Real Time De-Striping Algorithm for Geostationary Operational Environmental Satellite (GOES) P Sounder Images

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Abstract

The images in a short wave channel of GOES P Sounder show considerable striping effects. The study shows that there are two striping characteristics. The first is the detector to detector (D2D) striping caused by the overall sinusoidal oscillation behavior across East/West scan for each detector, and the second is the scan to scan (S2S) striping due to the overall differences between the East to West (E2W) and West to East (W2E) scan directions of a detector. A real time de-striping algorithm is presented in this paper, and it corrects both D2D and S2S striping on a scan to scan basis to minimize the impact to the latency requirement of the data processing in the ground system. The results show that the de-striping algorithm has been very effective in correcting both D2D and S2S stripings and efficient for the real time data processing.

1. Introduction

The Sounder instrument is one of the major scientific instruments on GOES[1]. It is a 19 channel radiometer with 18 infrared (IR) channels and 1 visible channel that senses the specific data parameters for atmospheric vertical temperature, moisture profiles, surface and cloud top temperature, and ozone distribution. There are 4 detectors in each channel evenly distributed in North/South direction with the detectors 1 and 3 aligned in one group and the detectors 2 and 4 aligned in the other group. The two groups are separated by 1120 µrad in East/West direction, which corresponds to 4 pixels separation. The Sounder data generation is scan based; each scan along East/West direction generates four lines for four detectors sensing simultaneously in each channel. The line id in a scan corresponds to the detector id. The scan directions alternates between East to West (E2W) and West to East(W2E) moving from North to South. The GOES P Sounder operation runs a fixed daily schedule, and it generates 2 images each hour with the daily fixed image starting times at the same geo-locations.

If the responses of detectors in a given channel to incoming signals are different, it creates the spatial non-uniformity on images, which is also referred as the image striping. The image striping creates data variations from one line to the next that are not part of the scene. It has been prominent in the short wave channel 15 images of GOES P Sounder, and it degrades the data quality and radiometric accuracy. Therefore, a de-striping algorithm to be implemented in the ground system is necessary to maintain the data quality.

The image striping is quite common in IR imaging with multiple sensors, and there have been very extensive discussions of de-striping algorithms in the literature[2]. It is also quite common

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in the spacecraft IR imaging[3, 4]. The de-striping algorithms are generally classified as calibration based and scene based. For the satellite IR data, the de-striping algorithms are scene based algorithm as the data calibration are part of the normal spacecraft instrument operations. For GOES P Sounder, the calibration for the data in Sounder IR channels are performed with the periodic sensing of the space data and the internal blackbody data for the temperature baseline.

The focus of this paper is to present a real time de-striping algorithm implemented in GOES ground system. The striping on GOES P Sounder images can be characterized by D2D and S2S stripings. The D2D striping are caused by sinusoidal oscillations across East/West scan of each detector in channel 15, and the S2S striping comes from an overall differences between E2W and W2S scan directions for each detector. The real time de-striping operations to correct both D2D and S2S striping has its own challenges. It requires that the de-striping algorithm not only be effective, but also be efficient so that it has minimum impact to the latency requirement of the real time data processing. Since GOES Sounder data processing is done on scan by scan basis, the real time de-striping operation has also to be made on scan by scan basis. This makes it impossible to use the traditional scene based striping correction approaches, which generally requires the whole image available before the corrections are made.

This paper is organized as following; section 2 discusses the characteristics of the image striping on GOES P Sounder images, section 3 presents the real time de-striping algorithm, section 4 presents the implementation and the results of the de-striping algorithm, and finally, the summary is presented on section 5.

2. The Striping Characteristics for GOES P Sounder Images

The optical responses of a sensor to the incoming signals in an image can be characterized by its histogram, and it is more convenient to use the accumulated histogram. For GOES P Sounder images, the responses to the incoming signals is not only dependent on the detector i, but also on the scan direction d. Therefore, the accumulated histogram is defined as

$$H_{i,d}(k) = \frac{1}{N_{i,d}} \sum_{l=0}^{k} \left(\sum 1 \in (l,i,d) \right)$$ [1]

where the first sum is to count the number of pixels with the value l for the detector i and the scan direction d, and the second sum is over the pixel value l. The parameter $N_{i,d}$ in Eq. 1 is the total number of the pixels in an image for the detector i and the scan direction d. The accumulated histogram starts at 0 and approach to 1 when the pixel value k reaches the maximum value of the image. It represents the percentage of the pixels with value less than k in an image. If there are stripings in a GOES P Sounder image, the histogram $H_{i,d}(k)$ diverges for different detectors with different scan directions. The divergence of the histogram can be characterized as the horizontal distances among the different histograms:

$$g_{i,d,i',d'}(P) = k - k'$$ [2]

where

$$H_{i,d}(k) = H_{i',d'}(k') = P \qquad [3]$$

The larger $g_{i,d,i',d'}(P)$ among the different histogram corresponds to the stronger striping effects. Generally, the striping term $g_{i,d,i',d'}(P)$ is a function of the pixel value k in Eq. 2. A common approach for de-striping algorithms is to transform different histograms $H_{i,d}(k)$ into a single reference histogram[2]. This approach has its own limitations. A histogram for an image can only be built when the whole image is available, thus, makes it impossible to use it in the real time operations. Furthermore, the histogram approach requires stripings to be independent of image coordinates, and this is not the case for the striping in GOES P Sounder images.

