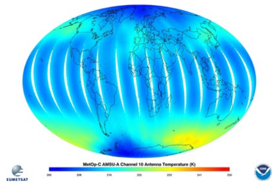

Metop-C AMSU-A and AVHRR Sensor Data Recorder (SDR) Data Calibration/Validation (CalVal): Status & Prospective

Banghua Yan and Xiangqian Wu

NOAA/STAR/Satellite Calibration and Data Assimilation Branch (SCDAB)

Other Contributors: Junye Chen[1], Khalil Ahmad[1], Stanislav Kireev[1], Haifeng Qian[1], Cheng-Zhi Zou[2], and Changyong Cao[3]

[1] GST, Inc. [2] NOAA/STAR/EMB [3] NOAA/STAR/SCDAB

Outline

- Background
- AMSU-A CalVal Activities
- AVHRR CalVal Activities
- Conclusions
- Path Forward

STAR Metop-C CalVal Team Members

Name	Organization	Major Task
Banghua Yan	NOAA/STAR	Metop-C CalVal project team lead, AMSU-A CalVal lead, project planning and schedule
Xiangqian (Fred) Wu	NOAA/STAR	AVHRR CalVal lead, AVHRR calval planning and schedule
Junye Chen	ProTech/GST	AMSU-A CPIDS (Lunar intrusion correction coefficients), SIOV and other CalVal tasks
Haifeng Qian	ProTech/GST	AMSU-A Prelaunch CPIDS TVAC data analysis, and AVHRR CPIDS
Cheng-Zhi Zou	NOAA/STAR	AMSU-A prelaunch TVAC-CPIDS lead
Stanislav Kireev	ProTech/GST	ICVS update to Metop-C, AVHRR SIOV and other postlaunch CalVal tasks
Khalil Ahmad	ProTech/GST	AMSU-A APC coefficients, SIOV and other CalVal tasks

Acknowledgement

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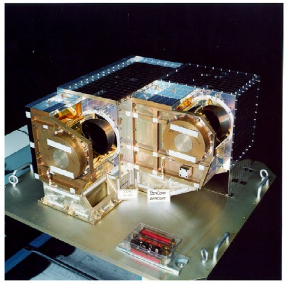
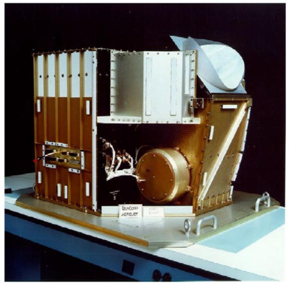
- OSPO Metop-C team: Dejiang Han, Renee Smith, Carl Gliniak, Donna Mcnamara, Paul Haggerty, Xiaoping Bao, Pierre E Youssef, and others
- NASA SIOV Team: Walter H Asplund, Eugene D. Guerrero, Michael A Honaker, and others.
- Northrop Grumman Corporation: AMSU-A and AVHRR instrument vendors
- STAR IT team: Matthew Jochum, Weiguo Han, and others
- STAR Management: Changyong Cao, Satya Kalluri, and others
- JPSS program: Lihang Zhou for providing JPSS Maturity Review process and criteria

METOP-C NOAA Instruments

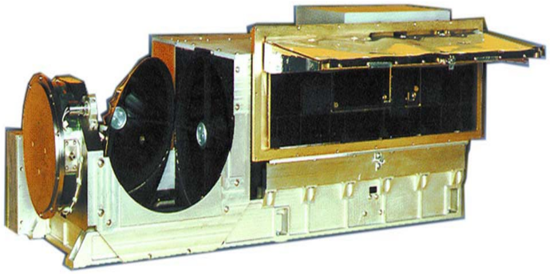
- METOP-C was launched at 00:47 UTC on November 7, 2018.
  - After METOP-A in 2006 and METOP-B in 2012.
  - Last of the METOP 1st generation.
- Carries several NOAA instruments as part of the Initial Joint Polar System (IJPS), including
  - An Advanced Microwave Sounding Unit (AMSU-A)
  - An Advanced Very High Resolution Radiometer (AVHRR)
  - A Space Environment Monitor (SEM)



AMSU-A1

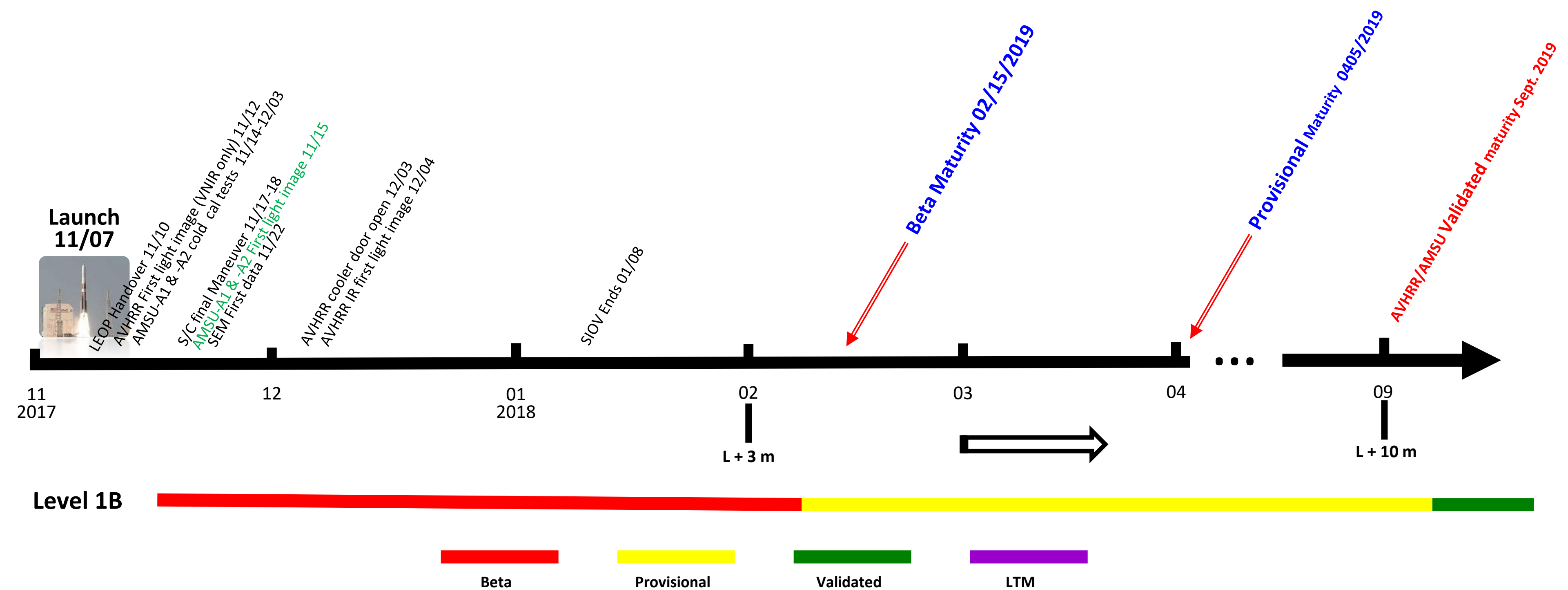


AMSU-A2



AVHRR

Metop-C AVHRR/AMSU Postlaunch CalVal Timeline



- Beginning of each color represents when product enters a given maturity stage.

AMSU-A Instrument Characteristics

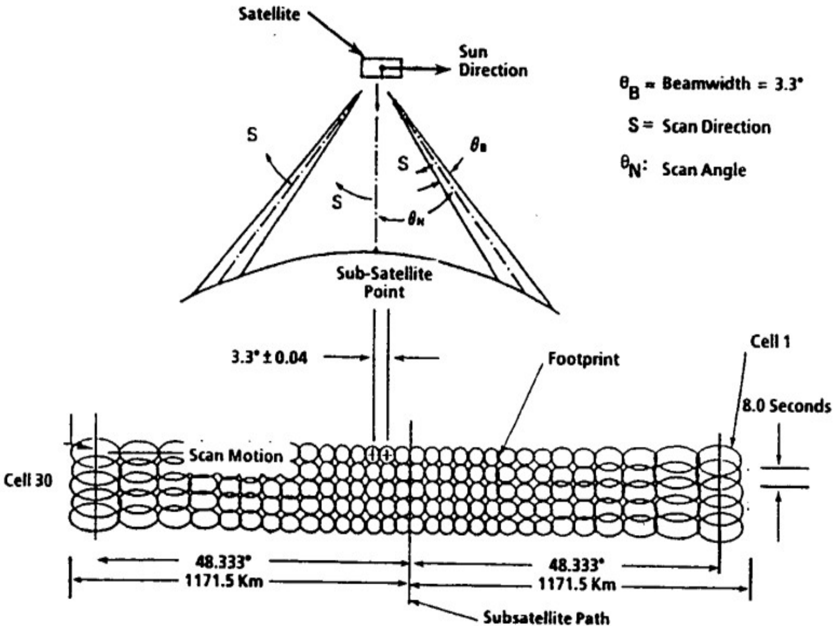


Figure AMSU-A Spatial Resolution (3.3°) and Swath (2343 km) Width*

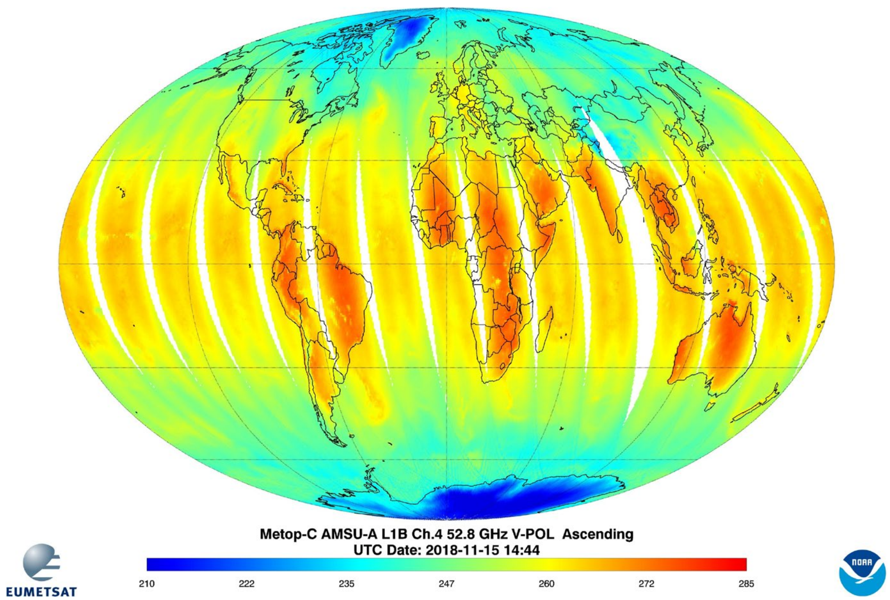
(Courtesy of Northrop Grumman)

Table AMSU-A Channel Descriptions*

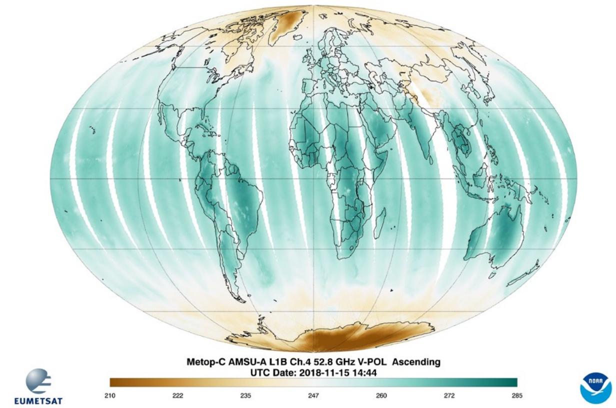
Channel Number	Center Frequency	No. of Pass Bands	Bandwidth (MHz)	Center Frequency Stability (MHz)	Temperature Sensitivity (K) NEDT	Calibration Accuracy (K)	Beam Diameter B (degrees)	Polarization
1	23800 MHz	1	270	10	0.3	2.0	3.3	V
2	31400 MHz	1	180	10	0.3	2.0	3.3	V
3	50300 MHz	1	180	10	0.4	1.5	3.3	V
4	52800 MHz	1	400	5	0.25	1.5	3.3	V
5	53596 MHz 115 MHz	2	170	5	0.25	1.5	3.3	H
6	54400 MHz	1	400	5	0.25	1.5	3.3	H
7	54940 MHz	1	400	5	0.25	1.5	3.3	V
8	55500 MHz	1	330	10	0.25	1.5	3.3	H
9	57290.344 MHz = f_{LO}	1	330	0.5	0.25	1.5	3.3	H
10	f_{LO} ±217 MHz	2	78	0.5	0.4	1.5	3.3	H
11	f_{LO} ± 322.2 ± 48 MHz	4	36	1.2	0.4	1.5	3.3	H
12	f_{LO} ± 322.2 ± 22 MHz	4	16	1.2	0.6	1.5	3.3	H
13	f_{LO} ± 322.2 ± 10 MHz	4	8	0.5	0.8	1.5	3.3	H
14	f_{LO} ± 322.2 ± 4.5 MHz	4	3	0.5	1.2	1.5	3.3	H
15	89.0 GHz	1	1500	130	0.5	2.0	3.3	V

(*Reference: AMSU-A SYSTEM OPERATION AND MAINTENANCE MANUAL, NASA/Goddard Space flight Center)

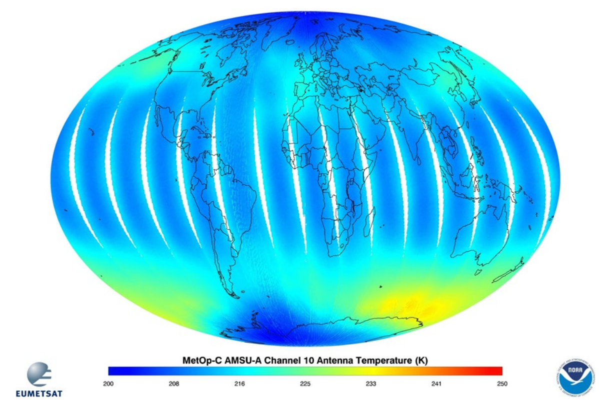
First Light for Metop-C AMSU-A (November 15, 2018)



