Mitigation of Significant Data Noise in F17 SSMIS Observations since October 2017

Huijie Dong and Xiaolei Zou *

Joint Center of Data Assimilation for Research and Application, Nanjing University of Information Science & Technology, Nanjing 210044, China; hdong@nuist.edu.cn
* Correspondence: xzou@nuist.edu.cn

Abstract: Special Sensor Microwave Imager Sounder (SSMIS) temperature sounding observations have been made available since the launch of the Defense Meteorological Satellite Program (DMSP), F16, on 18 October 2003. These conical-scanning observations of brightness temperature are ideal for investigating long-term structural changes in tropical cyclones throughout the globe. The SSMIS temperature sounding data started to contain significant across-track high-frequency striping noise spikes at a frequency of $0.14 \text{ s}^{-1}$ starting on 20 October 2017 for F17. A Fast Fourier Transform (FFT) was used to remove the noise in channels 1–7 and 24. The across-track striping noise is most significant for the four channels of the lowest peak weighting functions. The data noise is as large as 15 K for channels 1–3, 2.5 K for channel 4, 0.5 K for channels 5–7, and 0.75 K for channel 24. We found some remaining along-track striping noise around 0.5 K in channels 2–4, which is removed by employing a principal component analysis and an ensemble empirical mode decomposition combined method. An advantage for conical-scanning observations of brightness temperature to directly capture typhoon structures is then illustrated. Although buried under the data noise in the original data, the structural features of typhoon Lekima (2019) could clearly be seen after the noise mitigation. Lekima reached a typhoon intensity on 7 August 2019 and its center was characterized by a warm anomaly of more than 7 K around 200 hPa (channel 5) and a cold center of less than $-6 \text{ K}$ around 945 hPa (channel 2). This study prepares us for using satellite observations to understand the effect of climate change on tropical cyclone intensity and rain-band structures over the past two decades.

Keywords: SSMIS observations; DMSP F17; data noise; tropical cyclone

1. Introduction

The Special Sensor Microwave Imagers (SSM/I) aboard the US Air Force Defense Meteorological Satellite Program (DMSP) polar-orbiting satellite F8, which was launched on 18 June 1987, is the first microwave imager sensor. Since then, the SSM/1 and the Special Sensor Microwave/Water Vapor sounder (SSM/T2) have been on board the DMSP satellites F10/11/13/14/15. The legacy sensors SSM/I, SSM/T, and SSM/T2 were replaced by the Special Sensor Microwave Imager/Sounder instrument (SSMIS) on DMSP F16, F17, and F18, launched on 18 October 2003, 4 November 2006, and 18 October 2009, respectively. The SSMIS combines the three instruments of SSMT, SSMT/2, and SSM/I into a single sensor so that thermally-emitted radiation from the earth and the atmosphere can be simultaneously measured in all channels of SSMT, SSMT/2, and SSM/I. There are 24 channels with their central frequencies being located from 19 to 183 GHz [1]. The SSMIS provides observations in sounding channels at a significantly higher spatial resolution than its predecessors.

SSMIS is a conical scanning microwave instrument that can provide observations of brightness temperature (TB) at microwave temperature and water vapor sounding channels as well as imager channels at the same single scan angle. This feature for fields-of-view to have a fixed scan angle is different from the Advanced Microwave Sounding Unit-A (AMSU-A) aboard the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting...
satellites NOAA-15/16/17/18/19 and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) MetOp-A/B/C, the MWTS aboard the Chinese polar-orbiting weather satellites in the new generation of the Feng-Yun three series (FY-3) FY-3A/B, the MWTS-2 aboard the FY-3C/D/E, and the Advanced Technology Microwave Sounder (ATMS) aboard the Suomi National Polar-orbiting Partnership (S-NPP) and NOAA-20. The launch dates for the first AMSU-A aboard NOAA-15, the first AMSU-A aboard EUMETSAT MetOp-A, the first ATMS aboard S-NPP, and the first MWTS-2 aboard FY-3C were 13 May 1998, 19 October 2006, 28 October 2011, and 23 September 2013, respectively.

