Building High-Quality SDR Products from NOAA Operational Satellites for Climate and Weather Applications

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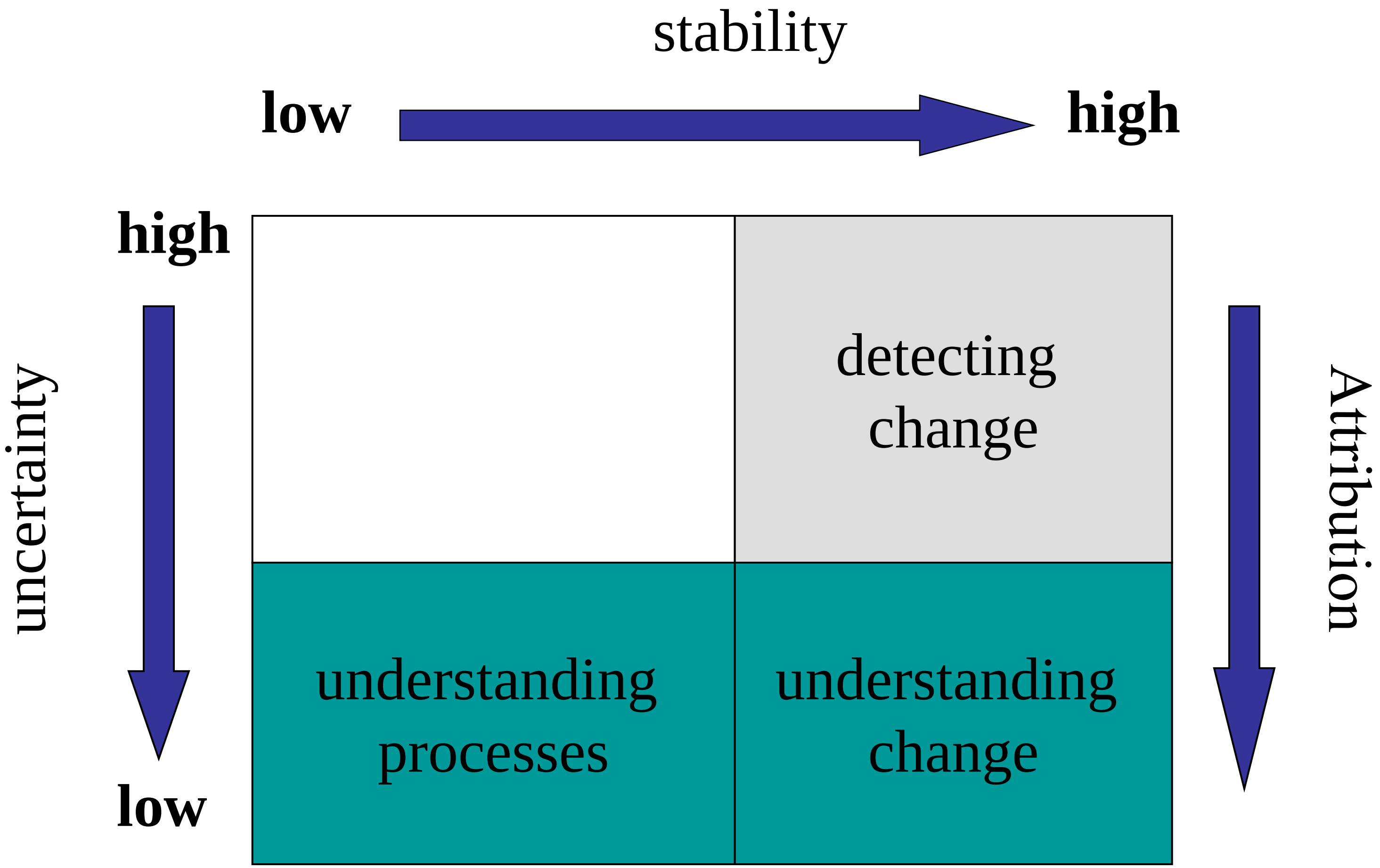
Outline

- Importance of instrument calibration for understanding climate change
- An SI (International System of Units) traceable technique for noise characterization
- In-orbit standard for characterizing the calibration accuracy
- Satellite sensor data record (or level 1 data) reprocessing
- Applications of Suomi NPP SDR data
- Summary and Conclusions

Desired Observations for Weather and Climate Applications

(After G. Stephens, 2003, J. Climate)



Stability: is affected by the derivative of calibration accuracy with time
Uncertainty: a root square of precision (noise) and accuracy

Detection of Climate Trend and Its Sensitivity to Measurement Precision and Data Length

For a time series of surface temperature, its linear trend can be derived as

$$a = \frac{12\sum_{i=1}^{M} x_i^o \left(t_i - \overline{t}\right)}{\left(M^3 - M\right)}$$

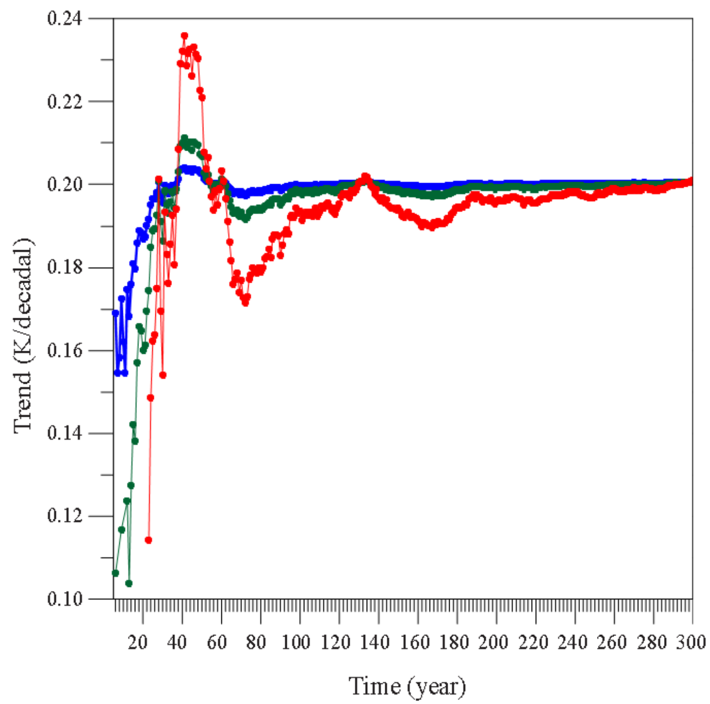


Fig. 1 Climate trend calculated from different lengths of time series with three different observation error variances: 0.1K (blue line), 0.3K (green line) and 1K (red line)

where ***a*** is a linear regression coefficient and is obtained by a least-square fit which minimizes the difference between observations and linear regression model. M is the record length in year.

Zou , X, 2012, Advances Meteor. Sci.&Tech. (1), 42-43

Climate Trend Error from Observations

The uncertainty of the trend (a) is

$$\sigma_a^2 = \frac{12\left(\sigma_o^2 + \sigma_n^2\right)}{M^3 - M}$$

where:

M —— Data length

σ_o^2 —— Observation error

σ_n^2 —— Natural variability

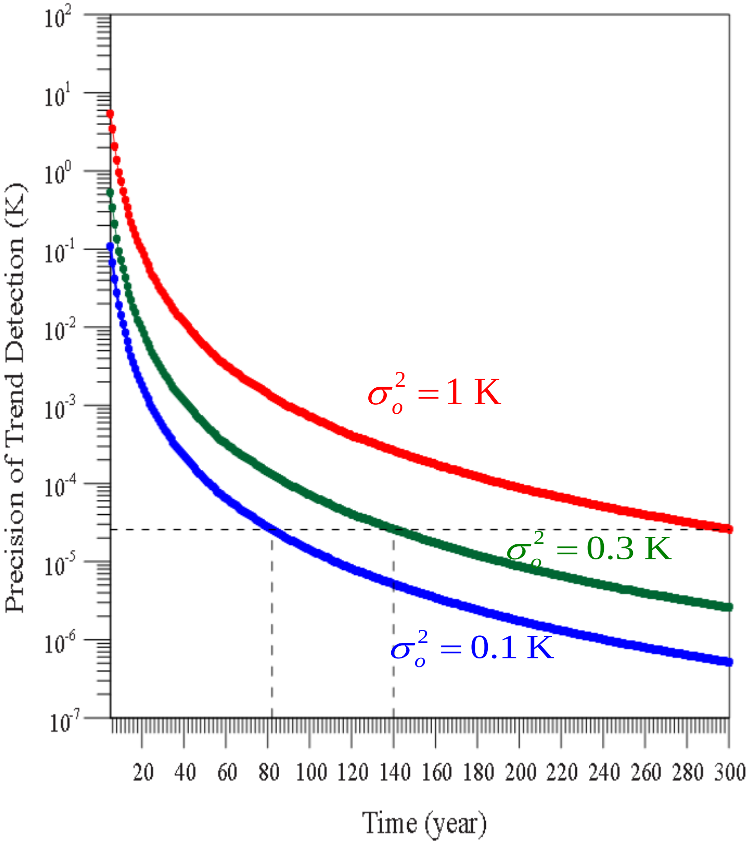


Fig. 2 Variations of σ_{trend} with respect to data length for the trends shown in Fig. 1

Zou , X, 2012, Advances Meteor. Sci.&Tech. (1), 42-43

Requirements for Construction of Satellite Climate Data Record

- Well characterizes the errors of satellite measurements
- Extends the data record length through cross-calibrating measurements
- Understands the stability of calibration accuracy
- Considers the natural variability in analysing the trend from satellite climate data record (CDR)

An SI Traceable Technique for Deriving the Noise of NOAA Sounding Instruments

- Allan variance was proposed by NIST for characterizing the random noise from a time series which has a variable mean
- It was never implemented for meteorological satellite instruments. Currently, all the NOAA instrument noises are computed by the standard deviation which is only valid for the stationary mean.
- With Allan variance, all the NEDT and NEDN can be SI traceable

Allan, D. W., 1987: Should the classical variance be used as a basic measure in standards metrology Instrumentation and Measurement, IEEE Trans. IM-36, 646-654,

