Advances in ATMS Sensor Data Record (SDR) Sciences

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19th International TOV Science Conference, Jeju, S. Korea
February 26, 2014

ATMS SDR Science Advances

- Background Information
  - ✓ ATMS instrumentation
  - ✓ SDR product maturity
- Radiometric Calibration
  - ✓ Non-linearity correction
  - ✓ Calibration accuracy
  - ✓ Lunar intrusion correction
- Noise Characterization
  - ✓ Standard deviation
  - ✓ Allan deviation
- SDR Algorithm
  - ✓ TDR to SDR conversion
  - ✓ Resampling SDR through Back-Gilbert theory
  - ✓ Xcal with respect to AMSU for climate applications
- Remaining Issues
  - ✓ Striping and characterization
  - ✓ Window channel biases
  - ✓ Full radiance calibration
- Summary and Conclusions

MSU			AMSU/MHS			ATMS		
Ch	GHz	Pol	Ch	GHz	Pol	Ch	GHz	Pol
			1	23.8	QV	1	23.8	QV
			2	31.399	QV	2	31.4	QV
1	50.299	QV	3	50.299	QV	3	50.3	QH
						4	51.76	QH
			4	52.8	QV	5	52.8	QH
2	53.74	QH	5	53.595 ± 0.115	QH	6	53.596 ± 0.115	QH
			6	54.4	QH	7	54.4	QH
3	54.96	QH	7	54.94	QV	8	54.94	QH
			8	55.5	QH	9	55.5	QH
4	57.95	QH	9	fo = 57.29	QH	10	fo = 57.29	QH
			10	fo ± 0.217	QH	11	fo±0.3222±0.217	QH
			11	fo±0.3222±0.048	QH	12	fo± 0.3222±0.048	QH
			12	fo ±0.3222±0.022	QH	13	fo±0.3222±0.022	QH
			13	fo± 0.3222±0.010	QH	14	fo±0.3222 ±0.010	QH
			14	fo±0.3222±0.0045	QH	15	fo± 0.3222±0.0045	QH
			15	89.0	QV			
			16	89.0	QV	16	88.2	QV
			17	157.0	QV	17	165.5	QH
						18	183.31 ± 7	QH
						19	183.31 ± 4.5	QH
			19	183.31 ± 3	QH	20	183.31 ± 3	QH
			20	191.31	QV	21	183.31 ± 1.8	QH
			18	183.31 ± 1	QH	22	183.31 ± 1	QH

🟩 Exact match to AMSU/MHS

🟨 Only Polarization different

🟧 Unique Passband

🟥 Unique Passband, and Pol. different from closest AMSU/MHS channels

Suomi National Polar-Orbiting Partnership (NPP) Satellite

Vern Suomi

SUCCESSFUL LAUNCH October 28, 2011 !

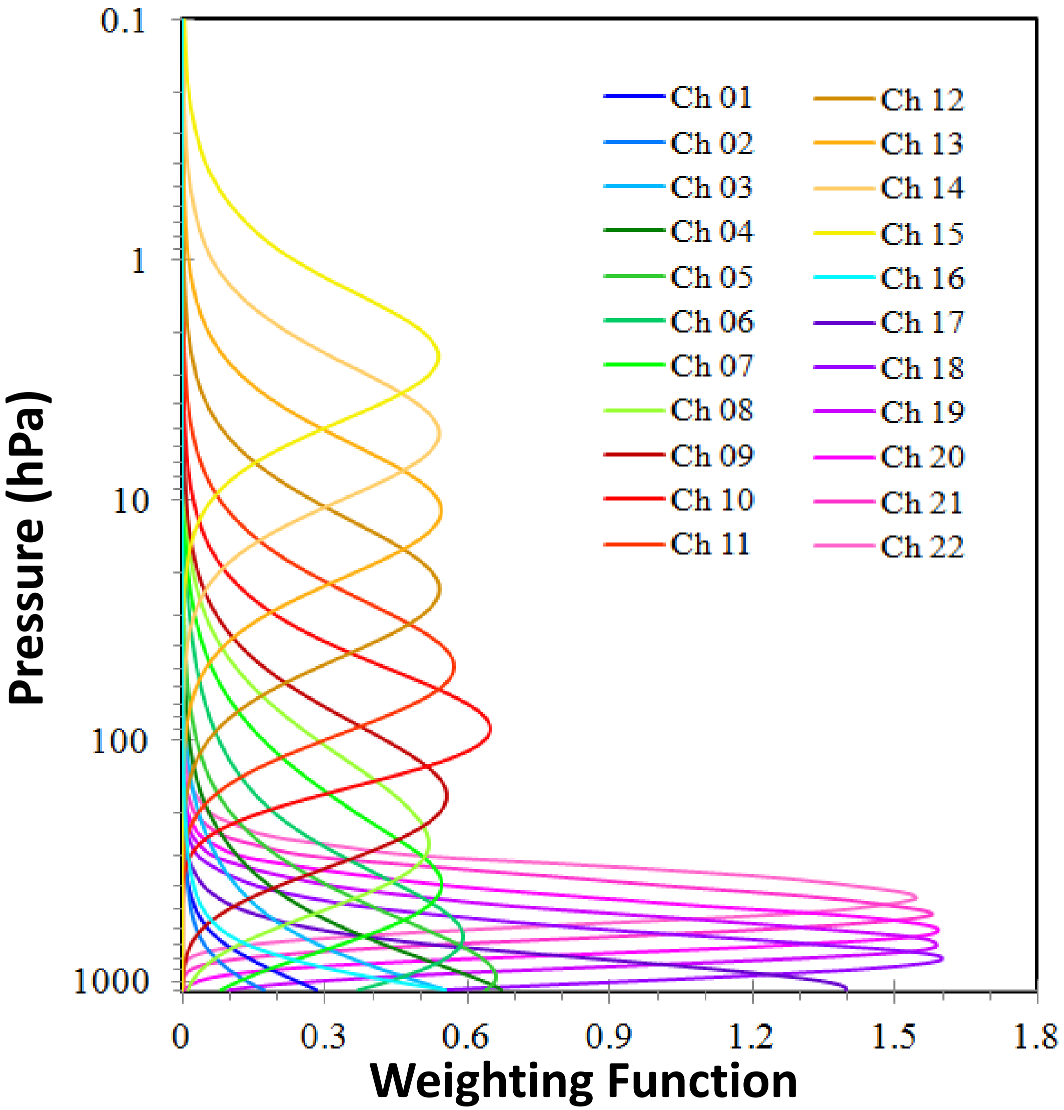
Drivers and Benefits

Maintains continuity of weather/climate observations and critical environmental data from the polar orbit: CrIS, ATMS, VIIRS. OMPS, CERES

Suomi NPP Instruments and Their Applications

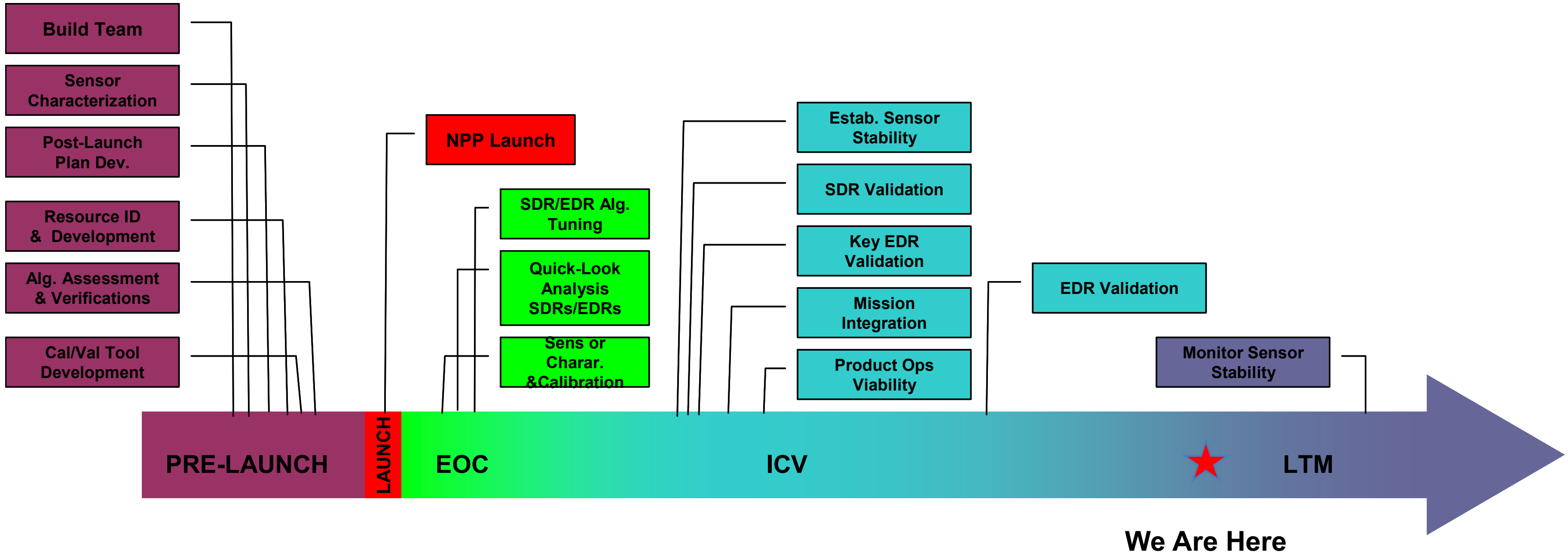
NPP/JPSS Instrument		NOAA Mission Benefits
	**Advanced Technology Microwave Sounder**	ATMS and CrIS together provide high vertical resolution **temperature** and **water vapor information needed to maintain and improve forecast skill** out to 5 to 7 days in advance for extreme weather events, including hurricanes and severe weather outbreaks
	**Cross-track Infrared Sounder**	
	**Visible Infrared Imaging Radiometer Suite**	VIIRS provides many **critical imagery products** including snow/ice cover, clouds, fog, aerosols, fire, smoke plumes, vegetation health, phytoplankton abundance/chlorophyll. All are required for environmental hazard monitoring and are useful for crucial economic sectors (transportation, fishing, energy, agriculture), all of which impact human health
	**Ozone Mapping and Profiler Suite**	Total ozone for **monitoring ozone** hole and recovery of stratospheric ozone and for UV index forecasts
	**Clouds and the Earth's Radiant Energy System**	Provide **climate quality measurements** of the Earth's outgoing radiation budget- longwave infrared, reflected solar flux, and incoming solar radiation, all of which are vital to climate monitoring

ATMS Channel Weighting Functions



SNPP Calibration/Validation Phases and Milestone Status

- Four Phases of Cal/Val:
  1. Pre-Launch; all time prior to launch – Algorithm verification, sensor testing, and validation preparation
  2. Early Orbit Check-out (first 30-90 days) – System Calibration & Characterization
  3. Intensive Cal/Val (ICV); extending to approximately 24 months post-launch – xDR Validation
  4. Long-Term Monitoring (LTM); through life of sensors
- For each phase:
  - Exit Criteria established
  - Activities summarized
  - Products mature through phases independently



Build Team

Sensor Characterization

Post-Launch Plan Dev.

Resource ID & Development

Alg. Assessment & Verifications

Cal/Val Tool Development

NPP Launch

SDR/EDR Alg. Tuning

Quick-Look Analysis SDRs/EDRs

Sens or Charar. &Calibration

Estab. Sensor Stability

SDR Validation

Key EDR Validation

Mission Integration

Product Ops Viability

EDR Validation

Monitor Sensor Stability

PRE-LAUNCH

LAUNCH

EOC

ICV

★

LTM

We Are Here

SNPP SDR Products Review for Declaring the Validated Maturity

Attendees for SUOMI NPP SDR Product Review Meeting in NOAA Center for Weather and Climate Prediction Auditorium

Review Outcomes: SNPP SDR Products Review Meeting was held on Dec. 18-20, 2013. NESDIS Senior Management Leads: Ms. Mary Kicza and Dr. Al Powell attended the review. The Cal/Val team scientists presented the results on their specific calval tasks and NWP and other users NWS/NOS offered their independent assessments of data product quality based on their intensive cal/val analyses. The review panel recommended that the CrIS, ATMS and VIIRS SDR products be ready to be declared validated scientifically. And three remaining issues were recommended to resolve before OMPS EV SDR goes to the validated stage: cross-track effects in NM need to be addressed; Stray-light improvements still needed in NP SDR; Artificial separation between EV SDR and Cal SDR should be eliminated

Significance: Suomi NPP CrIS and ATMS SDR products are continuing NOAA afternoon orbits sounding data for NWS NWP radiance assimilation. It is shown from CEP global forecast system (GFS) and ECMWF global models that uses of CrIS and ATMS data have similar or slightly better impacts on the global medium-range forecasts

Suomi NPP TDR/SDR Algorithm Schedule

Sensor	Beta	Provisional	Validated
CrIS	February 10, 2012	February 6, 2013	March 17, 2014
ATMS	May 2, 2012	February 12, 2013	March 17, 2014
OMPS	March 7, 2012	March 12, 2013	June 17, 2014
VIIRS	May 2, 2012	March 13,, 2013	April 17, 2014

Beta

- Early release product.
- Initial calibration applied
- Minimally validated and may still contain significant errors (rapid changes can be expected. Version changes will not be identified as errors are corrected as on-orbit baseline is not established)
- Available to allow users to gain familiarity with data formats and parameters
- Product is not appropriate as the basis for quantitative scientific publications studies and applications