Satellite microwave observations are much more transparent to cloud than infrared observations and could thus penetrate through different layers of the atmosphere to measure the atmospheric temperature and water vapor distributions from the surface to the stratosphere under almost all weather conditions. In the past, the AMSU-A TB measurements at the nadir (i.e., zero-scan angle) were used to calculate global climate trends. For example, Mo (2009) [2] calculated global climate trends based on 10-year TB observations of AMSU-A from NOAA-15 over Amazon rainforest areas and showed that this dataset well captured the surface and tropospheric warming and stratospheric cooling trends. Mo used a conventional linear regression method, which works well for detecting a trend from measurements that satisfy the assumption that data are linear and stationary. Considering global climate variability and change being the integrated result of atmospheric states that contain many coexisting, different-frequency oscillatory modes undergoing non-stationary and nonlinear evolutions, Qin et al. (2012) [3] applied a new adaptive data analysis method—Ensemble Empirical Mode Decomposition (EEMD)—to obtain a set of channel-dependent nonlinear trends based on the global, Northern Hemisphere and Southern Hemisphere averaged NOAA-15 AMSU-A TB observations at the nadir during the period from 26 October 1998 to 7 August 2010. They pointed out that the trends for the two upper tropospheric channels 7–8 are quite nonlinear, characterized by a global warming trend during 1999–2003, a global cooling trend in the Southern Hemisphere after 2003, and no significant trend in the Northern Hemisphere until after 2007. AMSU-A channels 7 and 8 are the two highest channels in the troposphere. Such a nonlinear evolution of warming and cooling trends in TB observations at channels 7 and 8 may reflect a lowering of tropopause height in the Southern Hemisphere from 2003 to 2010. Other studies for using satellite microwave TB observations to detect global climate change include those related to technical issues in calibration [4], orbital drift effect [5], and satellite-to-satellite merging techniques [6,7], as well as global warming trends in the lower troposphere from the three research groups using different data-processing procedures [6,8–13]. In the above researches, only the nadir or corrected-to-nadir observations were employed to eliminate the limb effects on AMSU-A observations.

Weather-related structures are not directly visible in TB observations from the across-track microwave radiometers (e.g., AMSU-A, ATMS, MWTS-2) due to a significant limb effect. This is the largest limitation of using these satellite observations to obtain the spatial distributions of climate warming and cooling trends or the weather structures and their evolutions (e.g., hurricanes). Although a limb correction algorithm [14,15] can remove the scan dependence in observations of targeting AMSU-A and ATMS channels, it employs two or more neighboring channels. By doing so, the vertical resolution of temperature sounding channels, which is already not very high, is further reduced. In addition, the size of the field-of-view of AMSU-A and ATMS observations increases with the scan angle. The FOV sizes at the largest scan angle are more than two times greater than those at the nadir. If located at or near the swath edge, the typhoon eye cannot be identified and the typhoon warm-core retrieval would contain large errors [16]. The conical scanning mode of the SSMIS does not suffer from these limitations of the cross-track scanning radiometers. It enables the sensor to maintain the same resolution of the size of 27 and 18 km in the along-track and across-track directions, respectively. These make SSMIS observations appropriate for analyzing the structural changes of weather systems and obtaining the local differences in global climate warming and cooling trends.
Since F16 was launched on 18 October 2003, the atmosphere temperature and water vapor sounding channel observations were used in monitoring and forecasting disastrous weather. Herndon et al. (2012) [16] found that there were some good linear relationships between the temperature anomalies near the typhoon center and the minimum sea-level pressure with the SSMIS channel-5 (55.5 GHz) observations, and in the typhoon center and the Minimum Sea Level Pressure (MSLP) detected by aircraft. Bell et al. (2008) [17] found that assimilation of the SSMIS temperature sounding channels’ observations had a neutral to positive impact on the medium-range weather forecast skills in the Southern Hemisphere and a neutral impact in the Northern Hemisphere in most cases.

The DMSP satellites F16, F17, and F18 have provided SSMIS observations for more than 17 years. It would be interesting to study the decadal change and variability of tropical cyclones, and the impacts of global warming on typhoon activity, including the occurring frequency, location, and intensity. Before being released to users, several corrections were applied to the SSMIS data such as corrections for solar and lunar intrusions into the warm load and cold sky mirror, cross-track bias correction, antenna pattern correction, correction for heating biases associated with sun glint angles, etc. [18]. However, after a period of operation, significant noise appeared in the SSMIS temperature sounding channels from all three DMSP satellites, F16, F17, and F18. For example, an across-track striping noise of more than 15 K appeared in the F17 SSMIS on the descending node on 20 October 2017 and on all ascending and descending nodes after 20 October 2017. The atmospheric weather structures are buried under the noise of a large magnitude.

As the first step, this paper investigates the noise in the F17 SSMIS temperature sounding channels. Section 2 gives a brief description of the SSMIS observations. Section 3 describes the method for extracting and mitigating the noise. Section 4 presents the results of the magnitude and characteristic features of the noise in the F17 SSMIS observations. Tropical cyclone structures that can be revealed from the F17 SSMIS observations are discussed in Section 5. Conclusions and future plans are provided in the last section.

2. SSMIS Data Characteristics

Since 2005, the SSMIS aboard F16, F17, and F18 contains a total of 24 channels to provide global microwave radiation measurements at frequencies ranging from 19 GHz to 183 GHz. Among the 24 channels, channels 1–7 and 19–24 are temperature sounding channels, channels 8–11 are water vapor sounding channels, and channels 12–18 are imaging channels [18]. The DMSP F16, F17, and F18 satellites all have sun-synchronous orbits with slightly different local equatorial crossing times (LECT). The LECT at the ascending node of F16, F17, and F18 is at 15:52, 18:03, and 18:33, respectively. After a few years since the launch date, the atmospheric temperature sounding channels of the SSMIS from all three DMSP F16, F18 satellites are contaminated by obvious noise, which jeopardizes any possible attempts to use these channels for climate change studies. Fortunately, there is no obvious noise in the other SSMIS channels.

