Analysis and Mitigation of Striping Noise in Two Water Vapor Sounding Channels of Global Precipitation Measurement (GPM) Microwave Imager

H. DONG
Center for Data Assimilation Research and Applications, Nanjing University of Information Science and Technology, Nanjing, China

X. ZOU
Center for Data Assimilation Research and Applications, Nanjing University of Information Science and Technology, Nanjing, China, and Earth System Science Interdisciplinary Center, University of Maryland, College Park, College Park, Maryland

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ABSTRACT

The Global Precipitation Measurement (GPM) Microwave Imager (GMI) plays an important role in monitoring global precipitation. In this study, an along-track striping noise is found in GMI observations of brightness temperatures for the two highest-frequency channels—12 and 13—with their central frequencies centered at 183.31 GHz. These two channels are designed for sounding the water vapor in the middle and upper troposphere. The pitch maneuver data of deep space confirmed an existence of striping noise in channels 12 and 13. A striping noise mitigation method is used for extracting the striping noise from the earth scene or deep space measurements of brightness temperatures by combining the principal component analysis (PCA) with the ensemble empirical mode decomposition (EEMD) method. A power spectrum density analysis indicated that the frequency of striping noise ranges between 0.06 and 0.533 s\(^{-1}\), where the right bound of 0.533 s\(^{-1}\) of frequency is exactly the inverse of the time (i.e., 1.875 s) it takes for the GMI to complete one conical scan line. The magnitude of striping noise in the brightness temperature observations of GMI channels 12 and 13 is about \(0.3 K\). It is shown that after striping noise mitigation, the observation minus model simulation (O\( - B\)) distributions of both the earth scene and deep space brightness temperatures show no visible striping features.

1. Introduction

Satellite microwave temperature sounders, humidity sounders, and imagers have provided complementary global observations of the global atmospheric and Earth surface variables for several decades. It is important to ensure the highest possible accuracy and precision of these observations before they are assimilated into numerical weather prediction (NWP) models. Although the Advanced Technology Microwave Sounder (ATMS) on board the Suomi–National Polar-Orbiting Partnership (SNPP) is a state-of-the-art instrument that combines its predecessor Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS) into a single instrument (Weng et al. 2012), a striping noise phenomena was found by Bormann et al. (2013) in the global distributions of the differences between ATMS observations (O) and model simulations (B), that is, O – B, of an upper-level temperature sounding channel. Such a striping noise had not been seen previously in the O – B global distributions of AMSU-A channels located at similar altitudes. Qin et al. (2013) subsequently showed that such striping noise existed in ATMS as well as in all other heritage humidity sounders (i.e., AMSU-B and MHS) observations. Striping noise found in ATMS, AMSU-B, and MHS observations could be caused by receiver gain fluctuations (i.e., the so-called 1/f noise) that are associated mainly with the radio frequency (RF) amplifiers that were used in front of the receivers of these instruments (Ulaby et al. 1981; Hersman and Poe 1981). No amplifier was placed in front of a receiver of AMSU-A.
In this study, we will show that striping noise also existed in brightness temperature observations of two water vapor sounding channels at the frequencies 183.31 ± 3 and 183 ± 7 GHz from the Global Precipitation Measurement (GPM) Microwave Imager (GMI). The GMI serves as the successor of the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) to continuously provide global precipitation measurements (NASA PMATF 2013). An instrument overview can be found in Newell et al. (2014, 2015) and Draper et al. (2015b), including the early on-orbit performance of the GMI (e.g., radiometric sensitivity, absolute calibration accuracy, and stability for each radiometric channel). The GPM Microwave Imager performance and calibration results can be found in Newell et al. (2014, 2015). An assessment of the GMI’s calibration stability was conducted using the GMI noise diodes (Draper et al. 2015a). Draper et al. (2015c) carried out an intercomparison of the GMI brightness temperature observations with those of the ATMS instrument and the MHS on MetOp-A of similar sounding capability for the high-frequency channels at 183.31 and 166 GHz. Having properly taken care of the differences in polarization, the earth incidence angle, resolution, and frequency band between the GMI and ATMS/MHS, it was shown that the GMI brightness temperatures agreed with the brightness temperatures of ATMS and the MHS on board MetOp-A within about 1 and 0.5 K, respectively, for moist atmospheric conditions. Having solved the GMI’s calibration problems associated with its sensitivity to the ambient magnetic field and the specification of the primary reflector’s cold space spillover by using deep space observations and the backlobe maneuvers, Wentz and Draper (2016) made a comparison between the absolutely calibrated GMI brightness temperature observations and the simulations from an ocean radiative transfer model (RTM) using the WindSat ocean retrievals collocated with the GMI observations as input. The root-mean-square error of the differences between the GMI measured brightness temperature and the WindSat simulations was estimated to be about 0.25 K for all GMI channels using 13 months of global data.