Figure 1 shows a typical Sounder channel 15 image for GOES P and its accumulated histograms. The accumulated histograms for detectors with different scan directions diverges considerably, Both D2D and S2S stripings are present in this image. The D2D striping features the line by line variation, and the S2S striping has the variation pattern in every 4 lines. An important characteristics in Figure 1 is that the striping term $g_{i,d,i',d'}(P)$ is approximately constant for most the pixel value k except when the value P of the accumulated histogram is approaching 1 or 0. Therefore, the de-striping presented in this paper assumes that the striping term $g_{i,d,i',d'}(P)$ is independent of the pixel value k.

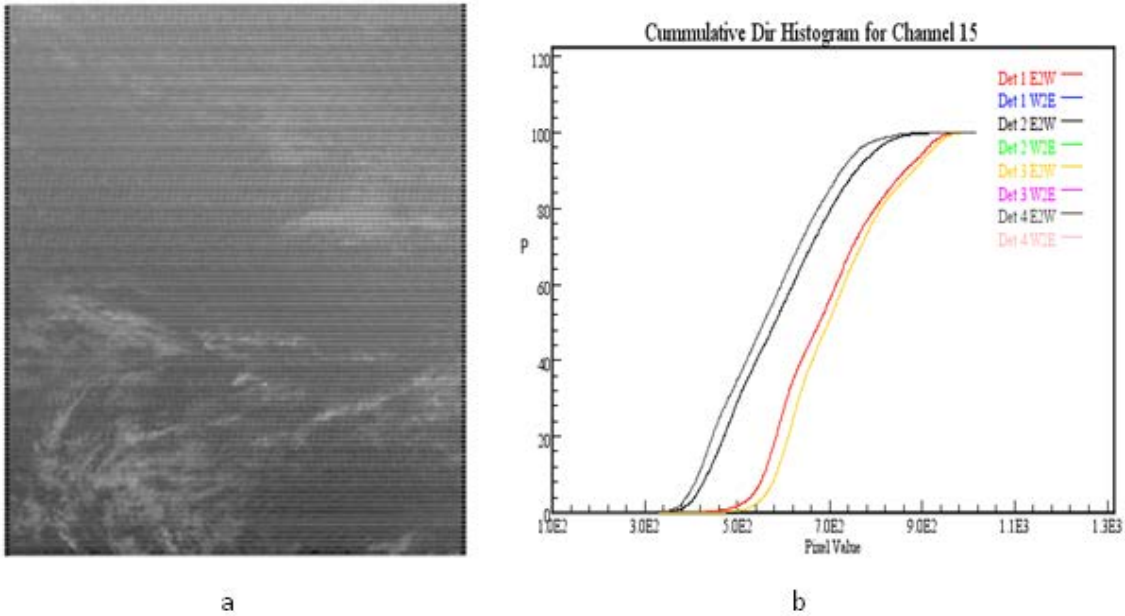a   b

Figure 1 the Striping in GOES P Sounder Channel 15 Images (a), and its accumulated histogram (b). The quantity p is the percentage of the pixels with the value less than the pixel value in x-axis.

The space scans provide an ideal place to investigate the dependence of D2D striping on the East/West coordinates, since the space data are expected to be constant and location independent. Figure 2 shows the space scan data as the function of the East/West coordinate for the four detectors in channel 15, which exhibits the considerable oscillation pattern that are the artifacts

of the detector scan motions. The oscillation pattern for the detector i in Figure 2 can be described by the following expression:

$$G^i(x) = A_0^i + A_1^i \sin\left(\frac{2\pi(x + \varphi^i)}{\lambda}\right)$$ [4]

The second term in Eq. 4 are the artifacts generated by the detector scan motions, which leads to the D2D striping. The wavelength λ is found to be 350 pixels. It is also found that the detectors 1 and 3 have the same phase, and so do the detectors 2 and 4. The phase for detector 1 and 3 are related to that of detectors 2 and 4 by

$$\varphi^{i=1} = \varphi^{i=3} = \phi^{i=2} + \frac{1}{2} = \varphi^{i=4} + \frac{1}{2} \ .$$ [5]

Because the phases for the detector 1 and 3 differ from the phase of the detectors 2 and 4 by 180 degrees, the maximum values for detectors 1 and 3 corresponds to the minimum values for detector 2 and 4 at the same location. This leads to the maximum of the difference between the pixel values of two neighboring detectors, which corresponds to the maximum D2D striping. Furthermore, the data show that all four detectors have approximately the same amplitudes A_1^i in Eq. 4, which makes it easier for the striping removal.
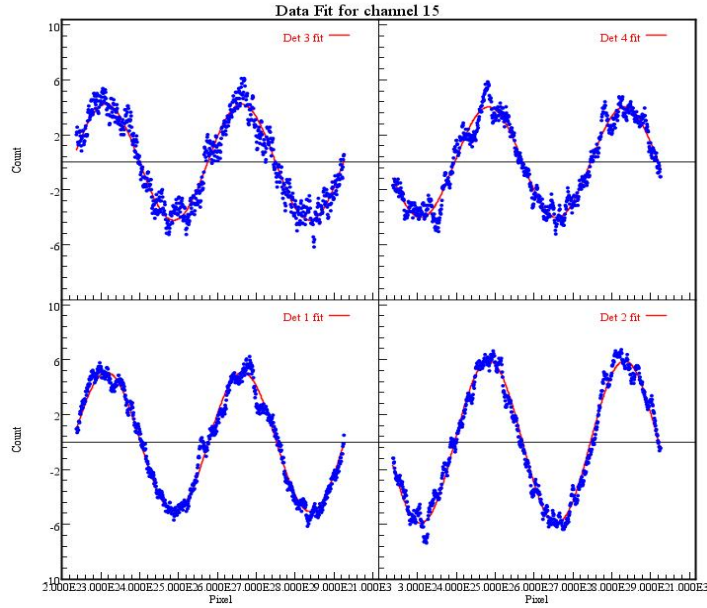