The SSMIS detects the earth’s surface with a fixed scanning angle of 45°. The time for the SSMIS to complete a scanning cycle is 1.9 s [19]. The swath width of the SSMIS is 1707 km. Channels 1 to 7 are lower atmospheric sounding (LAS) channels with their central frequencies located in the oxygen absorption region. They are used to detect the atmospheric temperature from the surface to about 40 hPa. The frequencies of channels 8 to 11 lie on the wings and near the peak of the 183-GHz water vapor absorption line and are used to detect the atmospheric humidity in the middle and lower troposphere. Channels 12 to 18 lie within atmospheric windows with frequencies ranging from 19 to 91 GHz and are used to determine the characteristics of the earth’s surface, cloud liquid and rain rate, and surface wind speeds over the ocean. Channel 17 (91 GHz) has the highest resolution of $13.2 \times 15.5 \text{ km}^2$, and its measurements were used to locate tropical cyclone centers in the ARCHER algorithm [20,21]. Unlike SSM/I, the SSMIS adopted 91 GHz instead of 85.5 GHz due to hardware considerations with the bore-sighted sounder channels at 183 GHz. The detecting channels with a frequency of 91 GHz are more sensitive to the
scattering of ice particles in tropical cyclones’ rainbands than those at 85 GHz. Ice scattering reduces the measured TB. SSMIS channel 8 at 150 GHz is very sensitive to active convective cells, which might be under-detected by only using an 85 or 91 GHz channel. The large amount of condensation-latent heat released by these convective cells leads to the rapid enhancement of tropical cyclones [22]. Channels 19 to 24 are located in the region of the highest absorption in the oxygen spectrum and are used to profile temperature in the upper stratosphere and mesosphere from 15 to 0.02 hPa [23]. Table 1 shows the channel number, frequency, bandwidth, noise equivalent differential temperature (NEDT), and pressure at the level where WF reaches the maximum following Berg [18].

Table 1. SSMIS channel number, frequency, bandwidth, noise equivalent differential temperature (NEDT), and pressure at the level where WF reaches the maximum. The sampling interval is $12.5 \times 37.5$ km$^2$ for SSMIS channels 1–7 and 24 and $12.5 \times 75$ km$^2$ for channels 19–23, and the size of FOV is $27 \times 18$ km$^2$, where the first and second numbers are in the along-track and across-track directions, respectively. The central frequency for channels 19–24 is $f_0 = 60.792668$.

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Frequency (GHz)</th>
<th>3-db Bandwidth (MHz)</th>
<th>NEDT (K)</th>
<th>WF Peak (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.3</td>
<td>380</td>
<td>0.4</td>
<td>Surface</td>
</tr>
<tr>
<td>2</td>
<td>52.8</td>
<td>389</td>
<td>0.4</td>
<td>945</td>
</tr>
<tr>
<td>3</td>
<td>53.596</td>
<td>380</td>
<td>0.4</td>
<td>650</td>
</tr>
<tr>
<td>4</td>
<td>54.4</td>
<td>383</td>
<td>0.4</td>
<td>399</td>
</tr>
<tr>
<td>5</td>
<td>55.5</td>
<td>391</td>
<td>0.4</td>
<td>165</td>
</tr>
<tr>
<td>6</td>
<td>57.29</td>
<td>330</td>
<td>0.5</td>
<td>86</td>
</tr>
<tr>
<td>7</td>
<td>59.4</td>
<td>239</td>
<td>0.6</td>
<td>49</td>
</tr>
<tr>
<td>24</td>
<td>$f_0 \pm 0.357892 \pm 0.050$</td>
<td>26.5</td>
<td>0.7</td>
<td>17</td>
</tr>
<tr>
<td>19</td>
<td>63.283248 $\pm 0.285271$</td>
<td>1.35</td>
<td>2.4</td>
<td>0.28</td>
</tr>
<tr>
<td>20</td>
<td>$f_0 \pm 0.357892$</td>
<td>1.35</td>
<td>2.4</td>
<td>0.17</td>
</tr>
<tr>
<td>21</td>
<td>$f_0 \pm 0.357892 \pm 0.002$</td>
<td>1.3</td>
<td>1.8</td>
<td>0.84</td>
</tr>
<tr>
<td>22</td>
<td>$f_0 \pm 0.357892 \pm 0.0055$</td>
<td>2.6</td>
<td>1.0</td>
<td>2.4</td>
</tr>
<tr>
<td>23</td>
<td>$f_0 \pm 0.357892 \pm 0.016$</td>
<td>7.35</td>
<td>0.6</td>
<td>6.4</td>
</tr>
</tbody>
</table>

A microwave TB measurement at a specific SSMIS channel quantifies the atmospheric radiation within a layer of the atmosphere near the altitude where the weighting function of the channel is the largest. It is approximately a linear function of the atmospheric temperature at that altitude. Figure 1 shows the weighting function of these channels calculated using the community radiative transfer model (CRTM) version 2.3.0 [24] with the US standard atmosphere profile as input. It can be seen that the vertical profiles of the weighting functions of the 13 temperature sounding channels are maximized at different layers of the atmosphere, implying that the TB observations quantify radiation from different layers of the atmosphere. Channel 1 has the lowest weighting function peak and channel 20 has the highest. The peak altitude of the weighting function increases from channels 1 to 7, then from 24 to 21, and finally 19 and 20.