(a) Channel 4 (release to EUMETSAT)



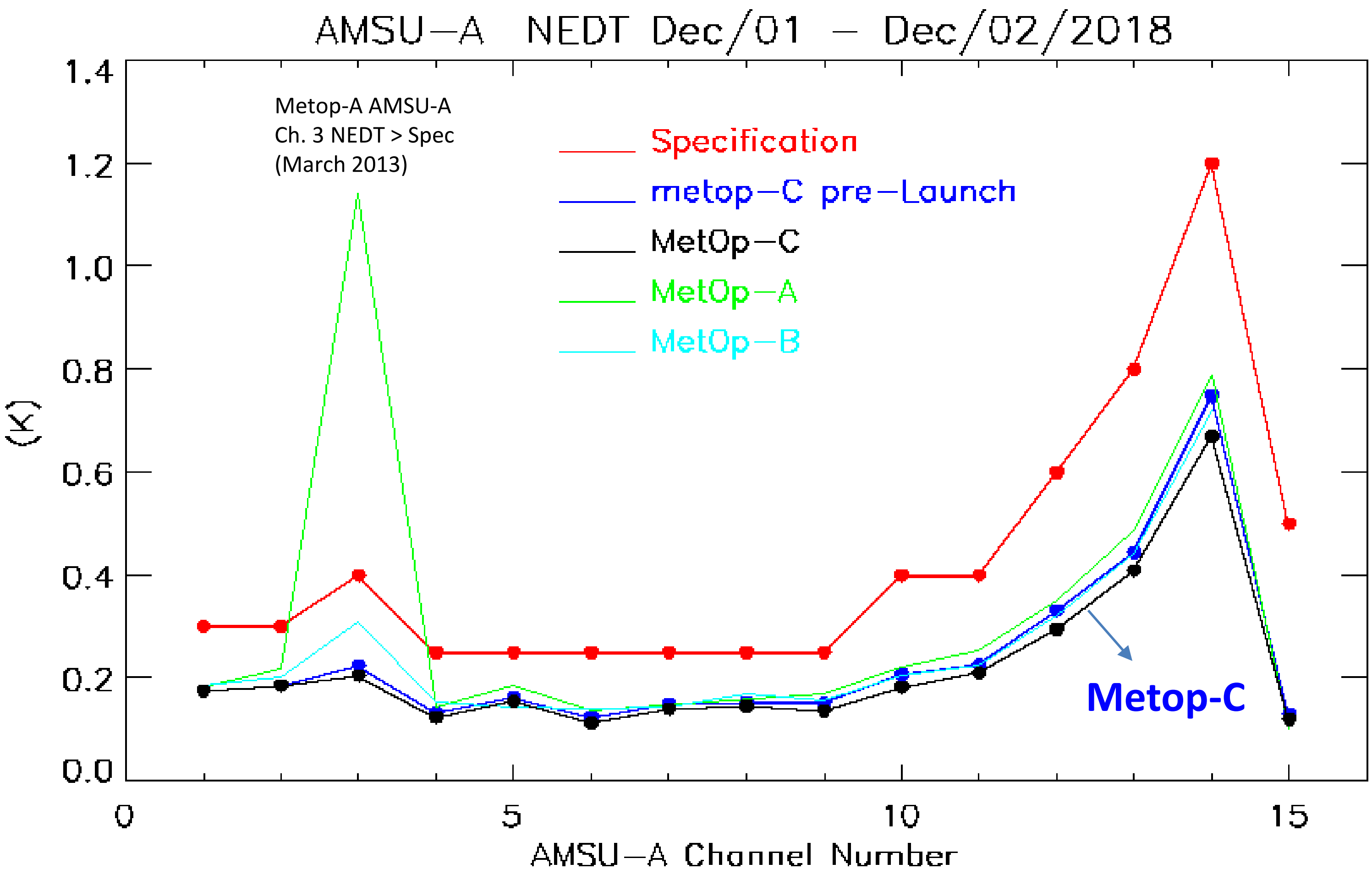
(b) Channel 4 (blind-color, release to NOAA)



(c) Animation of 15 Channels (release to STAR)

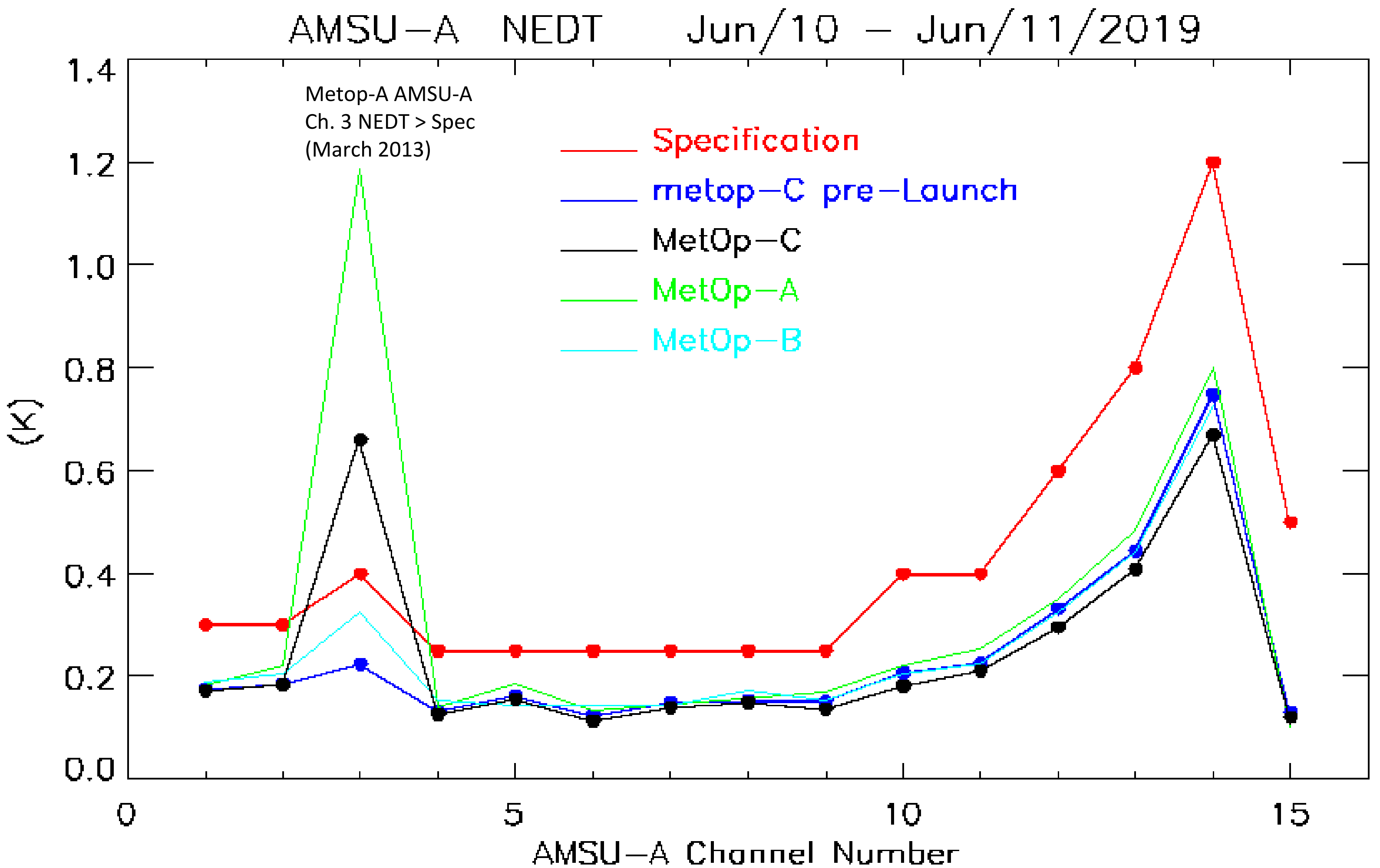
Figure Nine days after METOP-C was launched into low Earth orbit on November 6, 2018, the first day Advanced Microwave Sounding Unit-A (AMSU-A) science data was received on November 15, 2018. METOP-C is the third and final spacecraft of the European Meteorological Operational satellite program (Metop). The AMSU-A data are part of a series of instrument tests that will take place before the satellite is operational. The Metop-C satellite carries a variety of instruments including three NOAA sensors: AMSU-A, the Advanced Very High Resolution Radiometer (AVHRR), and the Space Environment Monitor (SEM). Both of AMSU-A and AVHRR will improve daily weather forecasts while continuing to monitor long-term changes in Earth's climate. SEM provides measurements to determine the intensity of the Earth's radiation belts and the flux of charged particles at satellite altitude.

Metop-A/B/C AMSU-A NEDT Comparison (1/2)



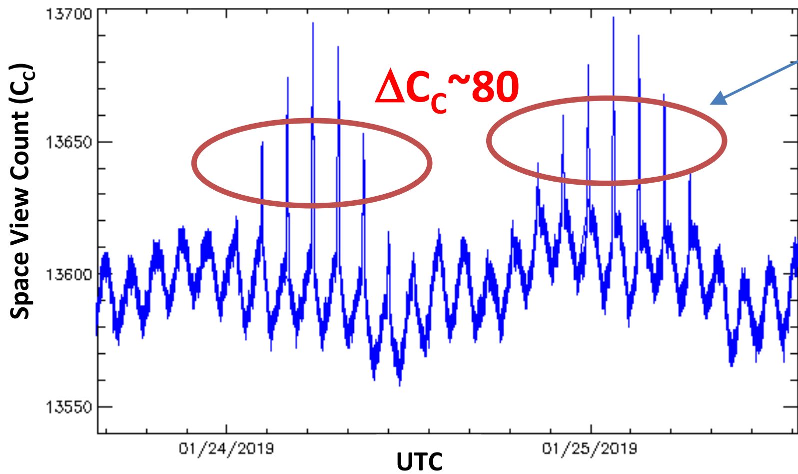
- In early SIOV period, instrument noise of Metop-C AMSU-A except for Ch. 3 is comparable with that of Metop-A/B AMSU-A
- Metop-C AMSU-A instrument shows slightly better noise performance than Metop-A/B AMSU-A

Metop-A/B/C AMSU-A NEDT Comparison (2/2)

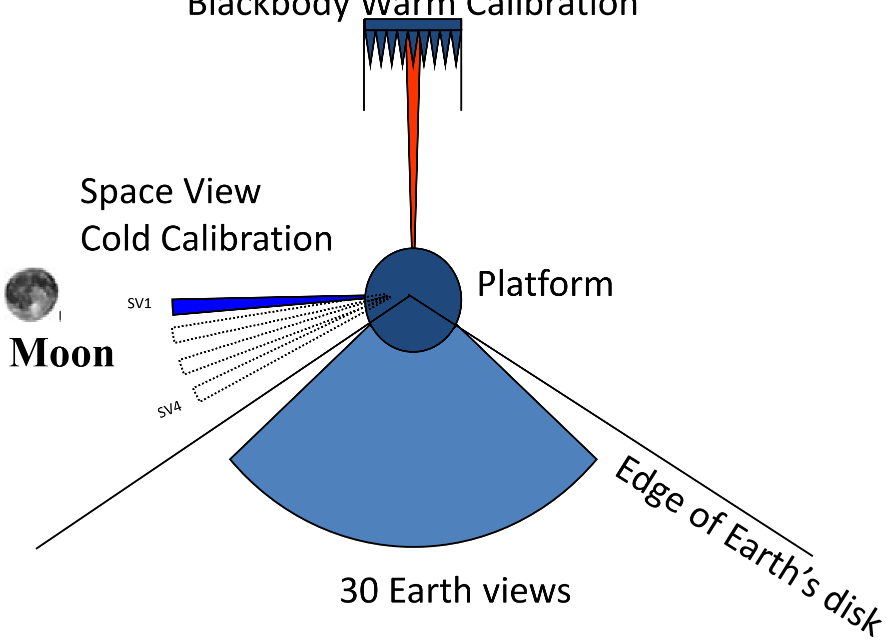


AMSU-A Lunar Intrusion Correction Validation

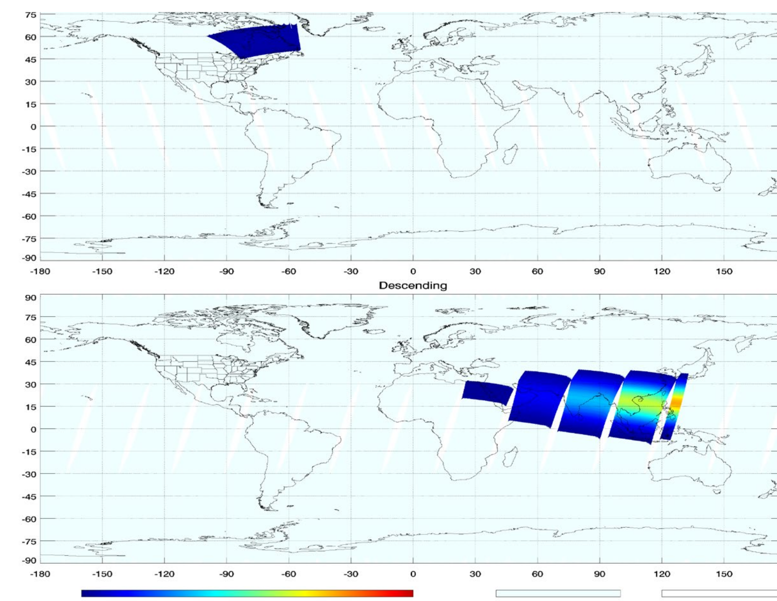
MetOp-C AMSU-A Space Count, Chan12, 2019-01-24