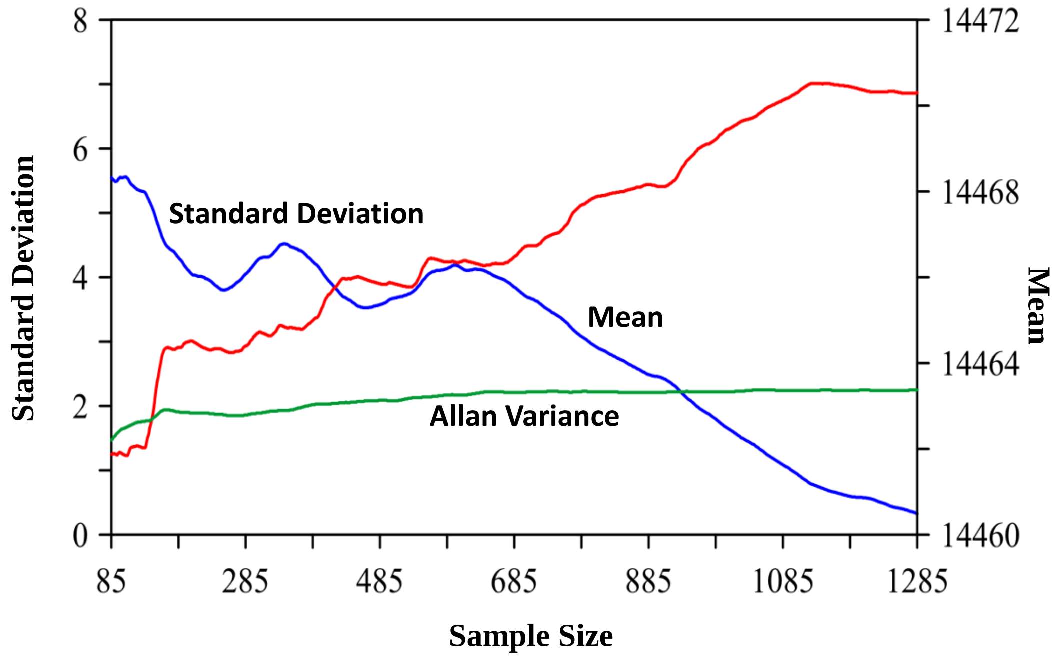
ATMS Noise Equivalent Temperature (NEDT)

For a time series with a stable mean, the standard deviation of the measurements can be used as NEDT:

$$\sigma_{ch} = \left[\frac{1}{4N}\sum_{i=1}^{N}\sum_{j=1}^{4}\left(\frac{C_{ch}^{w}(i,j)-\overline{C_{ch}^{w}(i)}}{\overline{G_{ch}(i)}}\right)^{2}\right]^{1/2}$$

For a non-steady mean such as ATMS warm count from blackbody target, Allan variance works the best for NEDT:

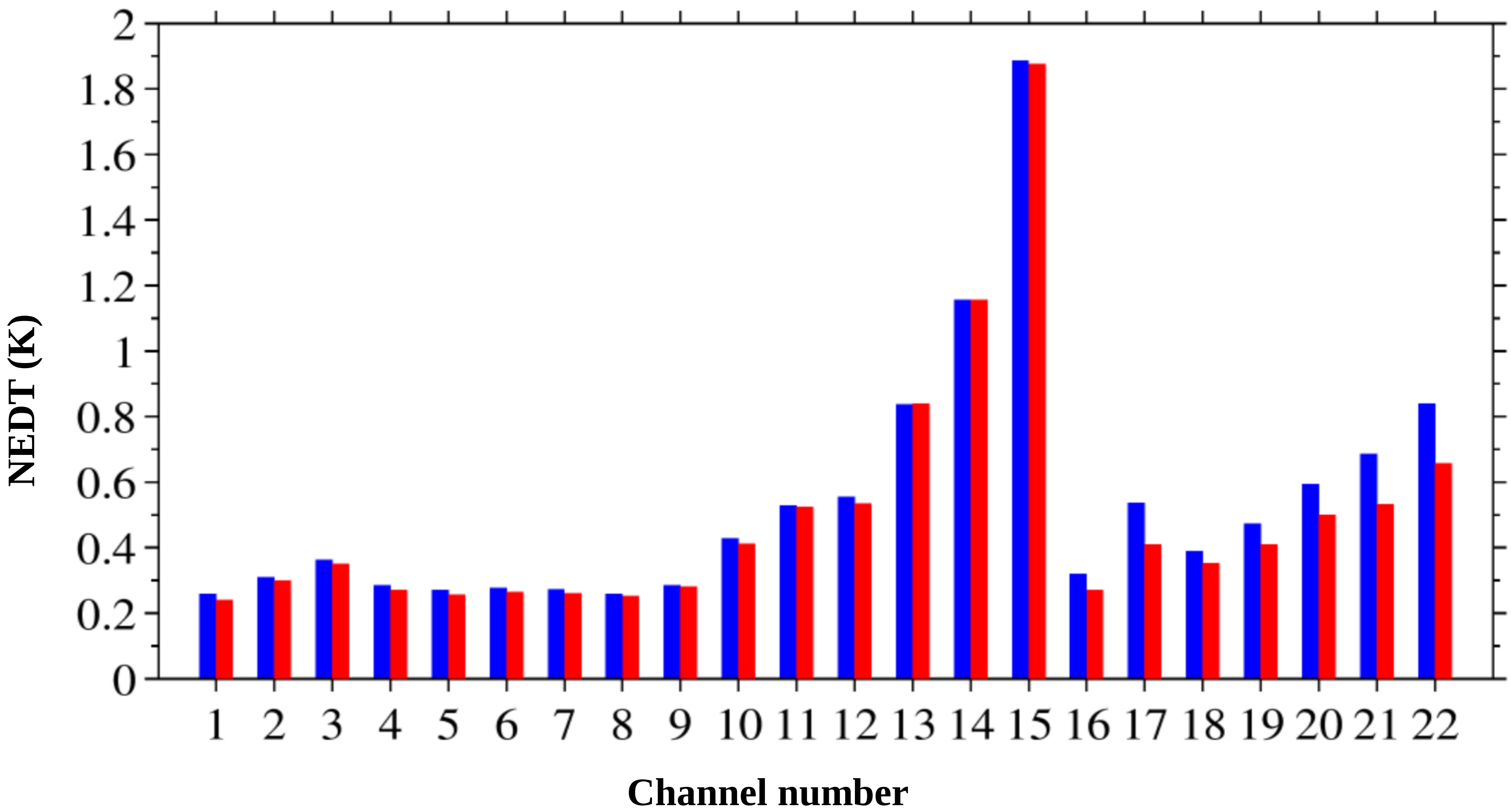
$$\sigma^{Allan}(m)=\sqrt{\frac{1}{2m^{2}\left(N-2m\right)}\sum_{j=1}^{N-2m}\left(\sum_{i=j}^{j+m-1}\left(C_{ch}^{w}(i+m)-C_{ch}^{w}(i)\right)\right)^{2}}$$



ATMS channel 1 warm count mean (blue, y-axis on the right), the standard deviation (red, y-axis on the left) and the overlapping Allan deviation (green, y-axis on the left) of the 17-scanline (m) average as a function of the total sample size (N).

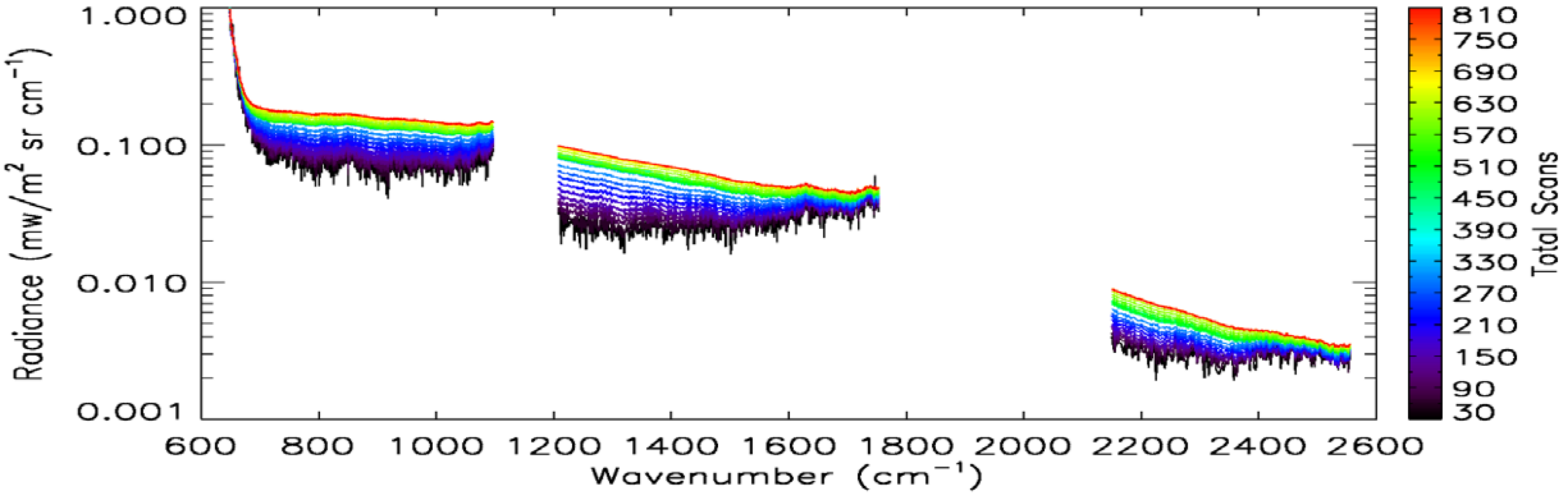
M. Tian, X. Zou and F. Weng, "Use of Allan Deviation for Characterizing Satellite Microwave Sounders Noise Equivalent Differential Temperature (NEDT)", IEEE Geosci. Remote Sens. Lett., Digital Object Identifier 10.1109/LGRS.2015.2485945

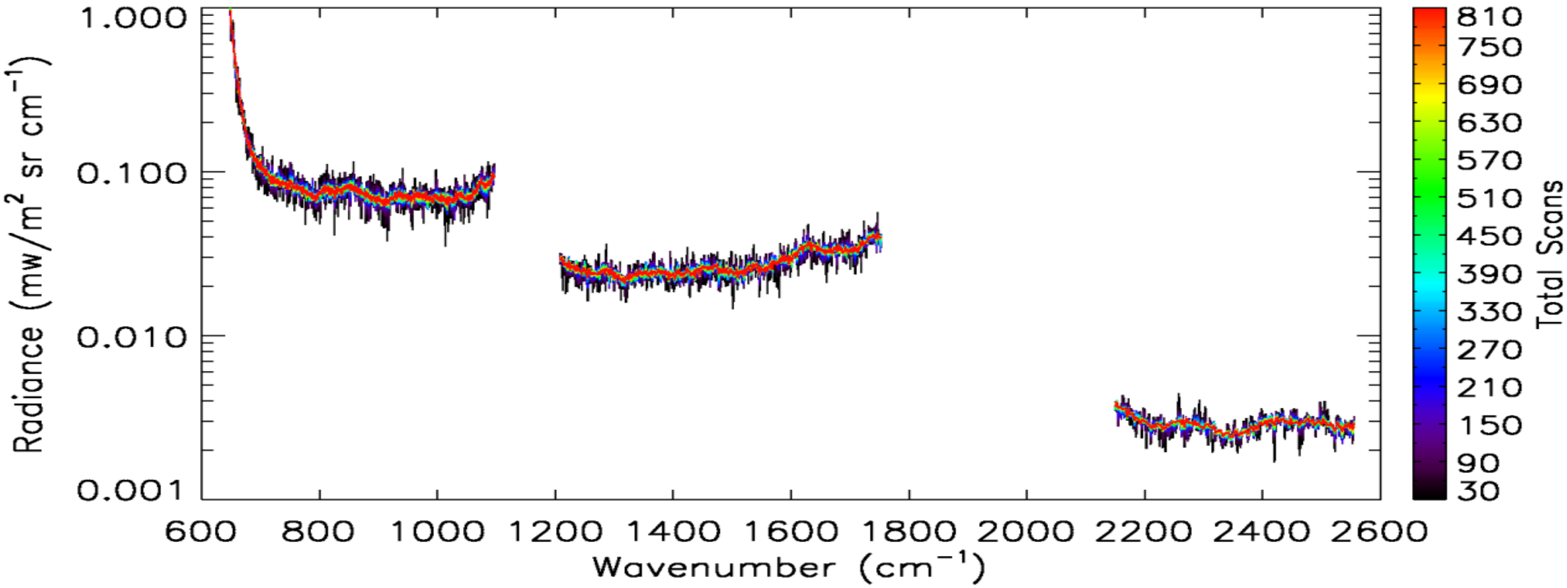
ATMS NEDT Computed from Standard and Allan Deviations



ATMS standard deviation (blue) and Allan deviation (red) with channel number. The sample size (N) is 150 and the averaging factor (m) for the warm counts is 17. The standard deviation is much higher than Allan deviation.