This study mainly focuses on the LAS channels of the SSMIS. The FOV size of the temperature sounding channels is 27 km and 18 km in the along-track and across-track directions, respectively. The sampling interval is 12.5 km and 37.5 km in the along-track and across-track directions, respectively. As mentioned above, significant noise appears in the LAS channels on 20 October 2017. Figure 2a presents the channel-1 TB observations over the two F17 SSMIS swaths from 12°N to 28°N at the ascending node on 20 October 2017. At this time, typhoon Lan is centered over the gap between the two swaths. The outer rainband structures of typhoon Lan are directly visible from TB observations over the two SSMIS swaths. However, a significantly large across-track striping noise appeared in the measurements at the descending node on 20 October 2017 (Figure 2b). The rainband features of Typhoon Lan are buried under the striping noise and are barely seen. We describe below a method of noise mitigation for the observations from the SSMIS LAS channels from F17.
Figure 1. Vertical profiles of weighting functions of SSMIS atmospheric temperature sounding channels, which are calculated from the US standard atmosphere profile using Community Radiative Transfer Model (CRTM, version 2.3.0).

Figure 2. TB observations from F17 SSMIS channel 1 at (a) the ascending and (b) descending nodes on 20 October 2017. The center position of Typhoon Lan is indicated by a hurricane symbol.
3. Method for Noise Mitigation

We propose a two-procedure method for eliminating the noise in the F17 SSMIS data. The first procedure removes the along-track high-frequency noise. At a fixed FOV index $i$, we may construct a data series from TB observations over an SSMIS swath:

$$
\mathbf{y}_i^o = \begin{bmatrix}
T^o_b(i, 1) \\
T^o_b(i, 2) \\
\vdots \\
T^o_b(i, N)
\end{bmatrix} = \begin{bmatrix}
y^o_{i,1} \\
y^o_{i,2} \\
\vdots \\
y^o_{i,N}
\end{bmatrix}, \quad (1)
$$

where $T^o_b(i, j)$ ($l = 1, 2, \ldots, M, j = 1, 2, \ldots, N$) indicates the observed TB at the $i$th FOV and the $j$th scanline, $M$ is the total number of FOVs along a single scanline ($M = 60$), and $N$ is the total number of scanlines of an SSMIS swath ($N \approx 3219$).

Using the discrete Fourier transform, we may express the data series in (1) as follows:

$$
y^o_{i,k} = \frac{1}{N} \sum_{m=0}^{N-1} C^o_{i,m} e^{im2\pi k/N}, \quad (k = 1, 2, \ldots, N), \quad (2)
$$

where $C^o_{i,m}$ is the amplitude of the wave with wavenumber $m$ and is defined by the inverse Fourier transform:

$$
C^o_{i,m} = \frac{1}{N} \sum_{k=0}^{N-1} y^o_{i,k} e^{-im2\pi k/N}, \quad (m = 0, 1, \ldots, N-1). \quad (3)
$$

Since it took 1.9 s for the SSMIS to complete scanning one scanline, the frequency for the wavenumber $m$ is $f_m = \frac{m}{N \times 1.9}$ ($m = 0, 1, \ldots, N-1$). The amplitude of TB observations decreases rapidly with increasing frequency. However, there is a sudden spike in large amplitude around a frequency of $0.14 \text{ s}^{-1}$ (Figure 3), which corresponds to wavenumber 856 and a wave of period of 3.7 scanlines. We may remove such high-frequency large amplitude signals by truncating the Fourier expansion at $m_t$ that is smaller than 856. The reconstructed TB observations are obtained by

$$
y^o_{i,k} = \sum_{m=0}^{m_t} C^o_{i,m} e^{im2\pi k/N}, \quad (k = 1, 2, \ldots, N). \quad (4)
$$

Figure 3. Cont.
The above procedure is repeated for all FOVs \((I = 1, 2, \ldots, M)\).

Having removed the along-track high-frequency noise, we continued with the second procedure to remove the remaining along-track striping noise in SSMIS channels 2–4. A principal component analysis (PCA) is carried out on a swath-by-swath basis. A data matrix \(A\) is firstly constructed from the TB observations with the across-track striping noise mitigated:

\[
\mathbf{A}^{\text{obs},1} = \begin{pmatrix}
T_b^{\text{obs},1}(1, 1) & \cdots & T_b^{\text{obs},1}(1, N) \\
\vdots & \ddots & \vdots \\
T_b^{\text{obs},1}(M, 1) & \cdots & T_b^{\text{obs},1}(M, N)
\end{pmatrix},
\]

where \(T_b^i(i, j) (i = 1, 2, \ldots, M, j = 1, 2, \ldots, N)\) indicates the observed TB at the \(i\)th FOV and the \(j\)th scanline, \(M\) is the total number of a scanline \((M = 60)\), and \(N\) is the total number of the observations.
scanlines of an SSMIS swath ($N \approx 3219$). From $A$ we may construct a covariance matrix $S = A_{\text{obs},1}^T (A_{\text{obs},1})^T$.