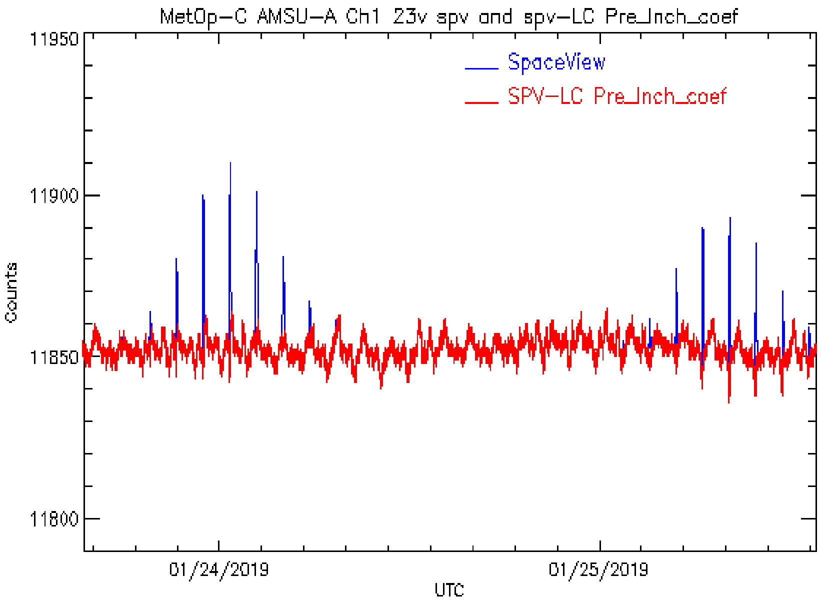
- Lunar contamination occurs whenever the Moon moves into the space view FOV.
- It happens about once a month, lasts for more than one day in each event.
- The **impact could be greater than 1K in broad area** in some AMSU-A channels because that the lunar surface brightness temperature is 120 ~ 380 K, much higher than the deep space background temperature of 2.73 K.

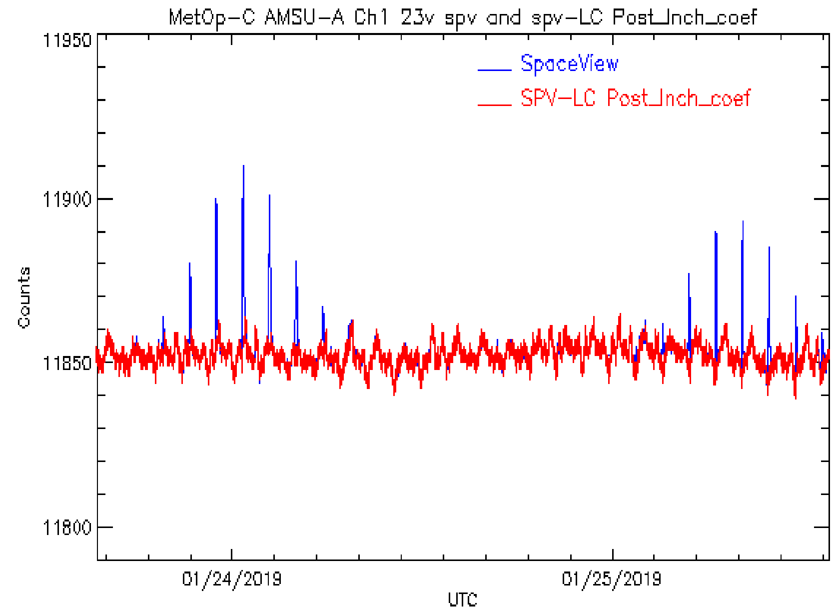


MetOp-C AMSU-A Lunar Contamination area in different channels
2019-01-24 **(animation)**



Lunar Intrusion Correction Comparison: Prelaunch and Postlaunch Coefficients





- Three lunar intrusion events occurred for Metop-C AMSU-A measurements so far: 11/27 ~ 11/28, 12/25 ~ 12/27/2018 and 01/23 ~ 01/25/2019
- New version of the coefficients were generated based on a regression method with Lunar intrusion SV cold counts for the second event on 12/25 ~ 12/27, 2018
- The coefficients are applied to the third intrusion It appears that the Lunar correction is largely improved by using newly derived post-launch coefficients. Even so, a further test is needed using more cases.

Antenna Gain Efficiency Parameters Generation

- Baseline Algorithm: AMSU-A operational APC algorithm (Mo 1999): only remove antenna sidelobe correction to **antenn temperature T_A to produce Earth scene brightness temperature T_B**

$$\boldsymbol{T_A} \approx F_e(\beta)\boldsymbol{T_B} + F_C(\beta)T_C + F_{SAT}(\beta)T_{SAT}$$

Earth scene (main beam) **Cold Space (sidelobes)** **Spacecraft (sidelobes)**

where (Mo 1999):

$$F_e(\beta) = \frac{f_e(\beta)}{N_\eta}, F_C(\beta) = \frac{f_C(\beta)}{N_\eta}, F_{SAT}(\beta) = \frac{f_{SAT}(\beta)}{N_\eta},$$

$$N_\eta(\beta) = f_e(\beta) + f_C(\beta) + f_{SAT}(\beta)$$

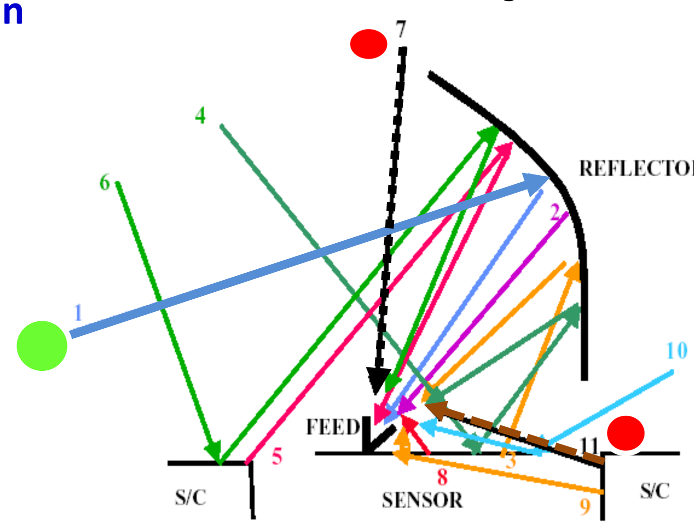
$$f_x(\beta) = \frac{1}{N}\int_{\theta_{x1}}^{\theta_{x2}} g(\theta)\sin(\theta)\,d(\theta)\ \ (with\ x = e, c, sat)$$

$$g(\theta) = \int_0^{2\pi} G(\alpha,\gamma)\mathrm{d}\Omega\ and\ N = \int_0^{4\pi} G(\alpha,\gamma)\mathrm{d}\Omega$$

$$G(\alpha,\gamma) = G_{Co}(\alpha,\gamma) + G_{cross}(\alpha,\gamma)$$

G(α,γ) is a sum of antenna pattern functions at co- and cross polarizations

Energy sources entering feed for a reflector configuration



Ideally, energy sources entering feed for a reflector configuration (Weng, 2018) consists of 11 items:

1. **Earth scene component**
2. Reflector emission
3. Sensor emission viewed through reflector
4. Sensor reflection viewed through reflector
5. Spacecraft emission viewed through reflector
6. Spacecraft reflection viewed through reflector
7. **Spillover directly from space**
8. Spillover emission from sensor
9. Spillover reflected off sensor from spacecraft
10. Spillover reflected off sensor from space
11. **Spillover emission from spacecraft**

AMSU-A Bias Scan Dependence Analysis

- The JCSDA CRTM (version 2.3.0) is applied to Metop-C AMSU-A observations to compute O – B
  - O: AMSU-A TA (1B) or TB measurements
  - CRTM version:
- TB is computed by using the following equation [Mo 1999]

$$T_B = a_0(\beta)T_A - b_0(\beta, T_C)$$

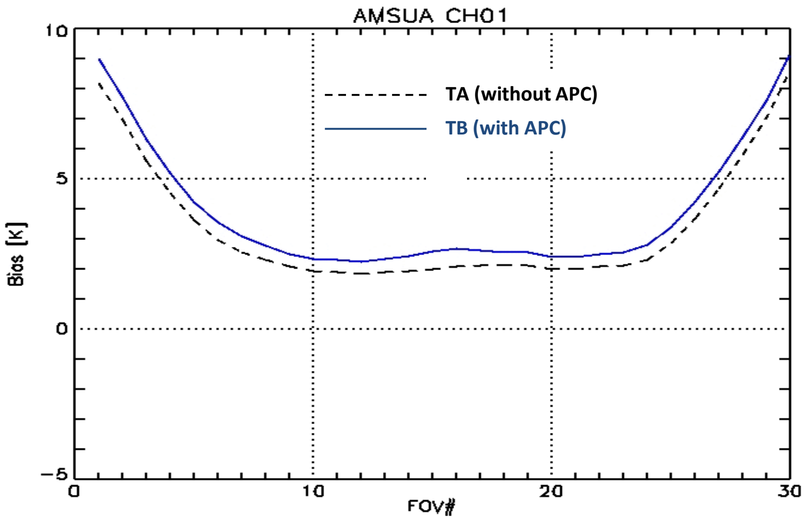
$$a_0(\beta) = 1 + \frac{f_C(\beta)}{f_e(\beta)} + \frac{\eta f_{SAT}(\beta)}{f_e(\beta)},$$

$$b_0(\beta, T_C) = \frac{f_C(\beta)T_C + \eta f_{SAT}(\beta)T_{SAT}}{f_e(\beta)}$$

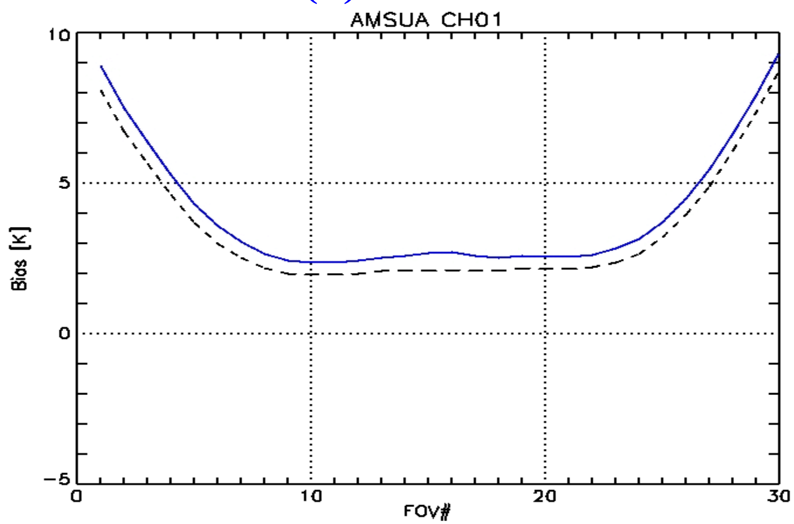
$$N_\eta = f_e(\beta) + f_c(\beta) + \eta f_{sat}(\beta)$$

- APC coefficients, $f_e(\beta)$, $f_c(\beta)$, $f_{sat}(\beta)$, were derived using antenna pattern function measurements.
- Results that the APC coefficients reduce O-B biases for all channels except for window channels where surface emissivity has a big uncertainty