Figure 2 Space scan values for 4 detectors, with phases for detectors 1 and 3 are different from the phases of detector 2 and 4 by 180 degrees.

The D2D striping affects the D2D performance metric, which is defined as the absolute values of the temperature difference between different detectors in an image

$$M_{i,j}^D = \frac{1}{N_d}\left|\sum_k T_i(k) - \sum_k T_j(k)\right|.$$ [6]

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The variable N_d in Eq. 6 is the number of pixels for a detector in an image, and it is the same for all 4 detectors. The GOES Sounder data are distributed with GOES Variable (GVAR) format, and the temperature for a pixel is derived from GVAR data[5]. The performance requirement for D2D metric for an image is less than 0.15 degrees. Figure 3 shows D2D metric for GOES P Sounder channel 15 images in less than 3 days period. The data shows that the D2D metric is small for $M_{1,3}^D$ and $M_{2,4}^D$, as they have the same phase in Eq. 4 so that the differences between these detectors are small, while other metrics are generally very large. The D2D striping is more prominent for about 12 hours per day with the maximum value around 6 degrees. The D2D metric is time dependent, however, the metric value has a 24 hour periodic behavior, which is due to the fact that GOES P Sounder operation operations run a fixed daily schedule. This shows that D2D striping is stable from one day to the next.

The S2S striping is due to an overall difference of a detector between E2W and W2E scan directions. This feature is generally location independent in an image and time dependent. The S2S striping impacts the detector S2S performance metric, which is defined as

$$M_i^S = \frac{1}{N_d}\left|\sum_k T_i(k \in E2W) - \sum_k T_i(k \in W2E)\right| \qquad [7]$$

for the detector i, where N_d is the total number of pixels for a detector in a scan direction.
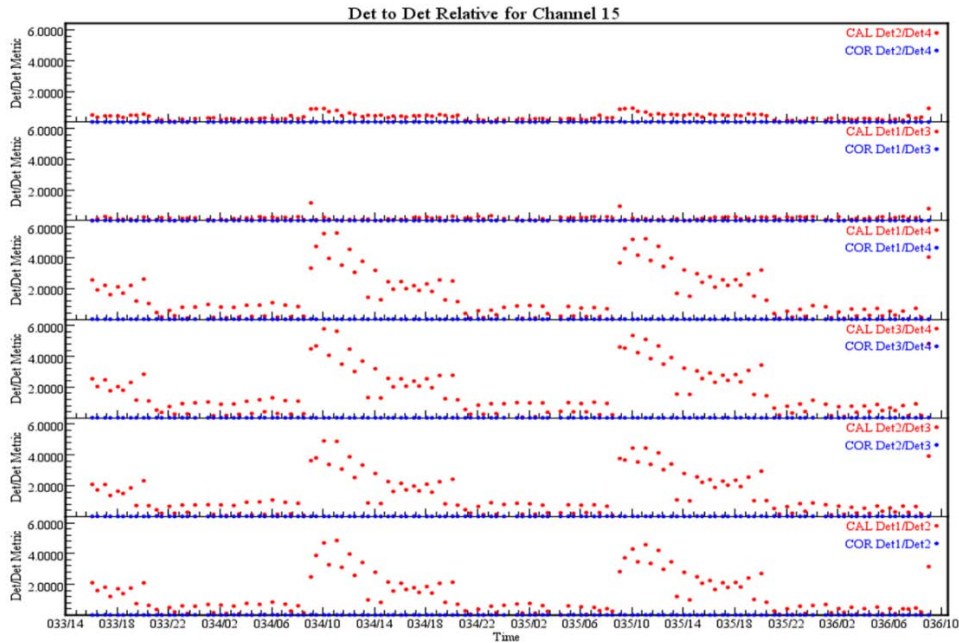