The second step is to obtain the eigenvalue ($\lambda_i$) and eigenvector ($\vec{e}_i$) of the symmetric matrix $S$:

$$S \vec{e}_i = \lambda_i \vec{e}_i (i = 1, 2, \ldots, M),$$

where $\lambda_1 > \lambda_2 > \cdots > \lambda_M$. The $i$th eigenvalue $\lambda_i$ quantifies the contribution of the $i$th eigenvector to the total variance of the data matrix $A$. We may write Equation (6) in matrix form:

$$SE = EA,$$

where

$$E = (\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_M), A = \begin{pmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_M \end{pmatrix}. $$

Since the eigenvectors $\vec{e}_i (i = 1, 2, \ldots, M)$ are orthogonal to each other, we have $E^{-1} = E^T$ and $S = EAE^T$.

The third step is to project the data matrix onto the space defined by the eigenvectors:

$$U = E^T A_{\text{obs},1}, U = \begin{pmatrix} -T \\ u_1^T \\ u_2^T \\ \vdots \\ -T \\ u_M^T \end{pmatrix}, \vec{u}_i = \begin{pmatrix} u_{i,1} \\ u_{i,2} \\ \vdots \\ u_{i,N} \end{pmatrix},$$

where $\vec{u}_i$ is the coefficient of the $i$th eigenvectors $\vec{e}_i$. Since $E^{-1} = E^T$, the data matrix can now be expressed as:

$$A_{\text{obs},1} = EU = \sum_{i=1}^{M} \vec{e}_i \vec{u}_i. $$

The along-track striping noise is found in the first eigenvector $\vec{e}_1$.

The fourth step is to remove the along-track striping noise in $\vec{e}_1$ so as to obtain a noise-mitigated first eigenvector $\vec{e}_1$, as well as the reconstructed TB observations:

$$A_{\text{obs},2} = \begin{pmatrix} T_{b,1}^{\text{obs},2} & \cdots & T_{b,1}^{\text{obs},2} \\ \vdots & \ddots & \vdots \\ T_{b,1}^{\text{obs},2} & \cdots & T_{b,1}^{\text{obs},2} \end{pmatrix} = \vec{e}_1 \vec{u}_1 + \sum_{i=2}^{M} \vec{e}_i \vec{u}_i. $$

The along-track striping noise in $\vec{e}_1$ is extracted and removed using the ensemble empirical mode decomposition (EEMD) method [25,26]. The EEMD method decomposes a time series of data into a set of mode functions with increasing frequencies. Specifically, the data in $\vec{e}_1$ $(e_{1,i}, i = 1, 2, \ldots, M)$ is decomposed into a set of “intrinsic mode functions” (IMFs) $C_m(i)$:

$$e_{1,i} = \sum_{m=1}^{L} C_m(i) + R_L(i).$$

The IMFs in the summation term in (11) are obtained from $m = 1$ to higher numbers in a step-by-step manner. When $m = 1$, set $R_{m-1} = e_{1,i}$. Identify all the local extrema (the combination of both maxima and minima) of $R_{m-1}$ and connect all these local maxima (minima) with a cubic spline as the upper (lower) envelope to obtain the local mean of the upper and lower envelopes $a_m(i)$. Then $C_m = R_{m-1} - a_m(i)$, and $R_m(i) = e_{1,i} - C_m(i)$. Set $m = m + 1$ and repeat the above procedure to obtain $a_m(i), C_m$ and $R_m(i)$. As $m$ increases,
the frequency of $C_m$ decreases. It will be shown that by subtracting the first two highest-frequency IMFs, $C_1$ and $C_2$, the along-track striping noise in the TB observations ($T_{\text{obs},1}$) at channels 2 and 3 can be removed. For channel 4, the first three IMFs ($C_1$, $C_2$, and $C_3$) must be subtracted.