The two water vapor sounding channels at frequencies 183.31 ± 3 and 183 ± 7 GHz are among the four new high-frequency channels that are added to the GMI in order to provide additional information of light rain, warm rain, and snowfall (Hou et al. 2014). Since GMI observations are important for precipitation retrieval as well as data assimilation in numerical weather prediction (NWP), striping noise—if it exists—could affect the accuracy and precision of GMI precipitation retrieval products and data assimilation results. The GMI is different from the cross-track microwave temperature and humidity sounders (e.g., ATMS and MHS) for which the striping noise could only be seen in the fields of the differences between observations and model simulations of the earth scene brightness temperatures (O − B) and the pitch maneuver data of deep space (Qin et al. 2013; Ma and Zou 2015). GMI is a conical-scanning radiometer. The striping noise could be seen not only from the (O − B) fields but also from the O fields of the earth scenes and the pitch maneuver data of deep space.

The paper is organized as follows: the GMI channel characteristics and model simulation are briefly described in section 2. In section 3, numerical results showing the striping noise visible in the brightness temperature observations of channels 12 and 13, and in the difference fields of the earth scene brightness temperatures between GMI observations and model simulations, a method similar to Qin et al. (2013) for mitigating the striping noise in GMI brightness temperature observations, are carefully reviewed. The effectiveness of striping noise mitigation for GMI observations are examined and the spectrum of the striping noise extracted are discussed in section 4. Section 5 presents an analysis and mitigation of striping noise of the pitch maneuver data of deep space views. Section 6 gives a brief summary and future work.

2. GMI channel characteristics and model simulation

a. GMI channel characteristics

The GPM mission aims to calibrate, unify, and improve global precipitation measurements. The GPM mission was led by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) (Farrar and Jones 2014). The GPM Core Observatory was launched into orbit at an altitude of about 407 km on 27 February 2014 (NASA GSFC 2014). The GPM satellite has a 65° inclination angle to allow for a global view of precipitation to as high as 70° latitude in both hemispheres. Such a GPM orbit gives a near-real-time monitoring of hurricanes and an accurate estimate of accumulative rain volume better than a sun-synchronous polar orbit with a higher inclination. The GMI is one of the principal instruments on board the GPM satellite. It serves as the successor of the TMI to continuously provide global precipitation measurements (NASA PMARF 2013). The GMI has more frequent revisiting times than a microwave imager on board a polar-orbiting satellite with a larger inclination angle than GPM. For example, the Advanced Microwave Scanning Radiometer-2 (AMSR-2) on board the Global Change Observation Mission–Water
The GMI (GCOM-W1) satellite has an inclination angle of 98.2°, allowing for global coverage of observations only twice daily (Kachi et al. 2008).

The GMI is a 13-channel conical-scanning microwave radiometer. The antenna of the GMI rotates at a constant Earth incidence angle of 52.8° for channels 1–9 (10.65–89 GHz) and 49.2° for channels 10–13 (166.0–183 GHz) (NASA GSFC 2014). The earth scene brightness temperature observations are taken over a 145° viewing sector to provide a total of 221 field of views (FOVs) over a single scan line. The GMI swath is 885 km wide. Each scan cycle takes 1.875 s. For channels 1–7, the GMI has an operational calibration cycle that repeats every two scans and uses a four-point calibration method. The main channel specifications are provided in Table 1.