Provisional

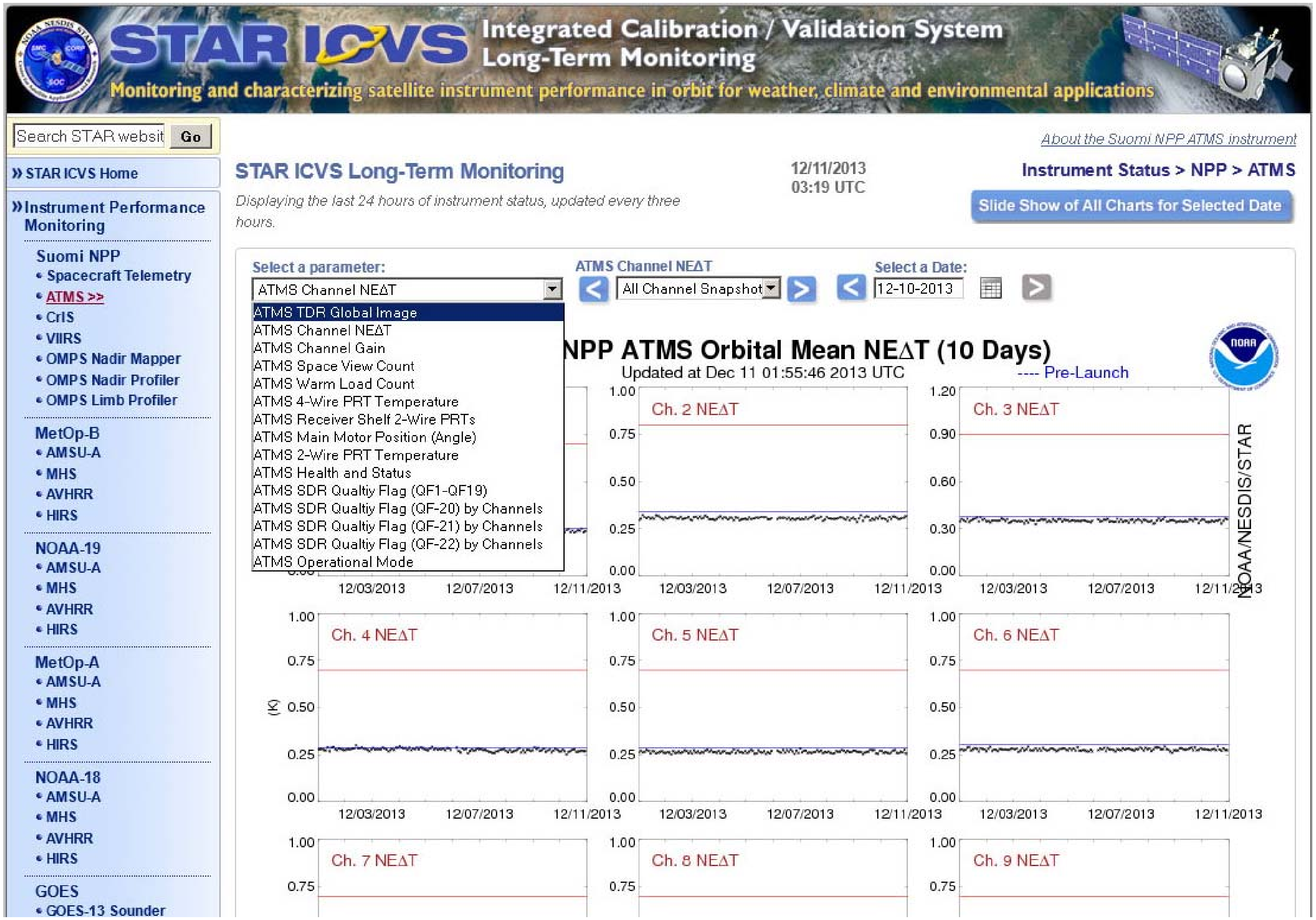
- Product quality may not be optimal
- Incremental product improvements are still occurring as calibration parameters are adjusted with sensor on-orbit characterization (versions will be tracked)
- General research community is encouraged to participate in the QA and validation of the product, but need to be aware that product validation and QA are ongoing
- Users are urged to consult the SDR product status document prior to use of the data in publications
- Ready for operational evaluation

Validated

- On-orbit sensor performance characterized and calibration parameters adjusted accordingly
- Ready for use in applications and scientific publications
- There may be later improved versions
- There will be strong versioning with documentation

Stable ATMS Performance Since SNPP Launch

http://www.star.nesdis.noaa.gov/icvs/status_NPP_ATMS.php



STAR ICVS Integrated Calibration / Validation System Long-Term Monitoring

Monitoring and characterizing satellite instrument performance in orbit for weather, climate and environmental applications

STAR ICVS Long-Term Monitoring

12/11/2013 03:19 UTC

Displaying the last 24 hours of instrument status, updated every three hours.

Instrument Status > NPP > ATMS

Select a parameter: ATMS Channel NEΔT

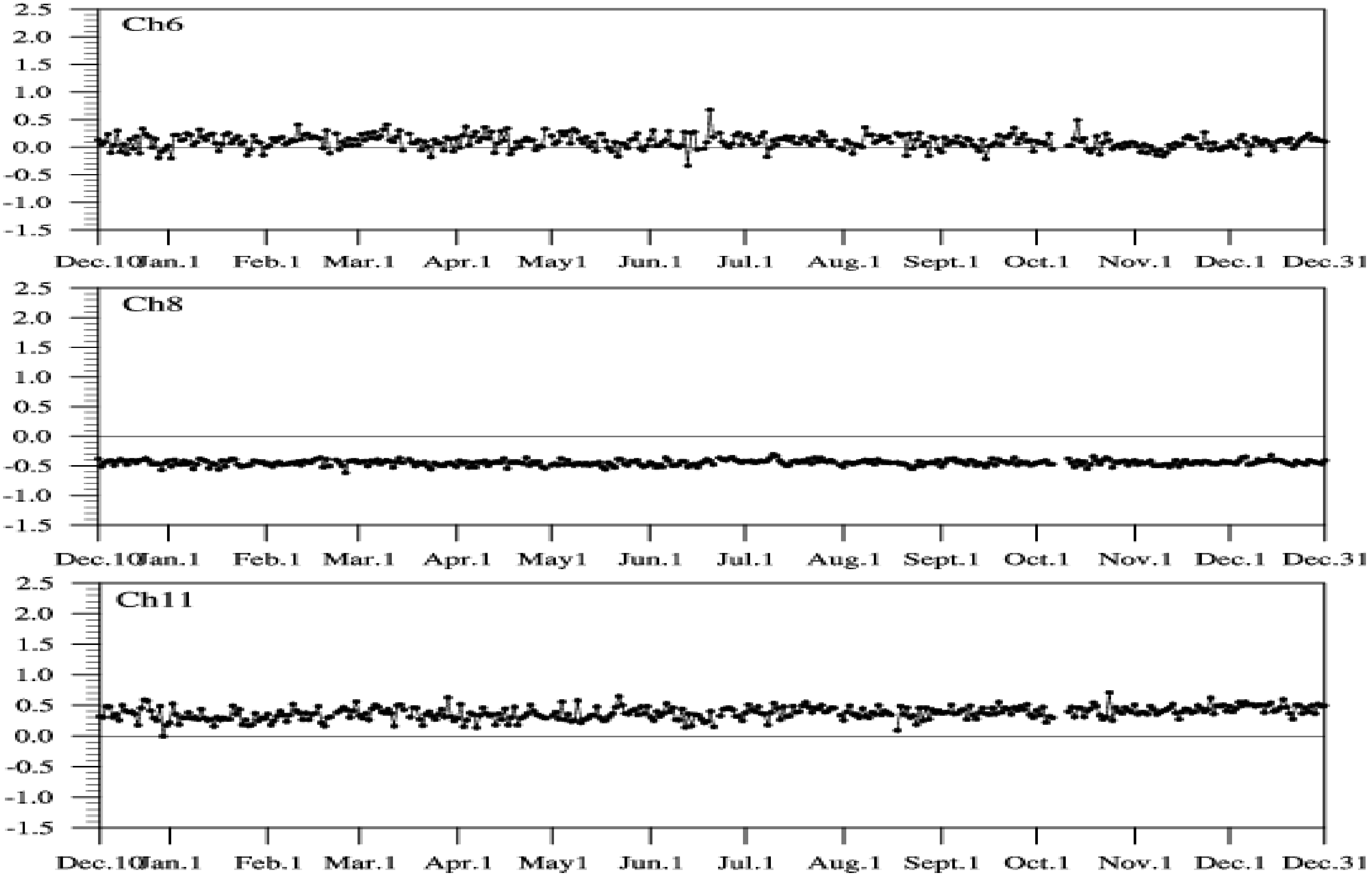
ATMS Channel NEΔT: All Channel Snapshot

Select a Date: 12-10-2013

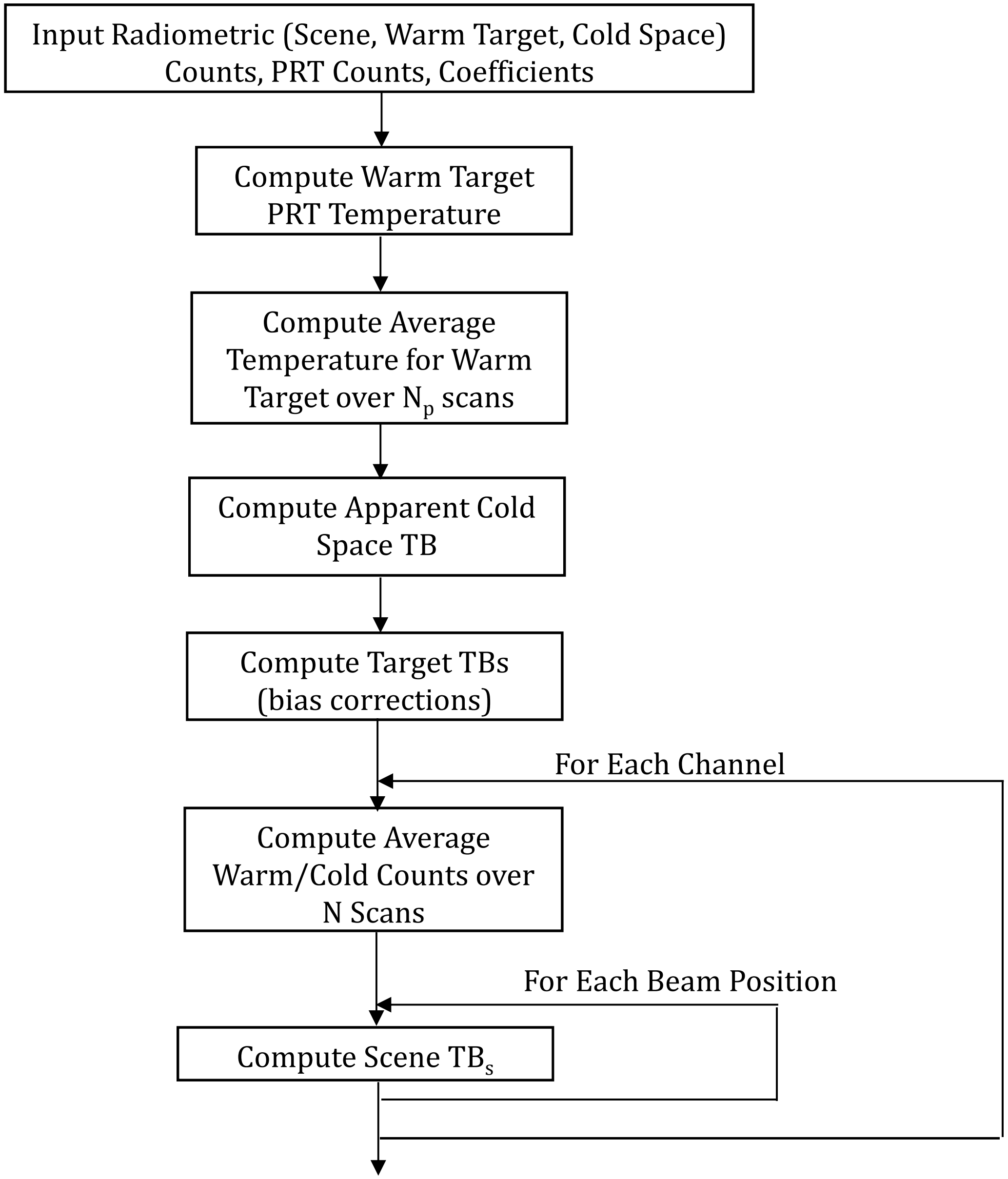
NPP ATMS Orbital Mean NEΔT (10 Days)

Updated at Dec 11 01:55:46 2013 UTC

Stable ATMS Bias between Obs and Sim (COSMIC)



ATMS Radiometric Calibration Flow Chart



Input Radiometric (Scene, Warm Target, Cold Space) Counts, PRT Counts, Coefficients

Compute Warm Target PRT Temperature

Compute Average Temperature for Warm Target over N_p scans

Compute Apparent Cold Space TB

Compute Target TBs (bias corrections)

For Each Channel

Compute Average Warm/Cold Counts over N Scans

For Each Beam Position

Compute Scene TB_s

ATMS Two-Point Calibration with Non-linearity Correction in Brightness Temperature

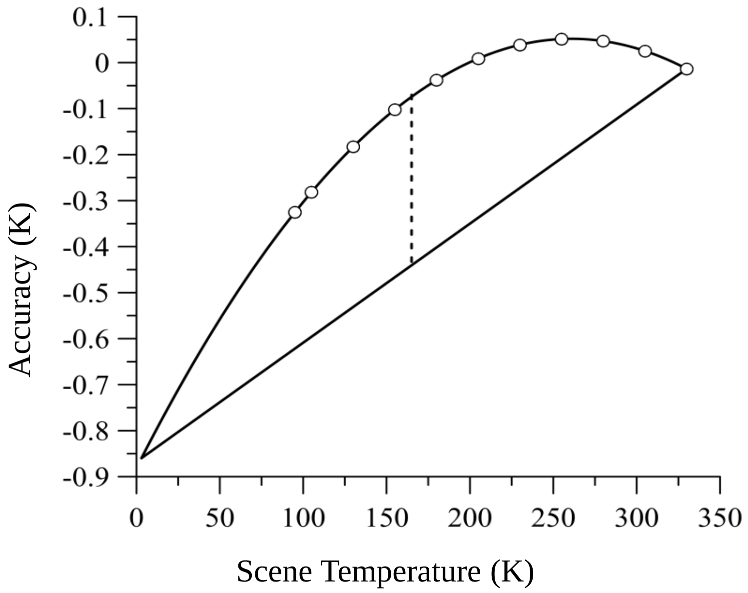
$$T_{b,ch} = T^{w}_{b,ch} + \frac{C^{s}_{ch} - \overline{C^{w}_{ch}}}{\overline{C^{w}_{ch}} - \overline{C^{c}_{ch}}}(T^{w}_{b,ch} - T^{c}_{b,ch}) + 4T_{NL}x(1-x)$$

$$\overline{C^{w}_{ch}}(i) = \sum_{k=i-N_s}^{i+N_s} \sum_{j=1}^{4} W_{k-i} C^{w}_{ch}(k,j)$$

$$\overline{C^{c}_{ch}}(i) = \sum_{k=i-N_s}^{i+N_s} \sum_{j=1}^{4} W_{k-i} C^{c}_{ch}(k,j)$$

$$\overline{G_{ch}}(i) = \frac{\overline{C^{w}_{ch}}(i) - \overline{C^{c}_{ch}}(i)}{\overline{T^{w}_{b,ch}}(i) - T^{c}_{b,ch}}$$