(a) 11-15-2018

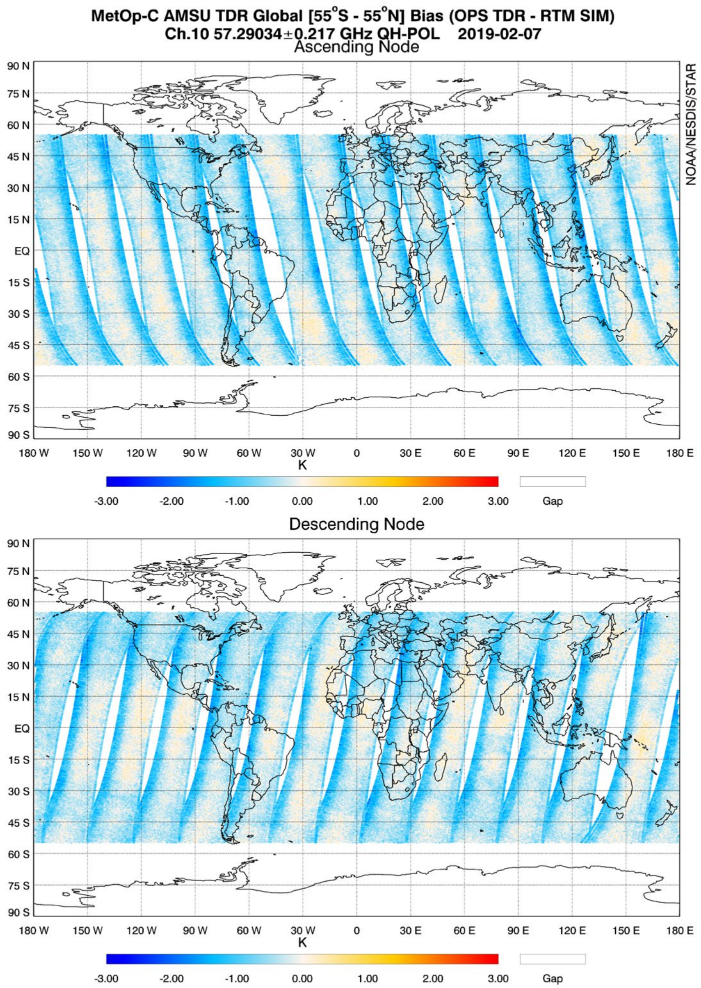


(b) 02-07-2019

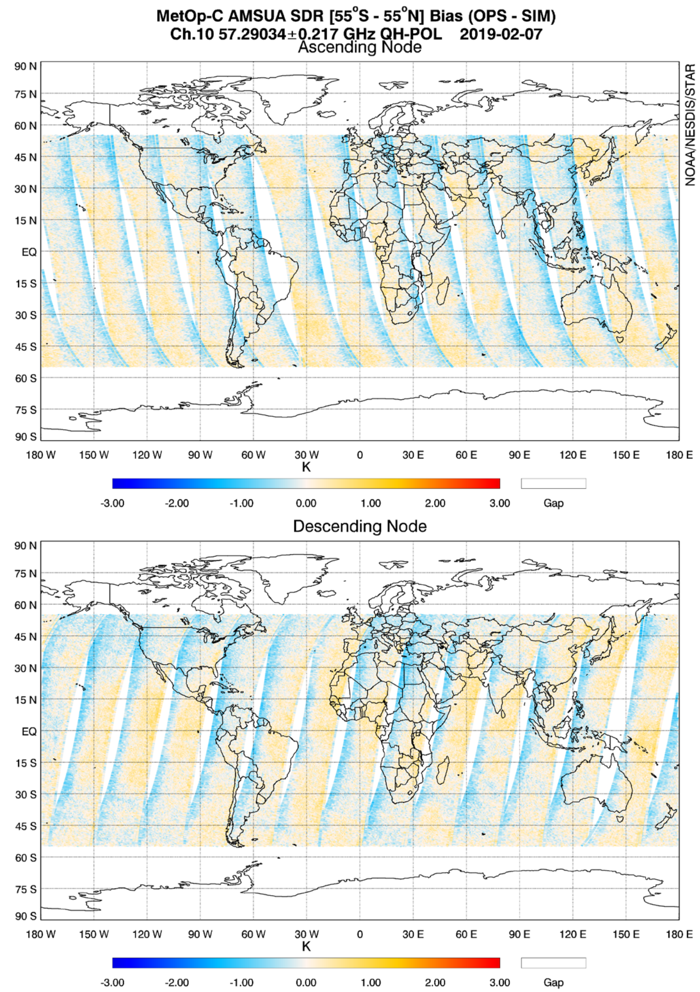


AMSU-A TA &TB Global Bias Distributions

(a) O (TA, No APC) - B



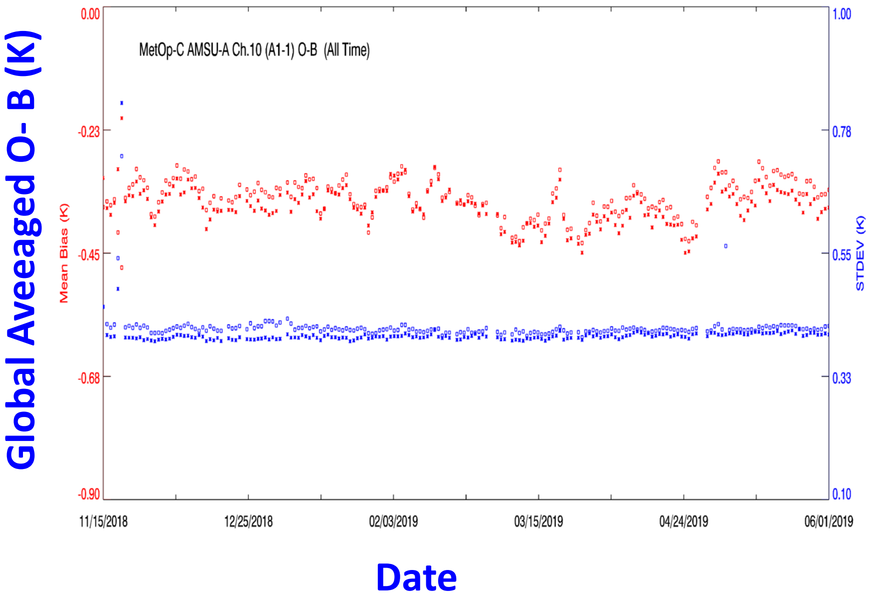
(b) O (TB, With APC) - B



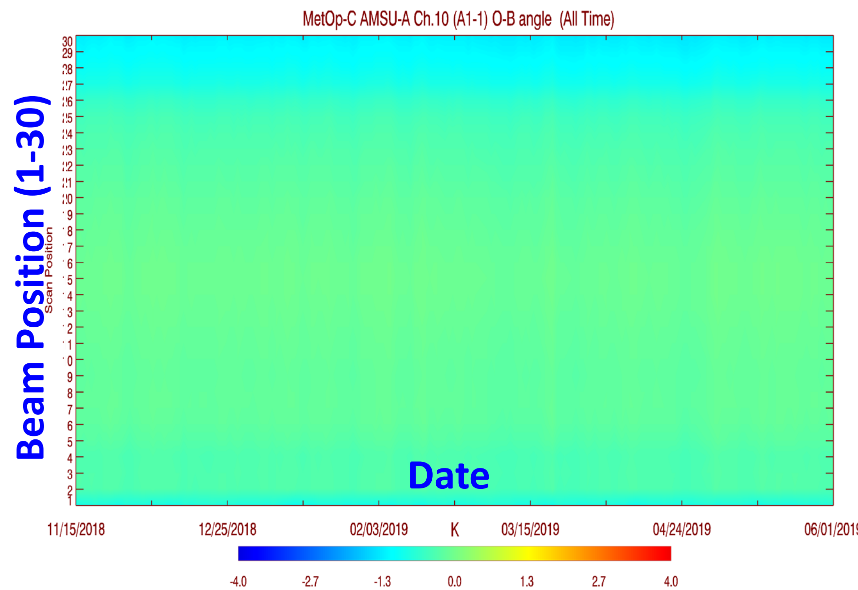
- With the APC, AMSU-A observations of brightness temperatures show smaller errors against CRTM simulations at all sounding channels
- At three window channels (Ch. 1, 2, and 15), the bias between O (SDR) – B is even larger primarily due to inaccurate surface emissivity there.

AMSU-A Data Bias Characterization: Global Averaged O – B Bias (Stability) Analysis

Global Oceanic Averaged O – B Bias (Animation)



Daily Mean Angular Dependent Bias (O-B) (Animation)

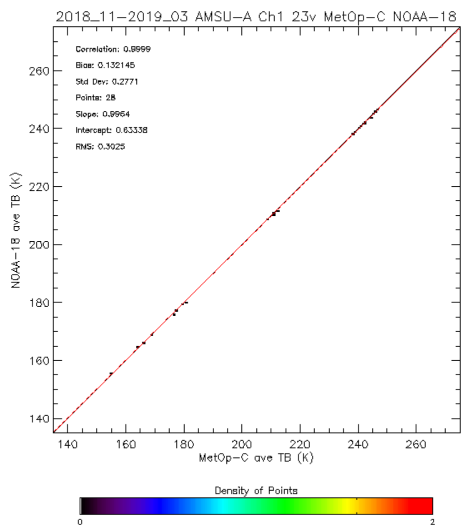


- Global averaged O – B bias at each channel was evaluated using selected data sets
  - Open ocean (cloud-free data, CLW <0.1 mm)
  - CRTM version 2.3.0
- O-B biases of Metop-C AMSU-A data at window channels are relatively large as expected, majorly due to CRTM simulation uncertainties
- O-B biases of Metop-C AMSU-A data at sounding channels are relatively stable a few days after the launch

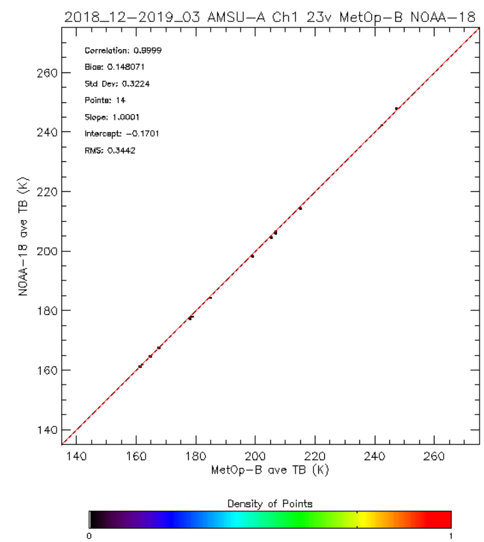
AMSU-A Cross-Sensor Bias Characterization: SNO Intersensor Comparison

- SNO intersensor comparisons were made among Metop-C AMSUA/B/C against NOAA-18/19 respectively.
  - Date: 2018-11-27 ~ 2019-03-27
- QC Criterion of inhomogeneity check
  - Standard deviation within observations of 4x5 box: less than 2K
- A good agreement was found between Metop-C and NOAA-18/19 measurements
- Further analysis is needed after more SNO cases are collected.