For GMI channels 8–13, all scans have a scan-by-scan calibration cycle and employ the heritage linear sensor radiometric calibration method (NASA GSFC 2014). A mixer/intermediate frequency preamplifier is used for the high-frequency channels 8–13 with their frequencies ranging from 89.00 to 190.31 GHz (Meissner et al. 2011), but not for the low-frequency channels 1–7 with their frequencies ranging from 10.65 to 36.50 GHz. Instead, the GMI adopts gallium–arsenide (GaAs)-based high-electron-mobility transistor/pseudomorphic high-electron-mobility transistor (HEMT/PHEMT) devices for the low-frequency channels. It is thus interesting to find out whether the receiver gain fluctuations associated with the radio frequency amplifiers also cause striping noise in the GMI observations of high-frequency channels.

### Table 1. GMI channel characteristics (Draper et al. 2015b).

<table>
<thead>
<tr>
<th>Channel</th>
<th>Central frequency (GHz)</th>
<th>Polarization</th>
<th>Beamwidth (°)</th>
<th>On-orbit NEdT (K)</th>
<th>EFOV at 407 km (km × km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.65</td>
<td>V</td>
<td>1.72</td>
<td>0.77</td>
<td>32 × 20</td>
</tr>
<tr>
<td>2</td>
<td>10.65</td>
<td>H</td>
<td>1.72</td>
<td>0.78</td>
<td>32 × 20</td>
</tr>
<tr>
<td>3</td>
<td>18.70</td>
<td>V</td>
<td>0.98</td>
<td>0.63</td>
<td>18 × 12</td>
</tr>
<tr>
<td>4</td>
<td>18.70</td>
<td>H</td>
<td>0.98</td>
<td>0.60</td>
<td>18 × 12</td>
</tr>
<tr>
<td>5</td>
<td>23.80</td>
<td>V</td>
<td>0.85</td>
<td>0.51</td>
<td>16 × 10</td>
</tr>
<tr>
<td>6</td>
<td>36.50</td>
<td>V</td>
<td>0.82</td>
<td>0.41</td>
<td>15 × 10</td>
</tr>
<tr>
<td>7</td>
<td>36.50</td>
<td>H</td>
<td>0.82</td>
<td>0.42</td>
<td>15 × 10</td>
</tr>
<tr>
<td>8</td>
<td>89.00</td>
<td>V</td>
<td>0.38</td>
<td>0.32</td>
<td>7 × 6</td>
</tr>
<tr>
<td>9</td>
<td>89.00</td>
<td>H</td>
<td>0.38</td>
<td>0.31</td>
<td>7 × 6</td>
</tr>
<tr>
<td>10</td>
<td>166.00</td>
<td>V</td>
<td>0.38</td>
<td>0.70</td>
<td>6 × 6</td>
</tr>
<tr>
<td>11</td>
<td>166.00</td>
<td>H</td>
<td>0.37</td>
<td>0.65</td>
<td>6 × 6</td>
</tr>
<tr>
<td>12</td>
<td>183.31 ± 3.0</td>
<td>V</td>
<td>0.37</td>
<td>0.56</td>
<td>6 × 5</td>
</tr>
<tr>
<td>13</td>
<td>183.31 ± 7.0</td>
<td>V</td>
<td>0.37</td>
<td>0.47</td>
<td>6 × 5</td>
</tr>
</tbody>
</table>

The modeled brightness temperatures at GMI channel frequencies are simulated with the Community Radiative Transfer Model (CRTM) (Weng 2007; Han et al. 2007). Input from the vertical profiles of temperature, water vapor, and pressure to CRTM is obtained from the European Centre for Medium-Range WeatherForecasts (ECMWF) analysis, which has a horizontal resolution of 0.25° × 0.25° and a total of 91 vertical levels.
from the surface to 0.01 hPa. Input from the ozone mixing ratio profile to CRTM is set to the U.S. Standard Atmosphere state. The GMI brightness temperatures are simulated assuming a clear-sky condition. Therefore, clouds and aerosols are set to zero in CRTM for GMI simulations conducted in this study.