CrIS Noise Equivalent Differential Radiance (NEDN) Computed from Standard and Allan Deviations





Chen, Y., F. Weng, and Y. Han, 2015: SI traceable algorithm for characterizing hyperspectral infrared sounder CrIS noise, 10.1364/AO.54.007889

Establish an in-orbit Standard for Characterizing Instrument Calibration Accuracy

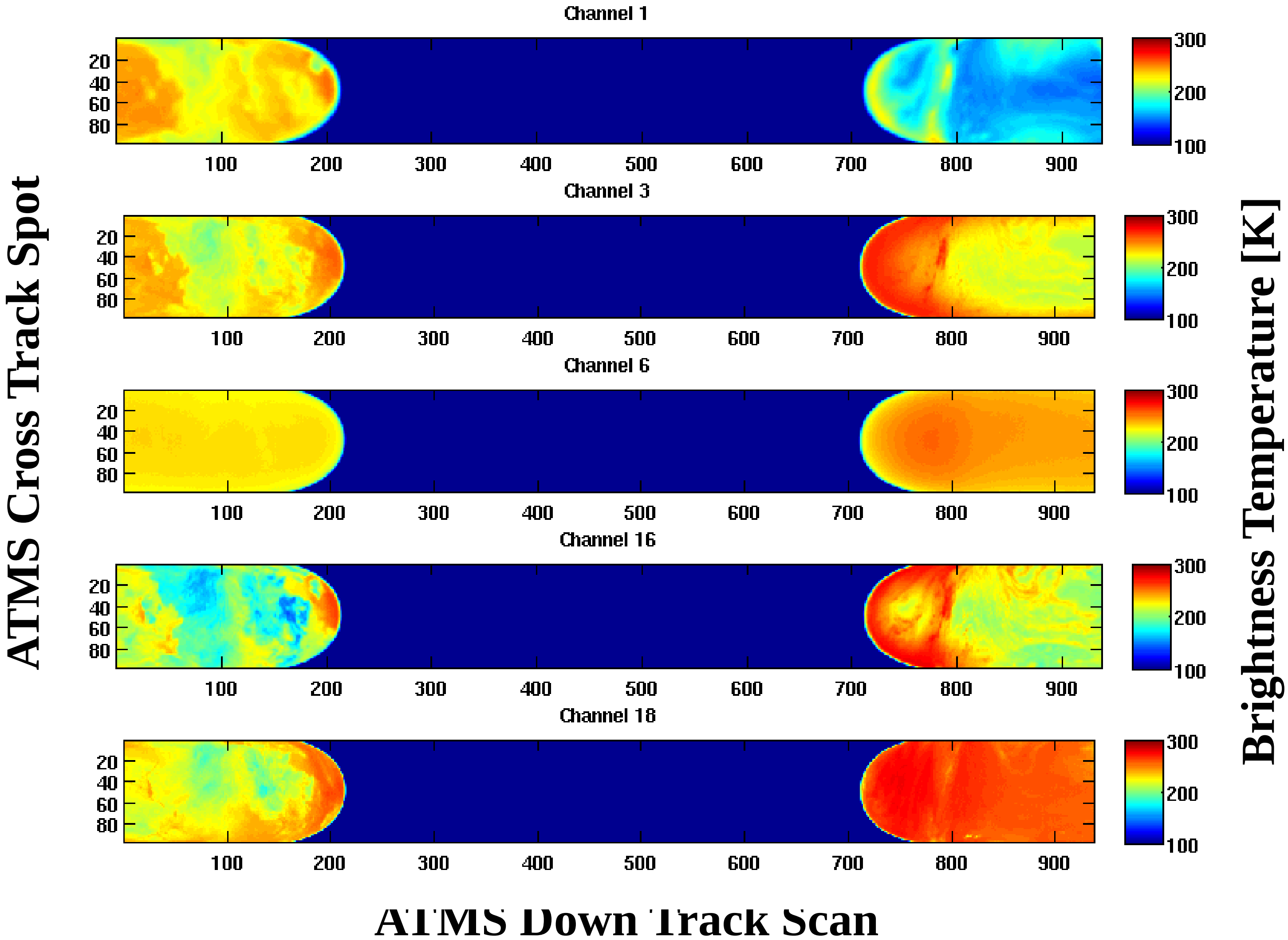
- Maneuvers Suomi NPP satellite to scan cold space and characterizes the scan angle dependent bias using physical models

- Develops the best practices for earth scene simulations using the forward models and high quality atmospheric profiles

- Uses stable earth scenes and terrestrial targets (e.g. moon and star) for monitoring the calibration stability

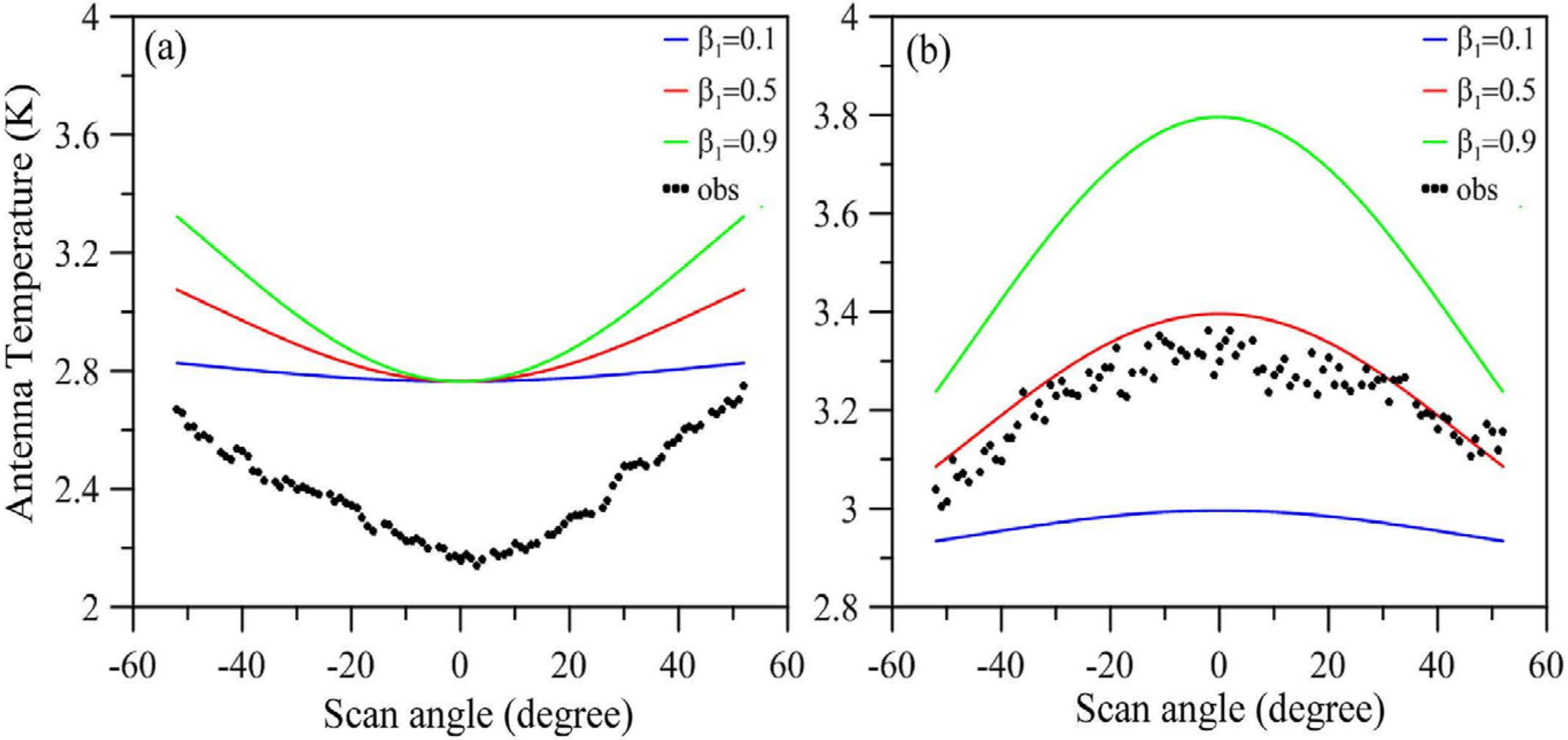
Weng, F., *H. Yang, X. Zou, 2012: On Convertibility from Antenna to Sensor Brightness Temperature for Advanced Technology Microwave Sounder (ATMS), IEEE Geosci. Remote. Sens. Letter, 10.1109/LGRS.2012.2223193*

ATMS Pitch Maneuver February 20, 2012



Slide courtesy of Vince Leslie,
MITLL

ATMS TDR Pitch Maneuver Data for Characterizing the Antenna Emission



SNPP ATMS pitch maneuver observations show channel related scan angle dependent feature, indicate the scan bias is not inherent feature of the scene

Effects of ATMS Flat Reflector Emission on Brightness Temperature

Quasi-V (TDR) :

$$R_{qv}^{c} = R_{qv} + \varepsilon_h (R_r - R_h) + [\varepsilon_v (R_r - R_v) - \varepsilon_h (R_r - R_h)]\sin^2\theta - \frac{R_3}{2}(1-\varepsilon_h)^{3/2} sin2\theta$$

Quasi-H (TDR):

