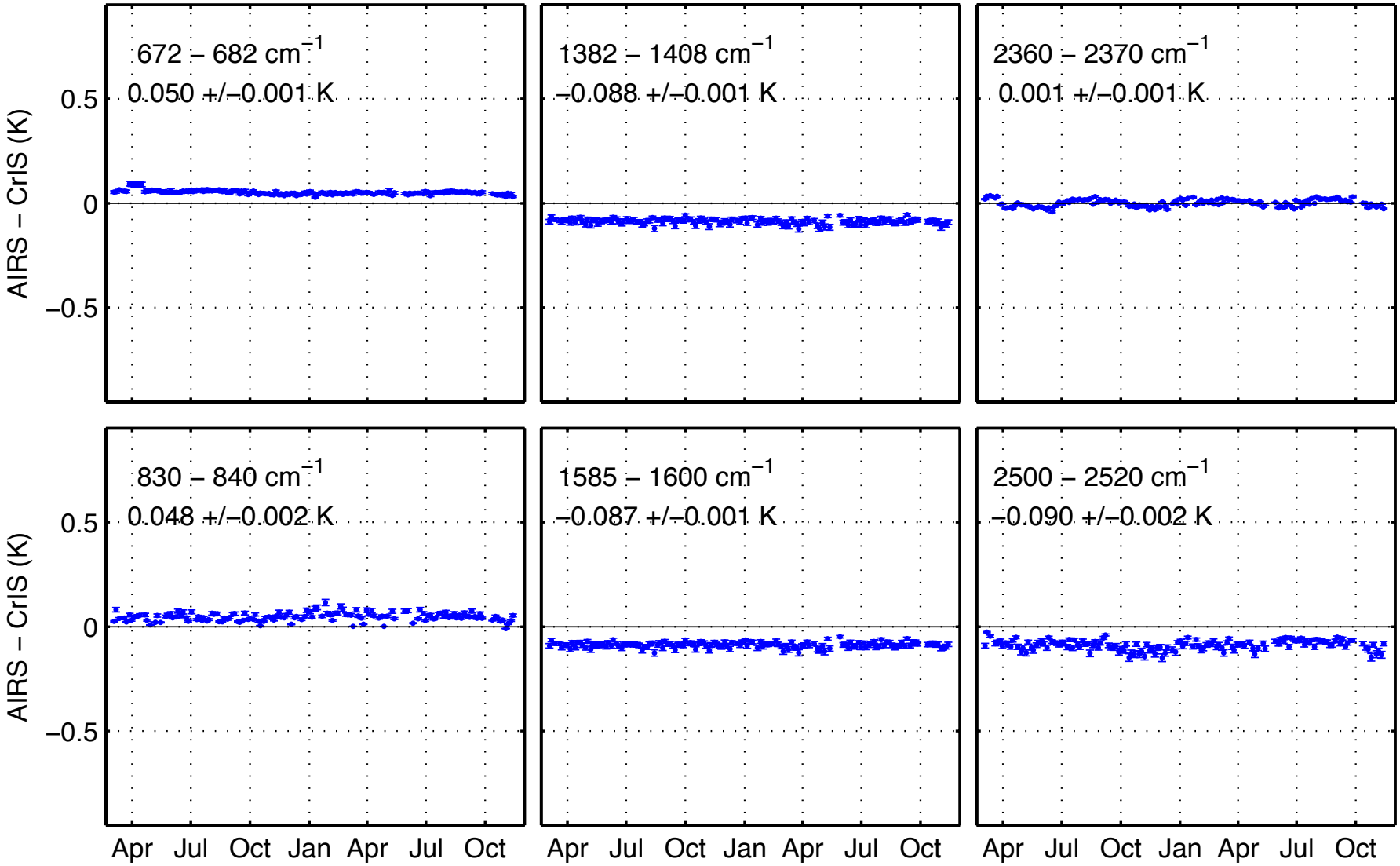




- LW differences display only small dependence on scene BT for both IASI and AIRS SNOs.
- MW differences are relatively independent of scene BT for IASI and for AIRS at 1382-1408 cm^{-1}; Differences for AIRS at 1585-1600 cm^{-1} range from ~+0.3K at 200K to -0.1K at 265K.
- SW differences are relatively flat above ~240K; Below ~230K larger differences between all three sensors are observed.
- Consistent with SNO results shown in L. Strow presentation, and reported by L. Wang et al. at NOAA STAR.