Figure 1 shows the weighting functions of the 13 GMI channels calculated from the U.S. Standard Atmosphere profile using the CRTM. Channels 1–9 are all surface channels. The peaks of the weighting function of channels 10 and 11 are located at the atmospheric boundary layer. The weighting functions of channels 12...
and 13, whose central frequencies are 183.31 ± 3 and 183 ± 7 GHz, have the highest peaks at about 600 and 800 hPa, respectively. The main purpose of these two channels is to measure the water vapor and precipitation in the troposphere.

3. Striping noise in GMI observations and a mitigation algorithm

a. Striping noise seen in GMI observations

A global distribution of GMI swaths at the ascending node is shown in Fig. 2a for the brightness temperature observations of channel 12 on 17 August 2014 (https://pmm.nasa.gov/data-access/downloads/gpm). It is seen that the GMI swaths extend between 70°S and 70°N, which is much broader than those of the TMI (figure omitted) due to a larger inclination angle as mentioned before. Therefore, the GMI can monitor global precipitations not only in the tropics but also in the middle latitudes. There is a large data void between any two GMI swaths, especially in the low latitudes.

The observed brightness temperatures of GMI channel 12 vary from below 245 K to more than 275 K. Such a variation of more than 30 K makes it difficult to detect any noise that is two orders of magnitude smaller than 30 K. To reduce the variation range of the GMI observations of brightness temperatures, we show the same brightness temperature observations in Fig. 2a in a zoomed area (Fig. 2b). We also show the differences between GMI observations and CRTM simulations in this small area (Fig. 2c). The observed brightness temperatures of GMI channel 12 in this small portion of the swath vary from below 264 to 272 K, which leads to an 8-K range of variations. A striping noise following the GMI conical scan lines becomes visible in both the O and O − B fields of channel 12.

Since channel 13 is located in an atmospheric layer lower than channel 12 (see Fig. 1), the observed brightness temperatures of channel 13 (Fig. 2d) are about 9 K higher than those of channel 12. The observed brightness temperatures of GMI channel 13 in this small portion of the swath vary from below 273 to 281 K. Similarly, striping noise is also seen in the brightness temperature observations of GMI channel 13 (Figs. 2d and 2e).

b. Mathematical formula of a striping noise mitigation algorithm

The same method as that used by Qin et al. (2013) will be used for extracting the striping noise in GMI observations. First, a data matrix $A$ consisting of the GMI observed brightness temperatures over a swath portion is constructed as follows:

$$A_{M \times N} = \begin{pmatrix} T_b^{\text{obs}}(1, 1) & \cdots & T_b^{\text{obs}}(1, N) \\ \vdots & \ddots & \vdots \\ T_b^{\text{obs}}(221, 1) & \cdots & T_b^{\text{obs}}(221, N) \end{pmatrix},$$

where $T_b^{\text{obs}}(k, j)$ indicates the brightness temperature at the $k$th FOV of the $j$th scan line, the FOV varies from 1 to 221, and $N$ is the total number of the scan lines involved in the data matrix $A$. The term $N$ has been set to 2400 (about 24000 km in the along-track direction), which is about the number of scan lines for a single swath from 70°S to 70°N, or vice versa.

A covariance matrix $S$ can be constructed as the product of the data matrix $A$ and its transpose $A^T$,

$$S = A A^T.$$ 

Therefore, $S$ is a symmetric real matrix. We may calculate the eigenvalues ($\lambda_i, i = 1, \ldots, 221$) and eigenvectors ($e_i, i = 1, \ldots, 221$) of $S$, which are defined as

$$S e_i = \lambda_i e_i, (i = 1, \ldots, 221),$$

where

$$e_i = \begin{pmatrix} e_{1i} \\ e_{2i} \\ \vdots \\ e_{221i} \end{pmatrix}.$$ 

The $i$th eigenvector $e_i$ is oftentimes called the $i$th principal component (PC) mode in the following discussions ($i = 1, 2, \ldots, 221$). The eigenvalue of the $i$th eigenvector $\lambda_i$ quantifies the contribution of the $i$th PC mode to the total variance of $A$. Equation (3) can be written in matrix form as follows:

$$S E = E \Lambda,$$

where

$$\Lambda = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \lambda_{221} \end{pmatrix}, \quad E = (e_1, e_2, \ldots, e_{221}).$$