Figure 3. the D2D metric for Sounder Channel 15 Images in 68 hours period. The data with the red dot are the D2D metric value for the images without striping correction, and the data with blue dot are the D2D metric value after the striping correction. See Section 4 for the detailed discussion of the results.
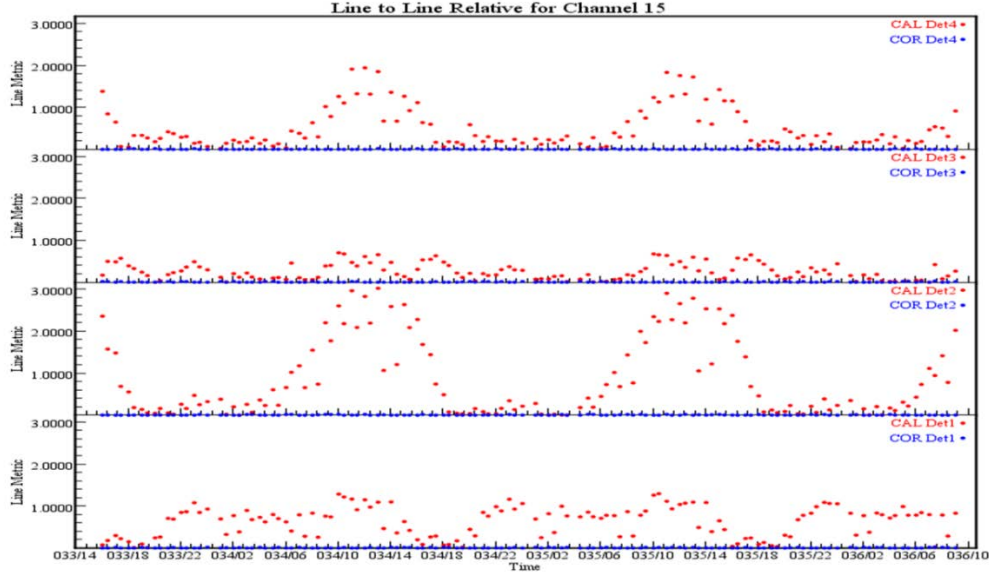
Figure 4. the S2S Metric for Sounder Images over about 3 days period. The data with red dot are the S2S metric value for the images without striping correction, and the data with blue dot are the S2S metric value after the striping correction. See Section 4 for the detail discussion of the results.

Figure 4 shows the time dependence of S2S metric for each detector in channel 15 images. The performance requirement is that S2S metric be less than 0.15 degree for an image. The data shows that S2S metric for channel 15 image is far exceeding the requirement, especially for detector 2 and 4. An important characteristic for S2S metric is that it is relatively stable for an image at a given time of the day, which is partly due to the fact that the GOES Sounder imaging operates at a fixed daily schedule. This makes the real time de-striping possible for an image by using the information retrieved from the previous the image at the same time but in previous day.

3. The De-Striping Algorithm

Generally, the value $G_{i,d}(x)$ of the Sounder calibrated data for the detector i with the scan direction d at the coordinate x in a scan can be written as

$$G_{i,d}(x) = G_{i,d}^{s}(x) + g_{i,d}(x) \quad [8]$$

where $G_{i,d}^{S}(x)$ is the scene value with random noises and $g_{i,d}(x)$ is the contribution from both D2D and S2S striping:

$$g_{i,d}(x) = g_{i,d}^{D}(x) + g_{i,d}^{S} \quad [9]$$

The D2D striping $g_{i,d}^{D}(x)$ in Eq. 9 is proportional to the second term in Eq. 4

$$g_{i,d}^{D}(x) = A_d \sin\left(\frac{2\pi(x+\varphi^i)}{\lambda}\right) \quad [10]$$

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The D2D metric data in Figure 3 suggest that the amplitudes A_d in Eq. 10 are approximately independent of the detector id, and the dependence of the D2D striping on the detector id mainly comes from the phase factor φ^i Eq. 10. The S2S striping term $g_{i,d}^S$ in Eq. 8 is independent of the image coordinate x, which is treated as a constant in an image. It should be pointed out that the striping function $g_{i,d}(x)$ is also generally the function of time t_j, which is the daily start time of the j-th image. The time dependence of the striping function will be discussed for the S2S correction.

Define an offset function for a scan as

$$G_d^O(x) = \frac{1}{4}\left(G_{1,d}(x) + G_{3,d}(x) - G_{2,d}(x) - G_{4,d}(x)\right) \tag{11}$$

Because of Eq. 4, the offset function $G_d^O(x)$ can be written as

$$G_d^O(x) = G_d^{OS}(x) + g_{i,d}^{OS} + A_d \sin\left(\frac{2\pi(x+\varphi^1)}{\lambda}\right), \tag{12}$$

where

$$G_d^{OS}(x) = \frac{1}{4}\left(G_{1,d}^S(x) + G_{3,d}^S(x) - G_{2,d}^S(x) - G_{4,d}^S(x)\right), \tag{13}$$

and

$$g_{i,d}^{OS}(G) = \frac{1}{4}\left(g_{1,d}^S(G) + g_{3,d}^S(G) - g_{2,d}^S(G) - g_{4,d}^S(G)\right), \tag{14}$$

The offset function $G_d^O(x)$ enhances the contributions from the D2D striping term and minimizes the contributions from the $G_d^{OS}(x)$ term. Generally, the term $G_{i,d}^S(x)$ represents the scene of an image, and it should be dominated by the long wavelength component. The long wavelength components in $G_{i,d}^S(x)$ should be very similar from one line to the next so that they are canceled in the offset term $G_d^{OS}(x)$, which leaves the short wavelength term that depends on the local scene or the noises. Since the wavelength λ for the D2D striping is 350 pixels, that is generally larger than the typical width of the GOES15 Sounder images, the long wavelength components in the offset function $G_d^O(x)$ are dominated by the D2D stringing term. This makes it possible to extract the D2D striping term from Eq. [12] using the Discrete Cosine Fast Fourier Transformation,

$$g_d^{OD}(x) = \sum_{k=0}^{N} w_k^D g_k^O \cos\left(\frac{\pi k x}{N}\right) \tag{15}$$

