Noise Characterization and Mitigation for Microwave Sounding Instruments

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Funded by: NOAA grant NA19NES4320002 (Cooperative Institute for Satellite Earth System Studies -CISESS) at the University of Maryland/ESSIC
Jan. 13, 2025

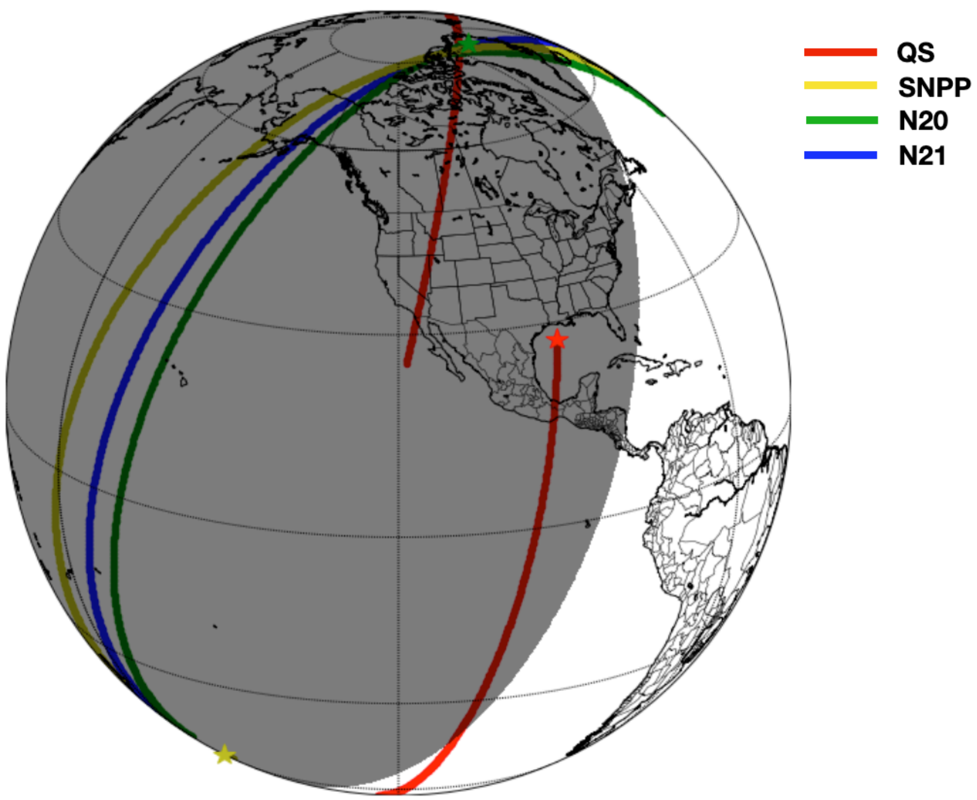
Short Summary of the Work

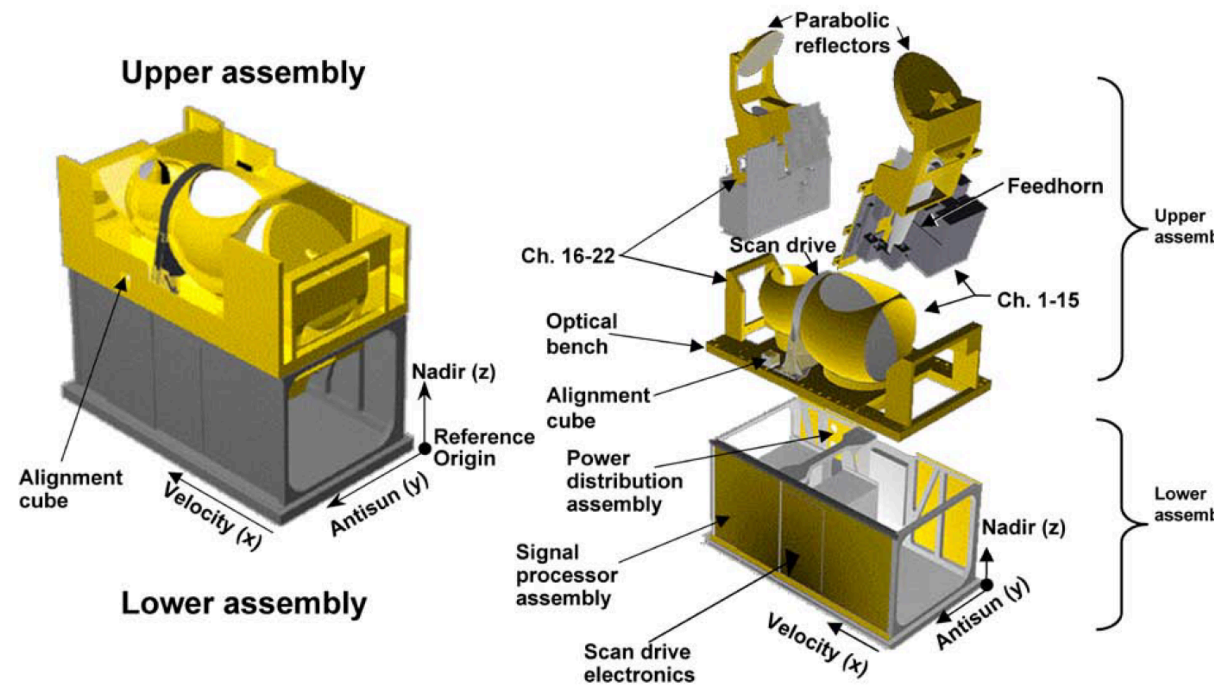
- Space-borne microwave sounding instruments have become vital data sources for weather prediction and climate change studies. However, its performance is vulnerable to degradation caused by receiver gain fluctuations, electronic 1/f noise, and other time varying receiver characteristics.

- For Numerical Weather Prediction (NWP) users, 1/f noise introduces inter-channel correlations, complicating the assimilation of affected observations and reducing their accuracy. Addressing this noise issue in ground data processing system is essential to enhance the utility of microwave sounding data.

- This work focuses on the characterization and mitigation of noise in current and future microwave sounding instruments, with particular emphasis on the impact of 1/f noise. Various methods are applied to quantitatively characterize noise features in both frequency and time domains. Additionally, the influence of calibration parameters on 1/f noise are analyzed. Based on these findings, we propose a mitigation algorithm for reducing noise during the on-orbit calibration of microwave sounding instruments, aiming to improve the quality of retrieved data for operational use.