The eigenvectors are orthonormal, that is, $E^{-1} = E^T$. By multiplying Eq. (4) from the right by the inverse matrix $E^{-1}$, we obtain

$$S = E \Lambda E^T.$$ 

Since $EE^T = I$, $A$ can be decomposed onto the eigenvectors of the covariance matrix as follows:
FIG. 3. (a) PCA1, (b) PCA2, and (c) PCA3 of the GMI observed brightness temperatures shown in Fig. 2b. Sum of the first three PCA components (d) before and (e) after striping noise mitigation. (f) Brightness temperature observations with the first three PCA components subtracted.
FIG. 4. Power spectrum density distributions of the (a) first, (b) second, and (c) third PC modes defined as the products of each of the first three PC components (e.g., $e_1$, $e_2$, $e_3$) with the first four IMFs ($C_m$; red, blue, green, and orange curves when $m = 1, 2, 3$ and $4$, respectively) decomposed from the PC coefficient $u_i$ of GMI channel 12 (183.31 ± 3 GHz) brightness temperatures.
\[
A = EE^T A = EU = \sum_{i=1}^{221} e_i u_i^T,
\]

where the PC coefficient matrix \( U \) can be written as

\[
U = E^T A = \begin{pmatrix}
  u_{1,1} & u_{1,2} & \cdots & u_{1,N} \\
  u_{2,1} & u_{2,2} & \cdots & u_{2,N} \\
  \vdots & \vdots & \ddots & \vdots \\
  u_{221,1} & u_{221,2} & \cdots & u_{221,N}
\end{pmatrix}
\begin{pmatrix}
  u_1^T \\
  u_2^T \\
  \vdots \\
  u_{221}^T
\end{pmatrix}.
\]

(7)

The vector \( u_i^T \) will be called the \( i \)th PC mode coefficient in the following discussions. It is reminded that \( e \) is a function of FOV and \( u_i^T \) describes an along-track variation (Qin et al. 2013).

An example is provided in Fig. 3 in which the first three terms in Eq. (6) are shown for the GMI observed brightness temperatures at channel 12. The first three PC modes explain more than 99.984%, 0.006%, and 0.003%, respectively, of the total variance of the observed brightness temperatures. The first PC component captures the latitudinal variations of the brightness temperatures in the along-track direction. The cross-track variation of the first PC component along the GMI scan lines is nearly constant. A striping noise is clearly present in all three PC components (Figs. 3a–c) and of track variation of the first PC component along the GMI scan lines.

3) Identify all the local maxima and minima, and connect all these local maxima (minima) with a cubic spline as the upper (lower) envelope to obtain the local mean of the upper (lower) envelope \( a_{i,m} \).

4) Obtain the \( m \)th IMF of the \( i \)th PC mode coefficient \( C_{i,m} \) by subtracting the \( a_{i,m} \) from the \((m-1)\)th residual \( R_{i,m-1} \):

\[
C_{i,m}(j) = R_{i,m-1}(j) - a_{i,m}(j).
\]

(9)

5) Set the \( m \)th residual \( R_{i,m} \) to \( a_{i,m} \) to obtain the \( m \)th residual:

\[
R_{i,m}(j) = a_{i,m}(j).
\]

(10)

6) Set \( m = m + 1 \), and repeat steps 3–5 until the residual \( R_{i,L} \) does not contain high-frequency noise that is not resolvable at the GMI observed frequency in the along-track direction of the GPM.

7) Repeat steps 1–7 with different white noise series to obtain an ensemble of the respective IMFs. The ensemble mean is taken as the EEMD IMFs.