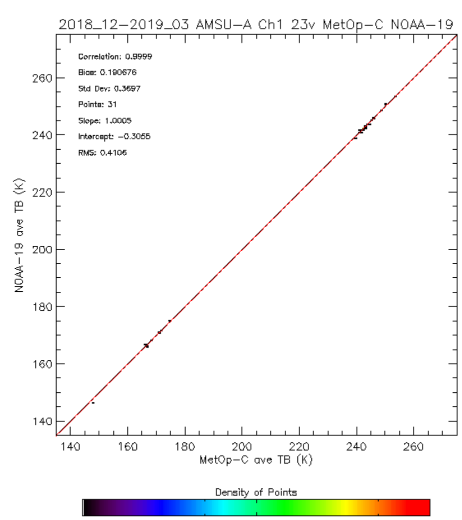
(a) Metop-C (M3) and NOAA-18



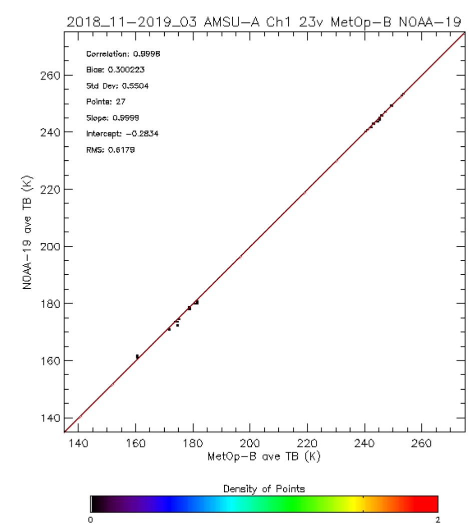
(b) Metop-B (M1) and NOAA-18



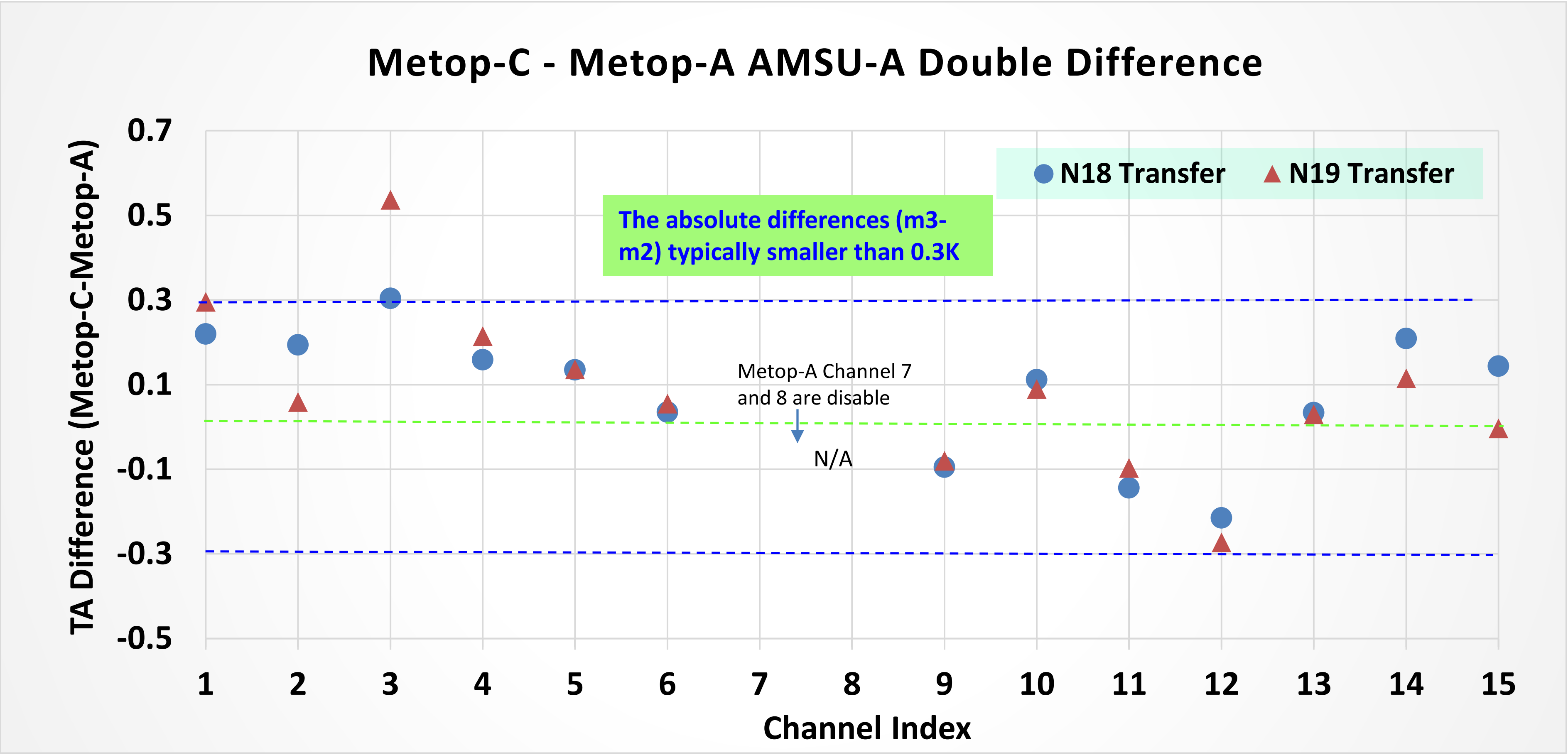
(c) Metop-C (M3) and NOAA-19



(d) Metop-B (M1) and NOAA-19

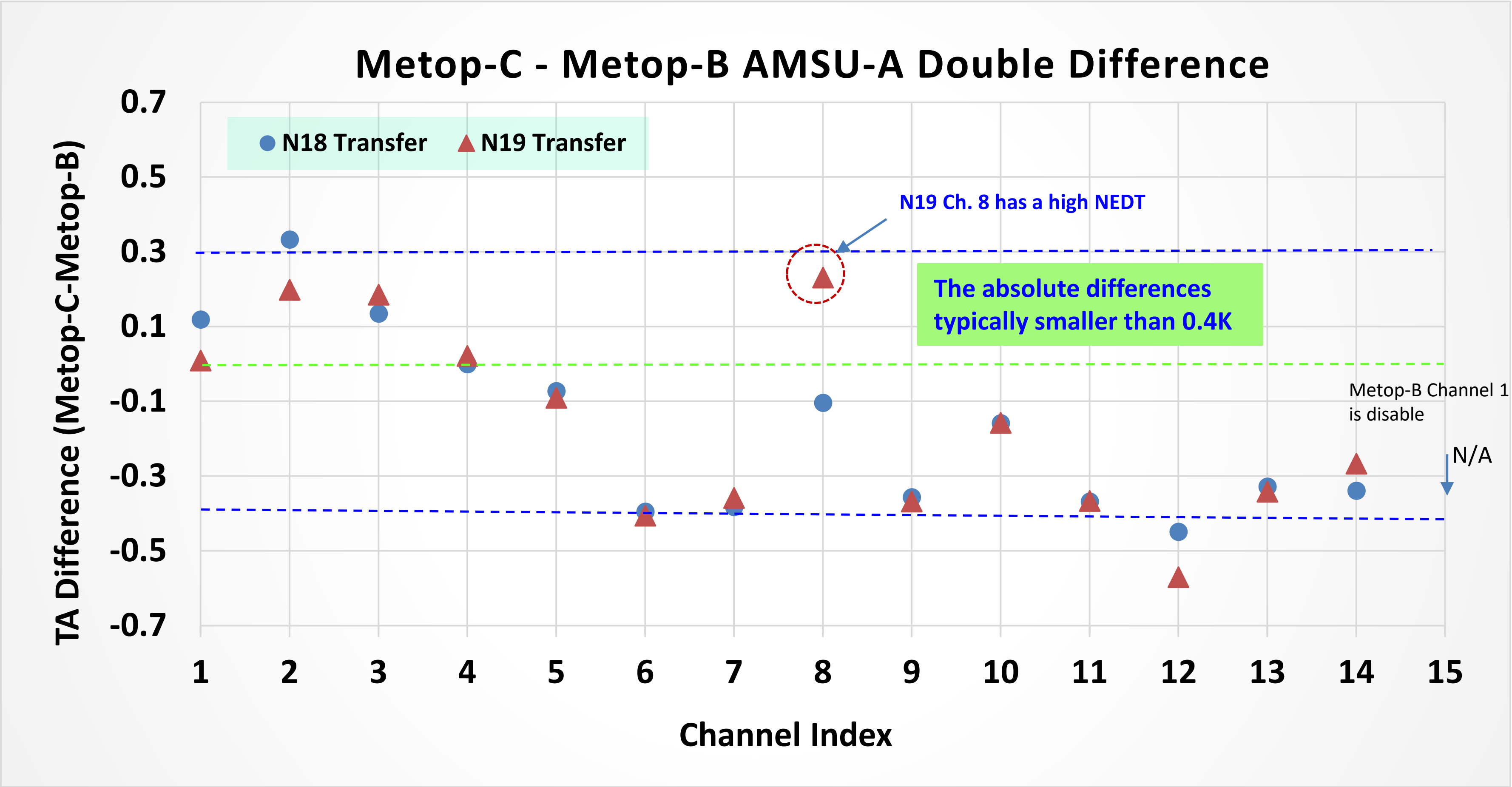


TA Difference between Metop-C and Metop-A (from Double SNO Intersensor Comparison)



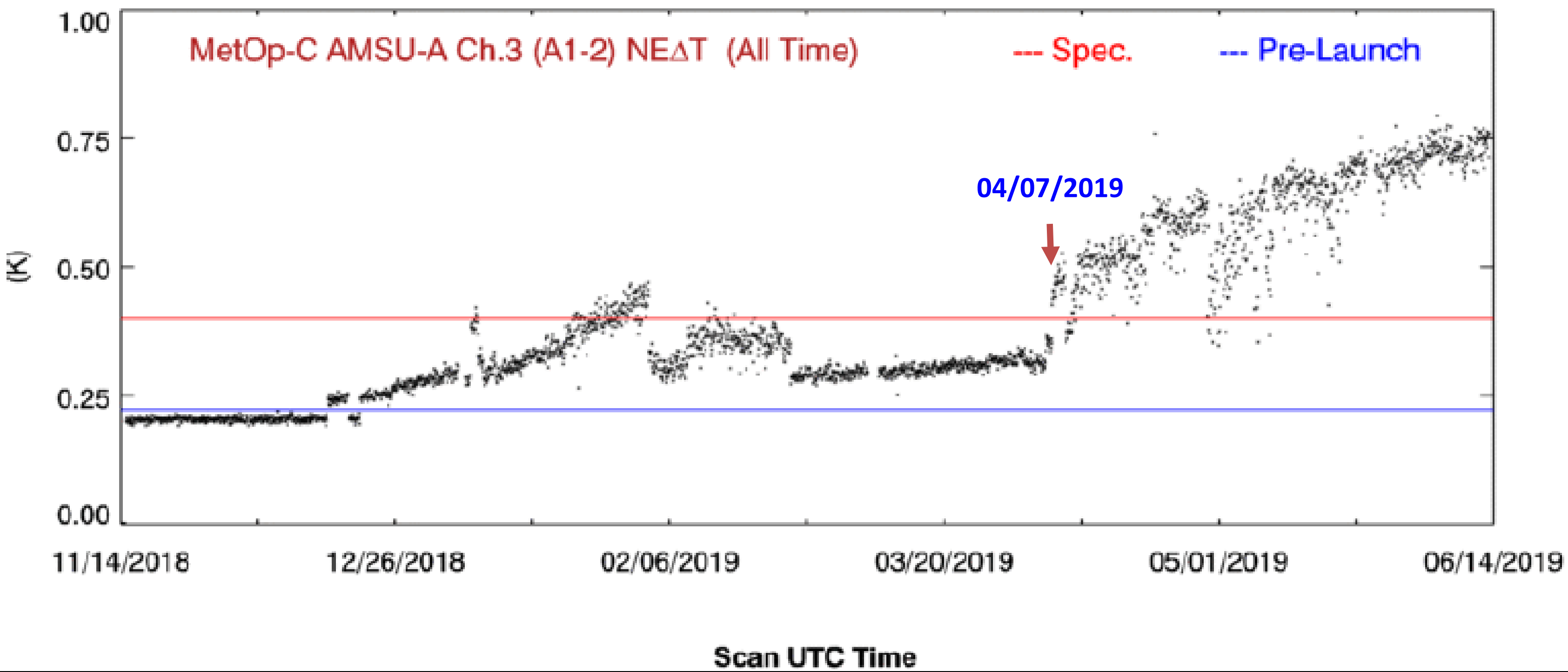
- Antenna temperatures from Metop-C AMSU-A are very comparable with those from Metop-A AMSU-A, except for channels 7 and 8 where Metop-A measurements are disable.
  - The differences (absolute values) at all channels except for channels 1 and 2 are typically smaller than 0.3K
  - The differences at window channels are relatively larger primarily due to residual surface inhomogeneity
  - The differences are very comparable from two SNO references of NOAA-18 and NOAA-19 AMSU-A, except for window channels.

TA Difference between Metop-C and Metop-B (from Double SNO Intersensor Comparison)



- Antenna temperatures from Metop-C AMSU-A are very comparable with those from Metop-B AMSU-A, except for channel 15 where Metop-B measurements are disable.
  - The absolute differences at all channels except for channels 1 and 2 are typically smaller than 0.4K
  - The absolute differences at window channels are relatively larger primarily due to residual surface inhomogeneity
  - The differences are very comparable from two SNO references of NOAA-18 and NOAA-19 AMSU-A, except for channels 1, 2 and 8.

Anomalies Analysis # 1: Channel 3 NEDT Issue

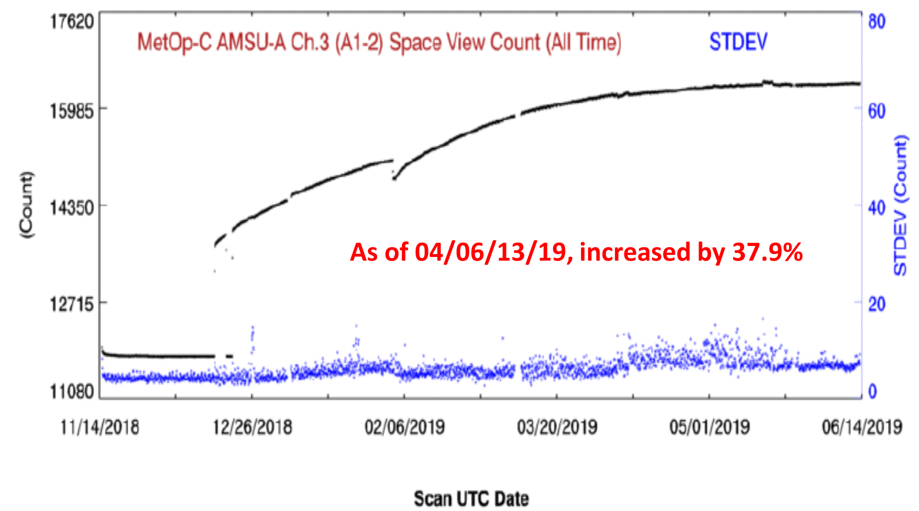


Channel 3 shows an unstable noise (NEdT) change since the launch and ever stabilized to within specification on Feb. 26, 2019 through April 7, 2019. However, it remains frequently above Spec after that.

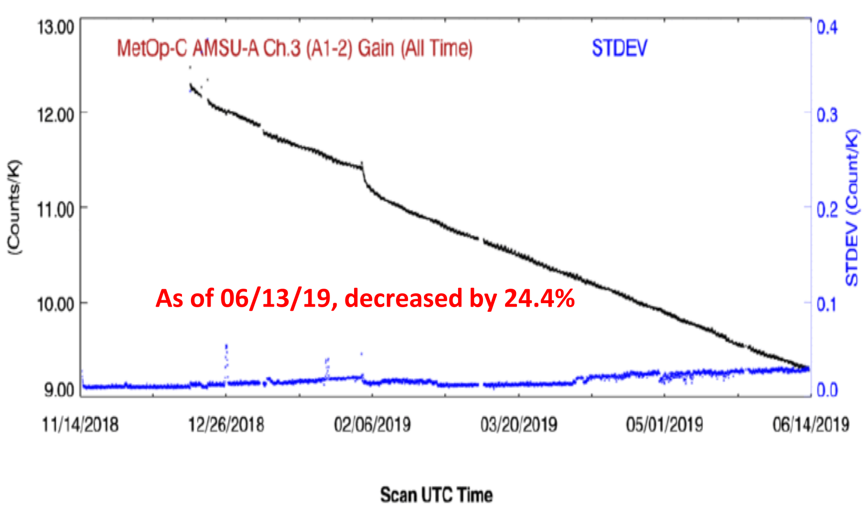
Anomalies Analysis # 2: Channel 3 Gain Issue

- The counts at channel 3 display a rapid increase since launch.
    - As of 06/13/2019, the warm count and cold count has been increased approximately 22.8% and 37.8% respectively compared 2nd day of the data
- The channel gain has been decreased by 24.4%