ATMS Instrument Characteristics



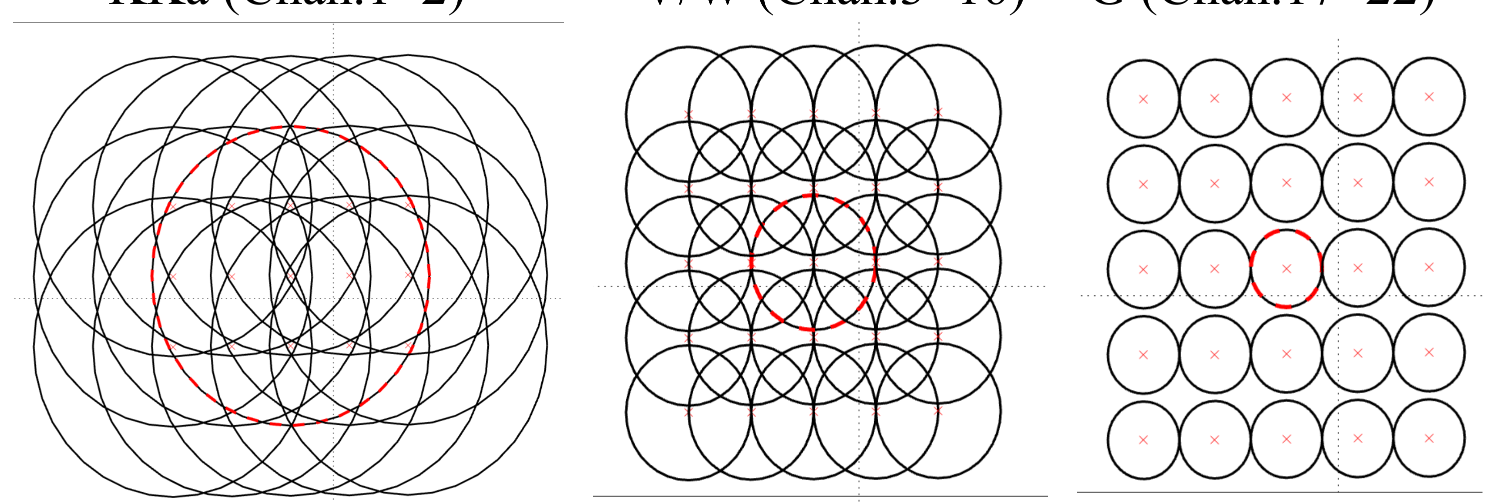


Instrument Characterization

Ch	RF path Ant	RF path Feed	RF path Rcvr	Center frequency [MHz] Value	Center frequency [MHz] Stab	Bandwidth [MHz] Req	Bandwidth [MHz] True	NEDT [K] Req	Pol	Beamwidth [°] Req
1	A	1	a	23800	<10	<270	1x270	0.5	V	5.2
2	A	1	b	31400	<10	<180	1x180	0.6	V	5.2
3	A	2	c	50300	<10	<180	1x180	0.7	H	2.2
4	A	2	c	51760	< 5	<400	1x400	0.5	H	2.2
5	A	2	c	52800	< 5	<400	1x400	0.5	H	2.2
6	A	2	c	53596±115	< 5	170	2x170	0.5	H	2.2
7	A	2	c	54400	< 5	400	1x400	0.5	H	2.2
8	A	2	c	54940	<10	400	1x400	0.5	H	2.2
9	A	2	c	55500	<10	330	1x330	0.5	H	2.2
10	A	2	d_1	57290.344 [f_0]	<0.5	330	2x155	0.75	H	2.2
11	A	2	d_1	f_0±217	<0.5	78	2x 78	1.0	H	2.2
12	A	2	d_2	f_0±322.2±48	<1.2	36	4x 36	1.0	H	2.2
13	A	2	d_2	f_0±322.±22	<1.6	16	4x 16	1.5	H	2.2
14	A	2	d_2	f_0±322.±10	<0.5	8	4x 8	2.2	H	2.2
15	A	2	d_2	f_0±322.±4.5	<0.5	3	4x 3	3.6	H	2.2
16	B	3	e	88200	<200	2000	1x2000	0.3	V	2.2
17	B	4	f	165500	<200	3000	2x1150	0.6	H	1.1
18	B	4	g	183310±7000	<30	2000	2x2000	0.8	H	1.1
19	B	4	g	183310±4500	<30	2000	2x2000	0.8	H	1.1
20	B	4	g	183310±3000	<30	1000	2x1000	0.8	H	1.1
21	B	4	g	183310±1800	<30	1000	2x1000	0.8	H	1.1
22	B	4	g	183310±1000	<30	500	2x 500	0.9	H	1.1

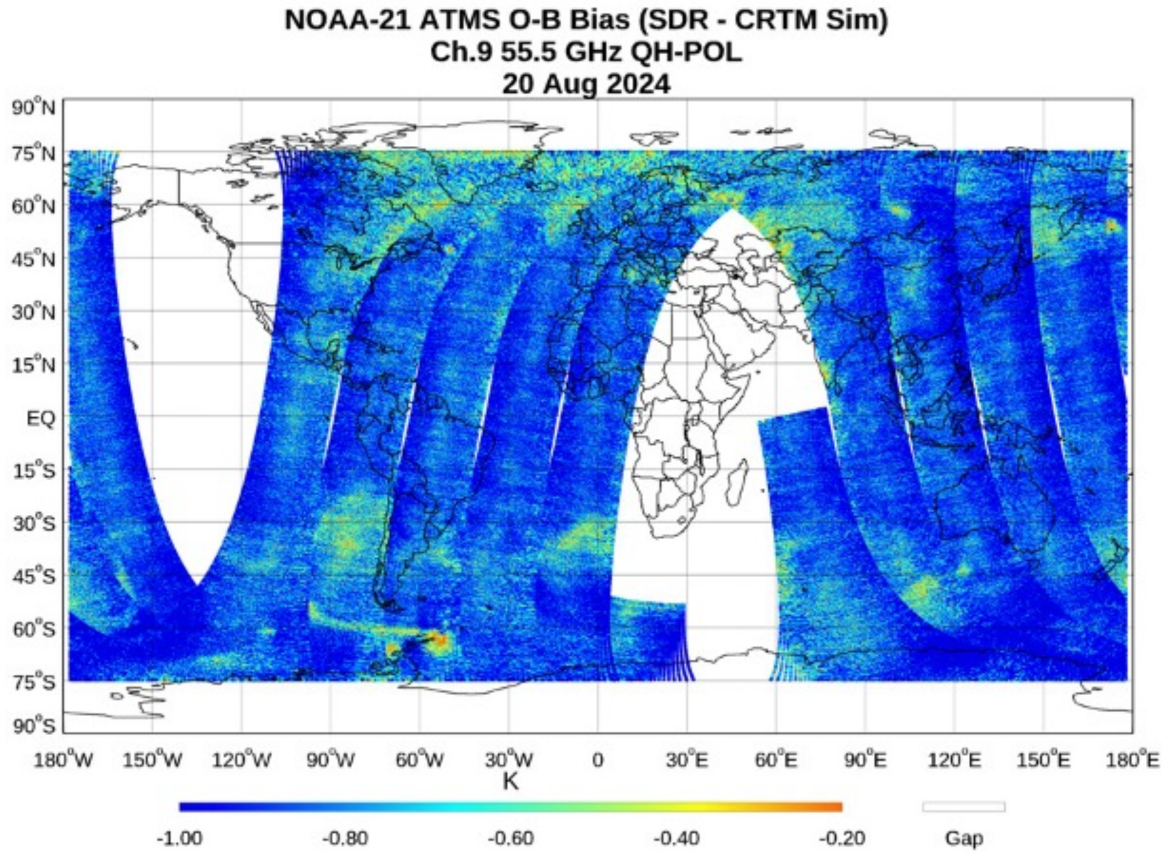
Scan Geometry of ATMS

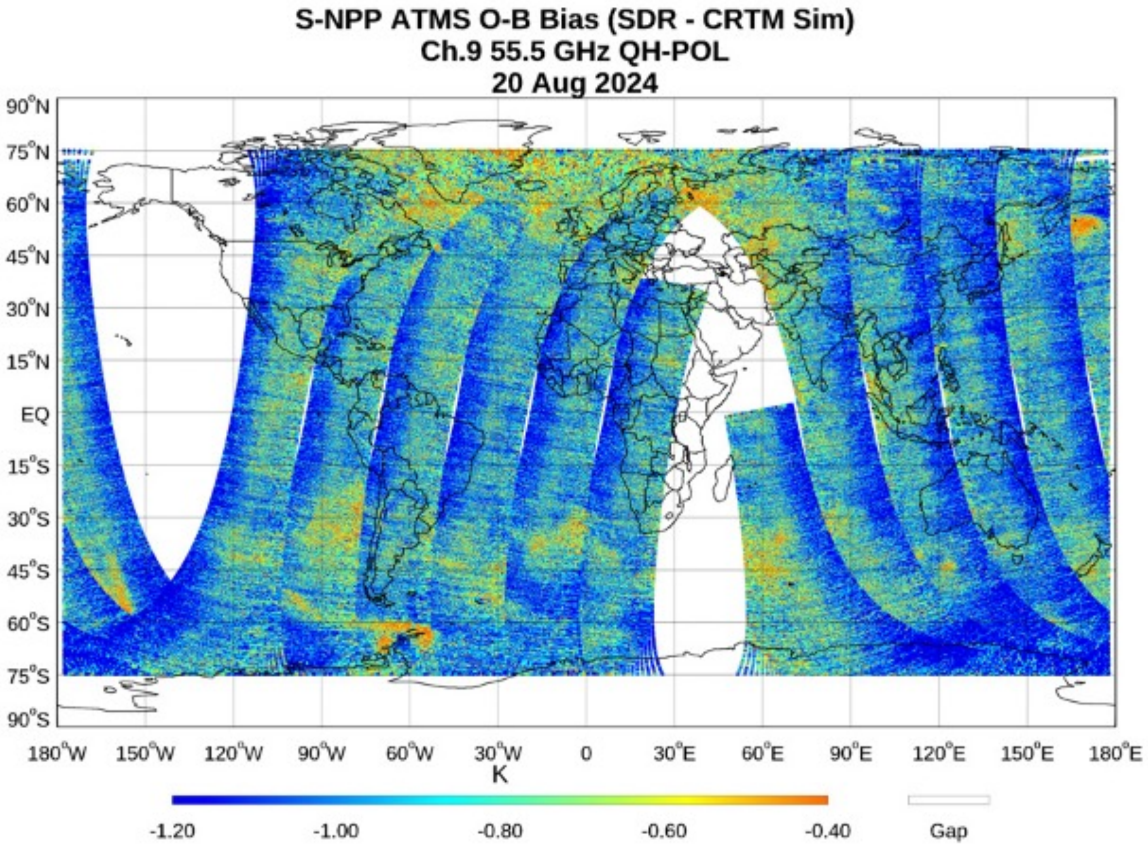
KKa (Chan.1~2) V/W (Chan.3~16) G (Chan.17~22)