Bias due to the reflector emission

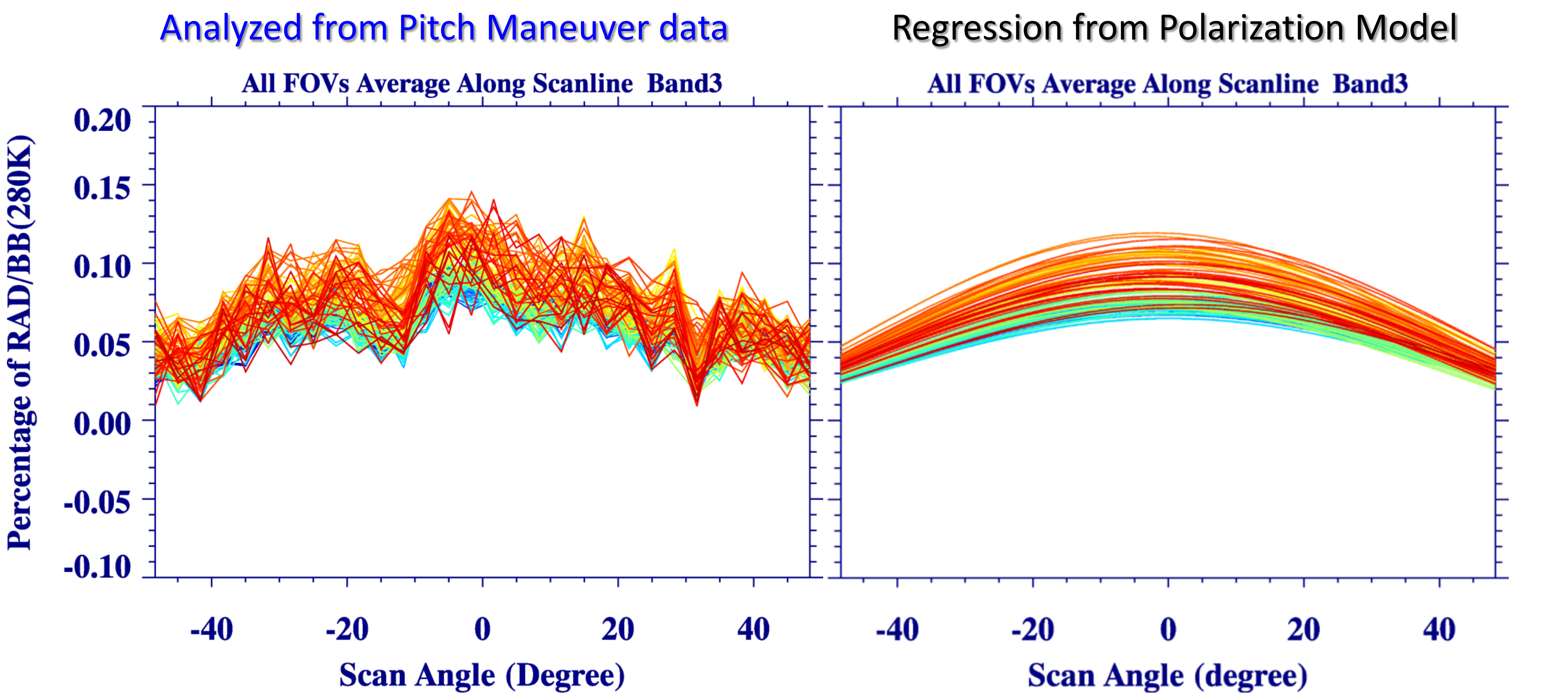
$$R_{qh}^{c} = R_{qh} + \varepsilon_h (R_r - R_h) + [\varepsilon_v (R_r - R_v) - \varepsilon_h (R_r - R_h)]\cos^2\theta + \frac{R_3}{2}(1-\varepsilon_h)^{3/2} \sin 2\theta$$

where

R_{qv} and R_{qh} are the radiances at quasi vertical and horizontal polarzation which are further related to the radiances at pure vertical and horizontal polarization, R_v and R_h. ε_v and ε_h are the reflector emissivity at the vertical and horizontal polarization. R_3 is the third Stokes radiance component of the scene. R_r is the radiance emitted from the reflector. θ is the scan angle. Note that $\varepsilon_v = 2\varepsilon_h - \varepsilon_h^2$ at an indent angle of 45 degree to reflector normal.

Yang, H. and F. Weng, 2015: Estimation of ATMS Antenna Emission from cold space observations, IEEE Geosci. Trans. Remote. Sens, in press

CrIS Shortwave IR Band 3 for All Channels during SNPP Pitch Maneuver Period



Different colors indicate different channels. The results are normalized by Planck Radiances at 287K.

Slide Courtesy of Likun Wang and Yong Han

ATMS Calibration Accuracy Assessment Using GPS RO Profiles

- **Time period of data search:**

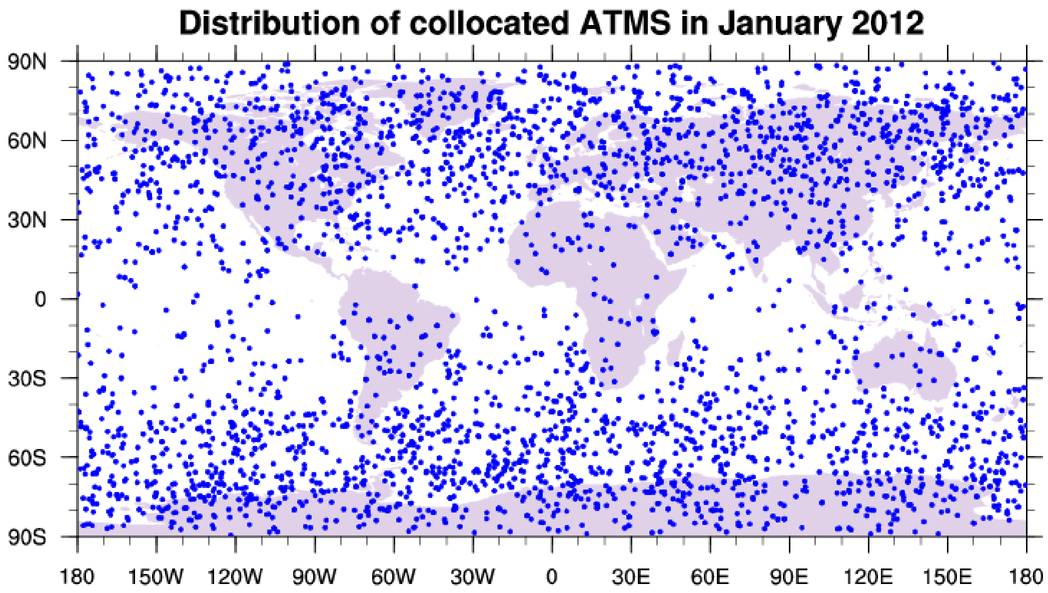
  January, 2012

- **Collocation of ATMS and COSMIC data:**

  Time difference < 0.5 hour

  Spatial distance < 30 km

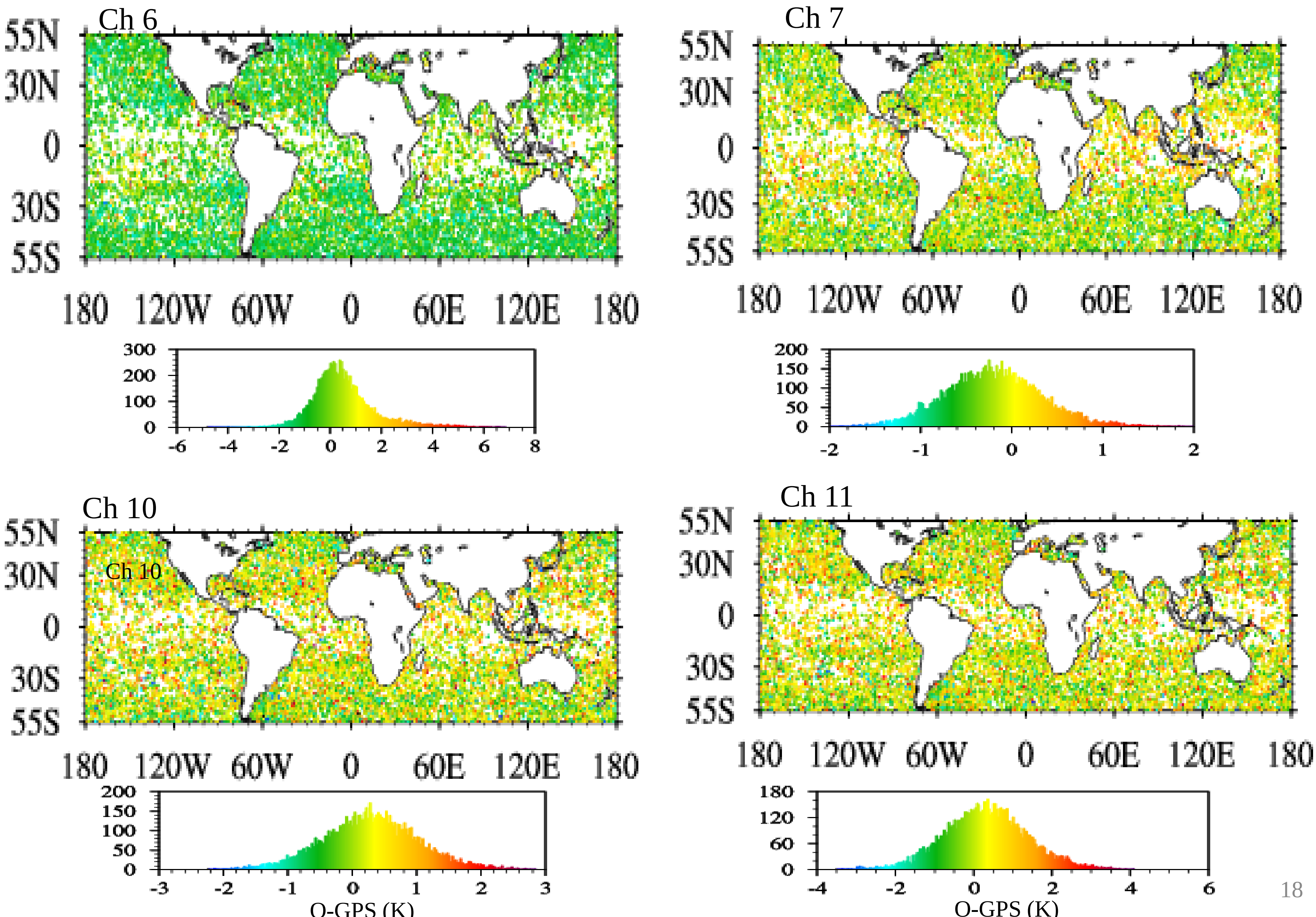
(GPS geolocation at 10km altitude is used for spatial collocation)