4. Results of the Noise Extracted from the F17 SSMIS Observations

4.1. The Along-Track High-Frequency Noise

The FY-17 SSMIS data became available on 26 March 2008, which is more than 1.4 years from the launch date of 4 November 2006. After 9.5 years of obtaining good quality data, significant noise is found in the LAS channels from the F17 SSMIS since 20 October 2017 (Figure 2). Figure 3a shows the TB observations at channel 1 over a complete SSMIS swath. A Fourier analysis is applied to the TB data series at each fixed FOV. Variations of amplitude with respect to wave frequency for the TB variations at the 30th FOV with respect to the scanline are shown in Figure 3b for channels 1–4 and Figure 3c for channels 5–7 and 24. As expected, the amplitude of TB observations decreases with increasing frequency for all channels. However, the amplitude has a sharp spike at a frequency of $0.14 \text{ s}^{-1}$, especially in channels 1–5. We decided to remove high-frequency noise by truncating the Fourier expansion at a frequency of $0.07 \text{ s}^{-1}$, which corresponds to a wave of a period of 7.5 scanlines. In order to see more clearly what happened to TB observations by such an action, we show TB observations at channels 1–6 over a portion of the swath in Figure 3a before (Figure 4) and after (Figure 5) the above noise mitigation. We see a significantly large across-track striping noise in the TB observations at channel 1 (Figure 4), which is quite similar to those shown in Figure 2b for the data at the descending node on 20 October 2017 when this noise first appeared. The same as in channel 1, the across-track striping noise in TB observations at channels 2–4 is also extremely large, so any weather features are barely seen. The across-track striping noise still exists in TB observations in channels 5–6 but with a much smaller magnitude.

Figure 4. Cont.
Figure 4. TB observations at channels 1–6 over a portion of the swath in Figure 3a.

Figure 5. Cont.
Having removed the along-track high-frequency noise, we can clearly see some weather-related features, such as the rainband features of typhoons Lekima and Krosa. Typhoons Lekima and Krosa were located at (22.4°N, 126.2°E) and (21.8°N, 140.2°E), respectively, when the SSMIS swath passed over them at about 2157 UTC 7 August 2019. Near the two typhoon centers, the TB observations at channels 4 and 5, whose weighting function peaks at about 399 hPa and 165 hPa, respectively, are higher than their environments. We noticed a small warm anomaly in the TB observations at channel 6 at the center of typhoon Lekima, but not Krosa, which suggests a deeper Lekima.

The differences between Figures 4 and 5 are presented in Figure 6, i.e., the high-frequency (i.e., >0.07 s\(^{-1}\)) noise extracted from TB observations at channels 1–6. The noise can be larger than 15 K for channels 1–3, 1.5 K for channels 1–3, and 0.5 K for channels 5–6. It seems that the random noise is of the same magnitude as the striping noise for channels 5–6 so we see both features for these channels in Figure 6. However, the along-track high-frequency noise for channels 1–4 is dominated by an across-track striping noise, whose magnitude is 5–30 times larger than the random noise seen in channels 5–7 and 24.
Figure 6. The along-track high-frequency noise in TB observations at channels 1–7 and 24 with frequencies higher than 0.07 s\(^{-1}\).

Figure 7a shows the TB observations at channel 1 after removing the along-track high-frequency noise over the same swath as that shown in Figure 3a. After eliminating the along-track high-frequency noise (Figure 7b), the unrealistic features of the original data (Figure 3a) disappear. A quantitative examination of the TB observations before and after removing the high-frequency noise is provided in Figure 7c. The original data of the observed TB are characterized by an oscillation of a period of around 3.6 scanlines, which is effectively removed by the first procedure of our proposed noise mitigation method.
Figure 7. (a) Same as Figure 3a except for having removed (b) the across-track high-frequency noise. (c) Along-track variations of channel-1 TB observations at the 30th FOV before (grey line) and after (black line) removing the high-frequency noise.
4.2. The Along-Track Striping Noise

A careful examination of TB observations at channels 2–4 after removing the along-track high-frequency noise over a portion of the SSMIS swath in Figure 5 suggests the existence of a type of along-track striping noise. We proceed to the second procedure for the proposed noise mitigation method in Section 3. Although the along-track high-frequency noise had already been removed, the first eigenvector of TB observations at channels 2 and 3 for all the 14 SSMIS swaths on 7 August 2019 shows across-track scan-angle-dependent wavy oscillations (Figure 8a,b). The wavenumber is five, which corresponds to an oscillation period of about 12 FOVs in the across-track direction. After having removed the highest-frequency across-track noise (Figure 8c,d), the first two high-frequency across-track noises (Figure 8e,f) also show similar behavior among the 14 swaths. Such an FOV-dependent oscillation is unnatural, thus the first two high-frequency IMFs are removed. The first eigenvector of TB observations at channel 4 is different from those of channels 1, 2, and 3 (Figure 9a). The TB observations exhibit an oscillation with a period of 2 FOVs over all the 14 swaths, and unsymmetric12-FOV oscillations with larger amplitudes at the beginning of the scanlines. A total of three high-frequency IMFs is removed (Figure 9b–d).

Figure 8. (a,b) The first eigenvector $e_1$ of TB observations at channels 2 (left panels) and 3 (right panels) over the 14 swaths (gray curves) on 7 August 2019 after already removing the along-track high-frequency noise (see examples in the second and third panels in Figure 5). (c,d) Same as (a,b) except for having removed the highest-frequency across-track noise (i.e., the first IMF). (e,f) Same as (a,b) except for having removed the first two high-frequency across-track noises (i.e., the first and second IMFs). Black curve is the mean of the 14 grey curves.
The spatial distribution of the noise was removed by this second procedure and the TB observations at channels 2–4 (Figure 10) over the same portion of the swath as those in Figure 5. The along-track noise has a magnitude of about 0.5 K (Figure 10). The residual along-track striping noise seen in the TB observations at channels 2–4 after removing the along-track high-frequency noise (Figure 5) disappeared. Figure 11 displays the same along-track striping noise in TB observations at channel 1 over the entire SSMIS swath as Figures 3a and 7a. Power spectral density for channels 2 (Figure 11b), 3 (Figure 11c), and 4 (Figure 11d) along all scanlines is indicated by a black box in Figure 11a.