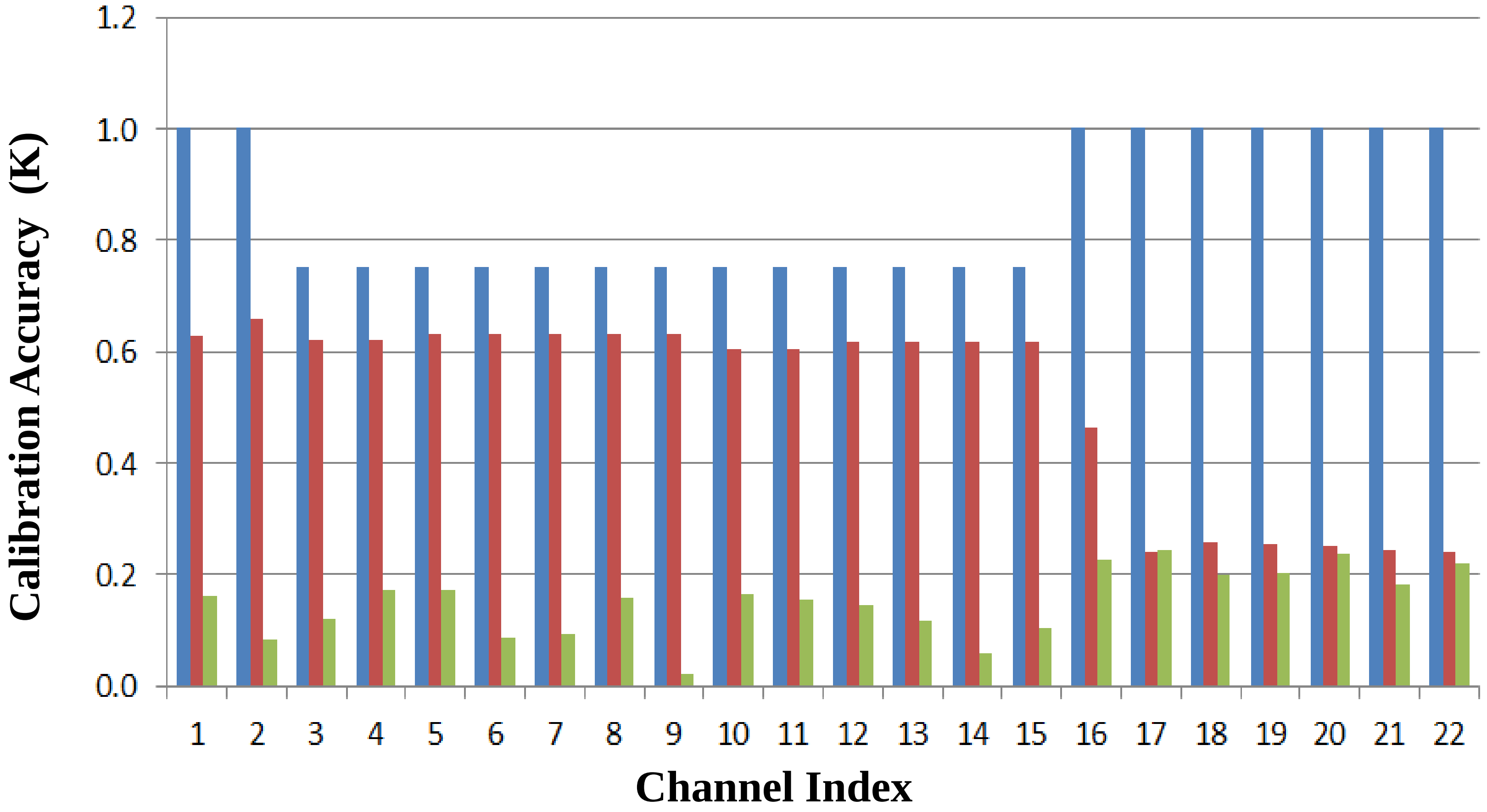
$$x = \frac{T_{b,l} - T_{c}}{T_{w} - T_{c}}$$



Nonlinearity of ATMS channel 1, calculated for cold plate (CP) at 5^{o}C for redundancy configuration 1 (RC1). Blue dots represent the measured scene temperatures. Black solid curve represents the regression curve. Dashed line represents the peak nonlinearity.

A dramatic difference from AMSU calibration is the treatment of nonlinearity term which is derived from the medium theorem and x is a parameter derived from the linear term.

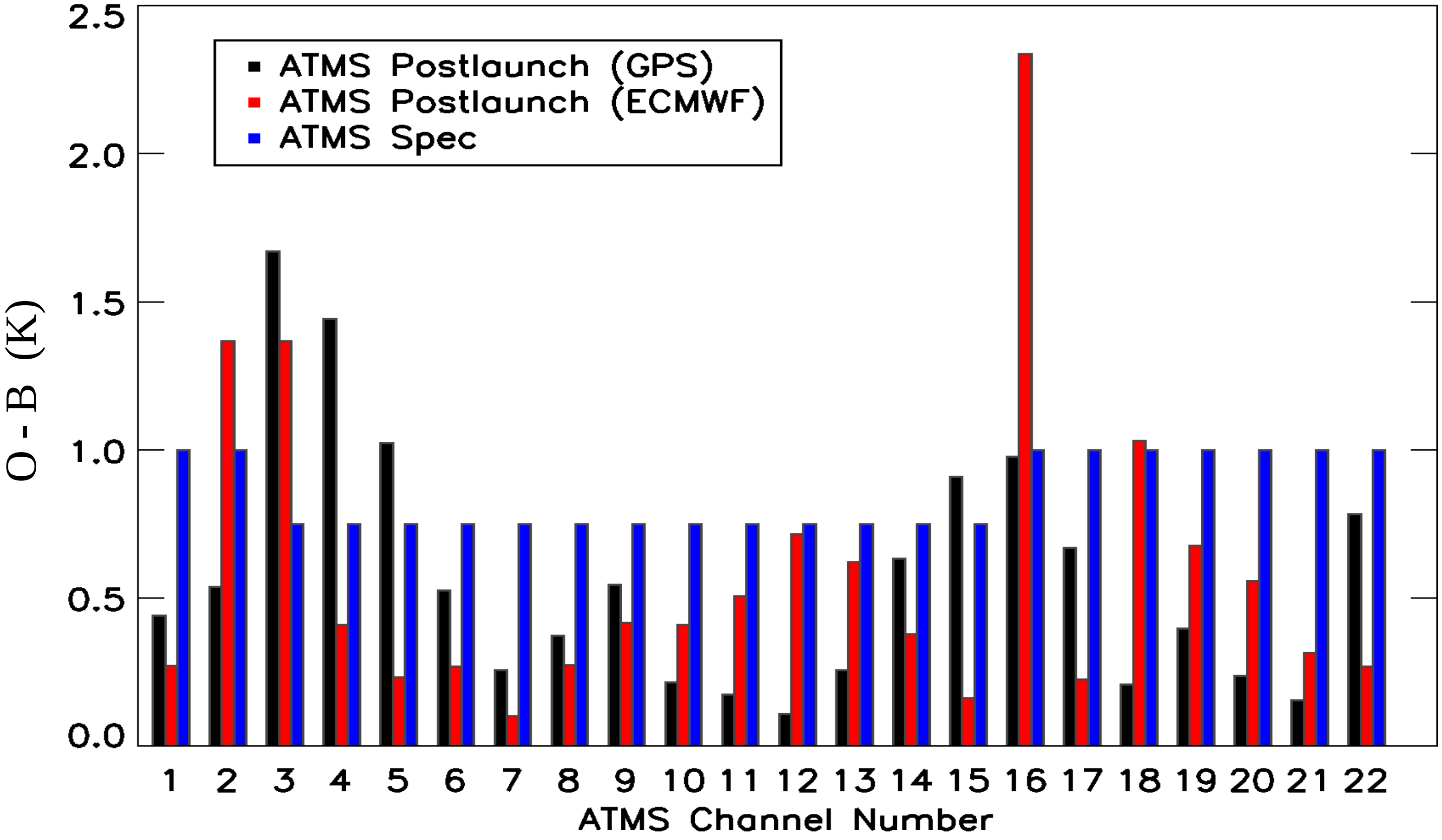
ATMS Pre-launch Calibration Accuracy through TVAC Data



Red – Calibration accuracy from a nominal Thermal Vacuum (TVAC) data,
Green – values obtained from the best TVAC best, and Blue – specification

Prelauncht ATMS calibration accuracy is quantified from six redundant configuration (RC) thermal vacuum (TVAC) data and exceeds/is better than the specification

ATMS Post-launch Characterization of Calibration Accuracy through O-B



On-orbit ATMS calibration accuracy is characterized using GPSRO and ECMWF data as input to RT model and is better than specification for most of sounding channels.

ATMS Lunar Intrusion Correction Algorithm

Brightness temperature increment arising from lunar contamination can be expressed as a function of lunar solid angle, antenna response and radiation from the Moon

Space view Tb or radiance increment:

$$\Delta T_{moon} = G * \Omega * T_{moon}$$

Antenna response function:

$$G = e^{\frac{-(\beta' - \alpha_0)^2}{2\delta^2}}, \quad with\ \delta = \frac{0.5 \cdot \theta_{3dB}}{\sqrt{2 \cdot log2}}$$

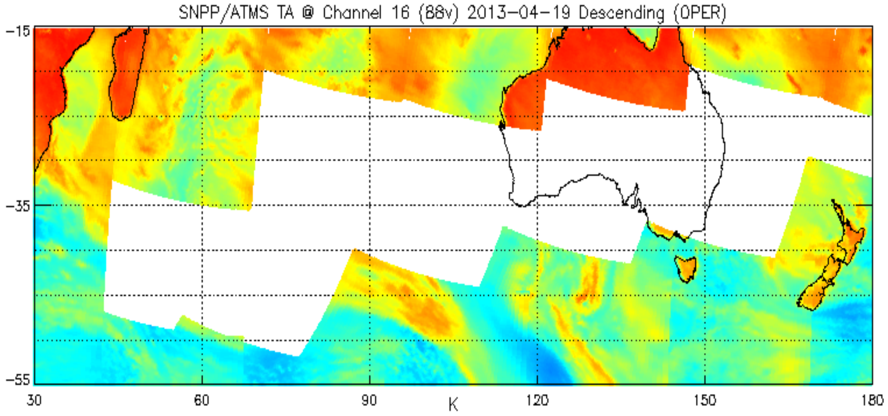
Weights of the Moon in antenna pattern:

$$\Omega_{moon} = \frac{\pi\left(\frac{r_{moon}}{D_{moon}}\right)^2}{\iint G(\theta,\varphi)d\theta d\varphi}$$

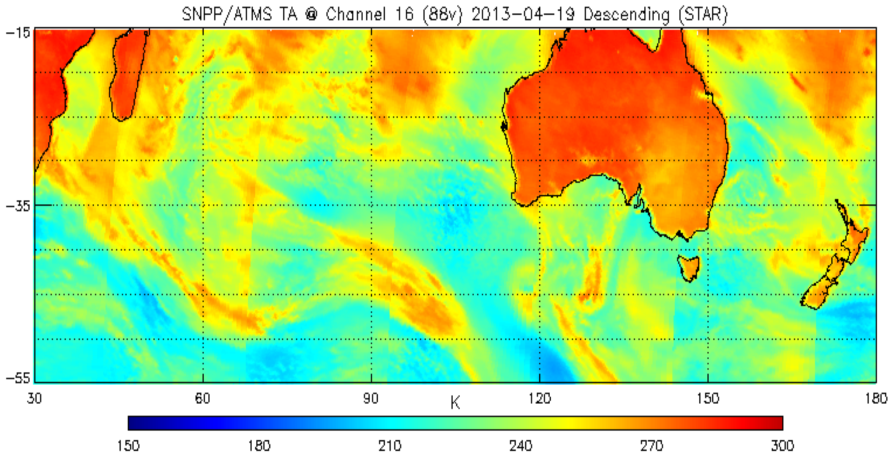
Brightness temperature of the Moon:

$$T_{moon} = 95.21 + 104.63 \cdot (1 - cos\Theta) + 11.62 \cdot (1 + cos2\Theta)$$

Without LI correction



With LI correction



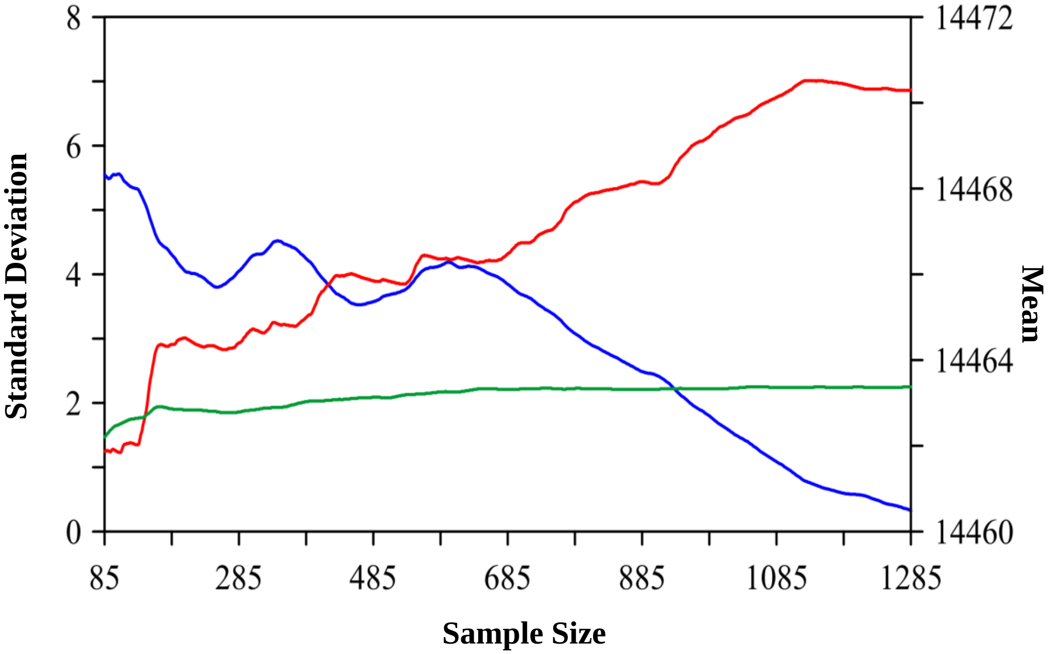
ATMS Noise Equivalent Temperature (NEDT)