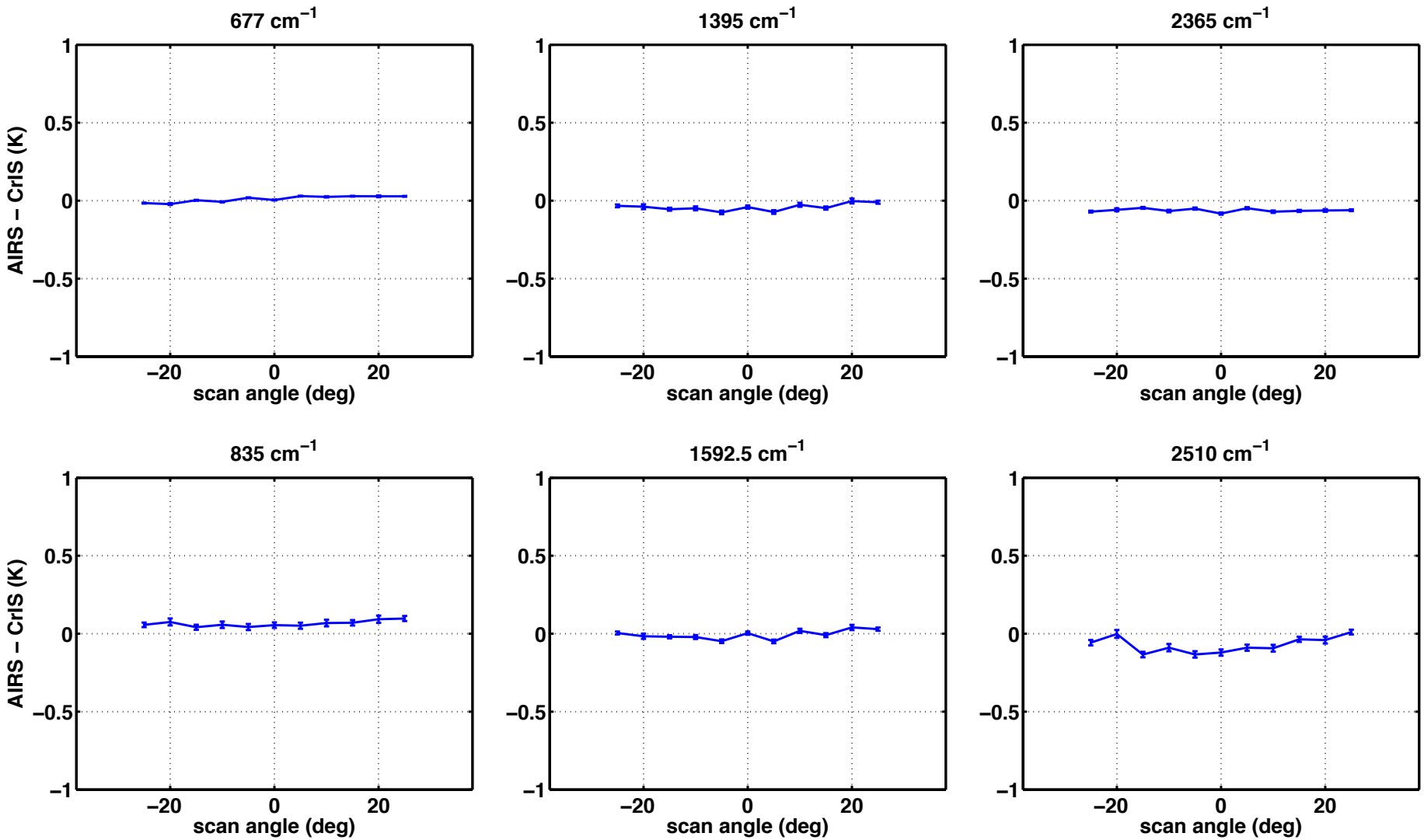
Summary of AIRS/CrIS SNO results

for 6 representative spectral regions, time series:



Summary of AIRS/CrIS SNO results

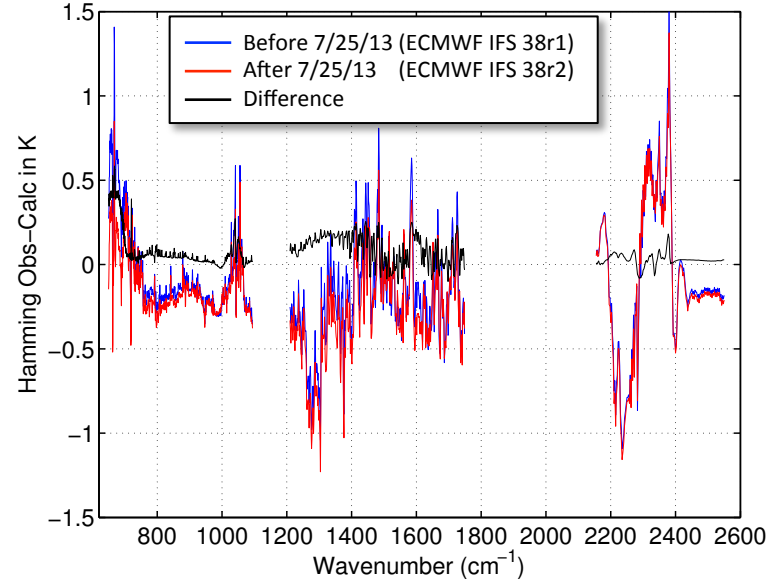
for 6 representative spectral regions, scan angle dependence:

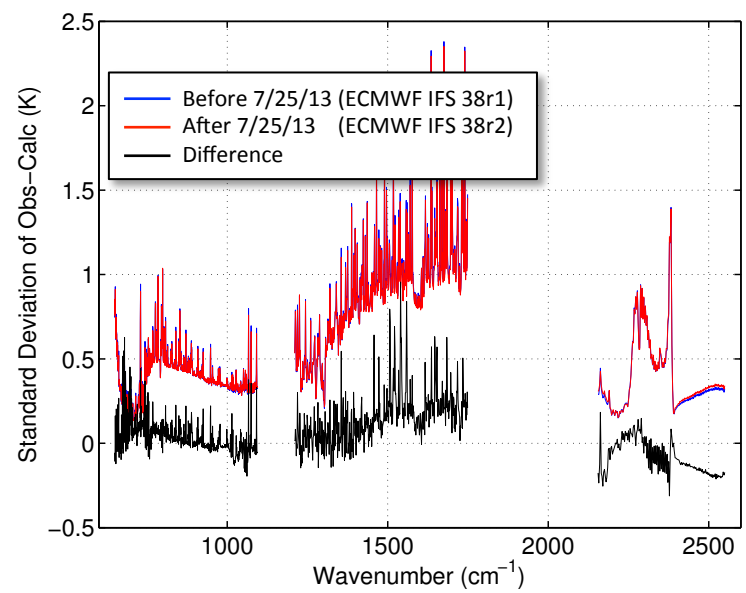


Clear Sky Obs-Calc Analyses

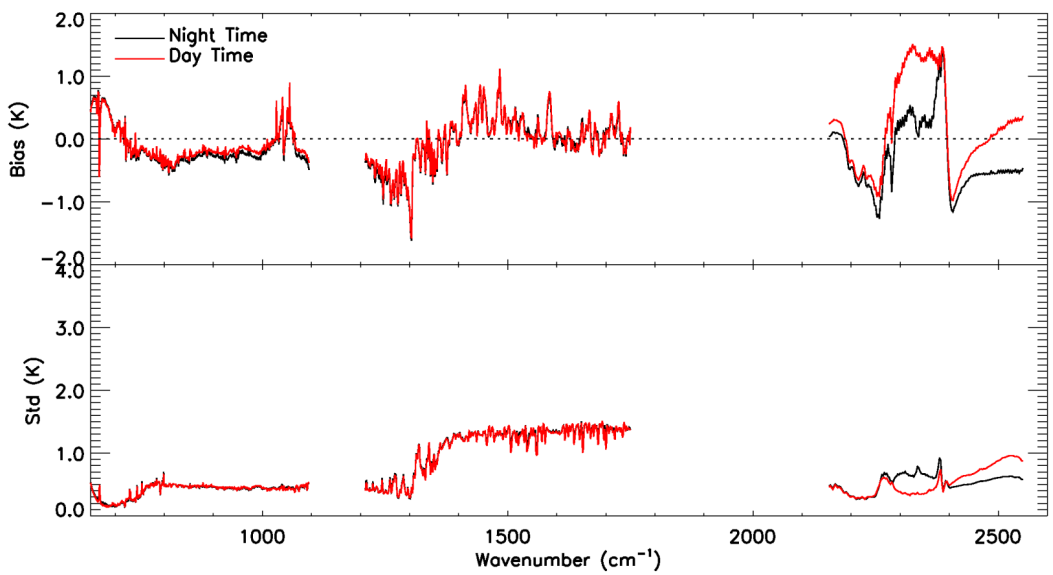
- Behavior of mean biases and standard deviation of obs-calcs are consistent with forward model and atmospheric state uncertainties and imply very good radiometric performance for CrIS.

c/o Larrabee Strow, UMBC:





c/o Yong Chen and Yong Han, NOAA STAR:



JPSS-1 and JPSS-2 CrIS

- JPSS-1
  - Main Difference from Suomi-NPP CrIS is a higher emissivity ICT
  - Expected performance is very similar to Suomi-NPP CrIS
  - Currently in testing phase; TVAC to take place later this year.
  - Launch in 2017

- JPSS-2
  - Requirements and design are being finalized. E.g.:
    - Remove spectral gaps
    - Phase change cells on ICT
    - Smaller footprints
  - Components being purchased
  - Launch in 2022

- **This record will be much more valuable for climate if combined with a coincident CLARREO mission.**

Summary and Conclusions

- The CrIS RU is very good, approximately a factor of 3 better than spec. This, along with the excellent spectral calibration performance and robust on-orbit operations, are very positive indications for the technical success of CLARREO and the ability to reach 0.1K 3-sigma on-obit.

- The CRIS SDRs have undergone extensive on-orbit cal/val, including comparisons with aircraft, VIIRS, AIRS, IASI, and clear sky calculations. Estimated RU and observed differences between the sensors are generally very good, but not insignificant for climate studies in general.

- CrIS post-launch cal/val results provide further demonstration of the same intercalibration methodology which will allow the CLARREO on-orbit 0.1K uncertainty and traceability to be transferred to concurrent operational sounders.