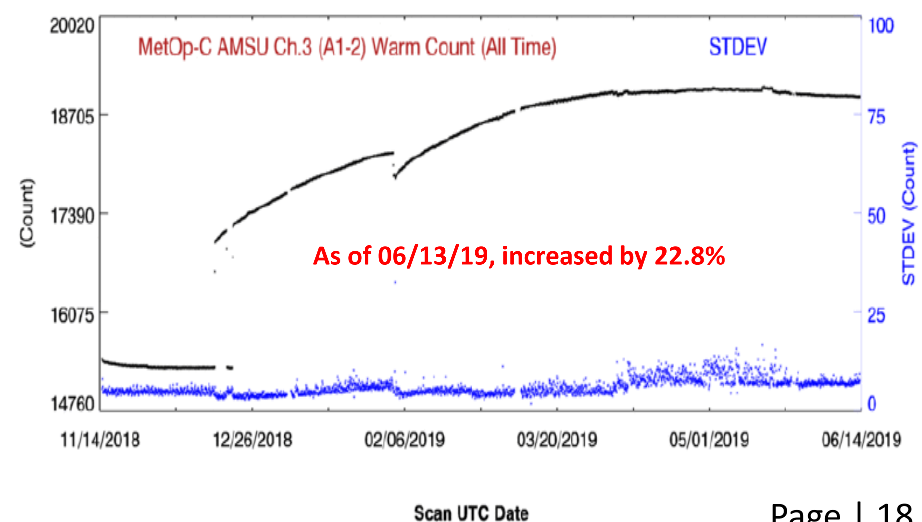
(b) SV Cold Count



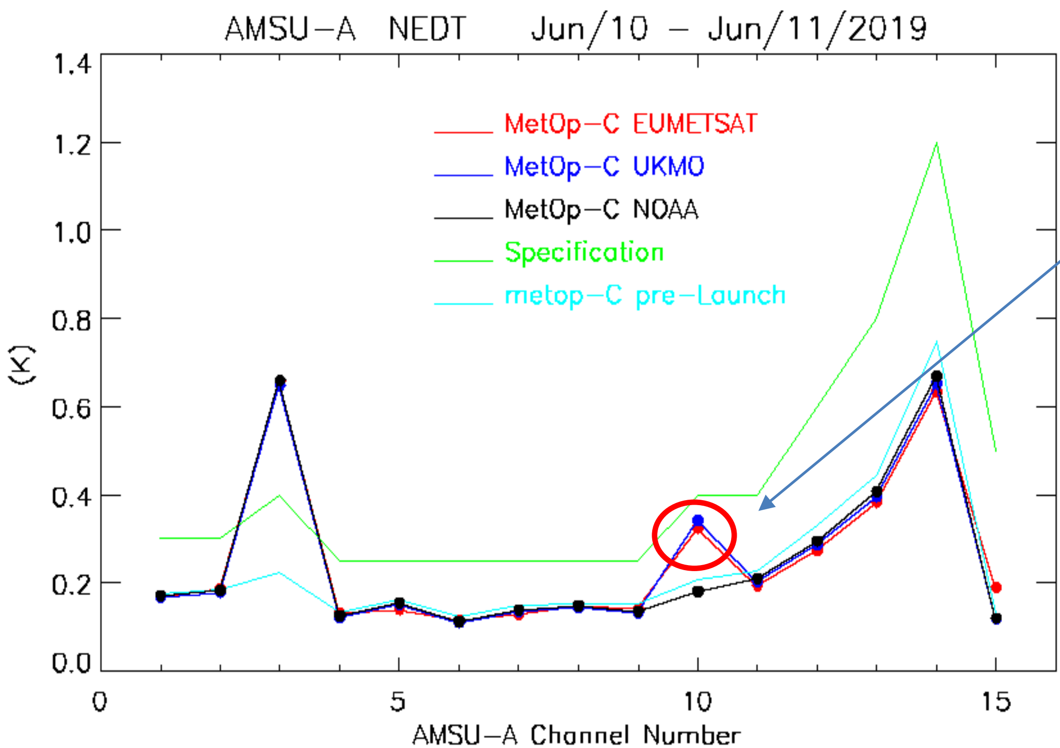
(a) AMSU-A Ch.3 Gain



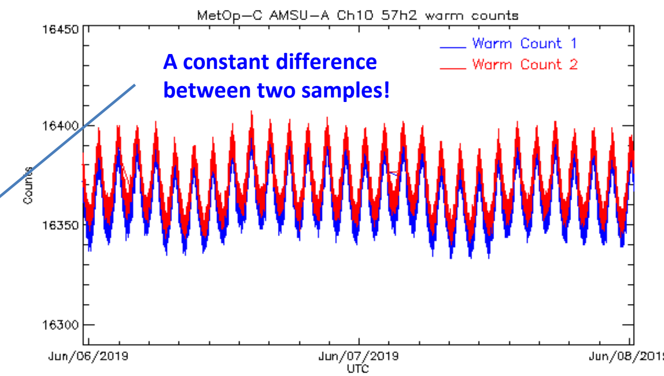
(c) Warm load Count



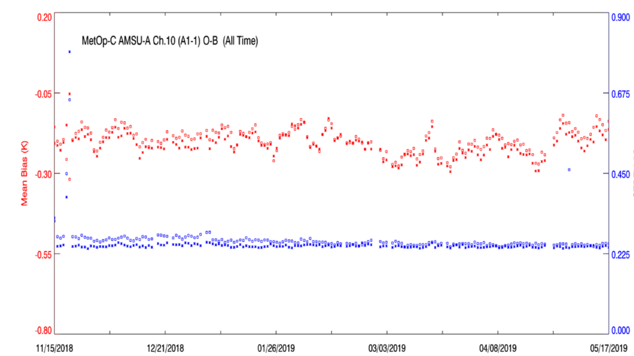
Anomalies Analysis # 3: CH.10 Warm Counts Uneven Change in Two Samples



Warm Counts (Two sample per scan)



< Global O-B >

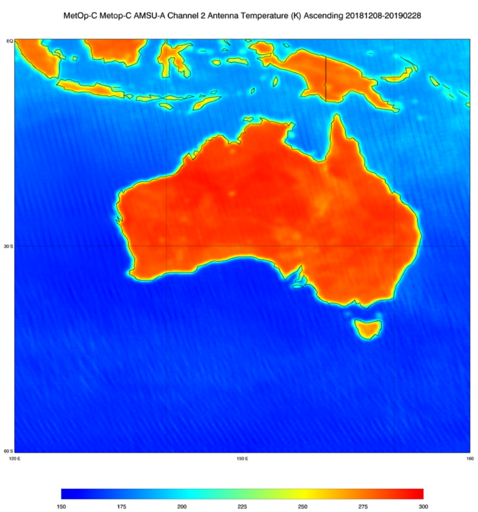


- For AMSU-A measurements of cold and warm counts, there are two samples per scan
  - Ch. 10, two samples show a large difference in particular at channel 10
- NEDT methods in both EUMETSAT and OKMO use standard deviation while the ICVS method use the Allan deviation method to estimate statistics of counts
  - Ch. 10 NEDTs from EUMETSAT and OKMO are much higher than the ICVS NEDT due to a large deviation of wo samples per scan

AMSU-A Geolocation Accuracy Sanity Check (1/2)

Averaged Antenna Temperature (TA) at Ch 2 from 12/28/2018 through 02/28/2019

Ascending



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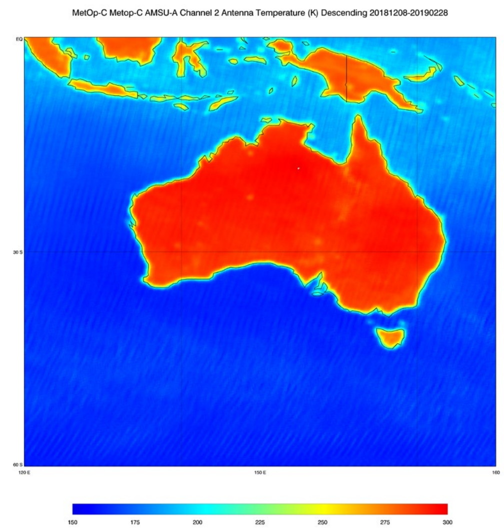
Descending



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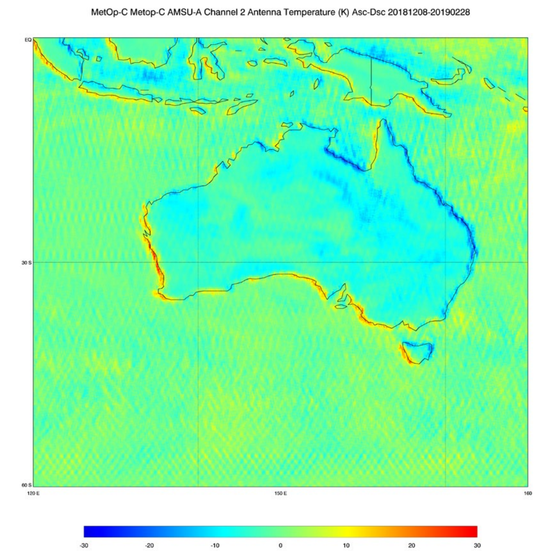
Ascending - Descending



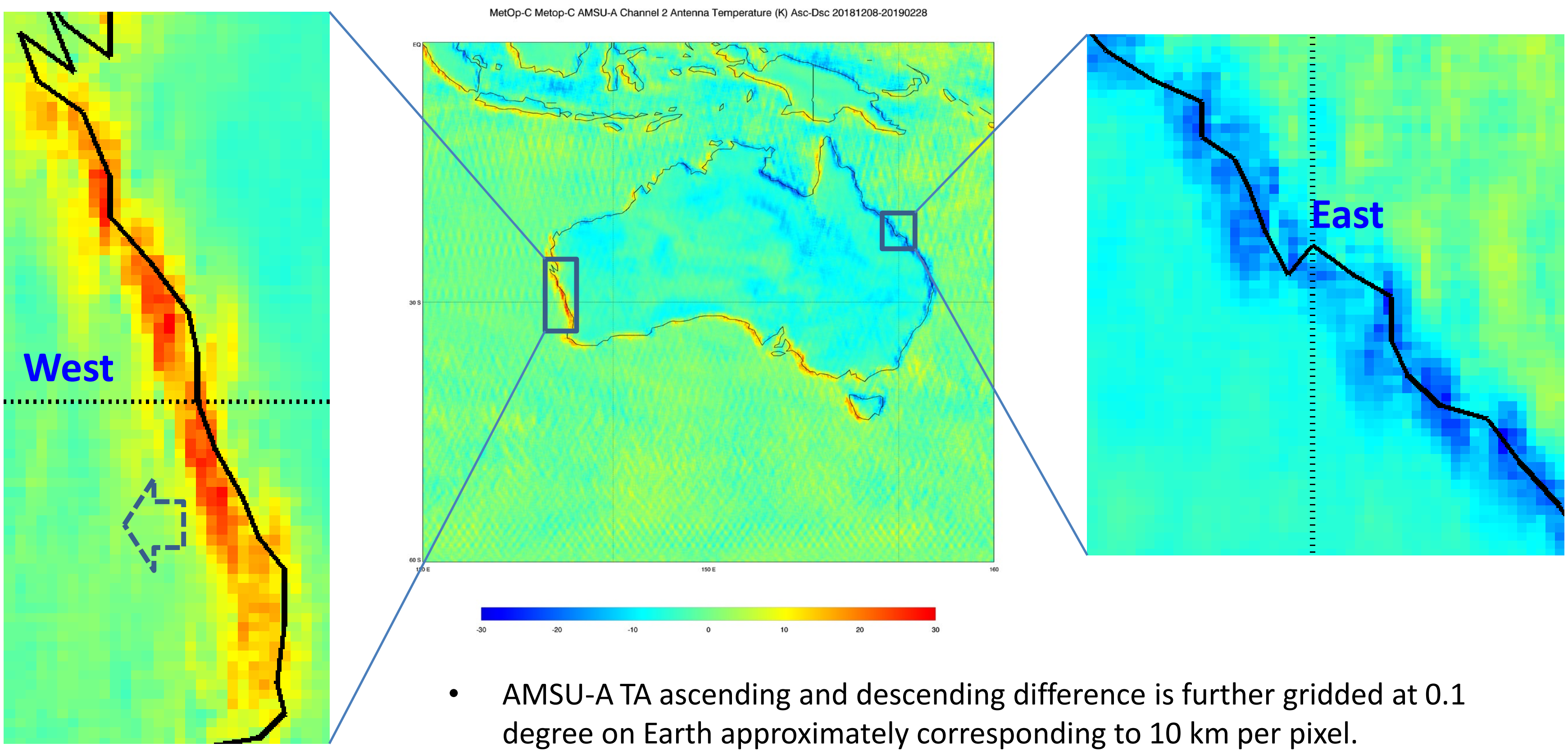
Methodology for AMSU-A geolocation error sanity check:

- Due to coarse spatial resolution, two months of AMSU-A data (TA) over Australia are averaged at window channels in ascending and descending respectively from 12/28/2018 through 02/28/2019.
- Generate TA difference between ascending and descending

(Courtesy of Legacy AMSU-A geolocation error sanity check methodology)

AMSU-A Geolocation Accuracy Sanity Check (2/2)

Ch. 2 TA Ascending - Descending



- AMSU-A TA ascending and descending difference is further gridded at 0.1 degree on Earth approximately corresponding to 10 km per pixel.
- The width of the highlighted part along the coast line is about 4~6 pixels. The geolocation error is about half of the width, about 2~3 pixels.
- The geolocation errors for Channel 1 and 2 seem to be about 20 ~ 30Km.
- Further investigation and mitigation are needed.