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

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

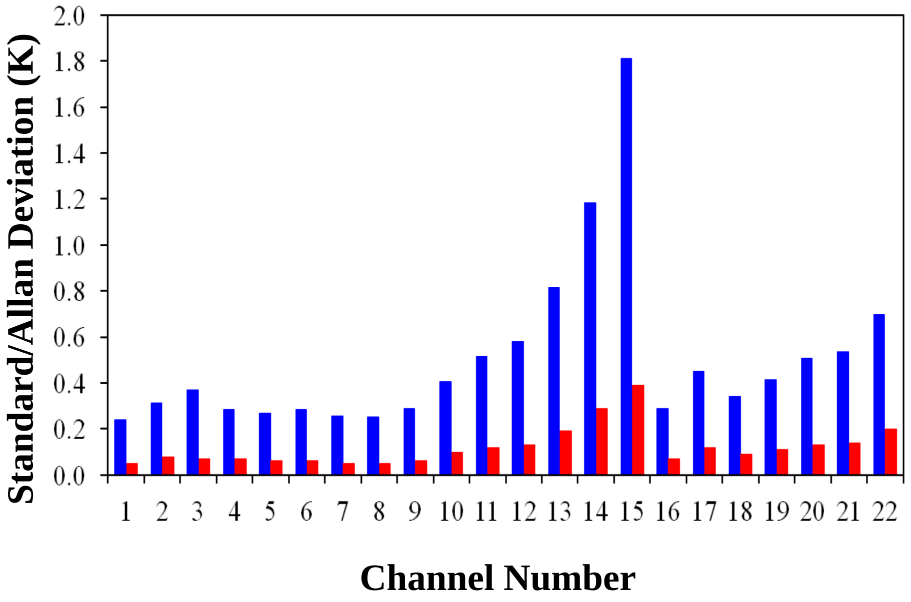
For a non-steady mean such as ATMS warm count from blackbody target, Allan deviation is recommended for NEDT:

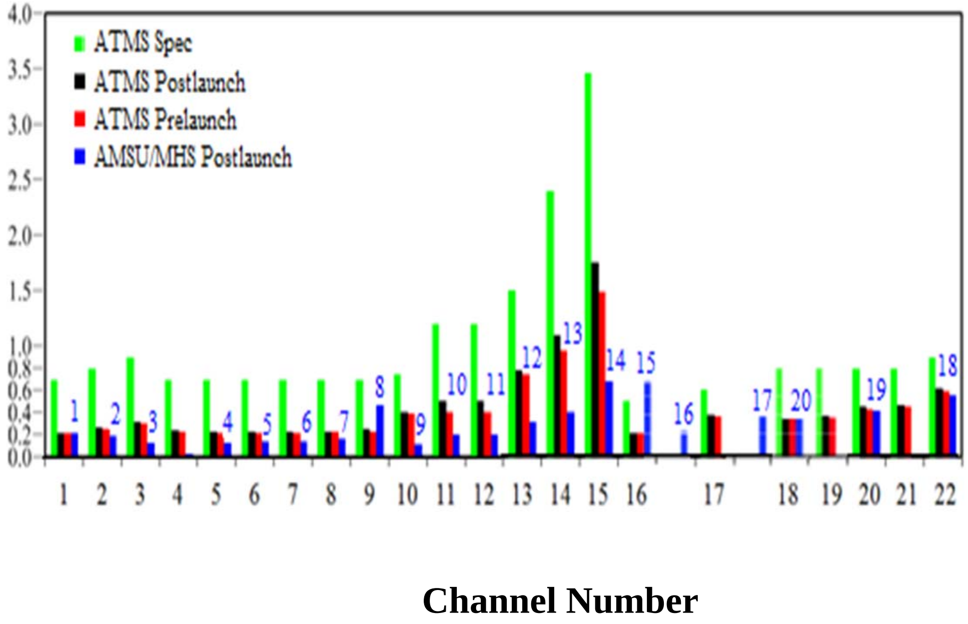
$$\sigma^{Allan}(m) = \sqrt{\frac{1}{2m^{2}\left(N-2m\right)} \sum_{j=1}^{N-2m} \left(\sum_{i=j}^{j+m-1} \left(C_{ch}^{w}(i+m) - C_{ch}^{w}(i) \right) \right)^{2}}$$



Variation of the mean (blue, y-axis on the right) and the standard deviation (red, y-axis on the left) and the overlapping Allan deviation (green, y-axis on the left) of the 17-scanline averaged warm counts with sample size.

ATMS Noise Equivalent Temperature (NEDT)





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.

On-orbit ATMS noise from the standard deviation is lower than specification but is higher than AMSU/MHS. ATMS resample algorithm can further reduce the noise comparable to AMSU/MHS

New ATMS SDR Algorithm including Spill-over and Side-lobe Corrections

For Quasi-V (TDR) :

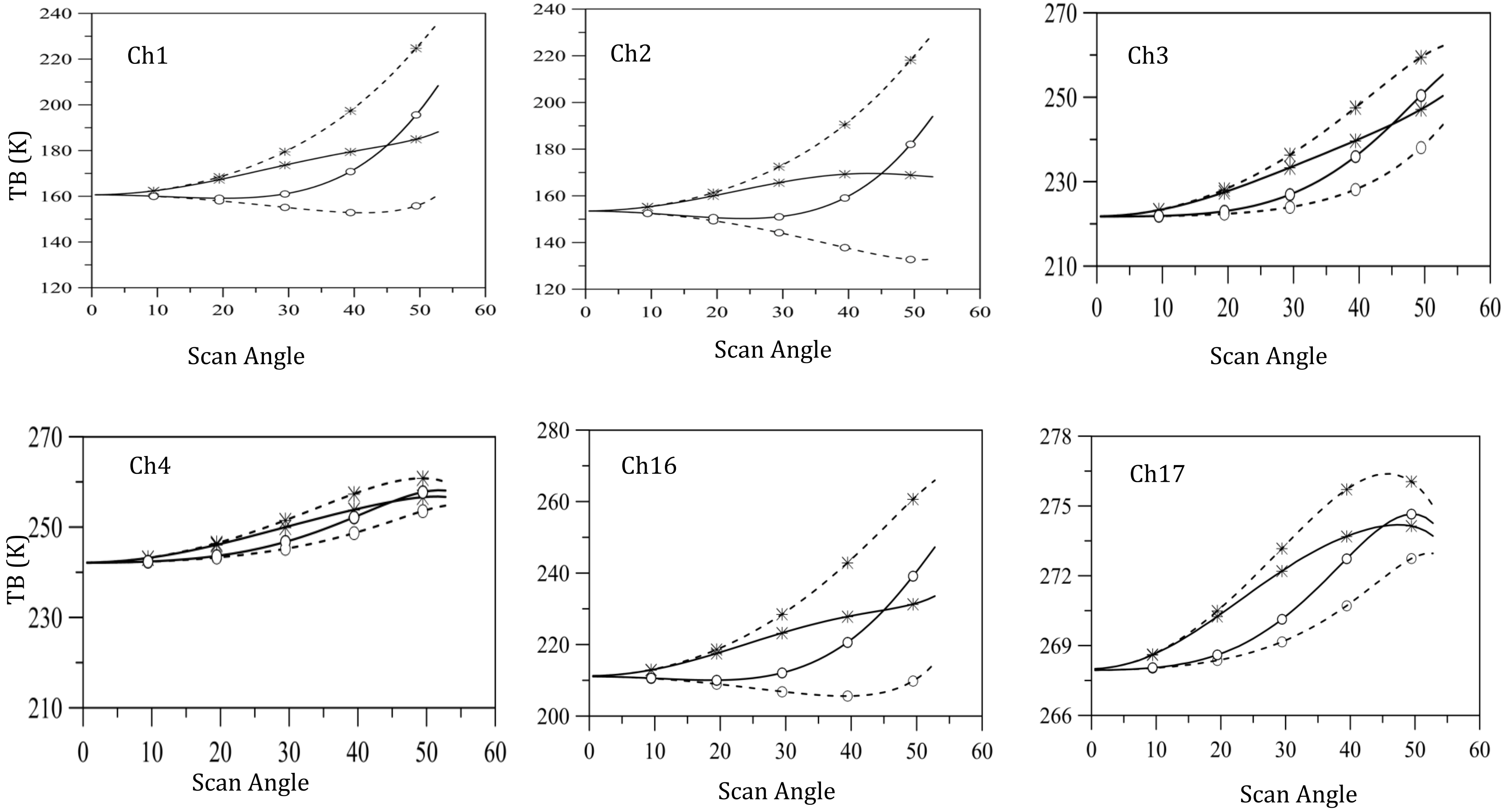
$$T_a^{Qv} = \eta_{me}^{vv} T_b^{Qv} + \eta_{me}^{hv} T_b^{Qh} + \eta_{se}^{vv} T_{b,se}^{Qv} + \eta_{se}^{hv} T_{b,se}^{Qh} + (\eta_{sc}^{vv} + \eta_{sc}^{hv}) T_{c,RJ} + S_a^{Qv}$$

For Quasi-H (TDR)

$$T_a^{Qh} = \eta_{me}^{hh} T_b^{Qh} + \eta_{me}^{vh} T_b^{Qv} + \eta_{se}^{hh} T_{b,se}^{Qh} + \eta_{se}^{vh} T_{b,se}^{Qv} + (\eta_{sc}^{hh} + \eta_{sc}^{vh}) T_{c,RJ} + S_a^{Qh}$$

***Weng, F.**, X. Zou, M. Tian, W.J. Blackwell, N. Sun, H. Yang, X. Wang, L. Lin, and K. Anderson, 2013, Calibration of Suomi National Polar-Orbiting Partnership (NPP) Advanced Technology Microwave Sounder (ATMS), J. Geophys. Res, **118**, 1–14, doi:10.1002/jgrd.50840 ,*

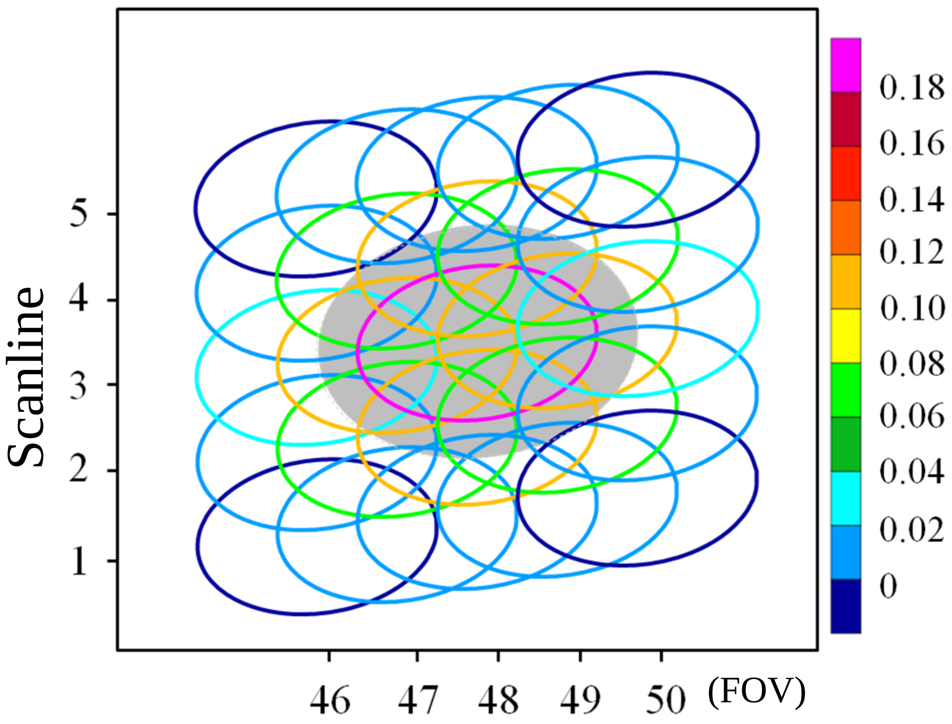
ATMS Polarization vs. Scan Angle



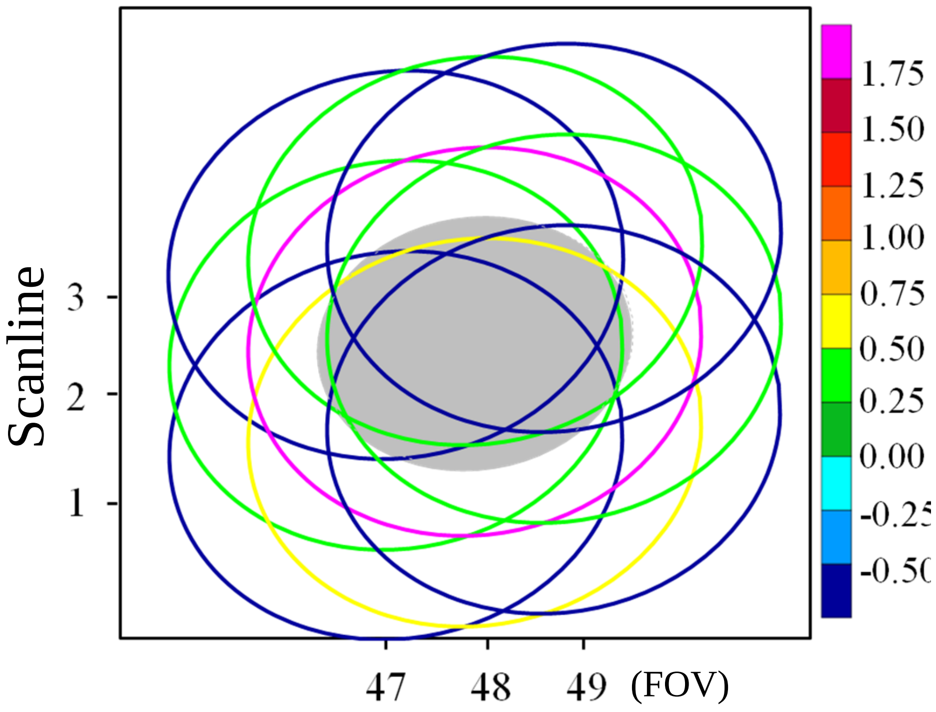
The brightness temperature with pure (dashed curve) and quasi- (solid curve) horizontal polarization (circle) and vertical (star) polarization states using the US standard atmospheric profile with sea surface wind speed being 5 m/s and sea surface temperature being 290 K.