Noise Characterization for Operational ATMS Instruments

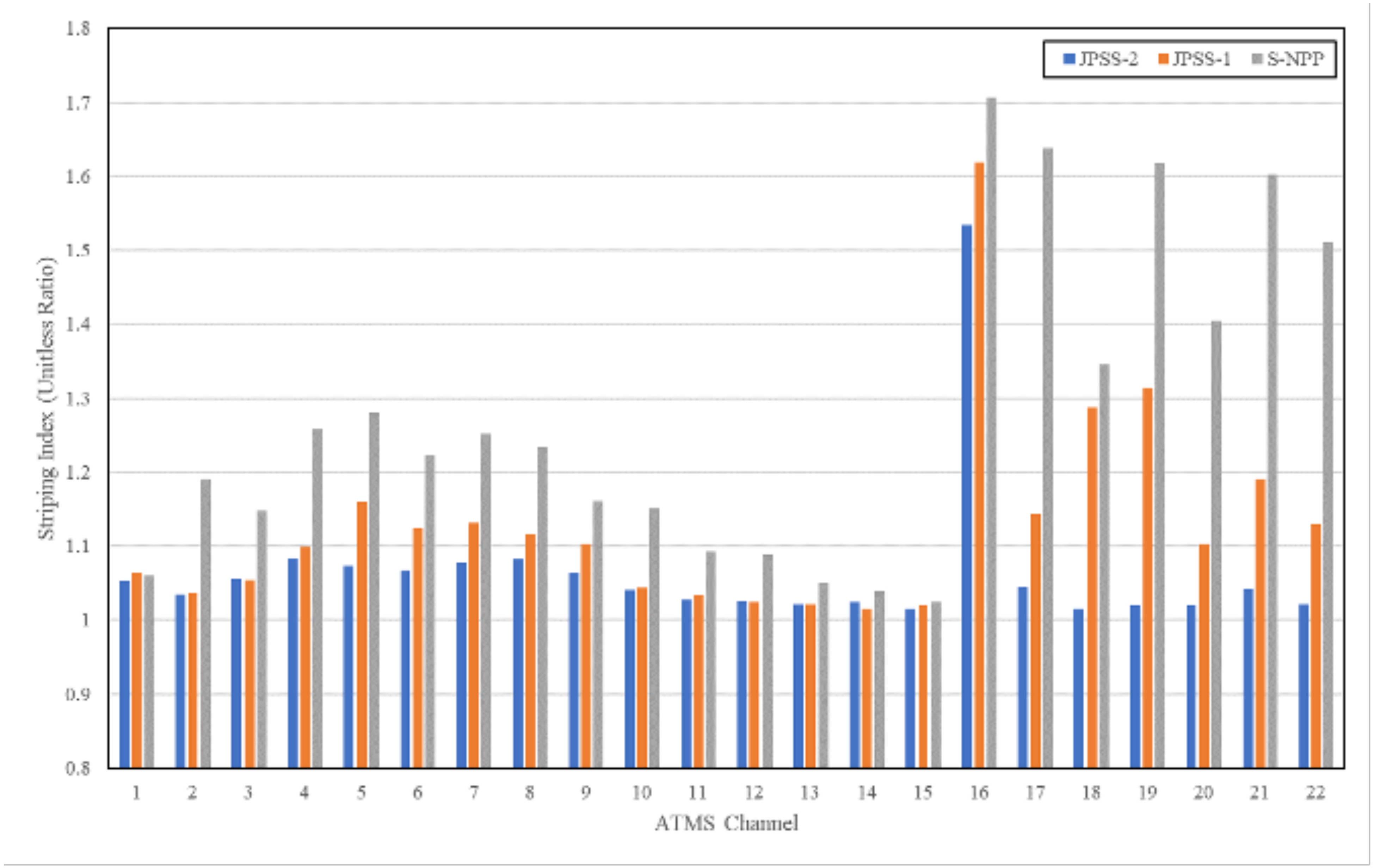
- Striping noise manifests in the ATMS observations as the low frequency noise in the along-track direction with stripped pattern.
- No significant striping noise were observed in current operational ATMS units onboard JPSS satellites
- Unlike the white noise with the Gaussian distribution, the low-frequency striping noise can not be reduced by simply average over the consecutive measurement samples





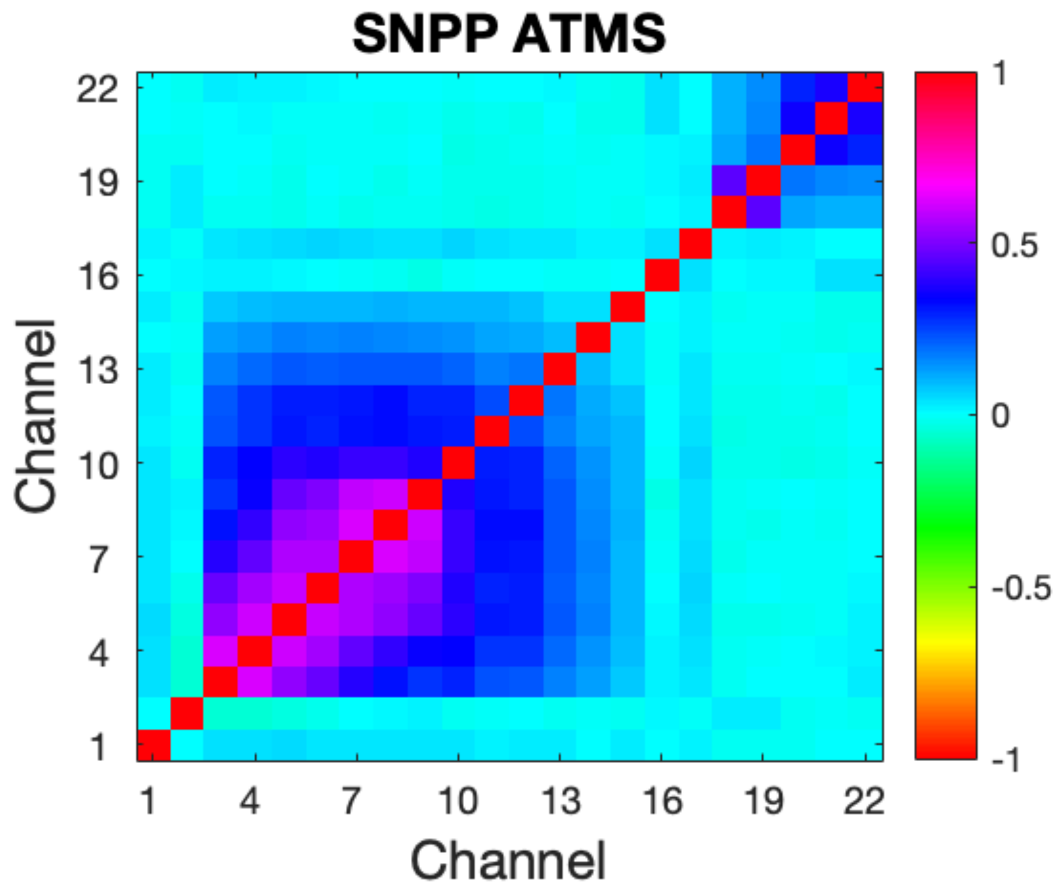
Metric for On-orbit Striping Noise Evaluation