A power spectral density analysis (Figure 11c,d) indicates that the second procedure of the noise mitigation method eliminates signals with their wavelengths centered around 12 FOVs for channels 2–4 and weak signals with their wavelengths centered around 2 and 4 FOVs for channel 4. The main features of the eliminated noise have a fixed scale for all the scanlines, whereas those eliminated by direct smoothing of the data are different for different scanlines, demonstrating the effectiveness of the proposed method for the elimination of the line-shaped noise in the SSMIS data; however, the true signal does not project onto the first PC and is left untouched by the proposed method.
Figure 10. TB observations at channels 2–4 (left panels) and the across-track noise (right panels) over same portion of the swath in Figure 3a as those in Figure 5.
Figure 11. The along-track striping noise in TB observations at channel 1 over the same swath as Figure 3a. (b,d) Power spectral density for data noise in channels (b) 2, (c) 3 and (d) 4 along all scanlines indicated by a black box in (a). The power spectral density at the 30th scanline in (d) is also indicated by a magenta curve.

5. Discussion on Tropical Cyclone Structures Directly Visible from SSMIS Observations

The SSMIS LAS channel measurements can present tropical cyclone structures related to rain, cloud, warm core, temperature, and water vapor. For example, the SSMIS observations captured the warm-core variations of Typhoon Lekima that occurred in August 2019 over the Pacific oceans. Figure 12 shows the best track provided by the Regional Specialized Meteorological Center in Tokyo. At 0600 UTC 2 August 2019, a tropical de-
pression formed in the Pacific, east of the Philippines. At 1200 UTC 6 August, the tropical depression developed into a named typhoon Lekima and moved northwestward. It continued to strengthen and became a super typhoon at 2300 UTC 7 August 2019. At 0145 UTC 10 August, Lekima made landfall on Chengnan Town, Taizhou City, Zhejiang Province. The maximum sustained wind speed near the typhoon center was 52 m·s⁻¹ at the time of landfall. Then, the typhoon weakened to a subtropical depression at 0000 UTC 14 August 2019. The maximum surface wind speed kept increasing from 0000 UTC 4 August 4 to 1200 UTC 8 August 2019, reaching a maximum sustained wind speed of 115 m·s⁻¹. It began to weaken gradually since then. The maximum radii of the 50-kt wind increased gradually to 100 km and maintained that value during the mature stage, whereas that of the 30-kt wind increased rapidly to 350 km and then decreased a little during the stage of maximum intensity. In other words, typhoon Lekima reduced its 30-kt size to increase its rotation speed to reach the maximum sustained wind speed. The DMSP F17 SSMIS went over Lekima six times during its mature stage, which is indicated in Figure 12.

Figure 12. (a) The best track and (b) the maximum sustained wind (black), the radii of 30-kt (red) and 50-kt (blue) winds for typhoon Lekima during its lifetime from 0600 UTC August 2 to 1800 UTC August 2019. The typhoon category is indicated for tropical depression (TD), tropical storm (TS), severe tropical storm (STS), typhoon (TY), and extra-tropical cyclone (L). The SSMIS observing time along the best track is indicated by stars and dashed lines in (a,b), respectively.

An along-the-track cross-section of TB observations at the LAS channel passing through the center of typhoon Lekima at 2157 UTC 7 August 2019 is presented in Figure 13. A hurricane symbol on the bottom x-axis marks the location of the eye. Consistent with what was shown in Figure 4, the original data show a zigzag noise variation with respect
to the scanline, with large magnitudes for near-surface channels 1–3 (Figure 1). After noise mitigation, the observed TB near the typhoon eye is warmer (colder) than its surroundings above (below) 500 hPa. Subtracting the TB observations at the 80th scanline to obtain the so-called TB anomalies, we see more clearly the warm core located near 200 hPa at the 39th scanline. It is more than 6 K warmer than the 80th scanline, which is about 500 km from the center. This cross-section is along the 5th FOV, which is near the edge of the SSMIS swath (see Figure 5); the eye, warm core, and near-center structures can still be clearly seen. This is because the size of the SSMIS FOV does not change with the scan angle. It would be impossible for measurements from cross-track microwave radiometers.

Figure 12. (a) The best track and (b) the maximum sustained wind (black), the radii of 30-kt (red) and 50-kt (blue) winds for typhoon Lekima during its lifetime from 0600 UTC August 2 to 1800 UTC August 2019. The typhoon category is indicated for tropical depression (TD), tropical storm (TS), severe tropical storm (STS), typhoon (TY), and extra-tropical cyclone (L). The SSMIS observing time along the best track is indicated by stars and dashed lines in (a) and (b), respectively.