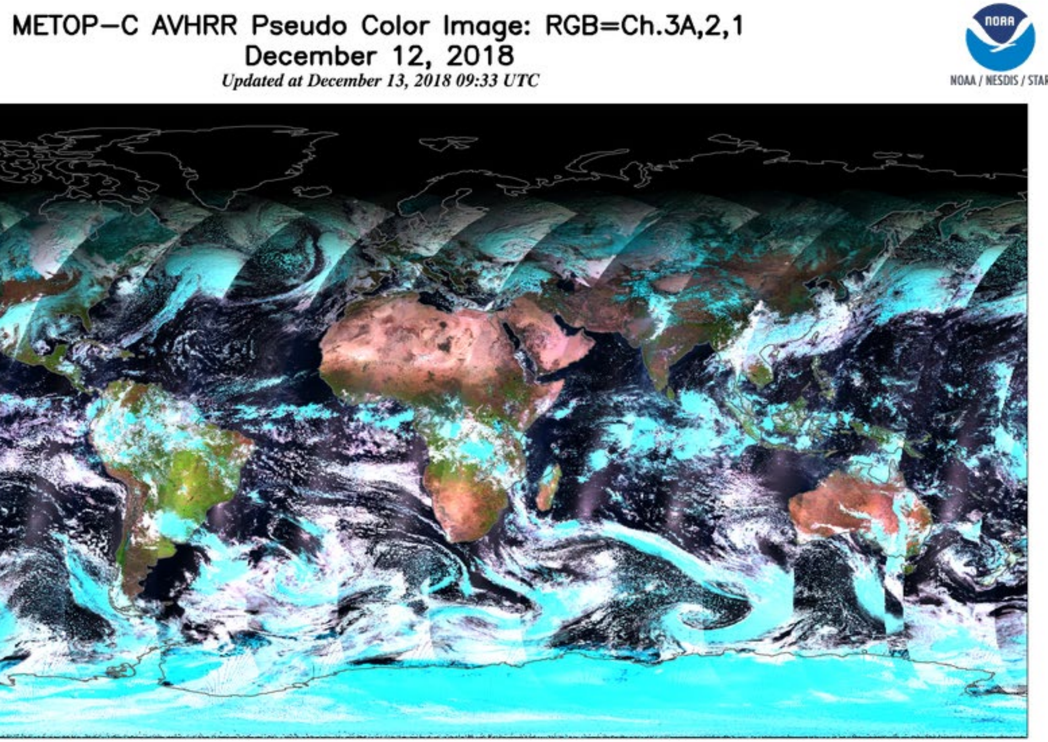
AVHRR Instrument Characteristics

Table AVHRR Instrument Characteristics

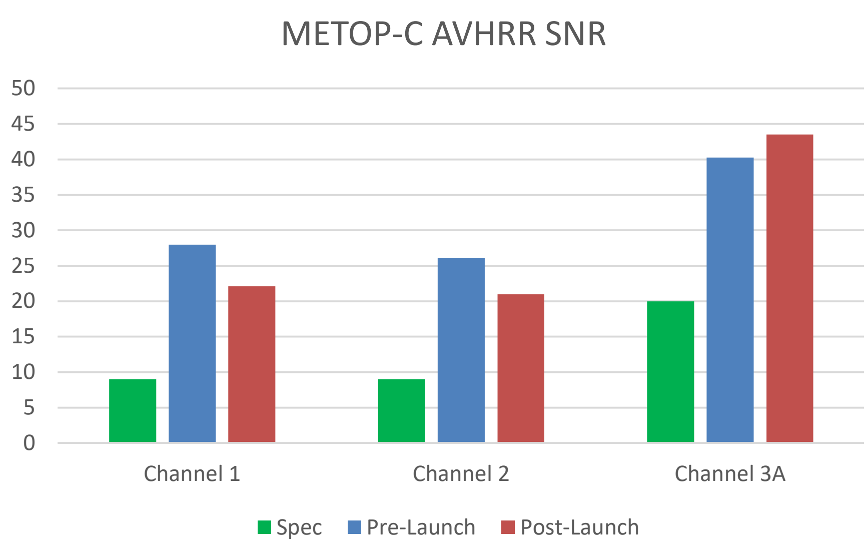
Parameter	Ch. 1	Ch. 2	Ch. 3A	Ch. 3B	Ch. 4	Ch. 5
Spectral Range (μm)	0.58-0.68	0.725-1.0	1.58-1.64	3.55-3.93	10.3-11.3	11.5-12.5
Detector Type	Silicon	Silicon	InGaAs	InSb	HgCdTe	HgCdTe
Resolution (N. Mi.)	0.59	0.59	0.59	0.59	0.59	0.59
IFOV* (milliradian)	1.3 sq.	1.3 sq.	1.3 sq.	1.3 sq.	1.3 sq.	1.3 sq.
S/N @ .5% Albedo	≥9:1	≥9:1	≥20:1	-	-	-
NEΔT @ 300K	-	-	-	≤.12K	≤.12K	≤.12K
MTF (Nyquist Freq.)	>0.30	>0.30	>0.30	>0.30	>0.30	>0.30

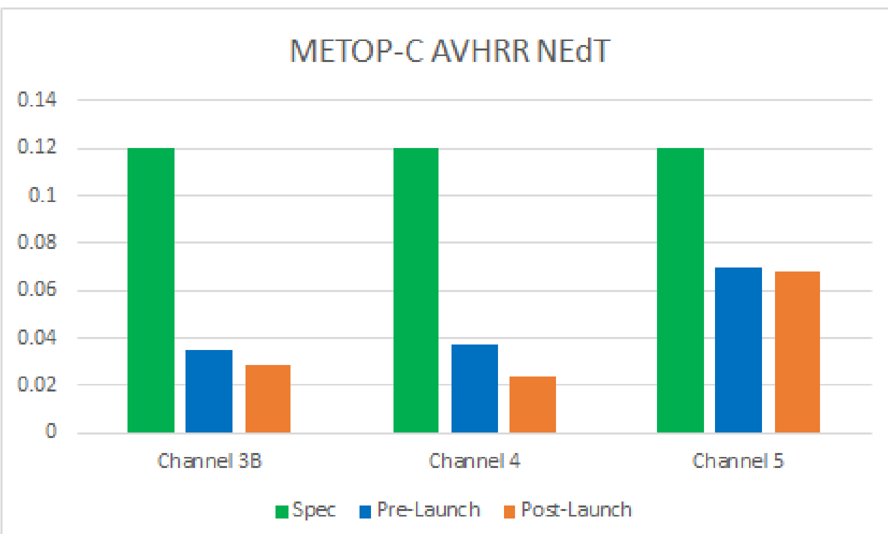
First Image (METOP-C VNIR)

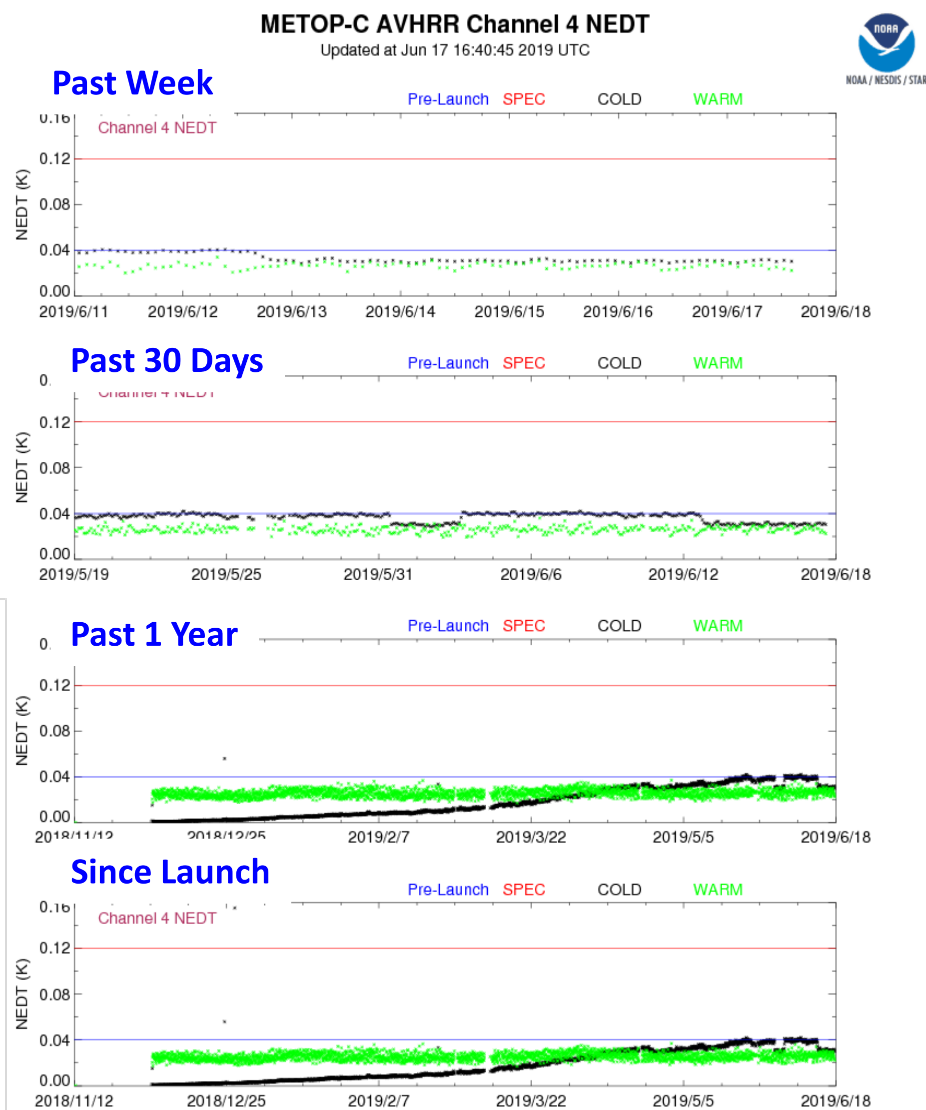
- At 0927 UTC on 12 November 2018, the AVHRR became the first instrument to acquire and disseminate its visible (0.64 µm) and near infrared (0.86 µm and 1.61µm) data.



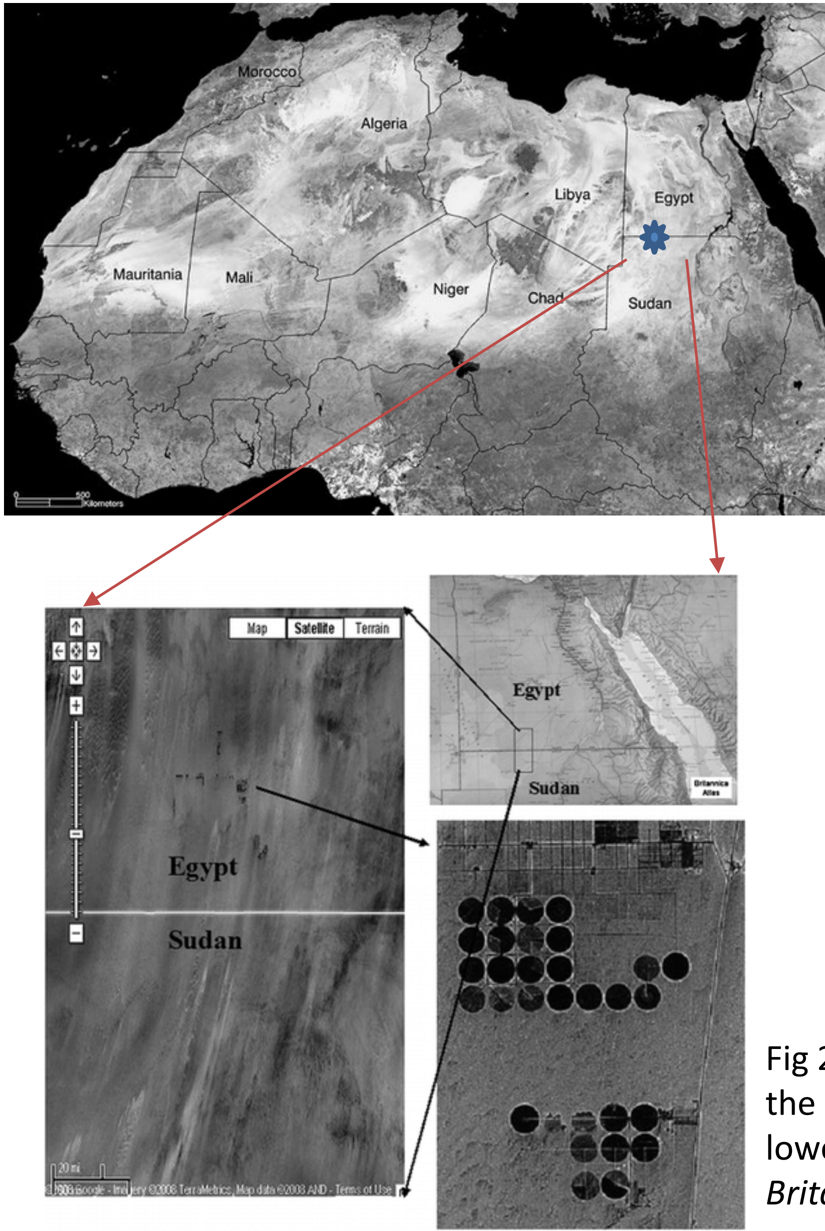
AVHRR Noise Consistency and Stability







AVHRR VNIR Vicarious Calibration Target: Libyan Desert



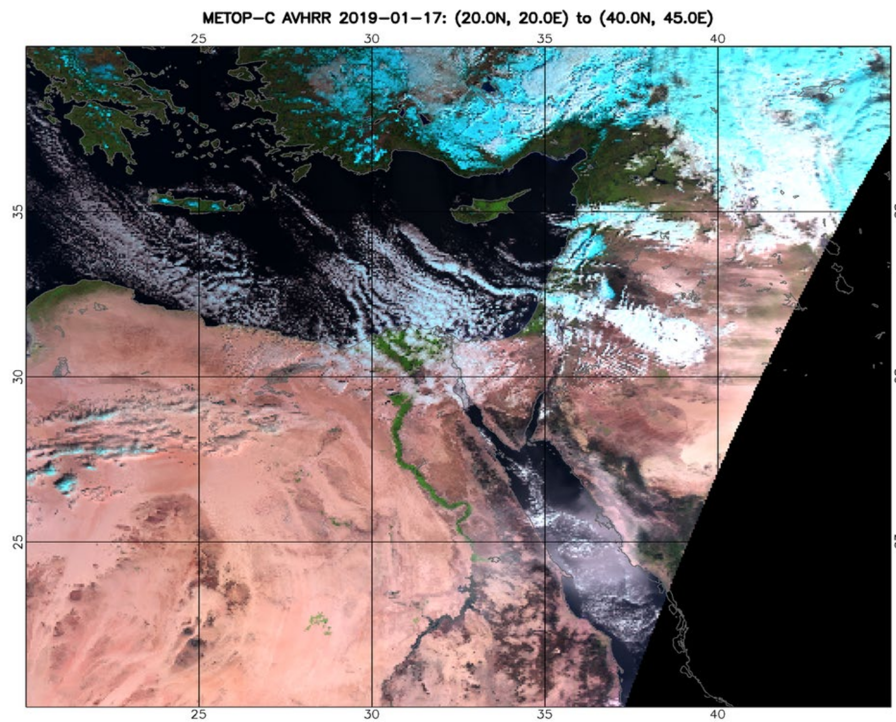


Fig1. (Top) Images of AVHRR METOP-C for local areas: North-Eastern part of Africa on Jan 17, 2019
--Stanislav Kireev