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where the Fourier component g_k^O is the Fast Fourier Transformation (FFT) of the offset function $G_d^O(x)$

$$g_k^O = \frac{2}{N}\sum_{x=0}^{N}w_k G_d^{OF}(x)\cos\left(\frac{\pi kx}{N}\right), \quad w_k = \begin{cases} 0.5 & k = 0, N \\ 1 & 0 < k < N \end{cases}. \qquad [16]$$

Since the FFT requires $N = 2^m$ so that the Offset function $G_d^{OF}(x)$ in FFT is related to the offset function $G_d^O(x)$ with the dimension M as

$$G_d^{OF}(x) = \begin{cases} G_d^O(x) & 0 \le x < M \\ G_d^O(2N - x - 1) & M \le x < N/2 \\ G_d^{OF}(M - x - 1) & N/2 \le x < N \end{cases} \qquad [17]$$

where

$$N = 2^m \text{ and } m = INT\left(\frac{\log M}{\log 2}\right) + 2 \qquad [18]$$
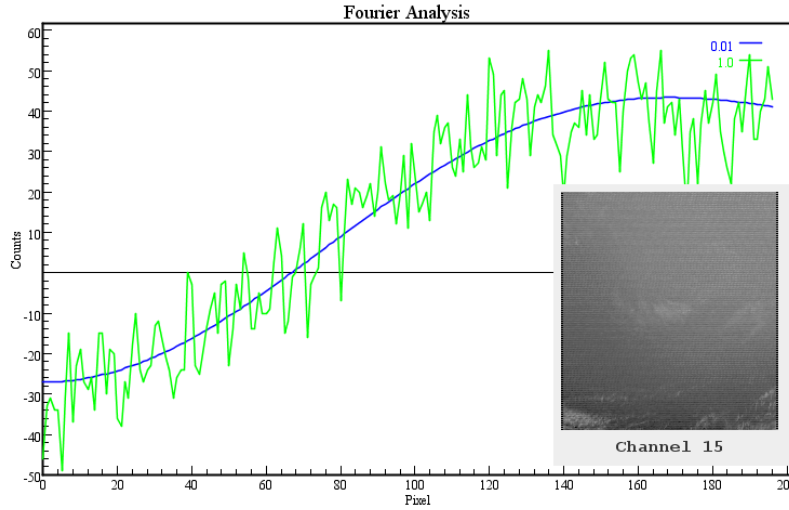

Figure 5 The Offset Functions for a typical scan in channel 15 image, which is also shown. The green line represents the raw value of the offset function. The blue line represents the D2D striping function extracted from the offset function. The size N=512, which corresponds to the 5 FFT components Eq. 15.

The weight factor w_k^D in Eq. [15] is

$$w_k^D = \begin{cases} w_k & k \le INT\left(\frac{2N}{175}\right) \\ 0 & k > INT\left(\frac{2N}{175}\right) \end{cases} \qquad [19]$$

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so that the variable g_d^{OD} contains only the very long wavelength component of the offset function so that the contributions from the scene $G_d^{OS}(x)$ are minimized or eliminated. This corresponds to the threshold wavelength 175 pixels, which is typically more than half of the width of a typical GOES 15 Sounder image. The simulations show that this threshold provides a very good approximation of the sine function in Eq. 10 in FFT.

Figures 5 and 6 shows the examples of the offset function $G_d^O(x)$ for two typical channel 15 images at two different geo-locations. The result shows that the offset function $G_d^O(x)$ for two images are indeed dominated by the D2D striping function in the long wavelength component, while the contributions to the function $G_d^{OS}(x)$ in Eq. 9 is mostly present in the short wavelength region, which are either from the scene in the image or from the noises that are shown to be significant. The main differences between Figures 5 and 6 are the phases of the D2D striping function are different, since the two images represents the different areas on Earth.
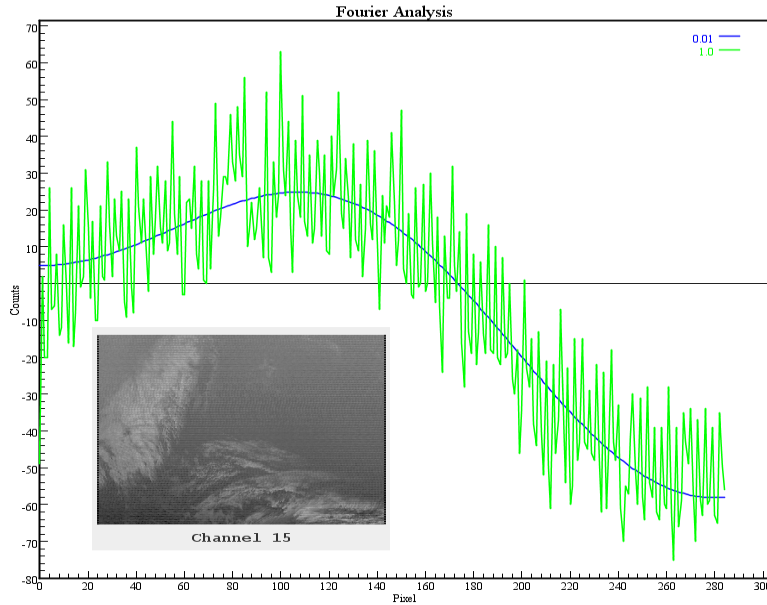

Figure 6. the offset function and the D2D striping function for another channel 15 image corresponding to different geo location on Earth. The size N=1024 corresponding to 11 FFT components in Eq. 11.