ATMS Resampling Algorithm using the Backus-Gilbert (BG) Method

ATMS Channels 3-16



ATMS Channels 1-2



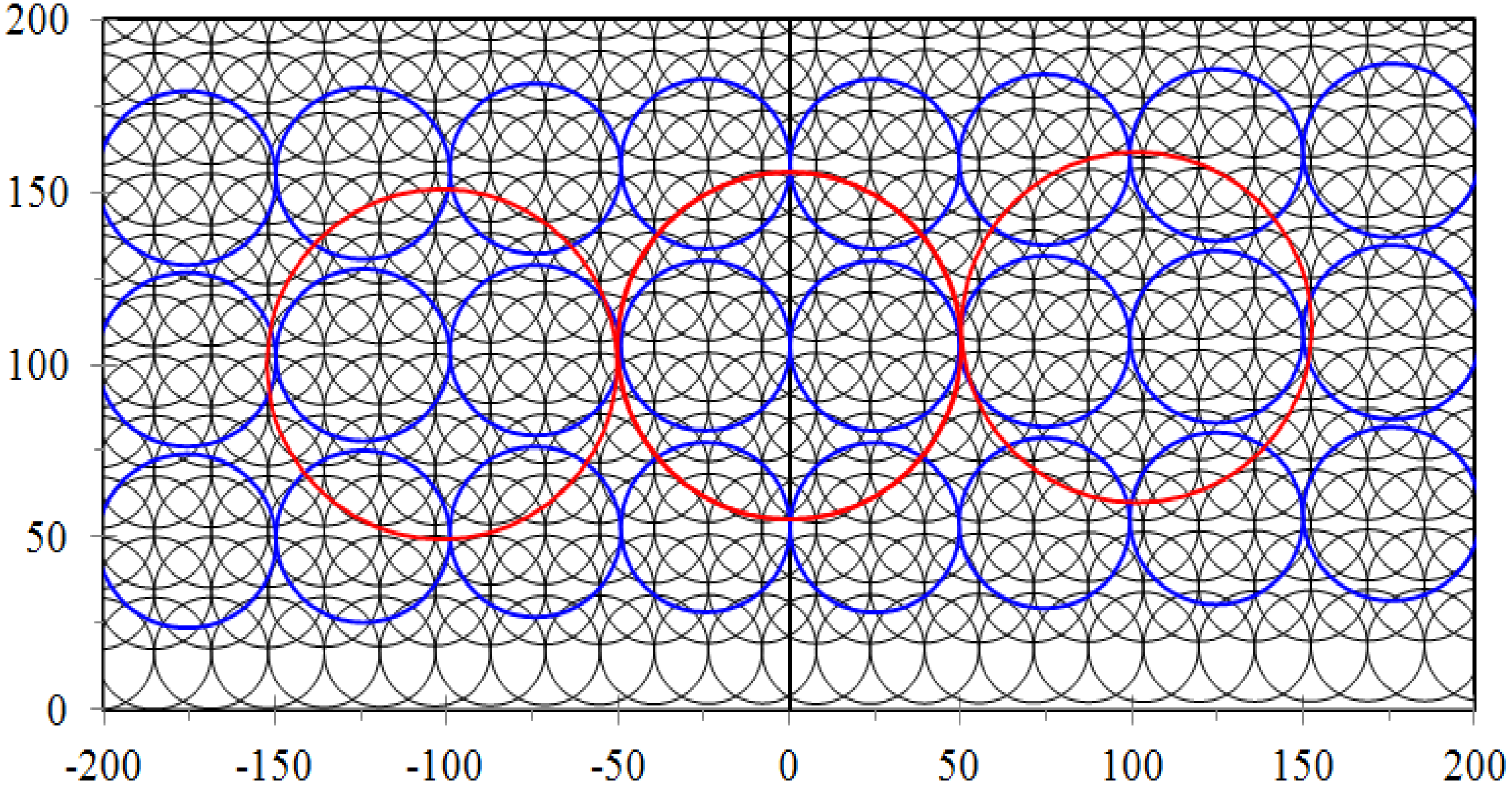
An effective AMSU-A target FOV: output of BG remap (shaded in gray)

ATMS effective FOVs: Circles with colors indicating the magnitude of BG coefficients

Three Generations of Microwave Sounding Instruments from MSU to AMSU/MHS to ATMS

ATMS Field of View Size for the beam width of 2.2° – black line

ATMS Resample to the Field of View Size for the beam width of 3.3°- blue line



ATMS Resampling Algorithm

$$T_b^{BG}(k) = \sum_{i=-N_{ch}}^{N_{ch}} \sum_{j=-N_{ch}}^{N_{ch}} w(k+i,j) T_b^{ATMS}(k+i,j)$$

$w(k+i,j)$ – B-G coefficients

$$N_{ch} = \begin{cases} 1 & \text{Channels 1 - 2} \\ 2 & \text{Channels 3 -16} \end{cases}$$

Stogryn, A., 1978: Estimates of brightness temperatures from scanning radiometer data. *IEEE Trans. Ant. & Prop.*, AP-26, 720-726.

T_b at Channel 1 within Sandy before and after Remap

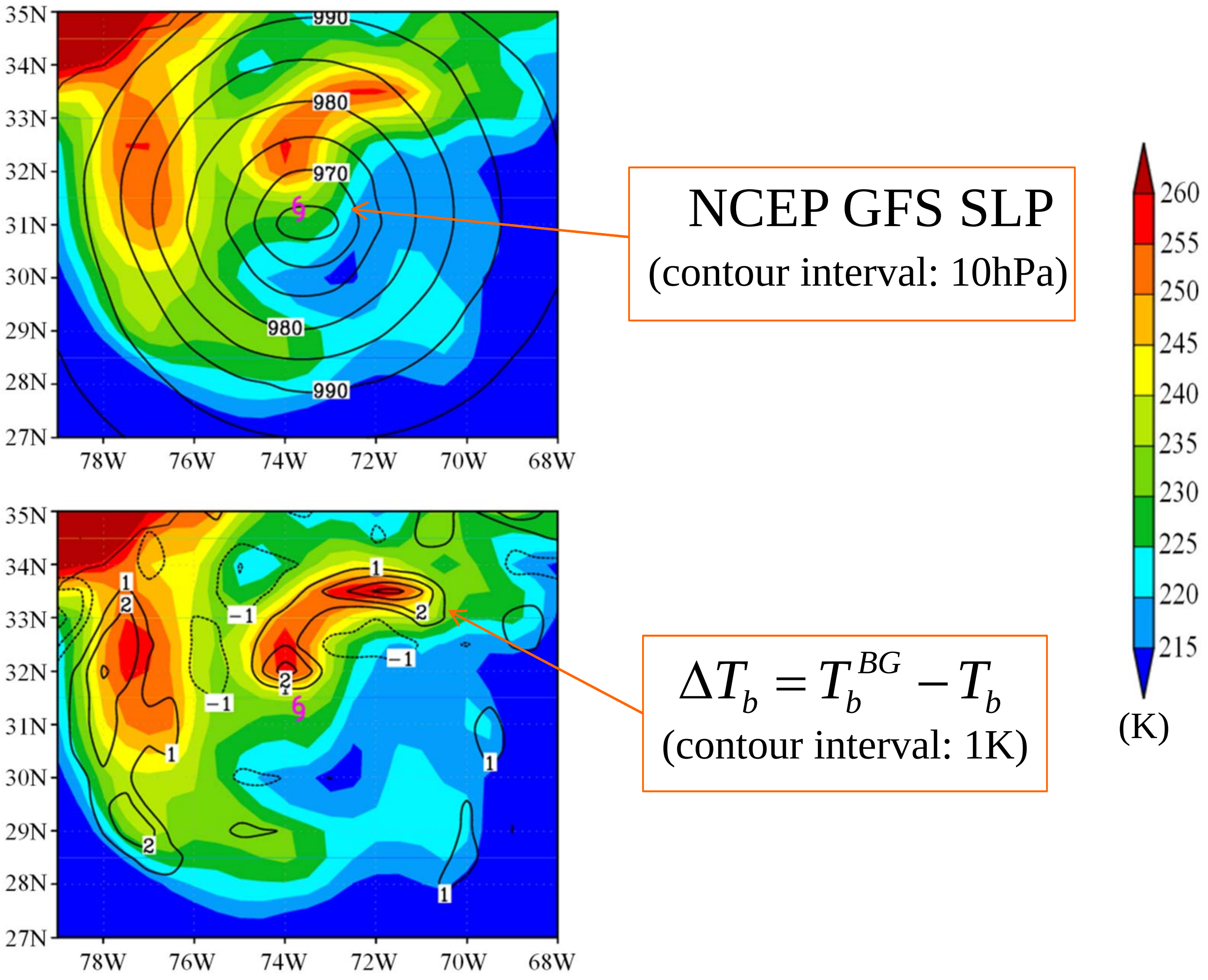
(0600 UTC October 28, 2012)

T_b

(original)

T_b^{BG}

(after BG)



NCEP GFS SLP

(contour interval: 10hPa)

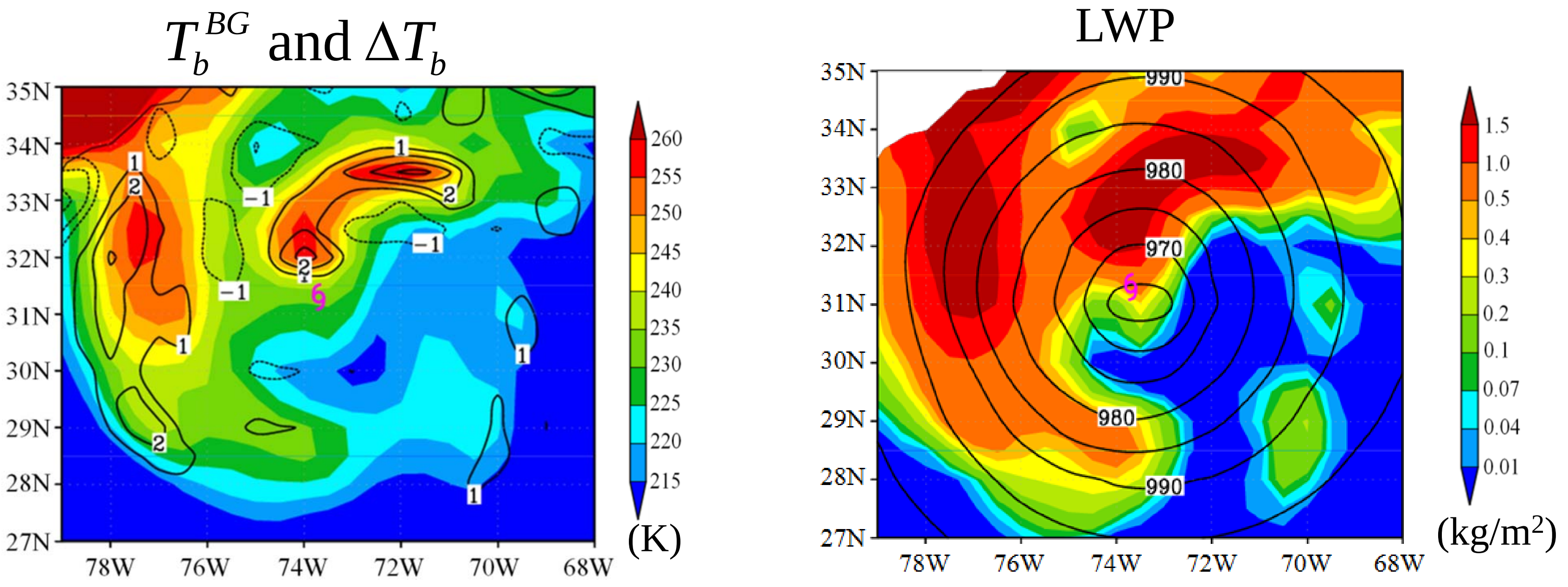
$$\Delta T_b = T_b^{BG} - T_b$$

(contour interval: 1K)

(K)

T_b at Channel 1 within Sandy before and after BG

(0600 UTC October 28, 2012)


T_b^{BG} and ΔT_b

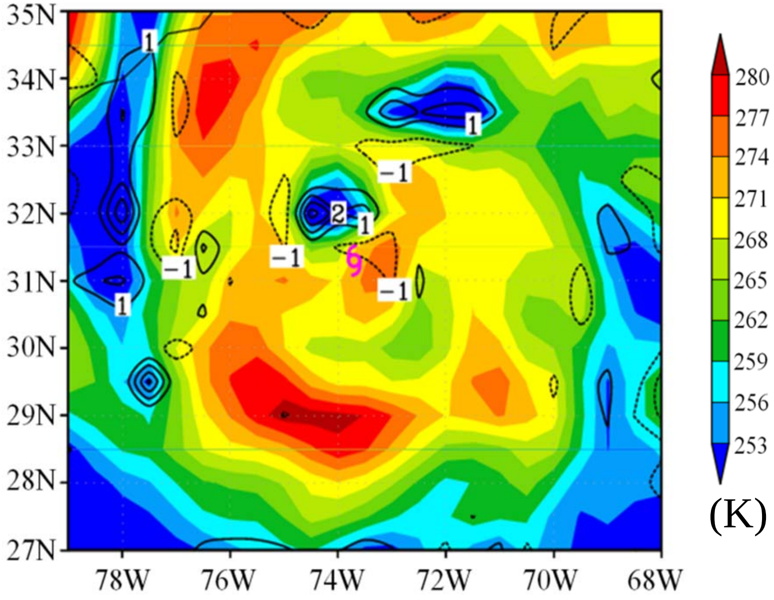
LWP

- The measured brightness temperatures at 23.8 GHz are higher over hurricane rainbands due to the contributions from cloud and water vapor emission
- The maximum brightness temperatures over cloud areas after remap are more than 2-3K lower than those before the remap
- The gradients of brightness temperatures near cloud edges become sharper