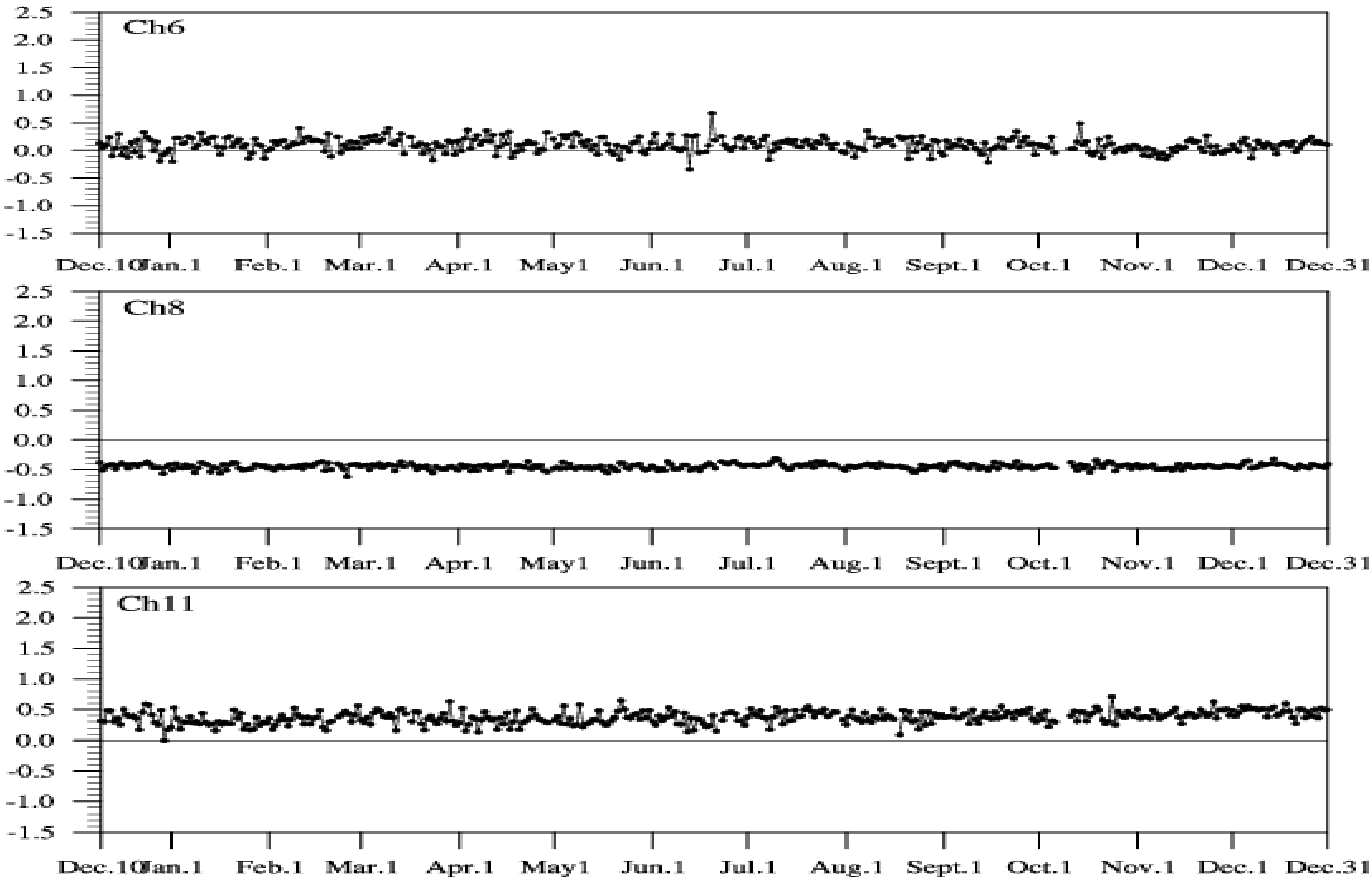
3056 collocated measurements

Slide Courtesy of Lin Lin

ATMS Bias Obs (TDR) - GPS Simulated



ATMS Bias Obs - Sim (GPS RO)

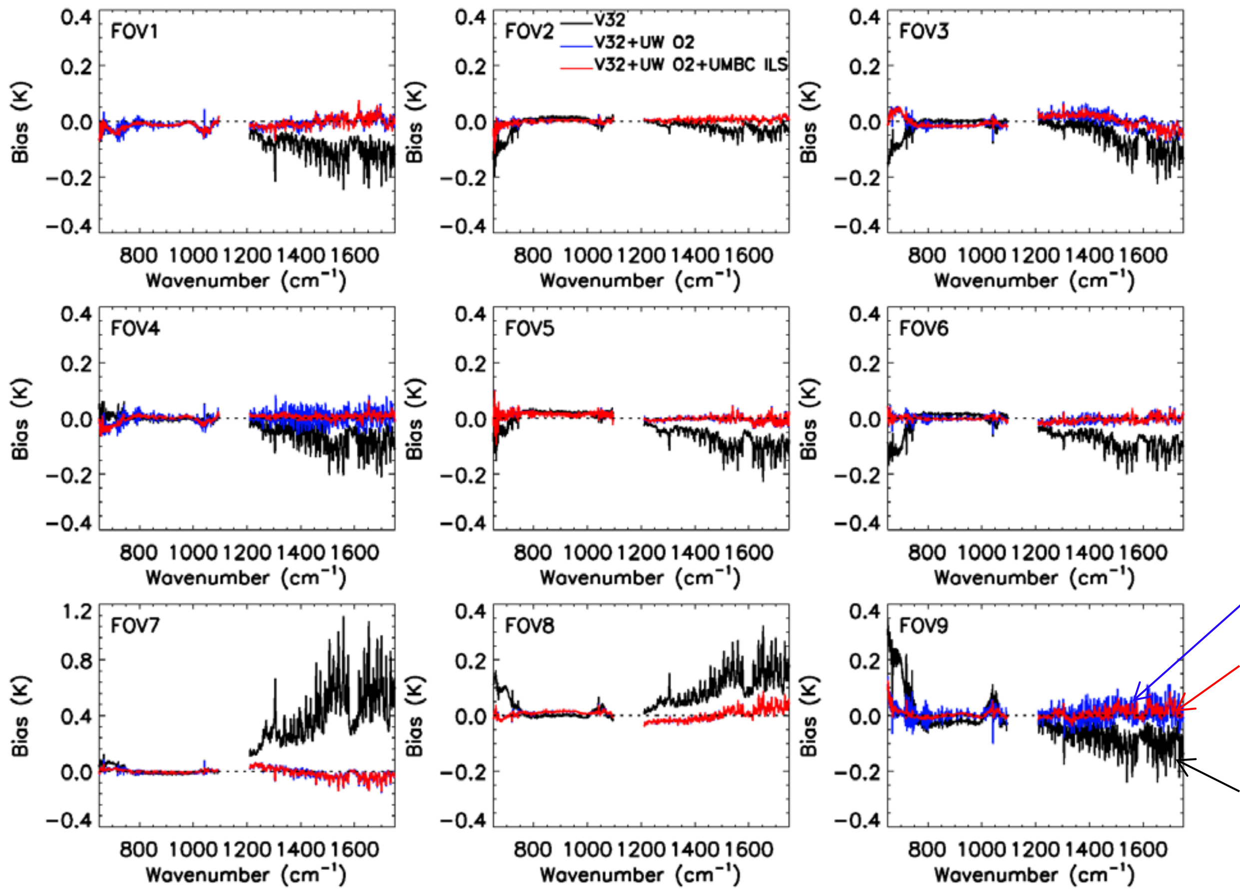


Slide courtesy of Lin Lin

CrIS Radiative Transfer Simulations

- Line by Line Radiative Transfer Model
  - Gaseous absorption
  - None Local Thermal Equilibrium emission correction
  - Short wave surface reflection
- Inputs to LBLRTM
  - Wavelength, solar and satellite viewing geometry, surface emissivity
  - Temperature and water vapor profile from ECMWF forecast fields
  - Climatology CO2, CO, CH4 profile
  - CrIS spectral response function
- Outputs from LBLRTM
  - Radiances at all 2211 channels and 9 FOVS
  - O-B at each FOV
  - Double difference of O-B between FOVs.

CrIS Individual FOV Bias wrt NWP Simulations



Total clear sky observation points ~400000

Blue: after nonlinearity coefficient change but before spectral coefficient change

Red: after nonlinearity coefficient and spectral coefficient changes

Black: before nonlinearity and spectral coefficient changes

$$BIAS_{FOVi} = \overline{(Obs - CRTM)_{FOV_i}} - \overline{(Obs - CRTM)_{all}}$$

The achieved uniformity of the spectral and radiometric uncertainties cross the 9 FOVs is important for NWP to maximize the use of the radiance data

Slide Courtesy of Yong Chen

Building in-orbit Truth for Characterizing the OMPS Earth View SDR Accuracy

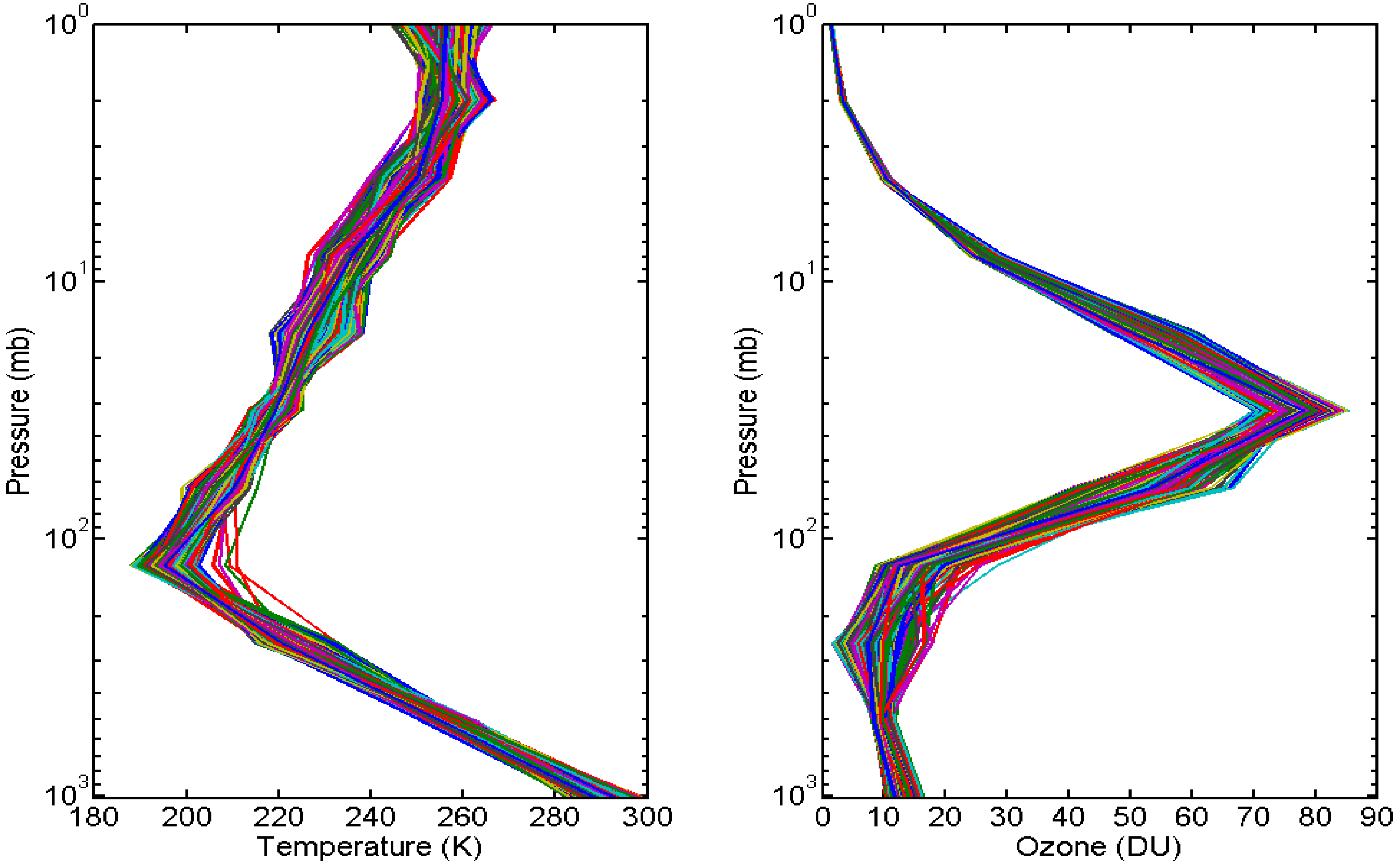
- Develop the “truth” simulated from the forward radiative transfer model at OMPS EV location (Macropixel)

- Radiative transfer model must include comprehensive scattering and absorption processes at UV regions

- Accurate understanding of atmospheric and surface status at OMPS EV location.