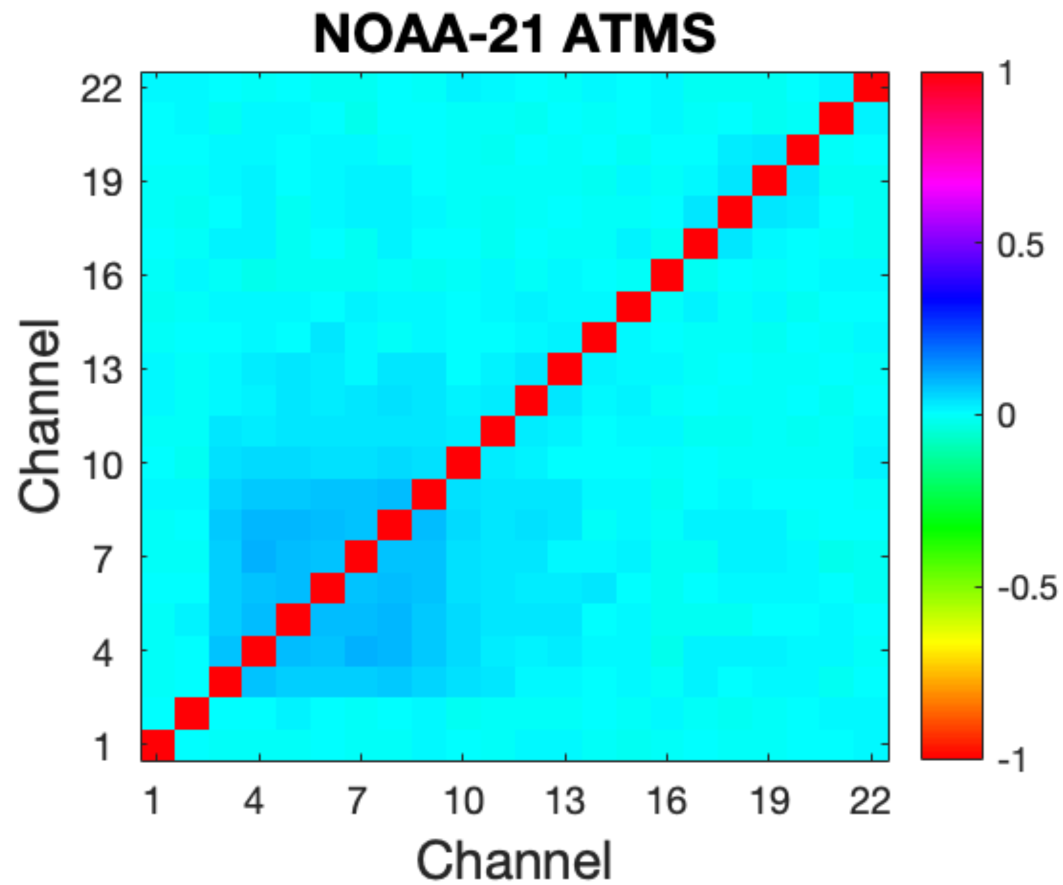
- The striping index $\kappa_{SI}$is used as a metric to quantify the significance of striping noise, defined as the ratio of variance in cross-track direction(\$\sigma_{CT}^2$to that in the along-track directionσ_{AT}^2: $\kappa_{SI} = \frac{\sigma_{CT}^2}{\sigma_{AT}^2}$
- A value of $\kappa_{SI} = 1$ indicates no striping noise, while values greater than 1 signify increasing striping.



Noise Error Channel Correlation

- ATMS observations are an important data source for NWP applications, the presence of notable error correlations are need to be properly characterized for a successful assimilation of the observations.
- Compare with other operational ATMS unit in NOAA 21, Significant increase of the inter-channel correlations in V and G-band channels are observed in SNPP ATMS
- Increase of the channel error correlation is closed correlated with the percentage of 1/f noise in the total noise

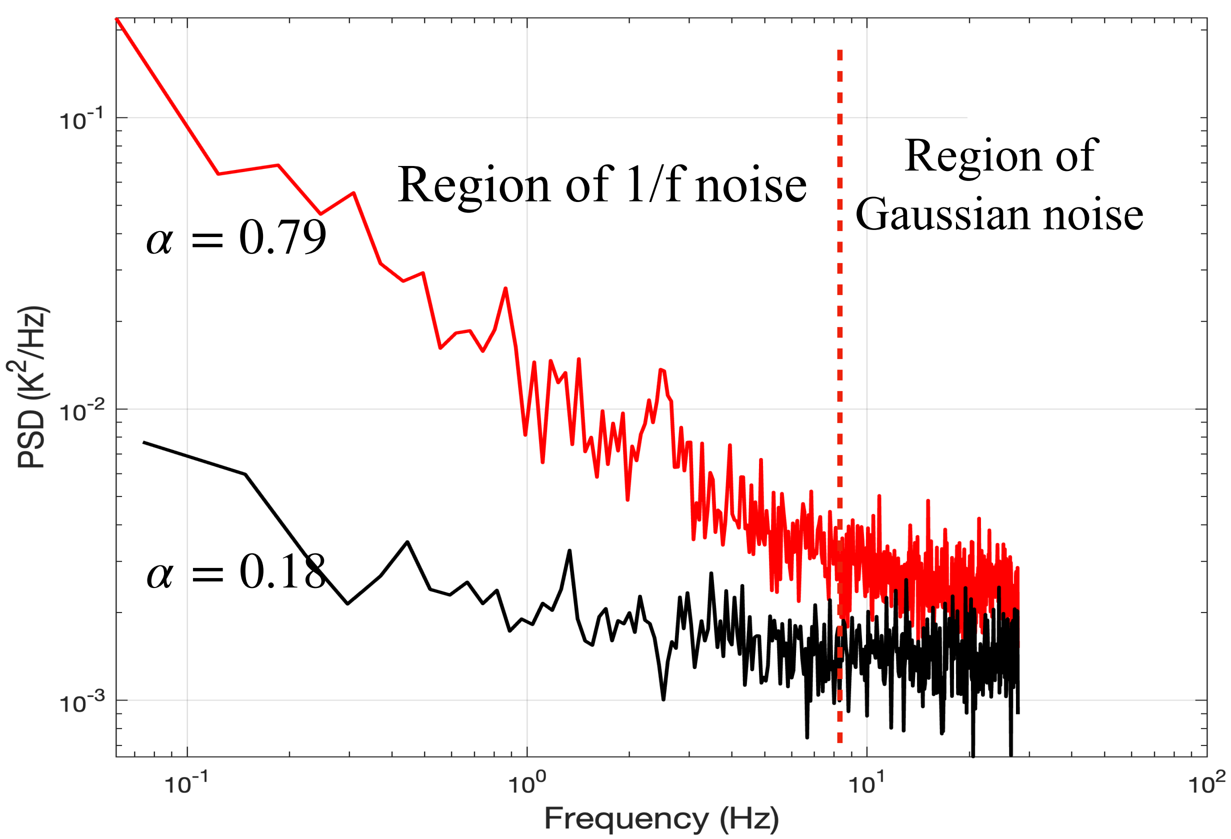




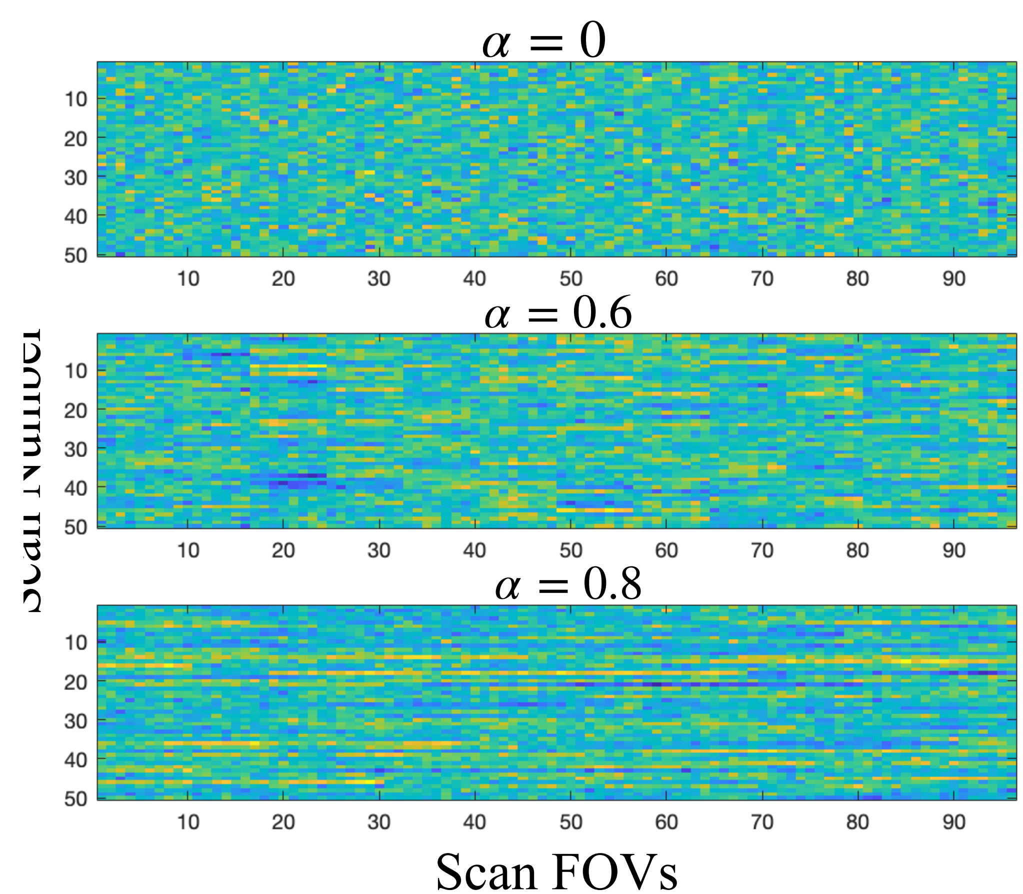
Root Cause of the Striping Noise — PSD Analysis