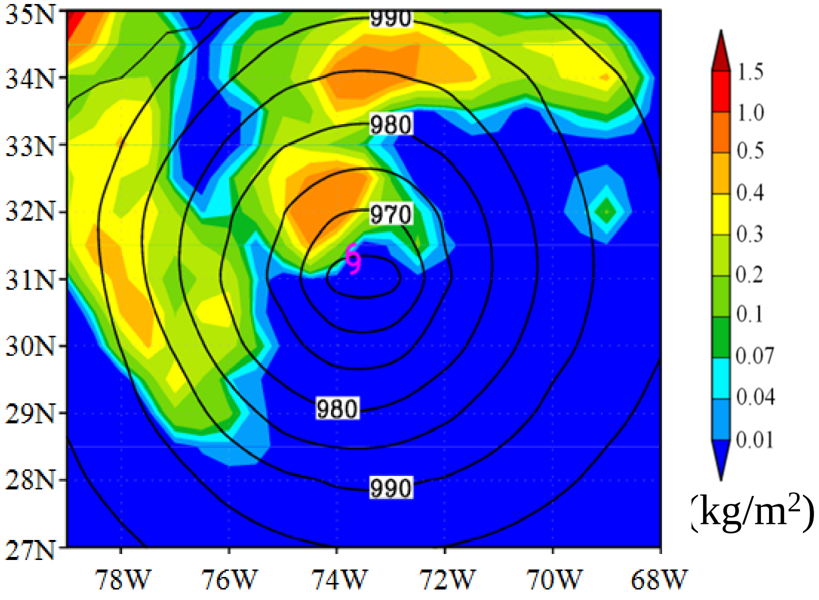
T_b at Channel 16 within Sandy before and after BG

(0600 UTC October 28, 2012)

T_b^{BG} and ΔT_b



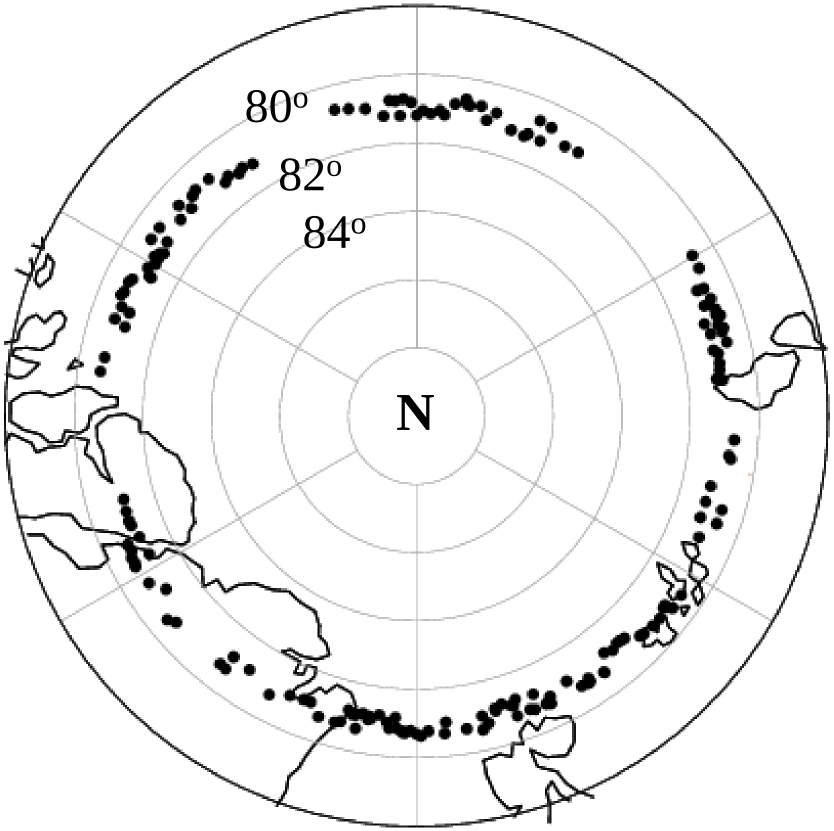
IWP



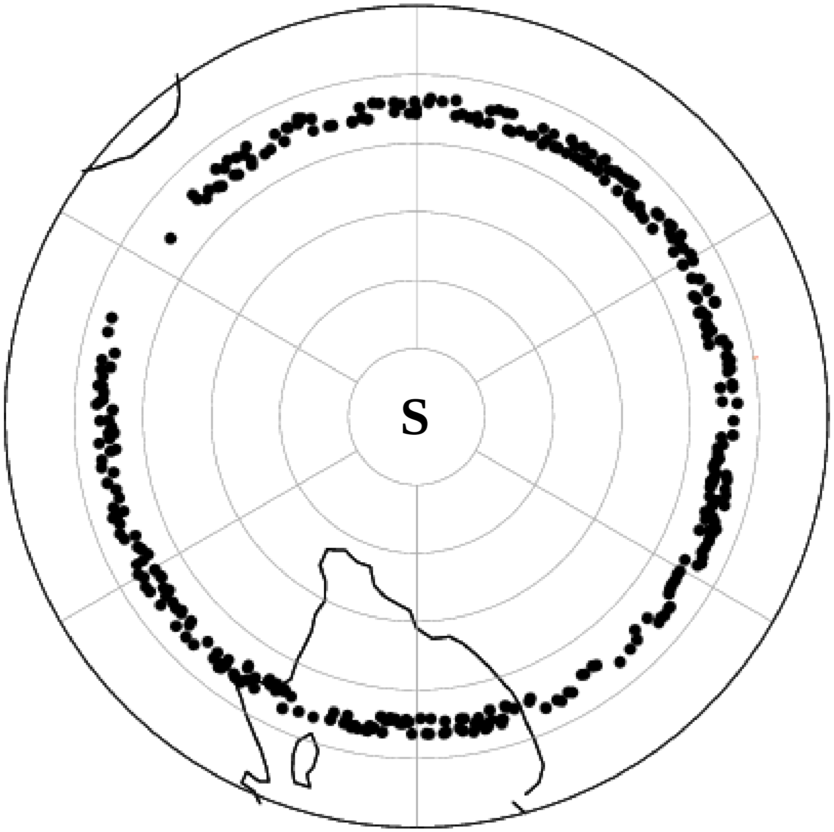
- The measured brightness temperatures at 88.2 GHz are lower over areas with ice cloud within hurricane rainbands due to ice scattering effect on radiation
- The minimum brightness temperatures over ice cloud areas after remap are more than 2-3K lower than those before the remap

Further Characterization of Bias between Resample ATMS vs. AMSU using SNO Data

Northern Hemisphere



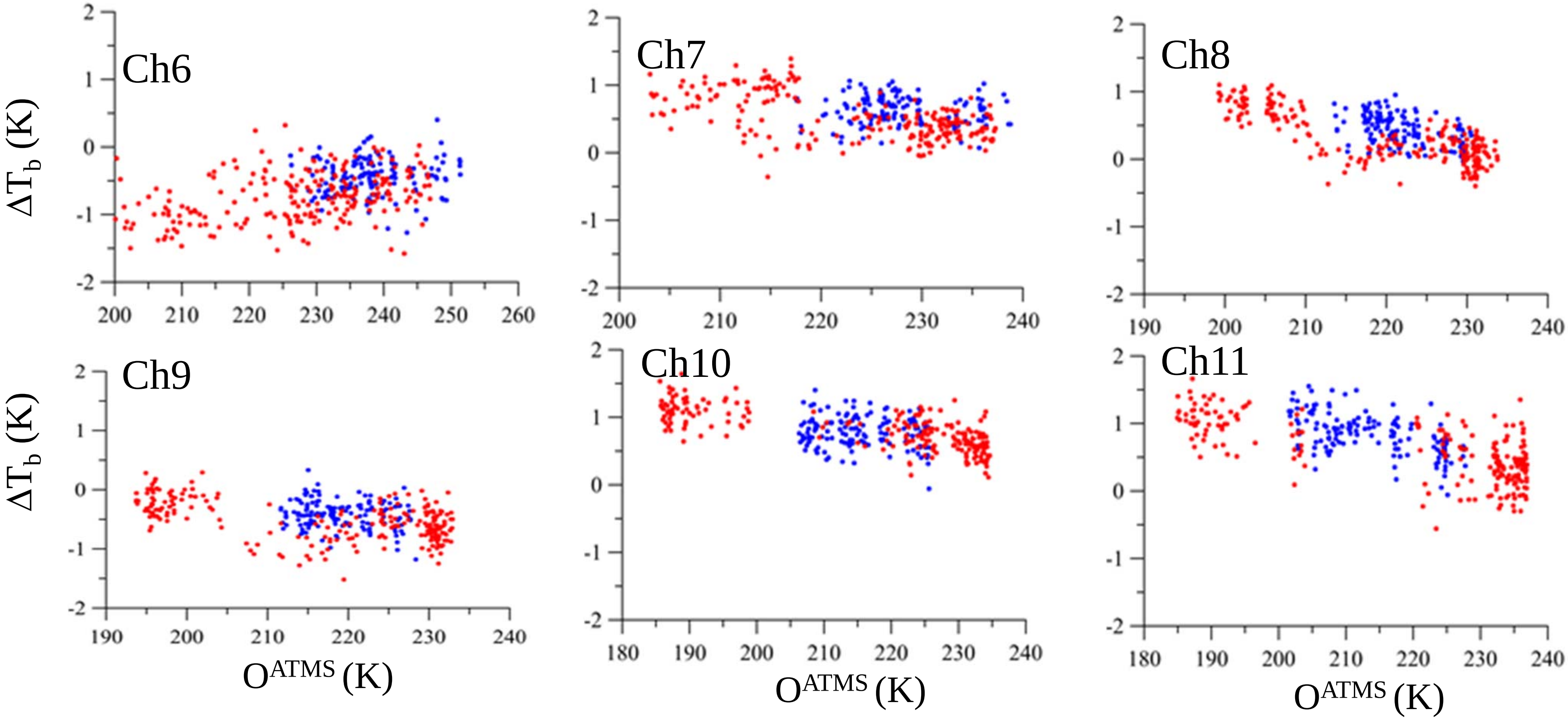
Southern Hemisphere

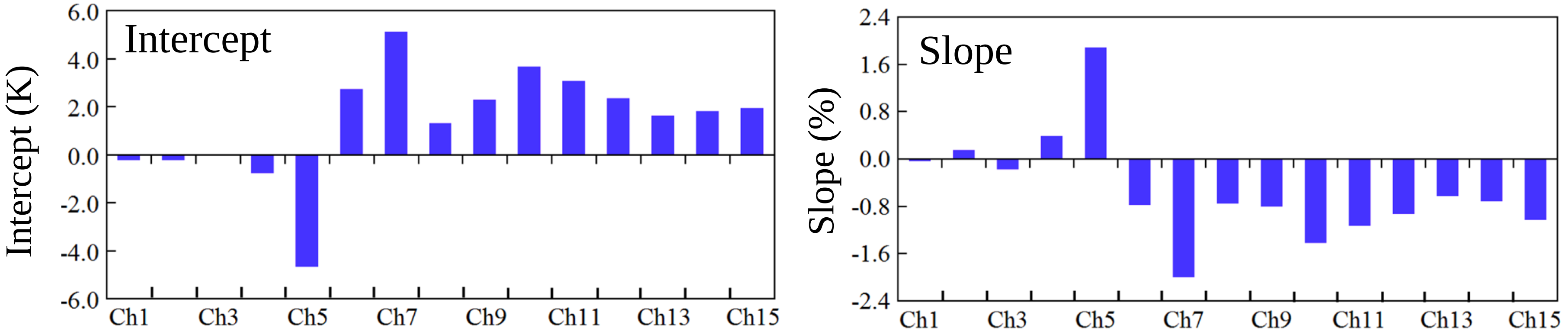


Time Period: January 1, 2012 - March 31, 2013

Collocation Criteria: 15 km and 60 seconds

Scatter Plots of ΔT_b(= O^{ATMS}– $O^{NOAA\text{-}18}$)
(Blue :Arctic and Red: Antarctic)

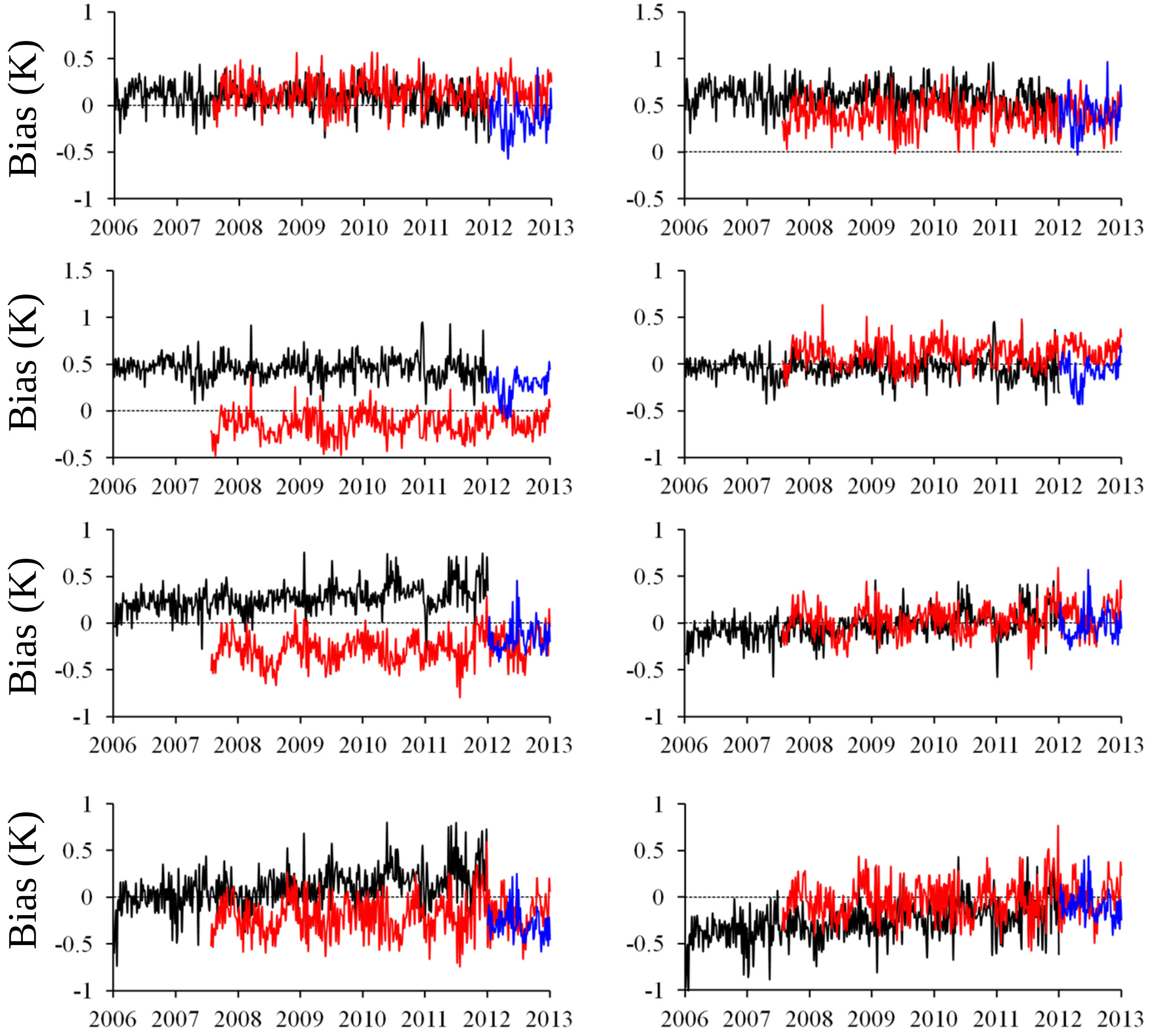




Biases in the Tropics (NOAA-15, MetOp-A, SNPP)