After the D2D striping function is determined for a scan in an image, the D2D striping corrections are made with the following formula:

$$G_{i,d}^d(x) = G_{i,d}(x) + \begin{cases} -g_d^{OD}(x) & i = 1,3 \\ g_d^{OD}(x) & i = 2,4 \end{cases}$$ [20]

The D2D striping corrected functions $G_{i,d}^d(x)$ have the same mean value for the whole as the uncorrected function $G_{i,d}(x)$ for the whole image. Generally, the function $g_d^{OD}(x)$ in Eq.15 also

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contains the contributions from the S2S striping, as the cosine FFT contains a constant term. Thus, the S2S striping function will also be corrected by the function $g_d^{OD}(x)$ so that the D2D striping corrected function $G_{i,d}^d(x)$ can be written as

$$G_{i,d}^d(x) = G_{i,d}^s(x) + g_{i,d}^{Sd} \qquad [21]$$

where the second term is an effective S2S striping after the D2D striping correction.

To obtain the effective S2S striping $g_{i,d}^{Sd}$, one can average the D2D corrected function $G_{i,d}^d(x)$ in Eq. 21 so that

$$\frac{1}{N_{i,d}} \sum_x G_{i,d}^d(x) = \frac{1}{N_{i,d}} \left(\sum_x G_{i,d}^S(x) + \sum_x g_{i,d}^{Sd} \right) \qquad [22]$$

Eq. 22 can be written as

$$g_{i,d}^{Sd} = M_{i,d}^d - M \qquad [23]$$

where

$$M_{i,d}^d = \frac{1}{N_{i,d}} \sum_x G_{i,d}^d(x) \qquad [24]$$

is the average value for the detector i with the scan direction d in an image, and

$$M = \frac{1}{N} \sum_{x,i,d} G_{i,d}^d(x) = \frac{1}{N_{i,d}} \sum_x G_{i,d}^S(x) \qquad [25]$$

is the average value for the whole image. We assume that the average value for the scene $G_{i,d}^S(x)$ is independent of the detector and scan direction indices, i, and d, and equals to the average value M of the whole image. Furthermore, it is required that the average value M for the whole image remains unchanged after the striping corrections are made.

Eq. 23 cannot be used directly in the real time striping correction, since it needs the whole image in the buffer to retrieve the effective S2S striping term that cannot be done on scan by scan basis. Because the S2S metric shows 24 hour periodical behavior, one could extract the S2S striping term $g_{i,d}^{Sd}$ from the images in the previous days and apply the correction to the image at the same time of the day. Figure 7 shows that the time dependence of the effective S2S striping term over the 5 days period. The data are retrieved from the images after the D2D striping corrections are made. If we consider the effective S2S striping $g_{i,d}^{Sd}$ as the function of time, the data in Figure 7 suggest the following relation

$$g_{i,d}^{Sd}(t_j) = g_{i,d}^{Sd}(t_j - T_0) \qquad [26]$$

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where $g_{i,d}^{Sd}(t_j)$ is the effective S2S striping term for the daily j-th image with the start time t_j, and $T_0 = 24$ hours. To reduce the noises in the effective S2S striping value, the average of the S2S striping value in the previous 2 days are used in the S2S striping correction:

$$g_{i,d}^{Sd}(t_j) = \frac{1}{2}\left(g_{i,d}^{Sd}(t_j - T_0) + g_{i,d}^{Sd}(t_j - 2T_0)\right) \qquad [27]$$