- The measured receiver power spectrum is the sum of two major components. At low frequencies from DC to 10Hz, the PSD is inversely proportion to the frequency and with higher magnitude, which matches the feature of $1/f$ noise. While at frequencies above 10Hz, a uniform Gaussian spectrum with low magnitude is apparent, which is known as the white noise.
- The PSD of the $1/f$ noise component can be modeled as an inverse function of the frequencies. The $1/f$ noise is the dominant noise component for the presence of the striping in observations

Noise Power Spectrum Density Analysis

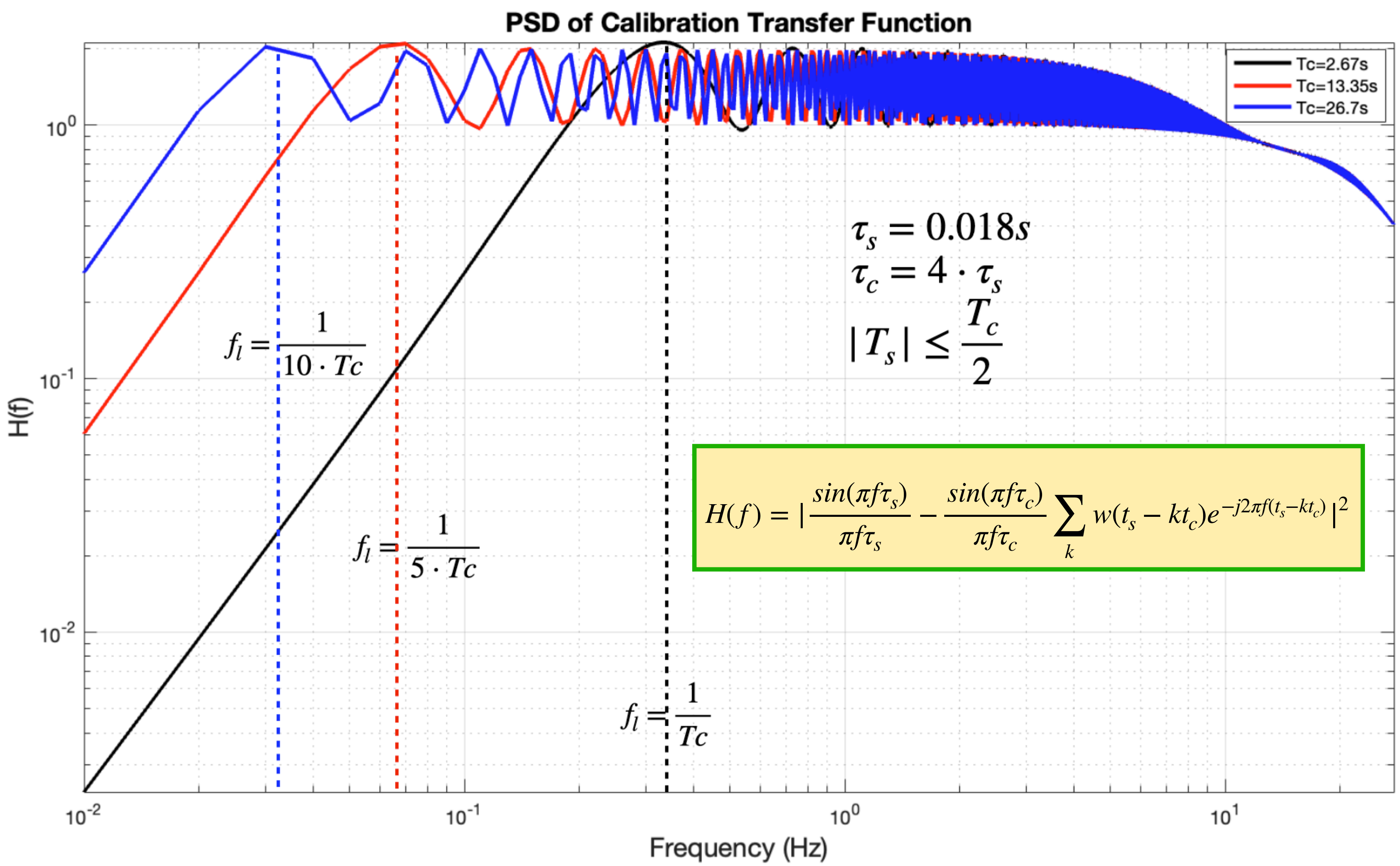


$$PSD(f) = a \cdot f^{-\alpha}$$



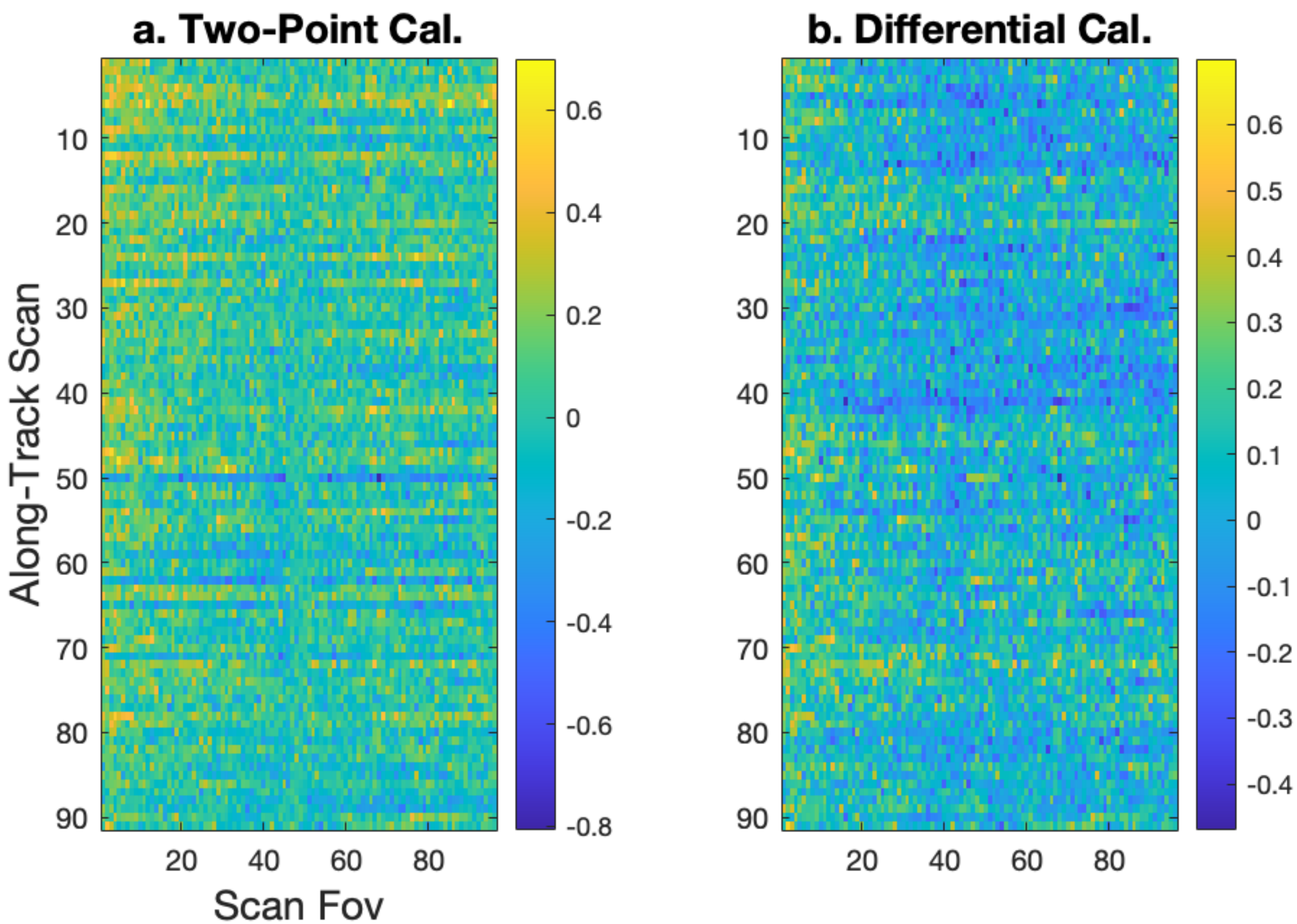
Impacts of Calibration Parameters on Instrument Noise Performance