In fact, the striping noise can be captured by the first few IMFs of the PC coefficients of the first few eigenvectors. By removing these high-frequency IMFs, the PC coefficient would vary smoothly in the along-track direction. Substituting the smoothed \( u_i \) into Eq. (6) gives the GMI brightness temperatures with the striping noise mitigated.

c. Impacts of IMFs on data spectrum lag correlation

To determine how many IMFs to be removed for striping noise mitigation, a spectral analysis is first carried out for each of the first four IMFs. Figure 4 shows the power spectrum density for the first four IMFs of the first three PC components. The frequency 0.533 s\(^{-1}\) corresponds to the period of 1.875 s for the GMI to complete one scan cycle, which is indicated in Fig. 4 by the black vertical line. Because the scan lines are connected sequentially in the data series for spectrum analysis, oscillations with periods shorter than 1.875 s or frequencies higher than 0.533 s\(^{-1}\) will be ignored to avoid artificial oscillations.
Fig. 5. Lag autocorrelations of the first five IMFs of the (a)–(c) first three PC components for brightness temperature observations of GMI channel 12.
The spectra of the first two IMFs of the first PC component have a peak between the frequencies from 0.01 to 0.533 s$^{-1}$ and reduce to a relatively smaller value ($\sim 10^2$) at low frequencies. Although the third IMF also has a spectrum maximum located within the frequency range from 0.01 to 0.533 s$^{-1}$, its spectrum at low frequencies is as large as $10^3$, which is an order of magnitude larger than that of the first two IMFs. It indicates that there may be weather signals included in the third IMF. For the fourth IMF, the spectrum is weak for all frequencies larger than 0.01 s$^{-1}$. In other words, the first two IMFs are mainly the striping noise and shall be removed from the first PC mode. In fact, Qin et al. (2013) also showed that the ATMS striping noise peaks in a frequency range between 0.01 and 0.375 s$^{-1}$, which is the inverse of the time it takes for ATMS to complete its one scan line.

### Table 2. Number of IMFs that are removed from the first three PC modes as striping noise.

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Central frequency (GHz)</th>
<th>IMFs (PCA1/PCA2/PCA3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>183.31 ± 3.0</td>
<td>2/2/2</td>
</tr>
<tr>
<td>13</td>
<td>183.31 ± 7.0</td>
<td>2/2/2</td>
</tr>
</tbody>
</table>

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For the second and third PC components, the spectrum of the first two IMFs are large in the frequency ranging from 0.01 to 0.533 s\(^{-1}\), but the third and fourth IMFs do not have any peaks in the range between 0.01 and 0.533 s\(^{-1}\). It means that some weak striping noise may exist in the first two IMFs of the second and third PC components.

Besides spectra, the lag autocorrelations of the first five IMFs of the first three PC components for GMI channel 12 are also examined (Fig. 5). It is seen that the lag autocorrelations remain small for frequencies much smaller than 0.533 s\(^{-1}\). The third and higher numbers of IMFs seem to contain weather signals at the time scales that the GMI data can resolve. Based on the results in Figs. 4 and 5, the first two IMFs of the first three PC mode are determined to be removed from striping noise mitigation in the brightness temperature observations of GMI channel 12 (see Table 2).

4. The effectiveness of striping noise mitigation for GMI observations

The effectiveness of striping noise mitigation for GMI observations can now be examined. Figure 6 shows an along-track variation of the PC coefficients for the first three PC modes (i.e., eigenvectors)—that is, \(u_i\) \((i = 1, 2, 3)\)—before and after removing the first two IMFs that capture the high-frequency oscillations in the original GMI data of channel 12. It is seen that the small jitter noises are effectively removed by the EEMD method, while the observed along-track variations are not altered. A comparison of the sum of the first three PCA components without striping noise mitigation (Fig. 3d) with that after striping noise mitigation (Fig. 3e) suggests an effectiveness of the proposed scheme of removing the first two IMFs in each of the first three PC components.

![Fig. 7. The O – B differences of brightness temperatures (left) after removing the stripping noise and (right) the striping noise for channels (a),(b) 12 and (c),(d) 13.](image)
The differences between GMI observations and CRTM simulations shown in Figs. 2c and 2e for indicating an existence of striping noise in the observations of GMI channels 12 and 13 can be reexamined after removing the striping noise in the observations. A striping noise following the GMI conical scan lines that was visible in Figs. 2c and 2e is not visible in Figs. 7a and 7c, suggesting an effective mitigation of striping noise in GMI observations. Figures 7a and 7c show the O – B distributions of brightness temperatures of GMI channels 12 and 13, respectively, after removing the striping noise within the region indicated by the black box in Fig. 2a. The striping noise extracted from the GMI data for channels 12 and 13 is shown in Figs. 7b and 7d, respectively. The magnitude of striping noise is around ±0.3 K for both channels.