before

after



ATMS channel 10

ATMS channel 11

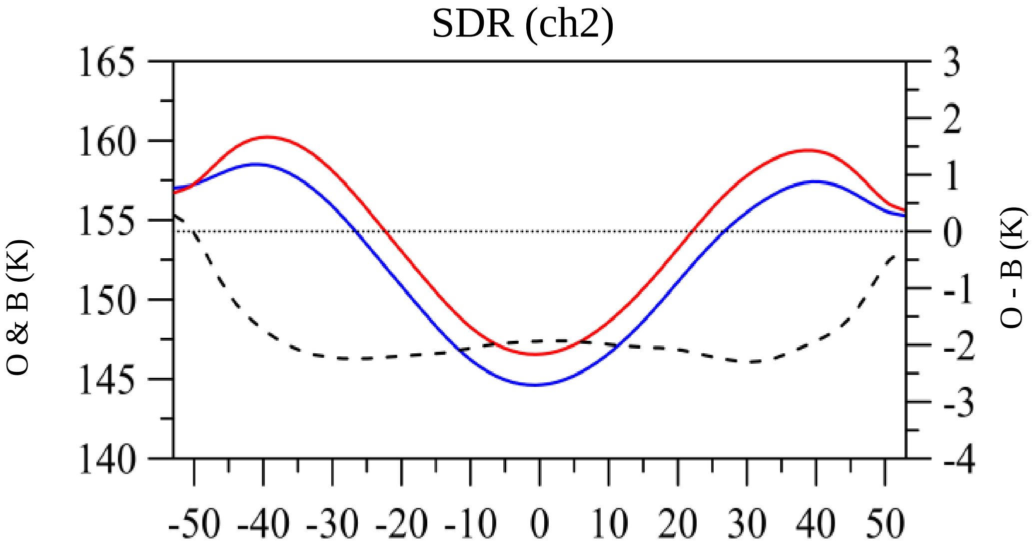
ATMS channel 13

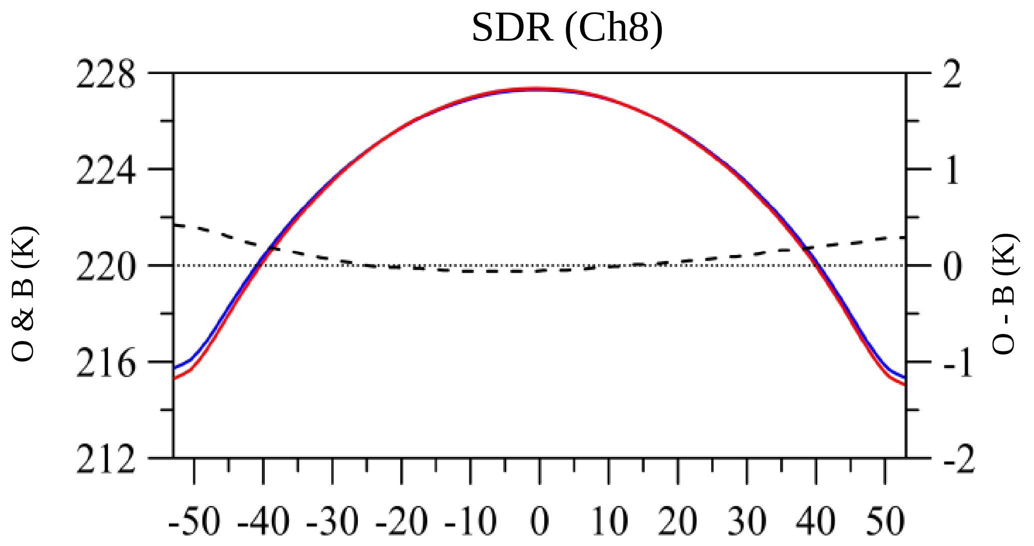
ATMS channel 14

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

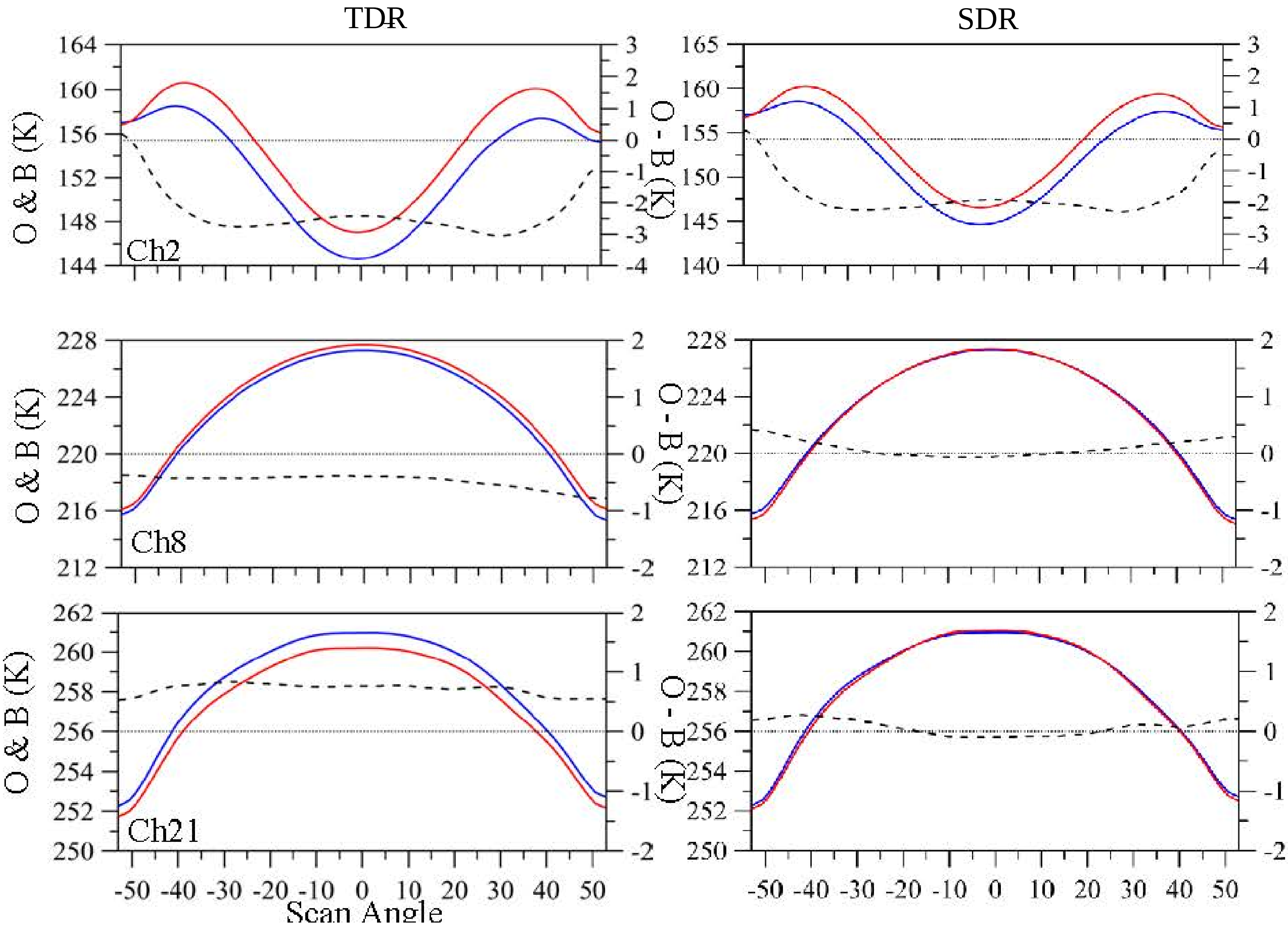
ATMS SDR Scan Angle Dependent Bias

- **Methodology:**
  - SDR angular dependent biases are assessed using ECMWF and CRTM simulations
  - Cloud-affected radiances are removed with cloud liquid water algorithm (Weng et al., 2003)
  - Also, the measurements with the surface wind speeds are less than 10m/s are used
- **Results:**
  - ATMS SDR sounding channels have small bias but less angular dependent
  - But window channels have some significant biases

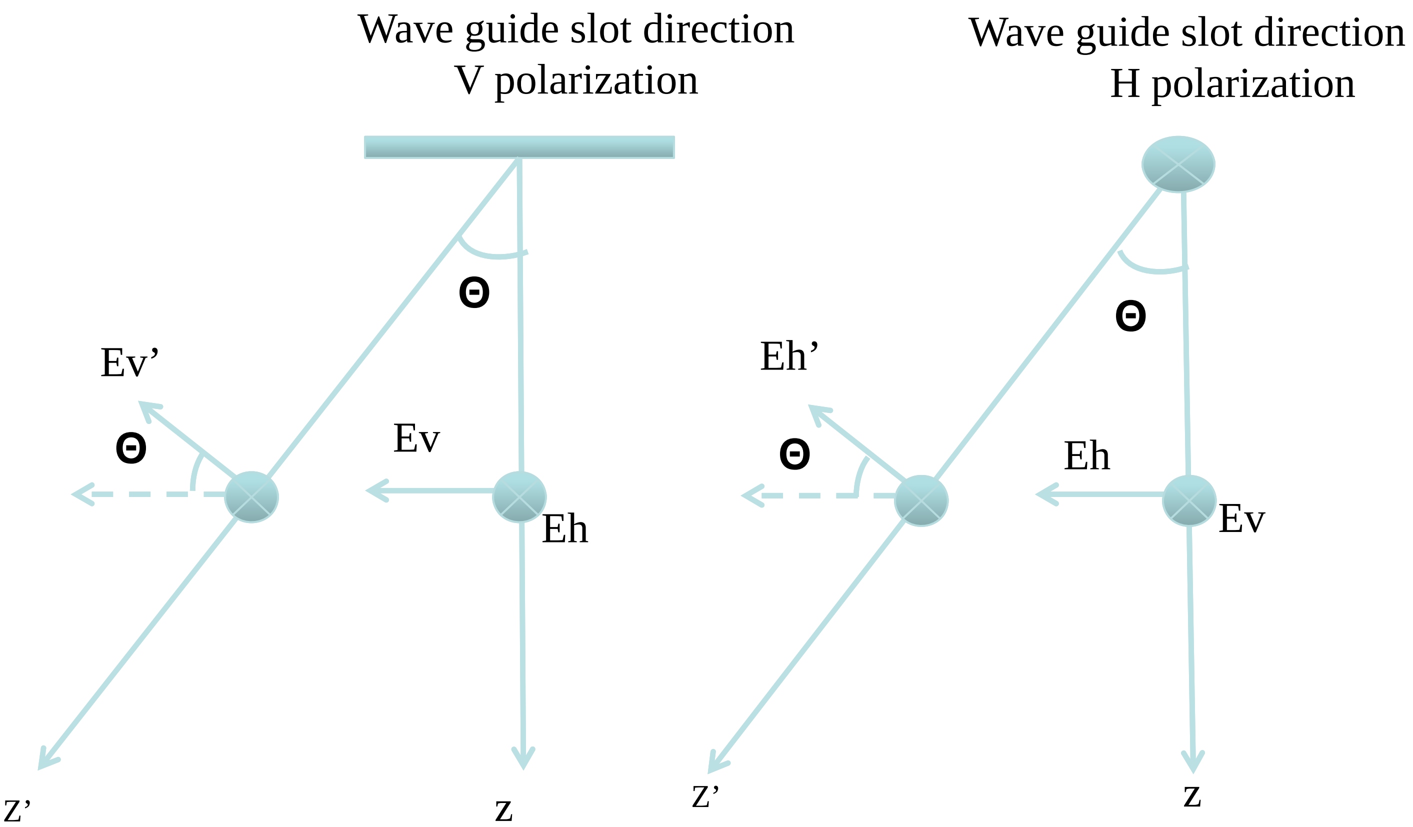




ATMS Scan Dependent O-B (TDR vs. SDR)