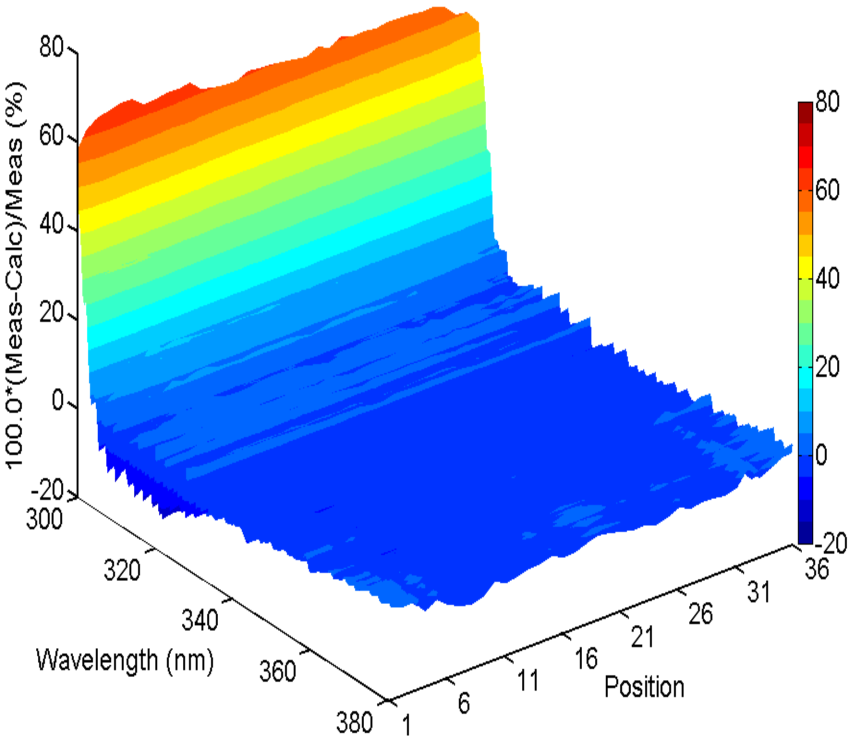
- The difference between observations and simulations is used as an estimate of on-board calibration accuracy

Co-located OMPS/MLS Temperature and Ozone Profiles

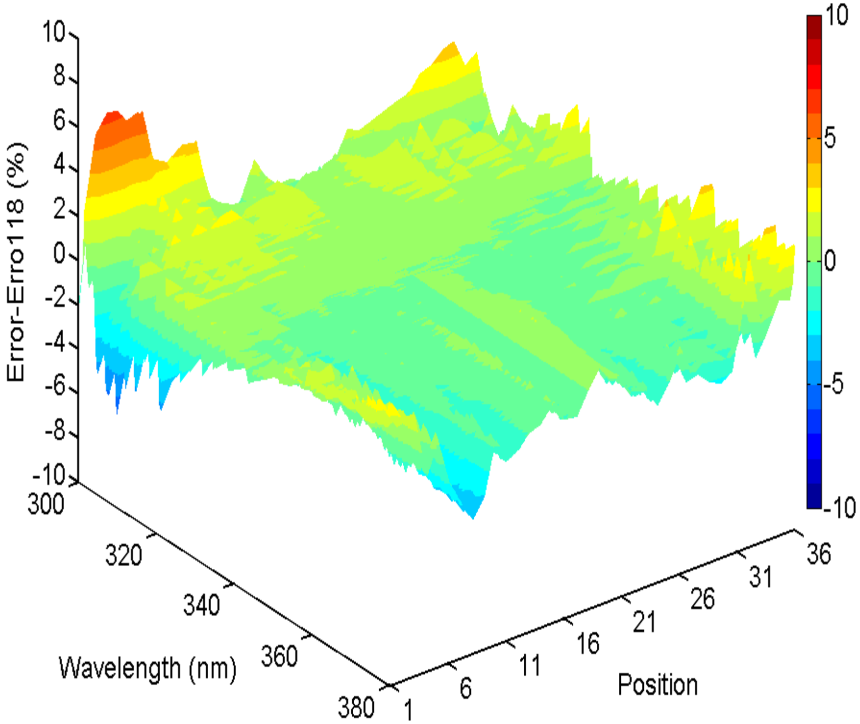


OMPS Observation minus Simulation (O-B)

Relative Error



Relative error wrt to Position 18 (nadir)

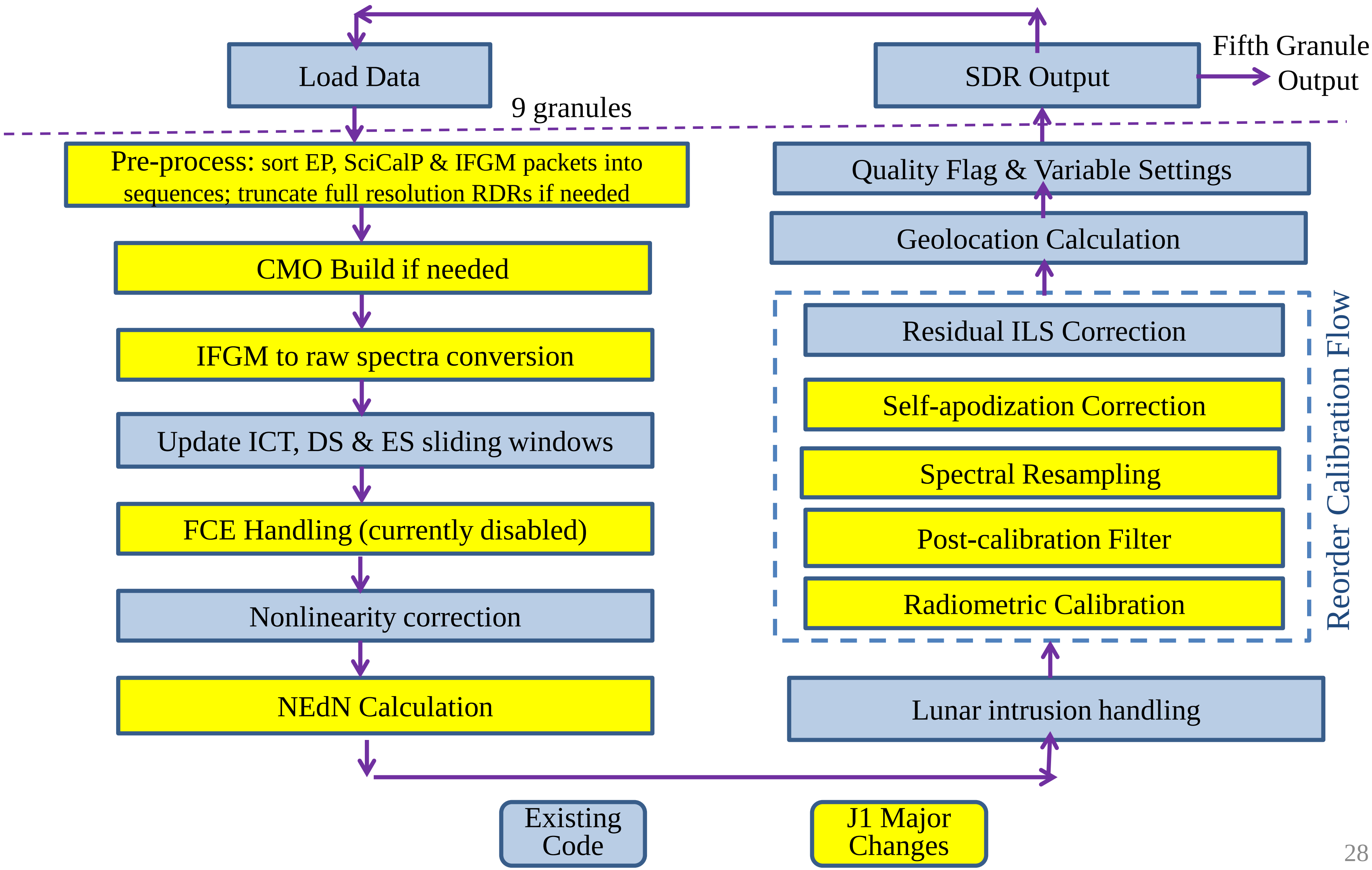


The bias in cross-track direction is generally less than 2% except at shorter wavelengths where simulations may become less accurate due to complex scattering process. The bias is also larger in side pixel locations

JPSS Mission Life Cycle SDR Reprocessing

- SNPP SDR Processing Changes since November 2011
  - CrIS SDR from normal to full spectral resolution
  - ATMS SDR from Rayleigh-Jean to full radiance
  - VIIRS SDR changes from F/H factor updates
  - Over 1000 discrepancy reports (DR) filed to fix the anomalies, update in PCT, LUT, engineering packages, etc.
- Major SDR Processing Upgrades from SNPP to JPSS-1
  - CrIS FSR will implement several new modules to reduce the ring effects)
  - ATMS SDR will have some new modules in correction of antenna emission
  - OMPS will add more modules to compress and aggregate the RDR
  - VIIRS DNB requires special upgrades in geolocation and aggregation
- Starting 2016, SNPP SDR products will be reprocessed every other year
  - SNPP ATMS, CrIS and OMPS - 2016
  - SNPP VIIRS – 2017