A spectrum analysis is applied to the striping noise (Figs. 8a and 8b) and the O – B fields of brightness temperatures before and after eliminating the striping noise (Figs. 8c and 8d) for GMI channels 12 and 13. It is seen that the striping noise spectrum is very close to the pink noise, which makes the O – B spectrum have an increasing trend, as the frequency is decreased starting from the value of 0.533 s⁻¹, which signals the presence of striping noise. The striping noise is effectively removed from the O – B fields in the frequency range between 0.06 and 0.533 s⁻¹ (Figs. 8c and 8d). These impacts of striping noise mitigation on data are similar to that of ATMS (Qin et al. 2013). It is worth reminding that it takes 2.67s (0.375 s⁻¹ in frequency) for ATMS to complete one scan line.

The reasons for the striping noise to appear in the two water vapor sounding channels of the highest frequencies may be associated with the use of a mixer/intermediate frequency preamplifier for the GMI high-frequency channels, and/or the receiver gain fluctuations. Further investigation is required to confirm the root cause of the striping noise in GMI observations.
FIG. 9. Count observations of deep space from the pitch maneuver data on 10 Dec 2014 for GMI channels (a)–(c) 12 and (d)–(f) 13 (left) without and (middle) with removing the (right) striping noise extracted from the pitch maneuver observations.
5. Striping noise and its mitigation from pitch maneuver data

The GMI deep space calibration data were made available on 10 December 2014. Figure 9 provides the count observations of the deep space from the pitch maneuver data for GMI channels 12 and 13 with and without removing the striping noise in the pitch maneuver observations. The magnitude of striping noise is about 15 in terms of count. The striping noise feature is weakly seen in the original deep space observations with a dozen of colors (left panels in Fig. 9) due to a large range of variation in counts from both channels. Deep space is a nearly homogeneous field. To see more clearly the striping noise feature in pitch maneuver data, we show in Fig. 10 along-track variations of counts at different FOVs (i.e., one FOV = one gray curve) of deep space views at GMI channel 12 before (Fig. 10a) and after (Fig. 10b) striping noise mitigation. A nine-point running average is carried out in the along-track direction for both (a) and (b).

![Fig. 10. Along-track variations of counts at different FOVs (gray curves) of deep space views at GMI channel 12 (a) without and (b) with striping noise mitigation. A nine-point running average is carried out in the along-track direction for both (a) and (b).](image)

...
FIG. 11. PCA1, PCA2, and PCA3 of the count observations of deep space from the pitch maneuver data for GMI channel 12 (upper) without and (middle) with removing the (lower) striping noise in the pitch maneuver observations made on 10 Dec 2014.
FIG. 12. As in Fig. 11, but for channel 13.
FIG. 13. As in Fig. 9a, but for channels 8–11.
for GMI channels 8–13, the fact that the striping noise occurred only in the last two channels (e.g., the GMI sounding channels 12 and 13 peaking in the troposphere) implies that the GMI receiver equipped with the radio frequency amplifiers is not the sole source of striping noise.

6. Summary and conclusions

The conical-scanning GMI instrument plays an important role in the GPM. This study carries out an investigation of systematic errors in the GMI brightness temperature observations, which must be eliminated before being used for the precipitation retrieval and data assimilation processes. An along-track striping noise is found to exist in GMI observations of high-frequency channels 12 and 13. A PCA/EEMD method similar to that developed for striping noise mitigation in ATMS observations is proposed, tested, and applied for striping noise mitigation of GMI observations. It was shown that the striping noise in GMI observations of the two highest-frequency water vapor sounding channels can be effectively eliminated by the proposed method but weather signals are not affected. The impacts of the striping noise on GPM precipitation retrieval products and data assimilation have yet to be investigated in future study.

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