ATMS SDR Biases Due to the 3rd Stokes Component



Wave guide slot direction
V polarization

Wave guide slot direction
H polarization

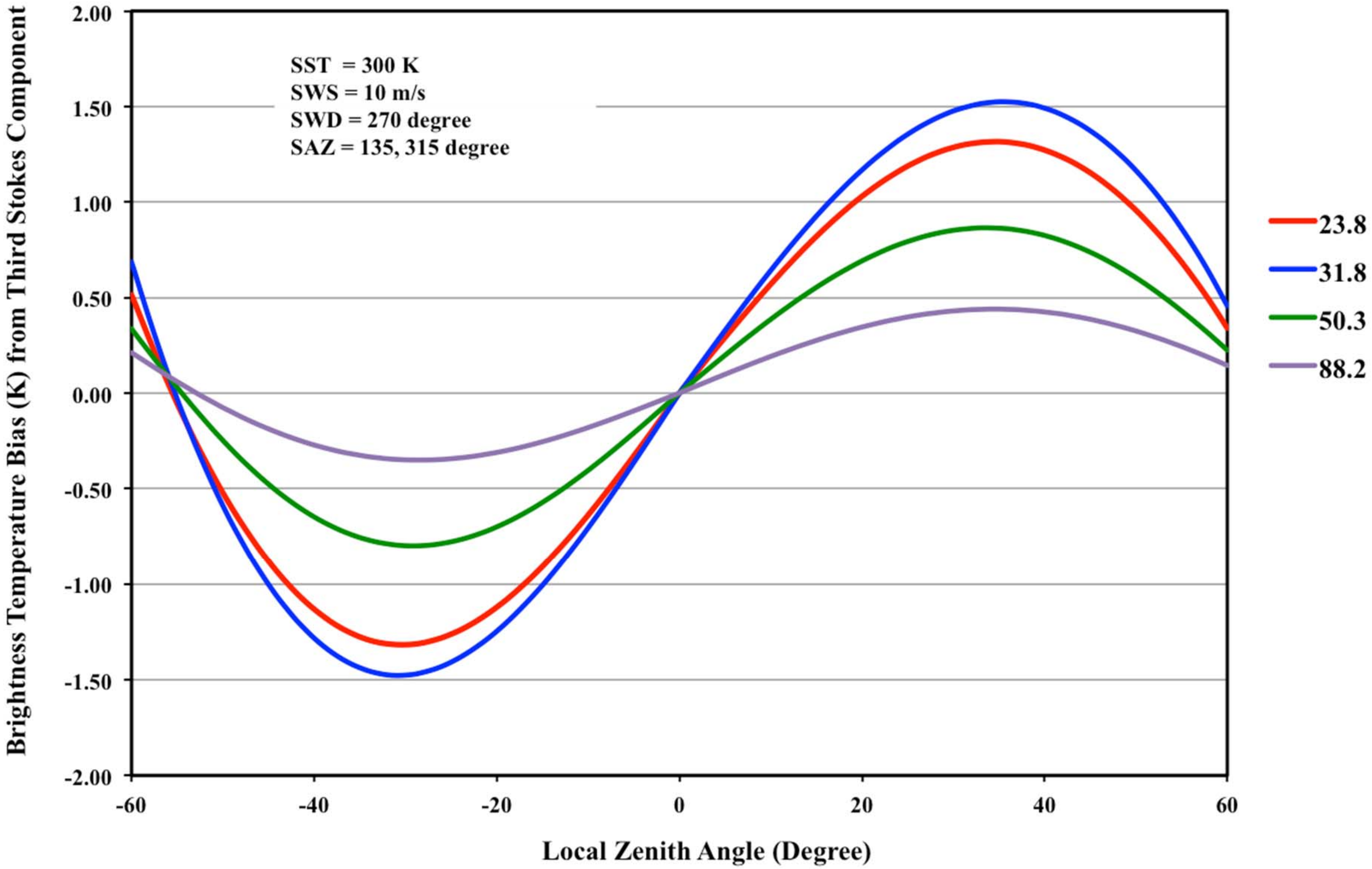
Eh vector is defined as the electronic vector perpendicular to wave propagation plane

$$\begin{bmatrix} T_B^{QV} \\ T_B^{QH} \\ T_B^{Q3} \\ T_B^{Q4} \end{bmatrix} = \begin{bmatrix} cos^2\theta & \sin^2\theta & 0.5\sin 2\theta & 0 \\ \sin^2\theta & cos^2\theta & -0.5\sin 2\theta & 0 \\ -\sin 2\theta & \sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} T_B^V \\ T_B^H \\ T_B^3 \\ T_B^4 \end{bmatrix}$$

$$T_B^{QV} = T_B^H \sin^2\theta + T_B^V \cos^2\theta + T_b^3 \frac{1}{2}\sin\theta$$

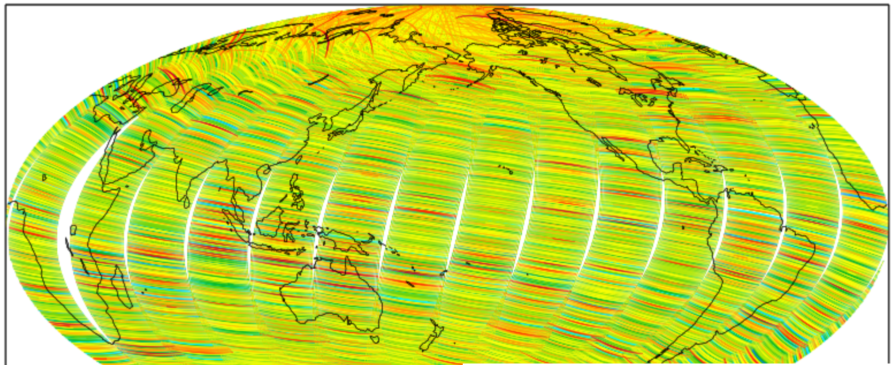
$$T_b^{QH} = T_b^H \cos^2\theta + T_b^V \sin^2\theta - T_b^3 \frac{1}{2}\sin\theta$$

ATMS SDR Difference w/o the 3^{rd} Stokes Component



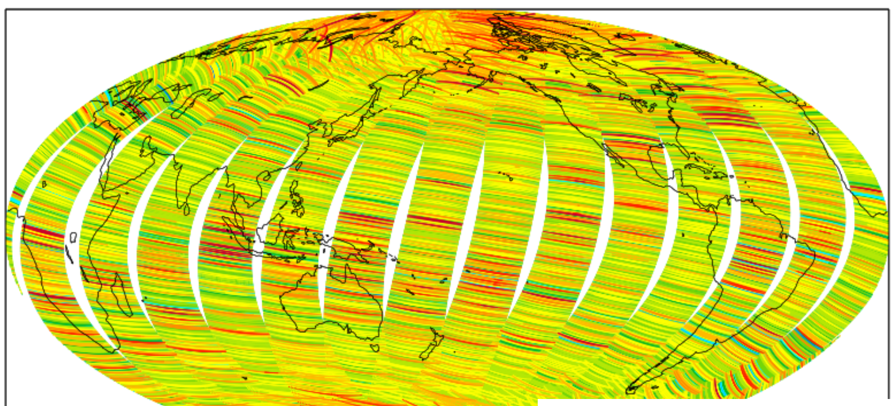
ATMS Striping Noise Shown in O-B

SNPP ATMS Ch 22

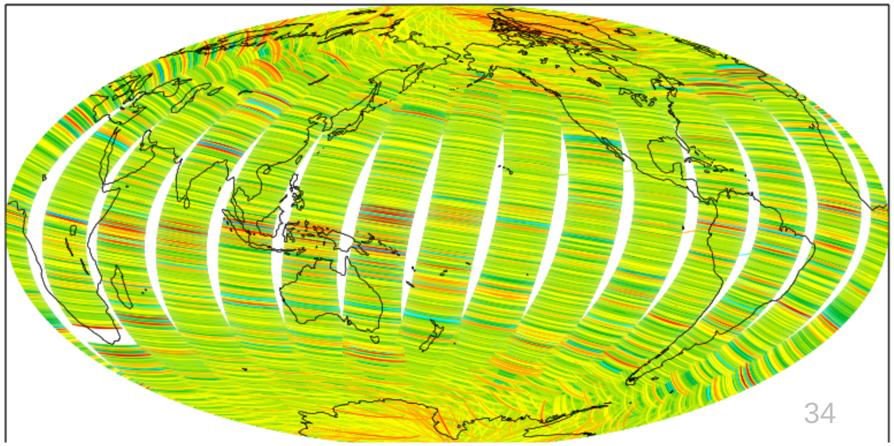


Striping noises are found in ATMS, MHS, and AMSU-B. The magnitudes of ATMS temperature and water vapor sounding channels are about ±0.3K and ±1.0K, respectively

NOAA-18 MHS Ch3

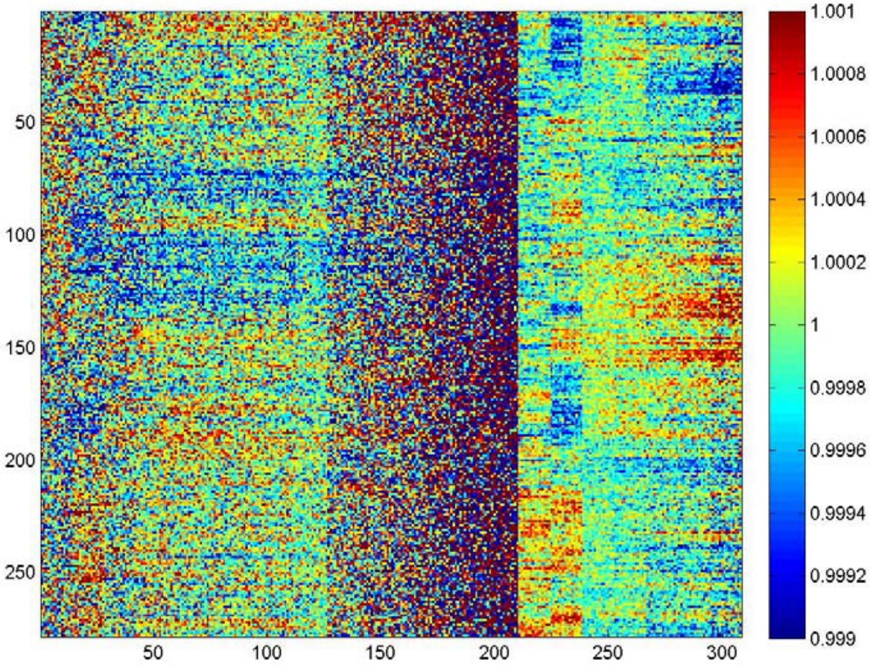


NOAA-16 AMSU-B Ch3

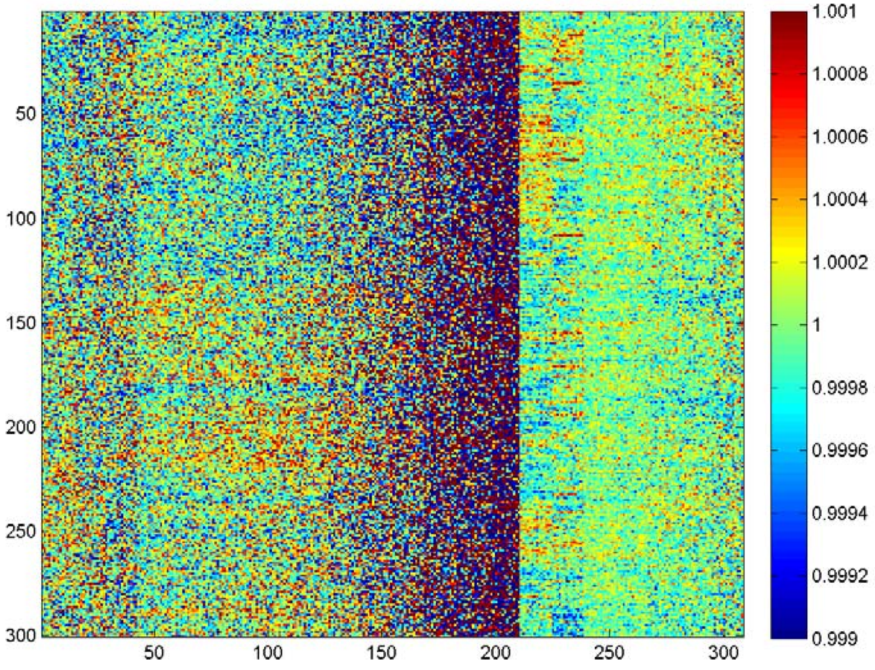


JPSS-1 ATMS TVAC Test Data Showing Less Striping Noise Compared to SNPP Data

SNPP TVAC Data (RC1 230K)



J-1 TVAC Data (1/10/14)



Preliminary TVAC data analysis shows J1 ATMS striping magnitude is smaller compared to SNPP ATMS. According to NGES, this smaller striping may be due to the reduced power noise stability in low noise amplifier (LNA) and IF modules.

Summary and Conclusions

- ATMS TDR/SDR data has reached a validated maturity *level (definition: on-orbit performance is characterized and calibration parameters are adjusted accordingly. The data is ready for use by the operational center and scientific publications)*
- ATMS SDR team made following major calval accomplishments:
  - On-orbit NEDT is well characterized and meets specification
  - Bias (accuracy) is well characterized
  - All the important quality flags are checked and updated
  - Calibration coefficients from TDR to SDR are updated
  - Lunar intrusion correction is tested and DR is submitted
  - ATMS and AMSU-A inter-sensor biases are well characterized and ATMS TDR data are now within AMSU-A family
  - STAR ICVS can provide long-term monitoring of ATMS instruments
  - All the calval sciences have been published through peer-reviewed process

Path Forward

- Suomi NPP
  - Refine ATMS scan bias corrections for TDR to SDR conversion with better characterization of xpol spill-over, W/G band slope (note intercept has been updated)
  - Develop ATMS radiometric calibration in full radiance to make the SDR data consistent with NOAA heritage AMSU-A/MHS
  - Refine striping mitigation algorithm for WG bands
- JPSS -1 and -2
  - Support of and participation in pre-launch testing, instrument characterization and calibration data development
  - Software update/improvement (implementations of new calibration algorithms, full resolution SDR and computation efficiency schemes), delivering the SDR code in January 2015.
  - Work with NGES to better characterize ATMS antenna (side-lobe, xpol spill-over, polarization twist angle) for J1/J2 mission
  - A comprehensive test data set derived from SNPP and J1 TVAC tests for J1 algorithm and software development and test
  - Support J1 and J2 waiver studies

ATMS SDR Documentation

ATMS CalVal results summarized in the following peer review papers

- Weng, F., X. Zou, X. Wang, S. Yang, M. Goldberg, 2012: Introduction to Suomi NPP ATMS for NWP and Tropical Cyclone Applications, *J. Geophys. Res. Atmos*, doi:10.1029/2012JD018144
- Weng, F., X. Zou, M. Tian, W.J. Blackwell, N. Sun, H. Yang, X. Wang, L. Lin, and K. Anderson, 2013, Calibration of Suomi National Polar-Orbiting Partnership (NPP) Advanced Technology Microwave Sounder (ATMS), *J. Geophys. Res.* Atmos., **118**, 1–14, doi:10.1002/jgrd.50840
- Qin, X. Zou, and F. Weng, 2013: Analysis of ATMS Striping Noise from its Earth Scene Observations Using PCA and EEMD Techniques**,** *J. Geophys. Res . Atmos.*, **118**, *doi:10.1002/2013JD020399*
- Weng, F., H. Yang, and 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
- Weng, F. and X. Zou, 2013: Errors from Rayleigh–Jeans Approximation in Satellite Microwave Radiometer Calibration System, *Appl. Optics*, 12, 505-508.
- Zou, X., F. Weng, B. Zhang, L, Lin, Z. Qin, and V. Tallaparada **:**2013: Impacts of assimilation of ATMS data in HWRF on track and intensity forecasts of 2012 four landfall hurricanes, *J. Gephys. Res. Atmos*, **118**, 1-19, doi:10.1002/2013JD020405
- Bormann, N., A. Fouiloux and W. Bell, 2013: Evaluation and assimilation of ATMS data in the ECMWF system, , *J. Gephys. Res. Atmos*, **118,** doi:10.1002/2013JD020325