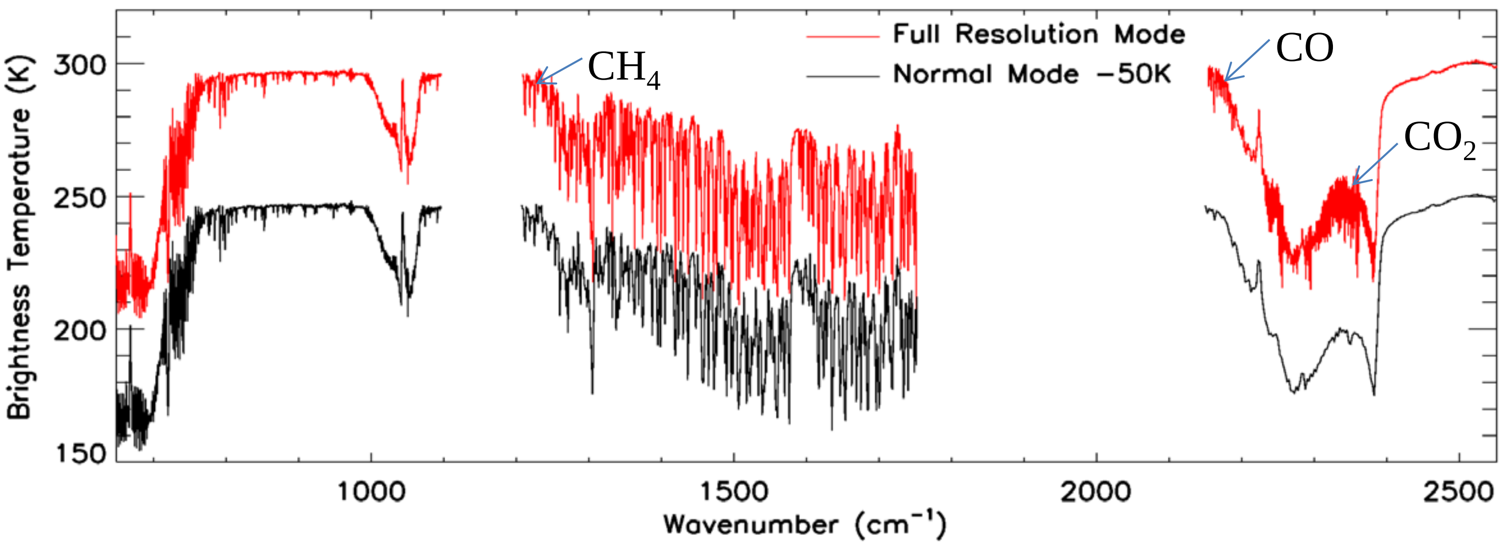
CrIS SDR Algorithm Change from SNPP to JPSS



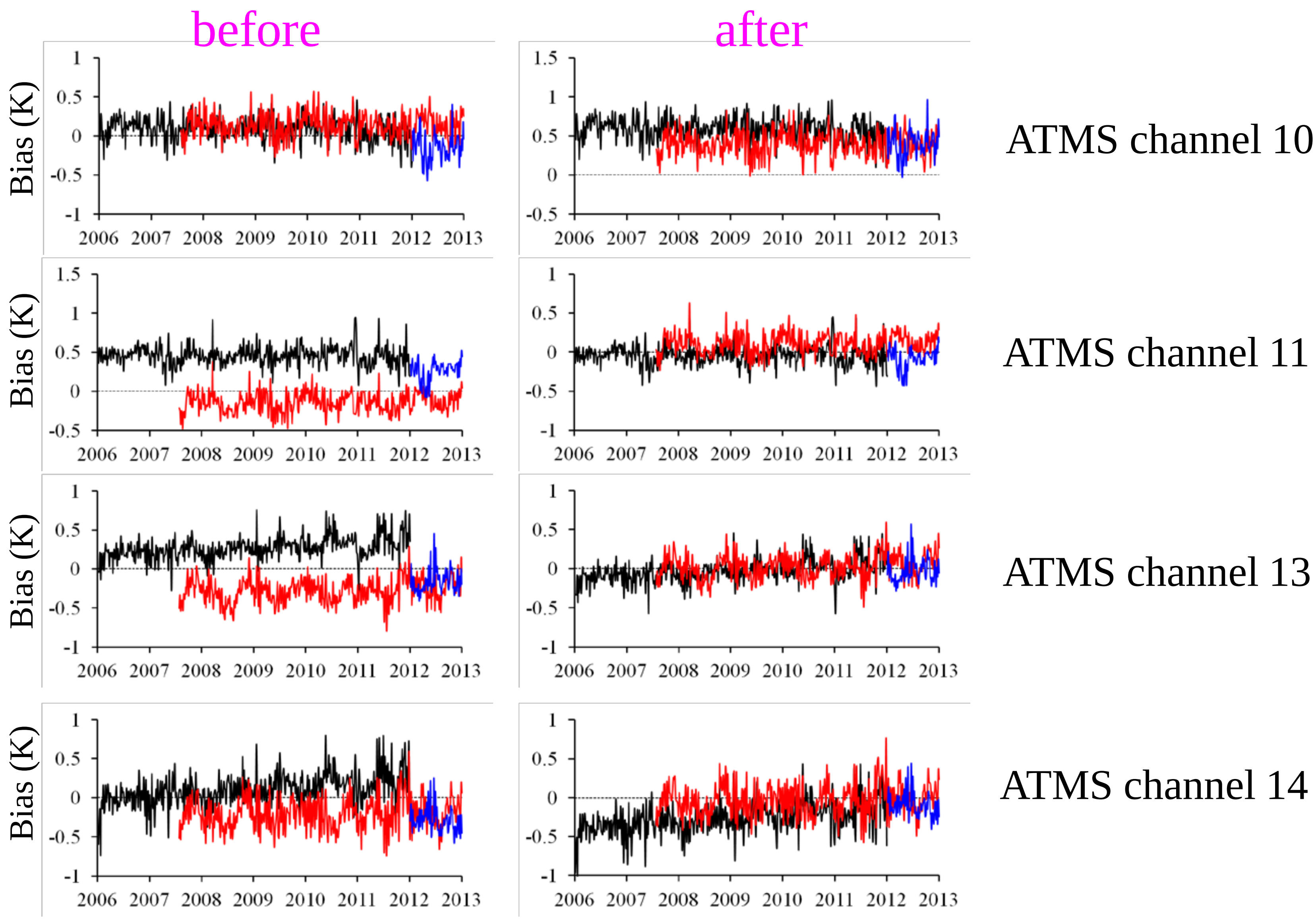
SNPP CrIS Full Spectral Resolution SDR

Frequency Band	Spectral Range (cm^{-1})	Number of Channel	Spectral Resolution (cm^{-1})
LWIR	650 to 1095	713 (713)	0.625 (0.625)
MWIR	1210 to 1750	865 (433)	0.625 (1.25)
SWIR	2155 to 2550	633 (159)	0.625 (2.5)

Red: Full resolution mode



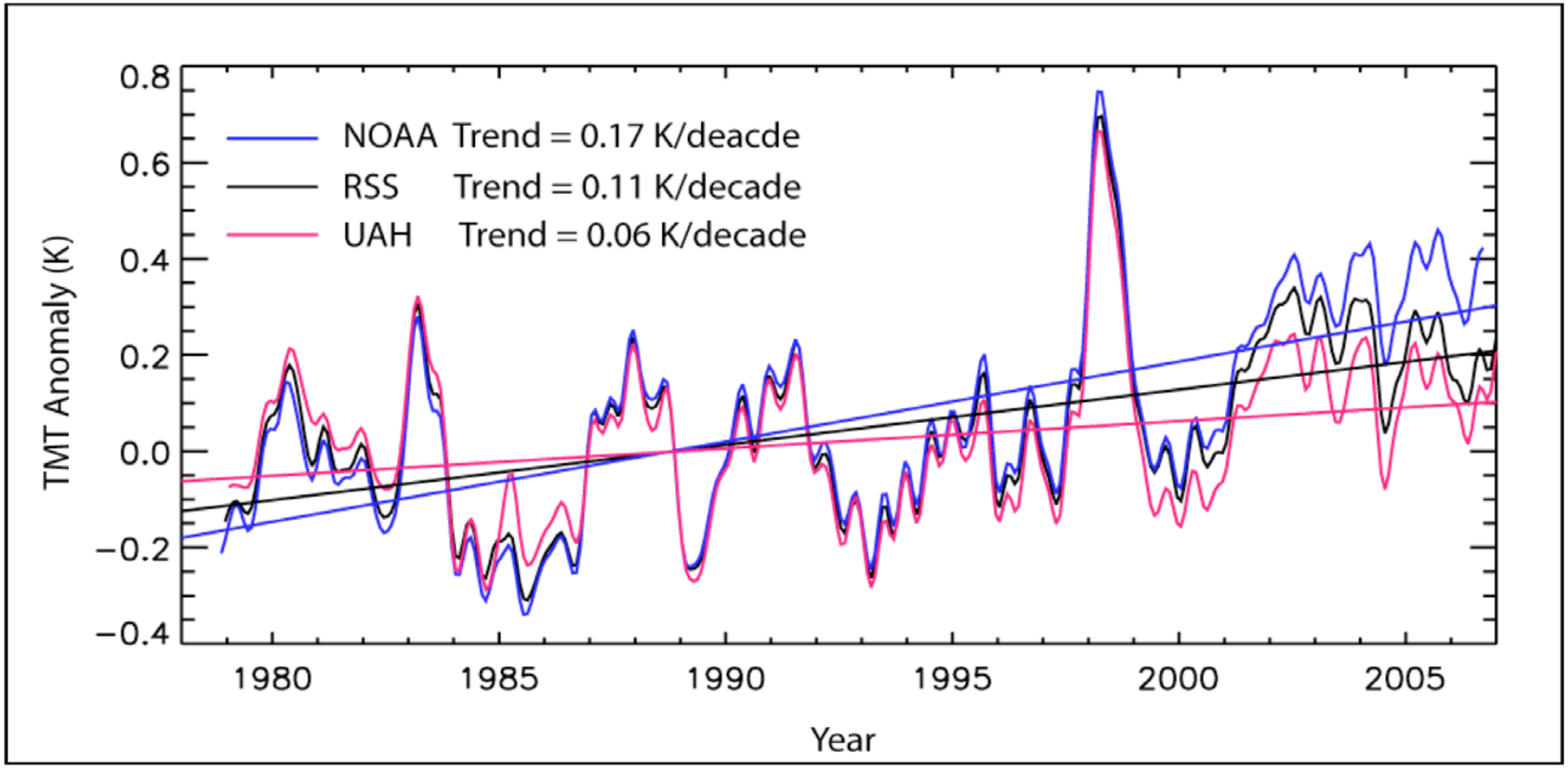
Biases in the Tropics (NOAA-15, MetOp-A, SNPP)



NOAA-18 is subtracted. The pentad data set within ±30^{o} latitudinal band.