Therefore, the effective S2S striping term used in the striping correction can be obtained from the images at the same time of day in the previous 2 days. Before the S2S striping is corrected, the data are collected for each scan used to calculate the mean values in Eqs. 24 and 25. At the end of each image, these mean values are calculated. The effective S2S striping terms in Eq. 23 are obtained for the whole image, and stored in the data buffer to be used for the image at the same time in the following day.
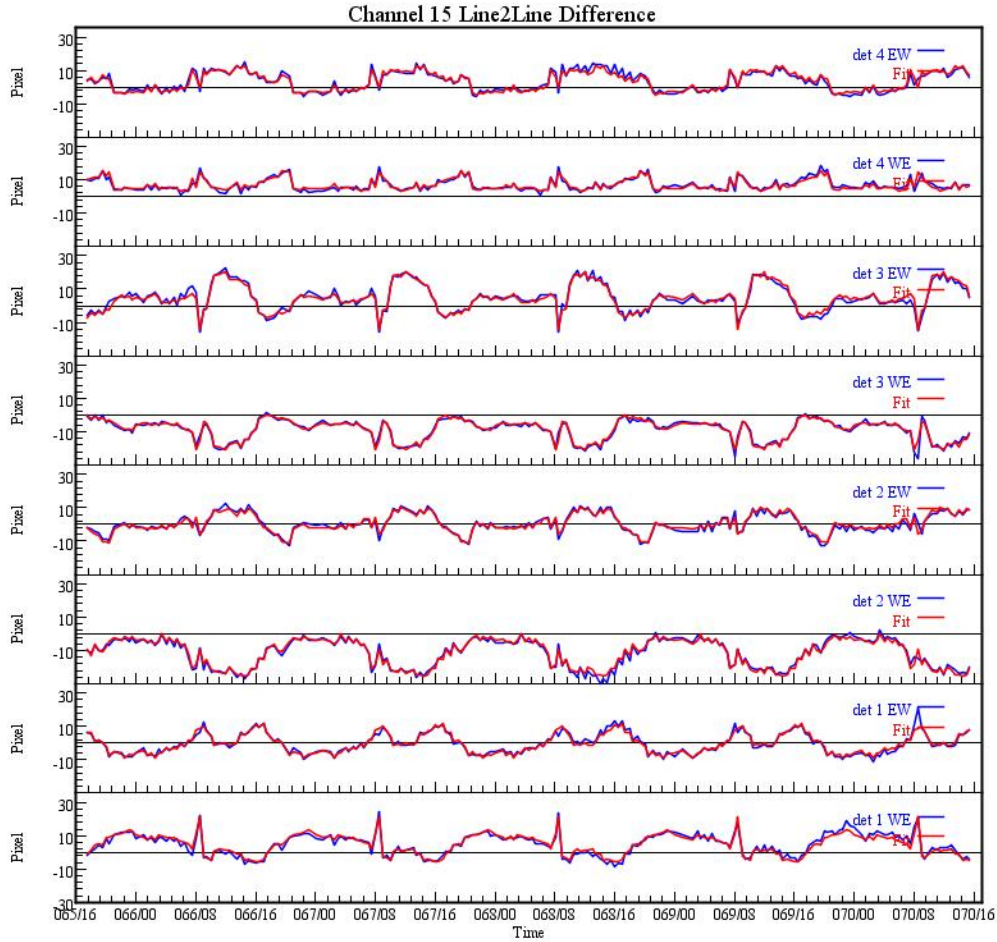

Figure 7 the effective S2S striping $g_{i,d}^{Sd}$ over 5 day's period for 4 detectors in channel 15 and E2W and W2E scan directions. The blue line is the retrieved data from the images after the D2D corrections are made. The red line represents the average value of the images at the same time of the day over the 5 days period.

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4. Implementation and Results

The implementation of the de-striping algorithm starts with the D2D striping corrections and follows by S2S striping corrections. The corrections are made on scan by scan basis with the following steps:

1. Retrieving the offset function in Eq. 11 from the scan data.
2. Calculate the Fourier spectrum of the offset function using Eqs. 16, 17, and 18.
3. Obtain the D2D striping function using Eq. 15.
4. Apply the D2D striping correction in Eq. 20.
5. Collecting the data for each detector and scan directions for each scan used to calculate the mean values in Eqs. 21 and 22.
6. Apply the effective S2S correction by subtracting $g_{i,d}^{s}(t_j)$ in Eq. 27 from the D2D striping corrected function $G_{i,d}^{d}(x)$.
7. At the end of each Sounder image, calculate the mean values of the image in Eq. 24 and 25 to obtain the effective S2S striping term in Eq. 23 and store it in a buffer to be used for the image next day in the same time.

The buffer for the effective S2S striping terms is a 2x48x8 element array. There are 8 effective S2S striping terms for each image corresponding to the 4 detectors with E2W and W2E scan directions. The image index is derived from the image start time. For example, the image start time at 06:30 Z corresponds to the index 13. The cosine FFT algorithm comes from Ref. [6], and the de-striping algorithm is implemented in both Java and c platform. The GOES P Sounder operation generates 47 images daily with the image start time at roughly on every hour and half hour. After the data in each scan are calibrated in the ground system, the de-striping algorithm for channel 15 scan data is invoked. The output of the de-striping algorithm are packed directory to the GVAR data, and rebroadcast to users. GVAR data also contains the un-calibrated raw data, which is not affected by the de-striping algorithm. The algorithm is very efficient, and has no the impact to the latency requirement of the Sounder data processing.
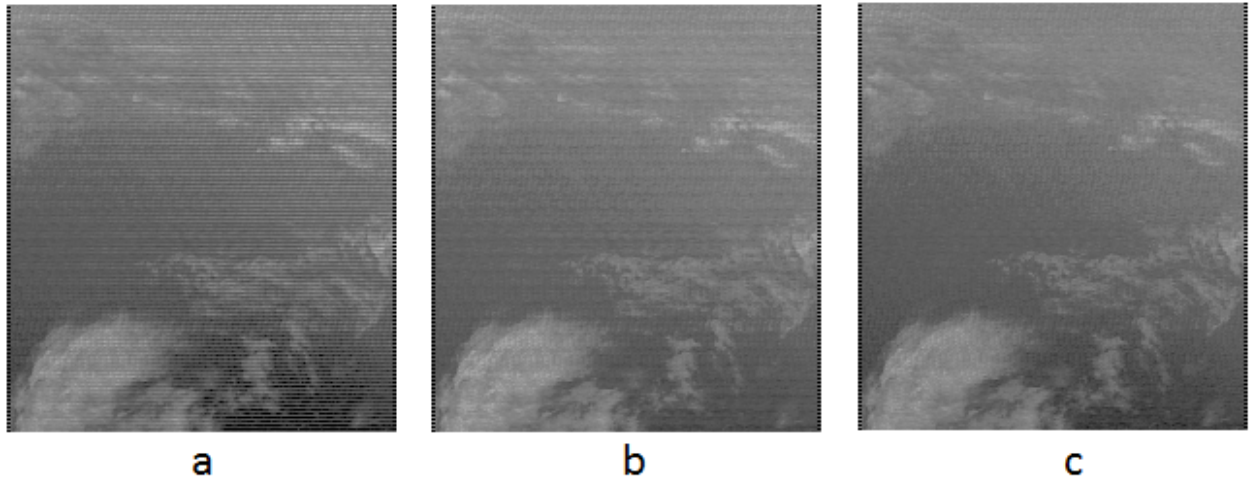