An along-the-track cross-section of TB observations at the LAS channel passing through the center of typhoon Lekima at 2157 UTC 7 August 2019 is presented in Figure 13. A hurricane symbol on the bottom x-axis marks the location of the eye. Consistent with what was shown in Figure 4, the original data show a zigzag noise variation with respect to the scanline, with large magnitudes for near-surface channels 1–3 (Figure 1). After noise mitigation, the observed TB near the typhoon eye is warmer (colder) than its surroundings above (below) 500 hPa. Subtracting the TB observations at the 80th scanline to obtain the so-called TB anomalies, we see more clearly the warm core located near 200 hPa at the 39th scanline. It is more than 6 K warmer than the 80th scanline, which is about 500 km from the center. This cross-section is along the 5th FOV, which is near the edge of the SSMIS swath (see Figure 5); the eye, warm core, and near-center structures can still be clearly seen. This is because the size of the SSMIS FOV does not change with the scan angle. It would be impossible for measurements from cross-track microwave radiometers.

Figure 13. (a) Along-track cross-sections of TB observations at channels 1–7 at the 5th FOV (indicated in the first panel in Figure 5) passing through typhoon Lekima’s center position at 2157 UTC 7 August 2019. (b) Same as (a) except for having removed the data noise. (c) Same as (b) except for having subtracted the TB observations at the 80th scanline.

The temporal evolution of the horizontal distributions of TB observations at channels 4 and 5 during the mature stage of typhoon Lekima is provided in Figures 14 and 15, respectively. There were six observing times of the SSMIS from 0938 UTC 6 August to 2309 UTC 9 August 2019. As Lekima intensified from a severe tropical storm at 0938 UTC 6 August to a typhoon at 1039 UTC 9 August 2019 (see Figure 11), both the intensity and size of the high channel-4 TB structures increased (Figure 14). It is also noticed that the observed high TB weakened at 2309 UTC 9 August 2019, which is after Lekima made landfall. The typhoon-related high TB structures are less visible from the channel-5 observations, which has its weighting function peaking at 165 hPa (Figure 15). The high TB center near the
center of Lekima has a weak intensity and small area on 6 August 2019. The channel-5 TB observations can be used to detect strong and deep typhoons.

![Figure 14](image1.png)

**Figure 14.** TB observations at channel 4 after noise mitigation at six different F17 SSMIS observing times, which are indicated on top of each panel. Also shown is the in black symbols. The best track position at the time closest to the SSMIS observations is indicated in green symbol.

![Figure 15](image2.png)

**Figure 15.** Same as Figure 14 except for channel 5, and the best track position at the time closest to the SSMIS observations is indicated in cyan symbol.
6. Conclusions

Since 2005, the SSMIS aboard the DMSP satellites has provided more than 17 years of TB observations. These observations could be used for analyzing the decadal change in the warm-core structure and intensity of tropical cyclones. They are unique for studying tropical cyclones for which radiosonde or radar observations are rarely available, especially in deep oceans. Unlike IR/VIS instruments, microwave sounders are less affected by cloud and can be used to retrieve the thermal structure of tropical cyclones. The SSMIS observations are also advantageous over those from the cross-track microwave radiometers AMSU-A, ATMS, and MWTS-2. The SSMIS observation resolution is homogeneous over the swath. The SSMIS also contains seven imager channels with a frequency at atmosphere windows, which has a high resolution for locating the typhoon eye, and is sensitive to ocean-surface wind speed, rain rate, cloud liquid water, total precipitable water, sea-ice edge, and age and soil moisture. Tropical cyclones can be analyzed with the LAS channels and the imaging channels simultaneously.

Unfortunately, since 20 October 2017, significant noise was found in the F17 TB observations of the SSMIS LAS channels that make weather-related signals unrecognizable. This reduced the reliable data length of the SSMIS for climate research. A noise-mitigation method is developed and tested to effectively remove the noise. After the noise mitigation, the typhoon-related structures are nicely captured by the SSMIS LAS channels.

It is not clear why the along- and cross-track noise suddenly appeared after years of proper operation of the instrument and what were the sources of the noise. In the future, we plan to look for possible sources of the noise and to explore the potential value of using long-term SSMIS observations for tropical cyclones in numerical weather forecasts and climate research. Significant noise has also been found in the SSMIS TB observations from FY-16 and F18 since approximately 2015 and has different characteristics to the noise reported here for F17. We may also develop appropriate noise mitigation methods for both F16 and F18. Two immediate benefits are extending the high-quality data length of the SSMIS and reducing the data void regions due to the SSMIS orbital gap from a single satellite.

Author Contributions: Conceptualization, H.D. and X.Z.; Data curation, H.D.; Formal analysis, H.D. and X.Z.; Funding acquisition, H.D.; Investigation, H.D. and X.Z.; Methodology, H.D. and X.Z.; Project administration, X.Z.; Resources, X.Z.; Writing—original draft, H.D.; Writing—review & editing, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Key R&D Program of China (2018YFC1506702).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References