Three MSU Groups Derived Different Global Tropospheric Temperature Trend

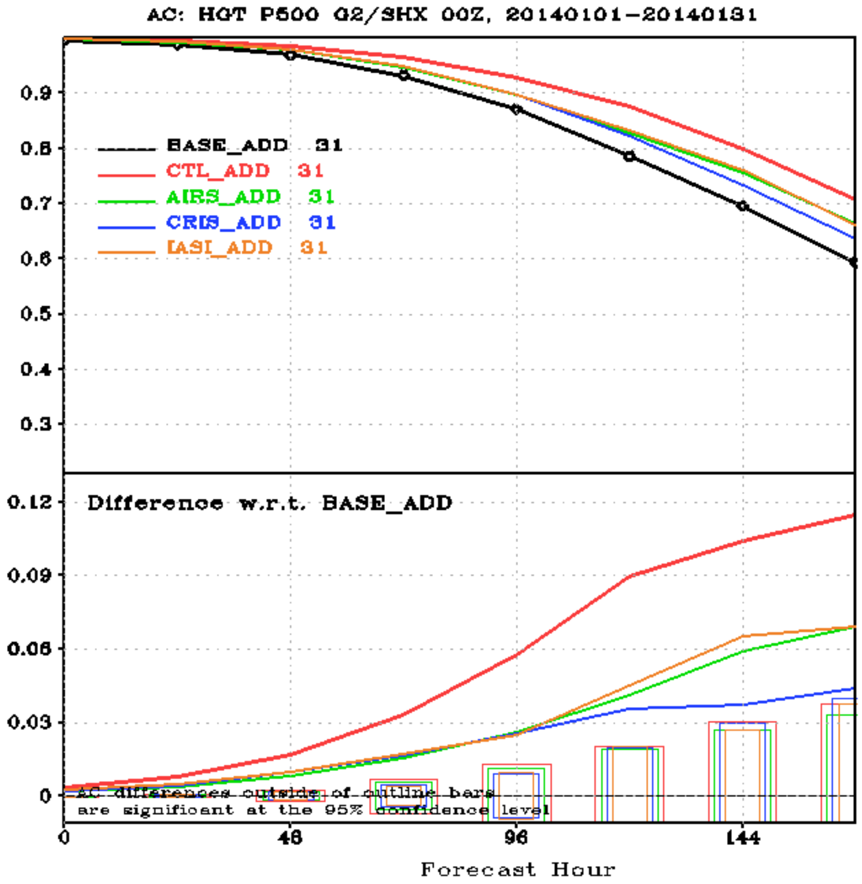
Example: Middle Tropospheric Temperature.

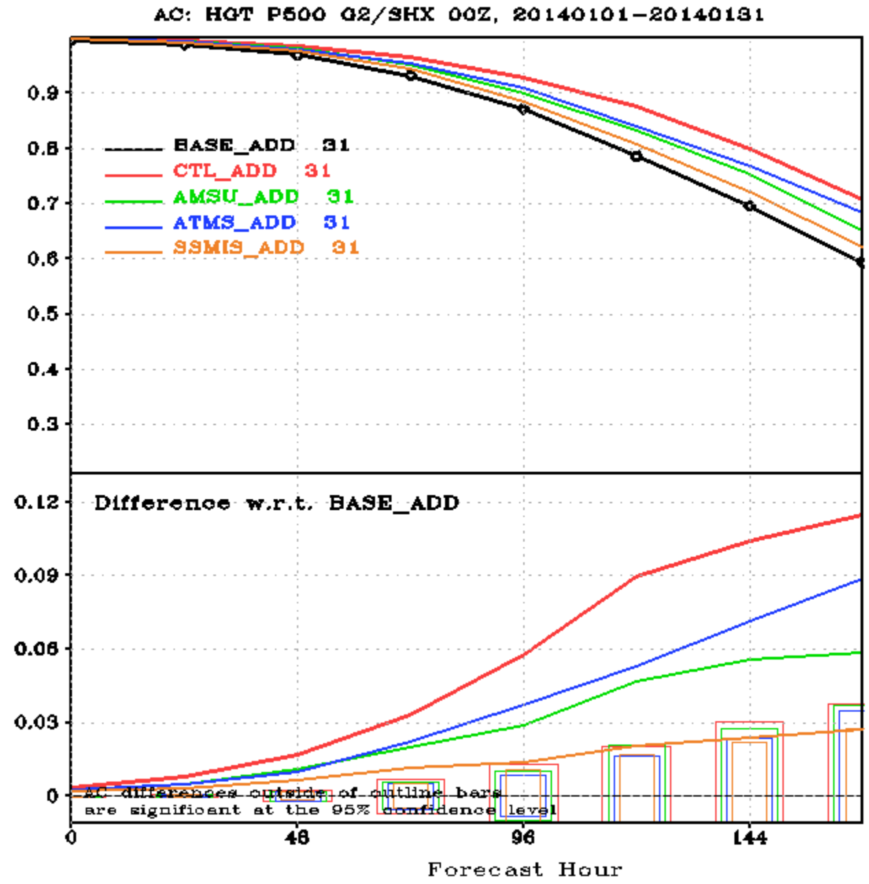


Slide courtesy of *Chengzhi-Zou*

Impacts of US Microwave Sounders in NCEP GFS

500 hPa Southern Hemisphere AC scores for 20140101 – 20140131 00Z

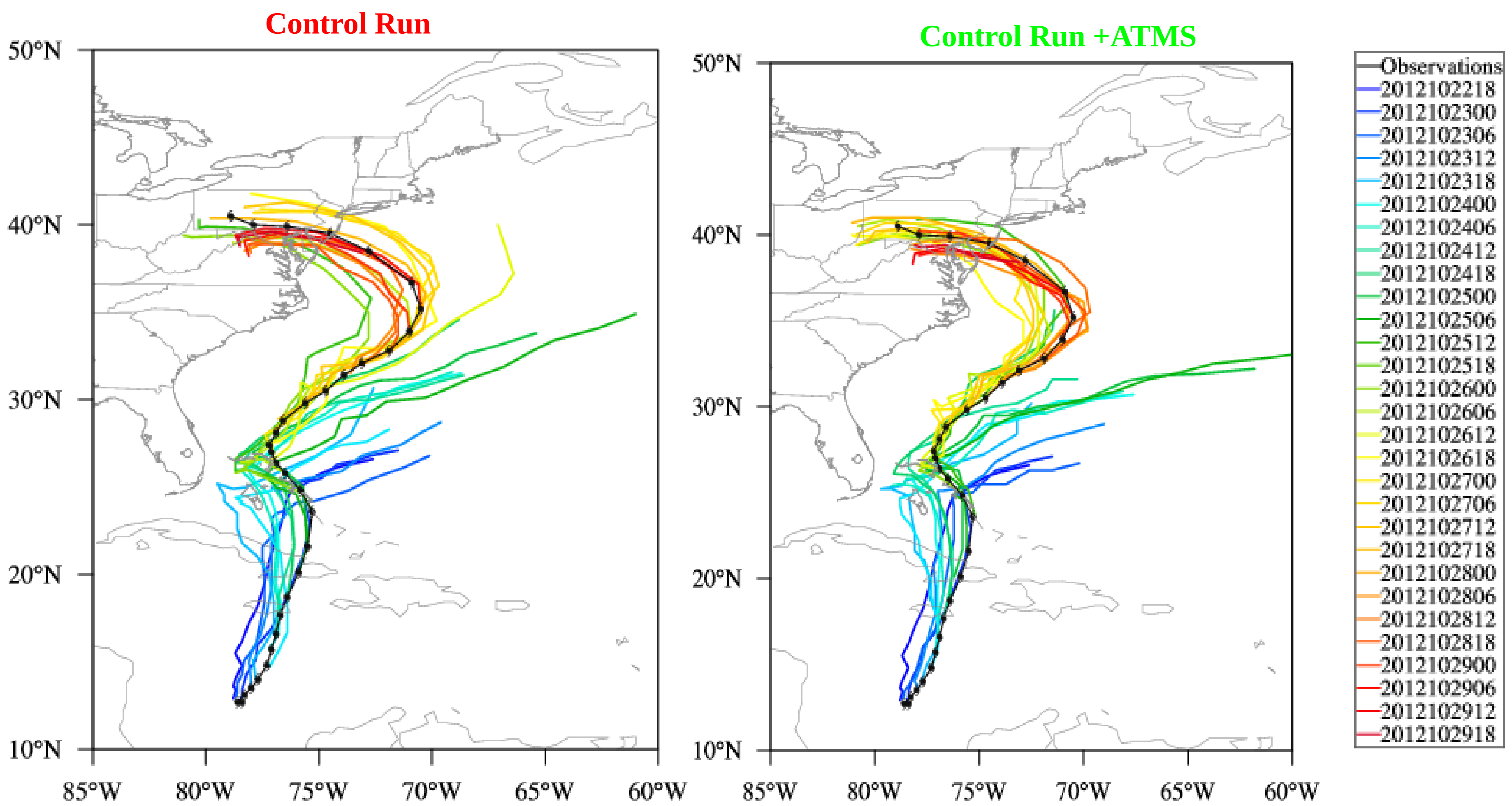




Assimilation of ATMS radiances in NCEP GFS produces a largest impact on global medium range forecast, especially over southern hemisphere. With respect to the baseline experiment that includes the conventional and GPSRO data, 75% forecast skill increase is attributed to ATMS radiance assimilation.

ATMS Impacts on Hurricane Sandy Forecast

2012 NCEP HWRF Version



Predicted vs. observed track for Hurricane Sandy during October 22 to 29. NCEP 2012 HWRF is revised with a high model top and is initialized with its own background 6 hour forecast for direct satellite radiance assimilation in GSI. Control Run: All conventional data and NOAA/METOP/EOS/COSMIC. It is clearly demonstrated that assimilation of Suomi NPP ATMS radiance data reduces the forecast errors of Hurricane Sandy's track

Summary and Conclusions

- ATMS, CrIS, VIIRS and OMPS onboard SNPP are well calibrated and their performances in orbit are very stable.
- An SI traceable technique was developed for computing the noise for microwave and infrared hyperspectral sounding instruments.
- In-orbit calibration standards are fully vetted with SNPP pitch maneuver data. The pitch maneuver data have led to great scientific understanding in calibration theory and to new radiative transfer in simulation of satellite measurements.
- In-orbit calibration standards are also explored through robust O-B where B is computed with GPS RO profiles, ECMWF analysis fields and other high quality atmospheric profiles as inputs to LBLRTM, CRTM, TOMRAD, VLIDORT.
- An SDR testbed is being established for JPSS mission life cycle reprocessing and a climate quality of SNPP SDR products will be generated in 2016 and 2017.
- WMO GSICS algorithms and data sets are being extended by JPSS mission for global consistent the SDR data quality.
- SNPP SDR products have been assimilated in many NWP centers and the impacts on the forecast skills are largely positive. The highest impacts are attributed to new instrument technology, calval sciences and data assimilation techniques.