Figure 8 the uncorrected image (a), the D2D striping corrected image (b), and the S2S striping corrected image (c).

Figure 8 should the uncorrected, D2D striping corrected, and S2S striping corrected images. Both D2D and S2S stripings have a very significant presence in the image. After the D2D striping correction are made, the S2S striping in Figure 8-b is still significant. Figure 8-c is the S2S corrected image with the average of the effective S2S striping term from the previous two days. The striping effects in Fig. 8-c is no-longer visible, and this shows that the approach for the S2S striping is very effective.

Figure 9 shows the corresponding accumulated histogram for the images in Figure 8. The accumulated histograms provide a measure of the effectiveness of the de-striping algorithm. The striping effects in Fig 8-a have a very diverse accumulated histogram for detectors with different scan directions, which is very similar to the histogram in Figure 1. Both D2D and S2S stripings are present in the image. The histograms converges significantly in Fig. 9-b after the D2D striping corrections are made. However, the S2S striping is still significant, and the divergence of the histograms has not been totally removed. After the S2S striping correction, Fig. 9-c shows that most of divergence in accumulated histogram has been removed.

The striping corrections improves the D2D and S2S metrics considerably, which are shown in Figure 3 and 4. Both D2D and S2S performance metrics are mostly within the requirement range after the striping corrections are made. This shows that the de-striping algorithm is providing a systematic striping removal for all GOES P Sounder channel 15 images.
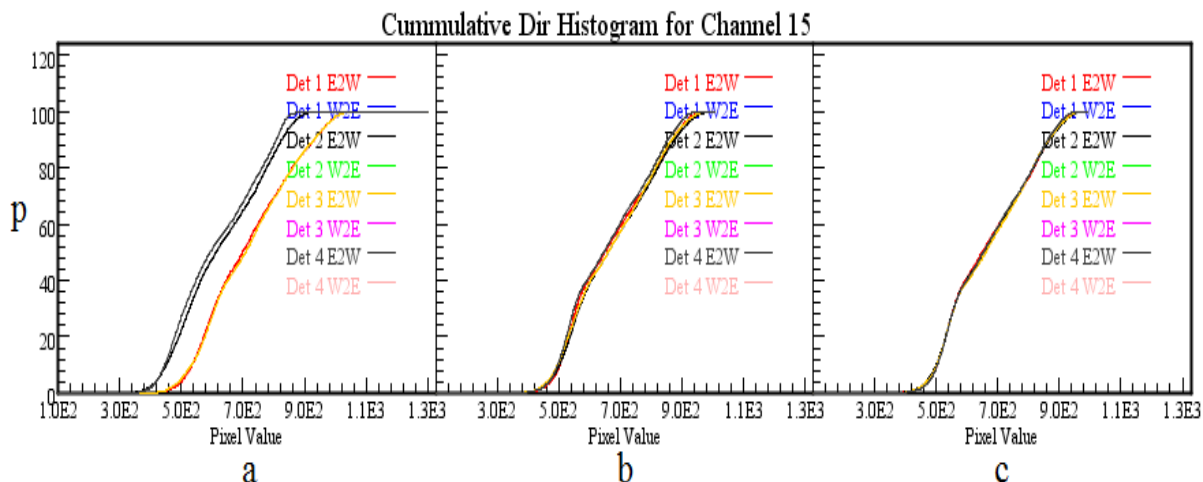

Figure 9, the accumulated histograms f or Fig. 8-a (a), Fig. 8-b (b) and Fig. 8-c (c)

5. Summary

The striping in GOES P Sounder channel 15 images shows both D2D and S2S striping characteristics. A real time de-striping algorithm presented here corrects both D2D and S2S stripings on scan by scan basis to minimize the impact on the latency requirement of the Sounder data processing in GOES ground system. The D2D striping component is concentrated in the high wavelength components in the offset functions, and it is extracted using the FFT algorithms. The S2S striping is independent of the pixel coordinate, and shows a 24 hours periodical

behavior. It is obtained from the difference between the mean value of a detector with scan direction in an image and the mean value of the whole image. It is found that the S2S striping term remains mostly unchanged for the images with the same time from one day to the next. For the real time S2S striping correction, the S2S value applied to the image is the average of the S2S striping value in previous two days.

The results show that the de-striping algorithm is effective and efficient, and the correct images meet the performance requirements for D2D and S2S metrics. The de-striping algorithm has been implemented in GOES ground system, which has gone through the functional, data validation and radiometric validation tests. It has become operational in GOES ground systems.

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