- the noise performance of a total power radiometer with periodic absolute calibration, such as ATMS, is fundamentally linked to the receiver output noise power spectrum, $S_r(f)$, and the calibration processor transfer function $H(f)$ (Michael Hersman and Gene Poe, 1981)
- The calibration transfer function depends on the radiometer parameters, including the observation integration time τ, calibration duration t_c, and the weighting function applied to calibration samples.
- Both integration time and calibration duration significantly affect the noise characteristic of the calibrated brightness temperature.



Mitigation of 1/f Noise in Calibration Process

- The mitigation for 1/f noise can be addressed in calibration process
- Differential calibration scheme is used instead of traditional 2-point calibration
- Adjustments of the calibration parameters to improve the rejection of 1/f noise in original measurements



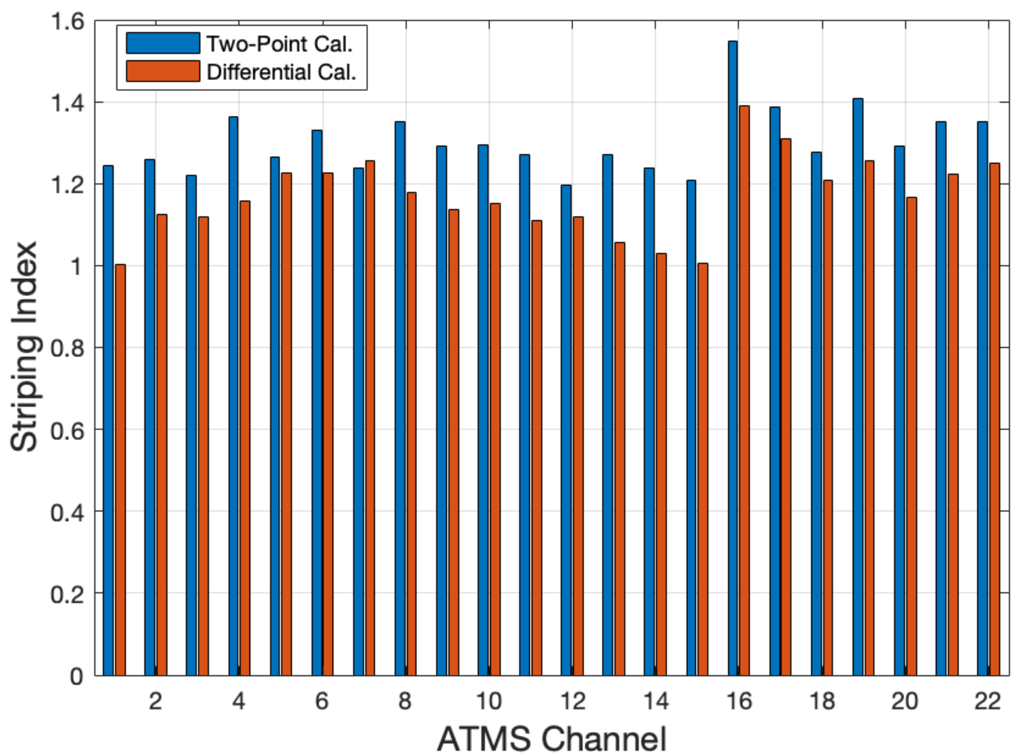
Evaluation of the Impacts of 1/f Noise Mitigation

To evaluate the impacts of the new calibration method on noise characteristics in the calibrated results, special datasets from the SNPP pitch maneuver observations were utilized in this study.

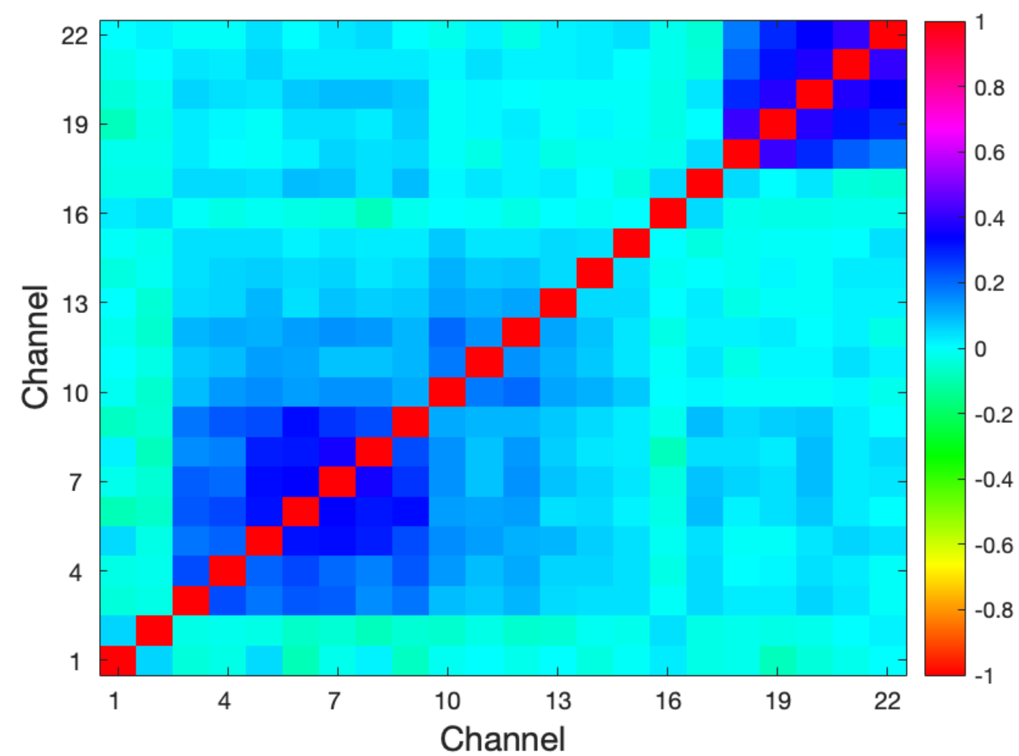
The results demonstrate that the new calibration algorithm effectively reduces the striping pattern in the calibrated brightness temperatures.

The striping index and channel correlation calculation results show that the striping noise was reduced by an average of 12\% for K/Ka and V bands, and 10\% for W and G bands by using the differential calibration algorithm,.