Fig 2. (Left) The Libyan Desert. Google Map images with TerraMetrics show the irrigation vegetation growth inside the calibration target (circles in the lower right). The geographical map (upper right) is courtesy of the *Britannica World Atlas*. -Fangfang Yu

AVHRR VNIR bands albedo of MetOp-A/B/C in Libyan Desert

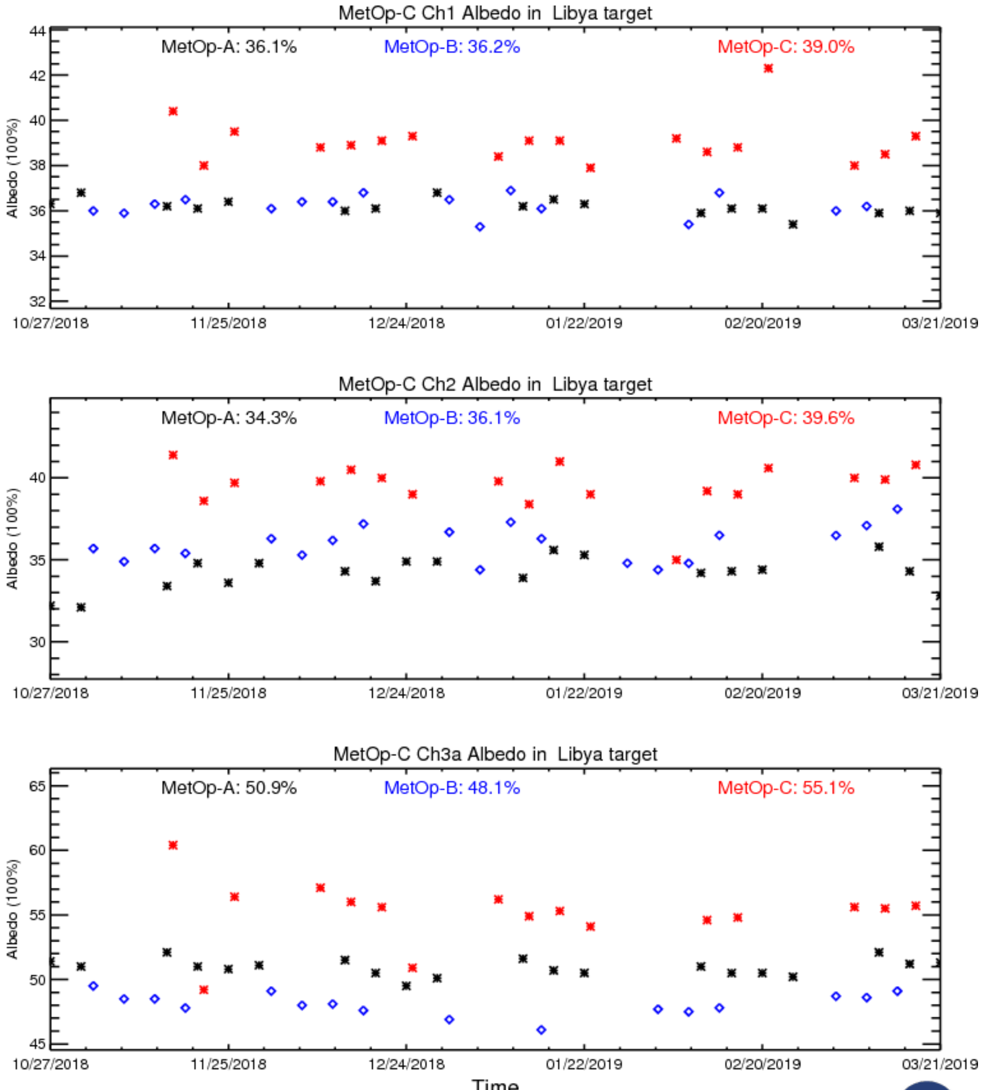


Figure: AVHR VNIR bands albedo for MetOp-A/B/C on Libyan Desert since 10/17/2018

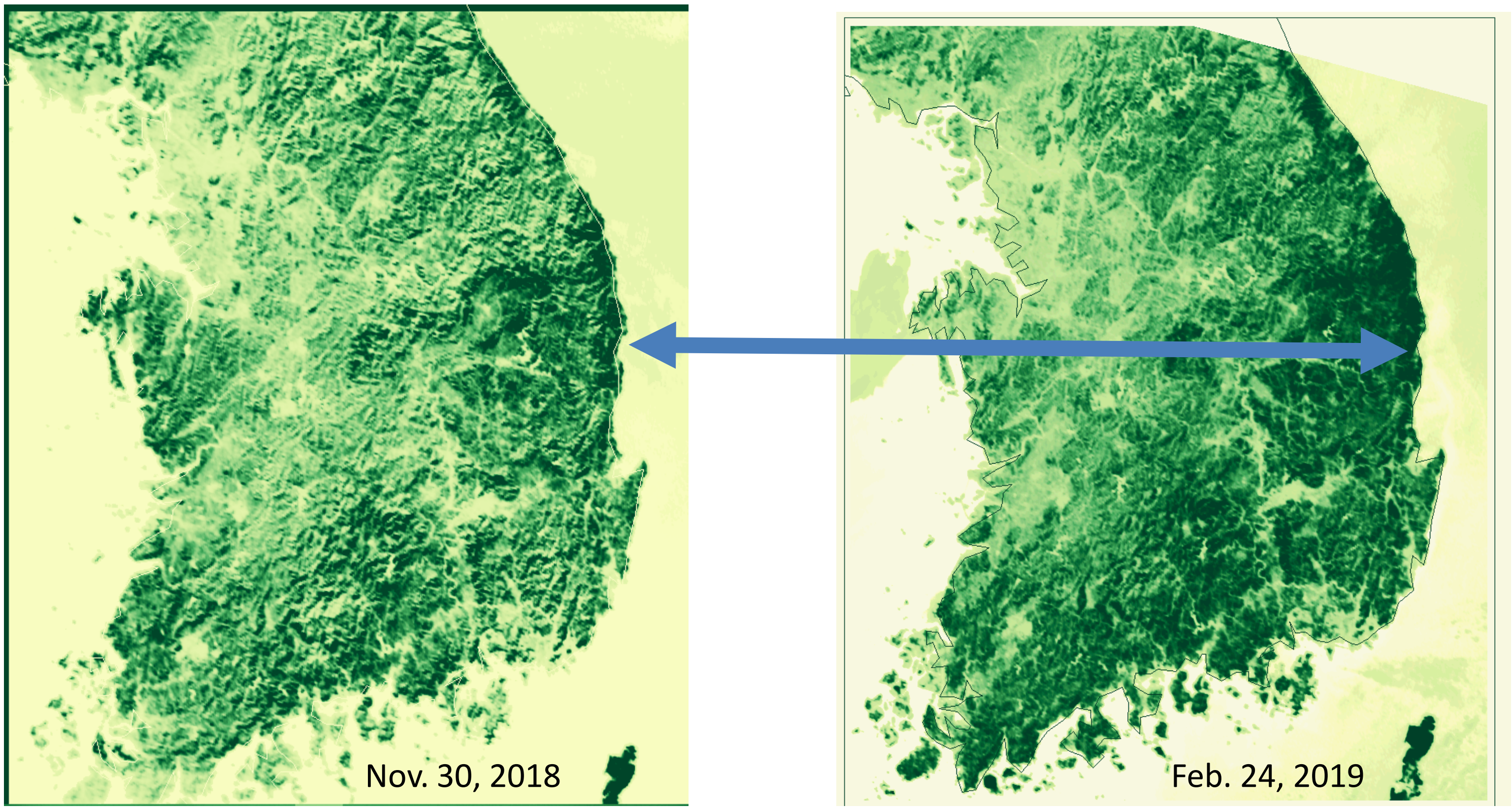
Summary:

- MetOp-C L1B imagery is available since 11/12/2018.
- Comparison of Albedos for the AVHRR of MetOp-A/B/C on the vicarious calibration target Libyan desert in Africa since 10/27/2018.
- The results shows that during the last three months, MetOp-C AVHRR channel 1-3 Albedos are higher than the ones of MetOp-A/B.

	Albedo(100%)		
	Ch1	Ch2	Ch3
MetOp_A	36.1	34.3	50.9
MetOp_B	36.2	36.1	48.1
MetOp_C	39	39.6	55.1

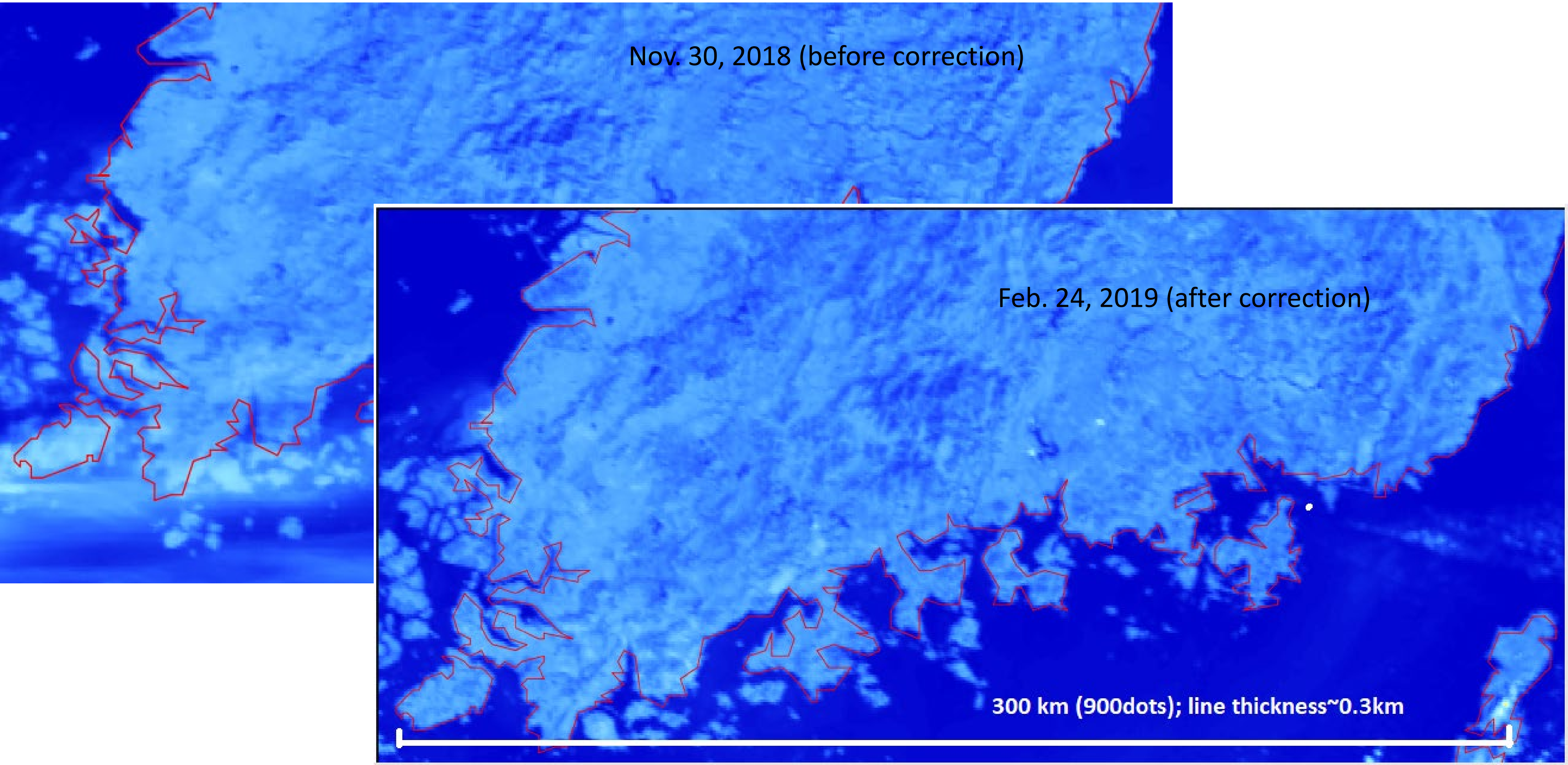
METOP-C AVHRR Navigation Verification

Before and After RPY Correction



- Metop C AVHRR geolocation initially was off by a few kilometers, but was corrected by OSPO since Dec. 7, 2018 by adjusting RPY and Max scan angle.
- Preliminary validation results show that the AVHRR FRAC geolocation meets the requirements, although quantitative evaluation is not performed.

Zoom in on South Korea



Conclusions

- The STAR Metop-C Cal/Val team has demonstrated that accuracy of Metop-C AMSU-A and AVHRR SDR data agrees generally with that of Metop-A/B,
  - Metop-C satellite products are declared operational since 04/05/2019
  - Data can be used by users to verify the accuracy of the data for quantitative scientific studies and applications
  - General research community is encouraged to participate in the QA and validation of the product, although certain known or potential differences remain.

- The users are to recognize that product validation and quality assurance work are ongoing.
  - Product validation and QA are ongoing and a few caveats still remains in the data.

Target: Metop-C AMSU-A and AVHRR validated maturity review in September 2019

Forward Path: AMSU-A

- Continue to monitor AMSU-A instrument and data quality
- Continue to monitor the channel 3 NEDT/gain and further assess impacts on SDR data quality
- Assess AMSU-A antenna temperatures at higher upper sounding channels using Cosmic-3 radio occultation data to confirm AMSU-A data bias characterizations
- Further validate the lunar intrusion correction coefficients
- Continue to conduct Metop-/AB/C (N18 and N19 AMSU-A as transfer) SNO intersensor comparisons

Forward Path: AVHRR

- Provide monthly update of visible and near infrared channel calibration coefficients
  - Ready for operation
- Conduct inter-calibration with METOP-C IASI
  - Code is ready for METOP-A/B
  - Waiting for METOP-C IASI data
- Prepare for the validated maturity review