Striping Index



Channel Correlation



Thermal Noise Mitigation Algorithm

- The challenge is to reduce the noise without significant degradation in spatial resolution
- Algorithm is developed based on the correlation of the scene and the correlation of the noise between the overlapped original measurements

The new observations will be rebuilt from the original measurements

$$Ta_{new}(\rho_0) = \sum_{i=1}^{n} a_i \cdot Ta_{org}(\rho_i)$$

Cost function is developed to include both spatial resolution degradation term and the noise term

$$Q = Q_0 \cos\gamma + \widehat{\sigma} w \sin\gamma$$

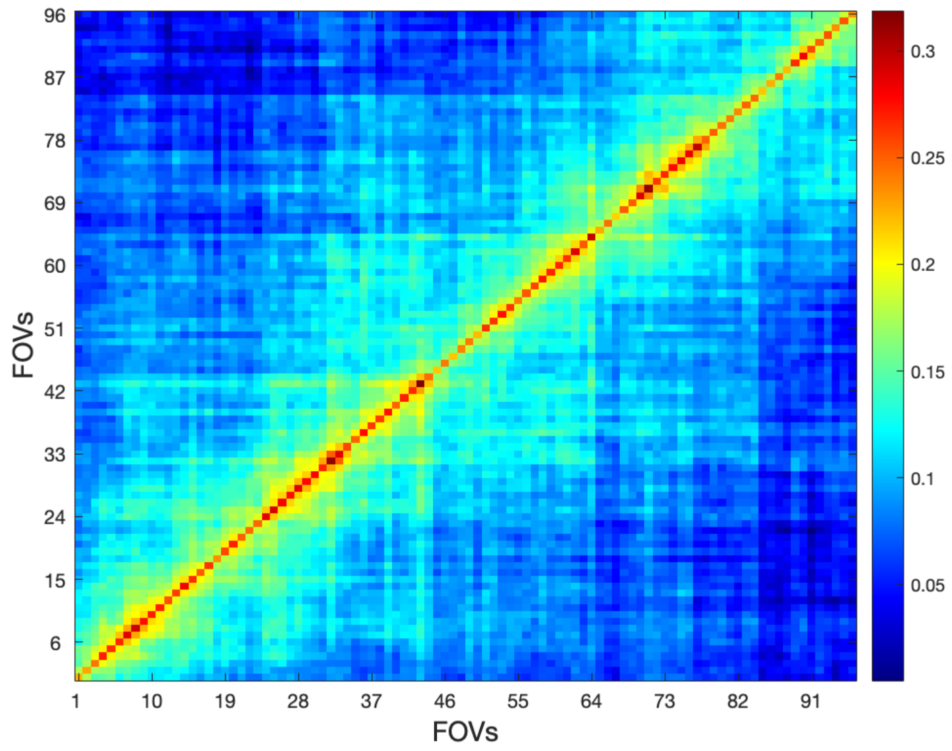
The scene correlation is quantified by the difference between the antenna pattern of the new observations and the original measurements

$$Q_0 = \int \left[\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} G_{ij}(\widehat{\rho}) - F(\widehat{\rho}_0, \widehat{\rho}) \right]^2 dA$$

The noise correlation is derived based on the noise observations from the ground TVAC tests

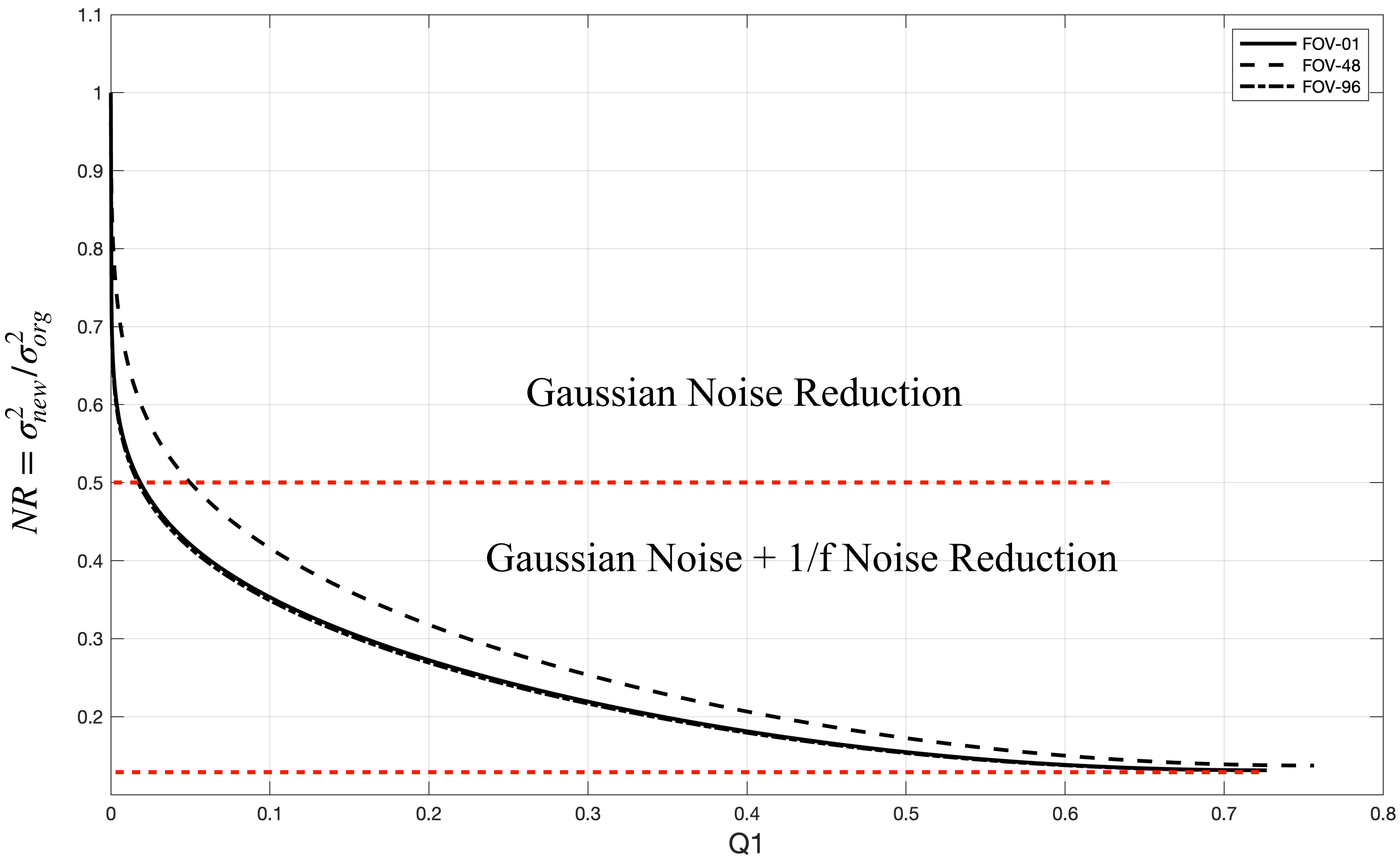
$$\Delta T_{noise}^2 = e = a^T E a$$

Noise Error Covariance Matrix for QS ATMS Chan.16



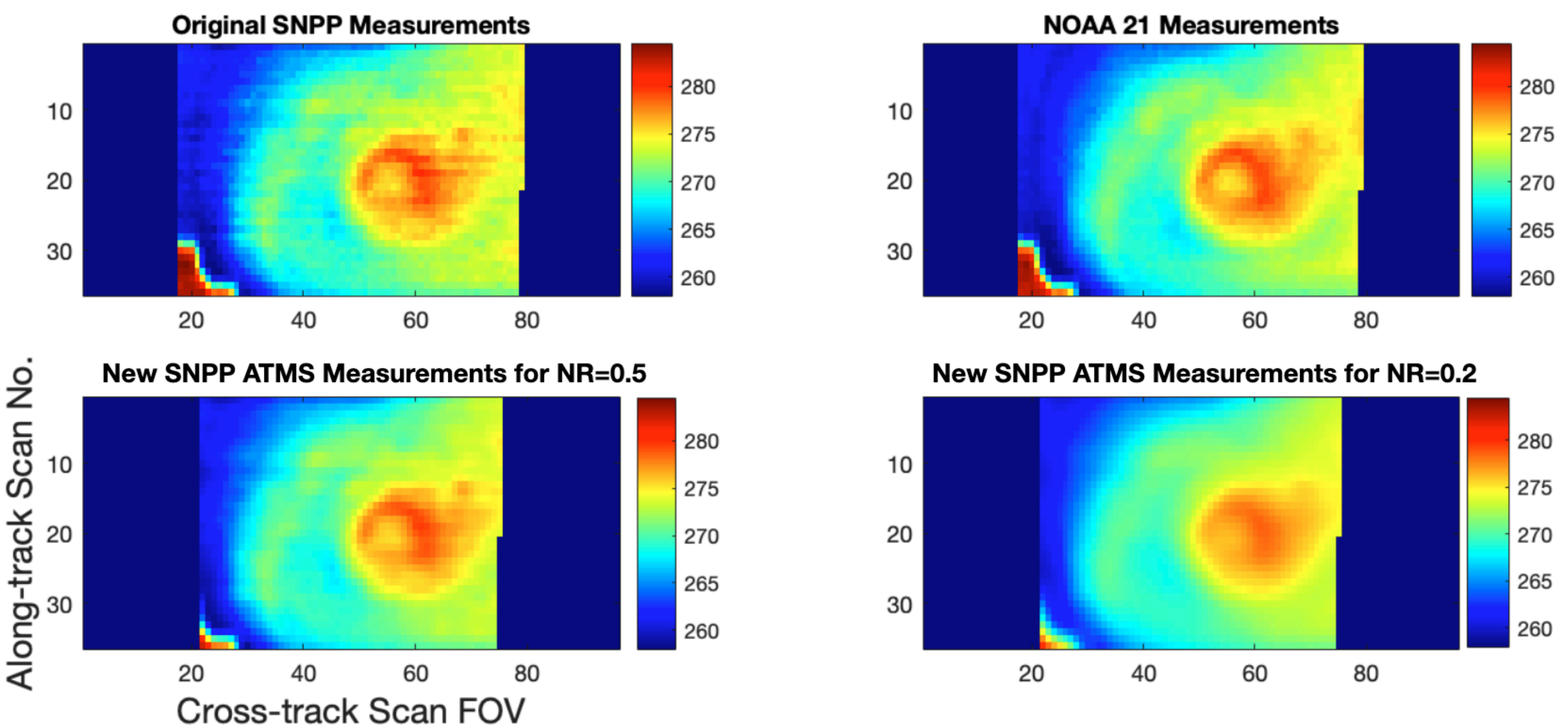
Trade-off Curve between Noise and Spatial Resolution

- An antenna pattern identical to the original antenna beam is chosen to be the target antenna pattern
- A dynamic window technique is used to find the overlapped original measurements within -5dB footprint of the target antenna beam
- The coefficients is derived at each of the 96 scan positions with γ change from 0 to $\pi/2$, for maximum noise at $\gamma = 0$ and the minimum of noise at $\gamma = \pi/2$ for the new observations
- Noise Ration (NR) is used as a metric to measure the noise reduction level in the new observations. For noise ration NR>0.5, the white noise components can be effectively reduced without significant degradation in spatial resolution; for NR<0.5, the 1/f noise can also be reduced but with an increased sacrifice in spatial resolution



Evaluation for the Noise Mitigation Algorithm

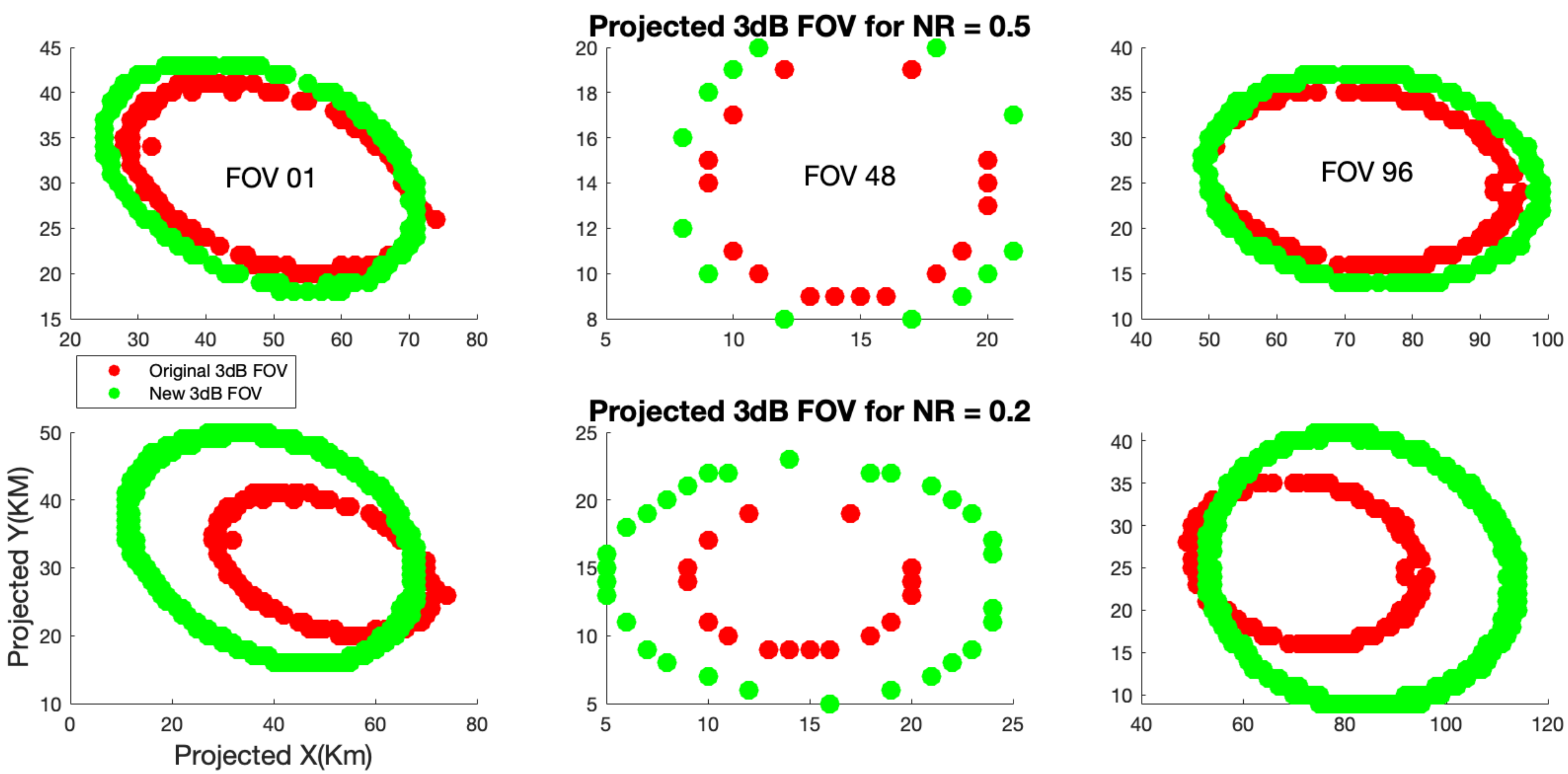
- The evaluation for the noise mitigation results is carried out based on the model-simulated datasets. Specifically, the simulated ATMS observations for Hurricane Sandy at 0600UTC October 28, 2012 are generated at 3x3 grid, based on the Community Radiative Transfer Model (CRTM) with the 66-hours forecast from Hurricane Weather Research and Forecasting model (HWRF) as the model inputs
- The noise spectrum datasets from the ground tests were used to generate the noise brightness temperature and being added into the simulated antenna temperature to simulate the original instrument observations
- The channel 16 is chosen for the study for the largely inhomogeneous scene in this channel, which makes it represent the worst case for the implementation of the noise mitigation algorithm



Degradation of Spatial Resolution

The footprint size of the original observation and the changes in new observations at the scan position 1, 48 and 96 are calculated with unit of Km. For NR=0.5, there is about average of 8km increase in footprint size for scan center, and 5Km increase for the edge of the scan. For NR=0.2, the degradation of the spatial resolution is 23Km in scan center, and 36Km in the scan edge.

Scan Position	X_{3dB}^{Org} (Km)	Y_{3dB}^{Org} (Km)	ΔX (NR=0.5)	ΔY (NR=0.5)	ΔX (NR=0.2)	ΔY (NR=0.2)
1	142.4	70.7	3.3	8.3	36.6	36.1
48	33.2	31.9	8.5	7.3	26.5	21.3
96	144.7	61.7	5.3	9.8	43.3	37.2



Conclusions and Future Work

- The presence of Significant striping noise in measurements degrades the quality of calibrated radiance products and negatively impacts on various applications. This work investigates the effects of striping noise and explores a new method to mitigate it during the calibration process. Preliminary results indicate that enhancing the calibration performance for 1/f noise rejection effectively reduces striping noise in calibrated measurements.

- Additionally, applying a dynamic window noise mitigation algorithm further reduces total noise to the required level. It is also observed that when white noise dominates the measurements, the proposed method effectively minimizes noise without significantly compromising spatial resolution.

- The proposed algorithm can be seamlessly integrated into the operational calibration process with minimal computational overhead. Future work will focus on testing the method for broader operational applications.