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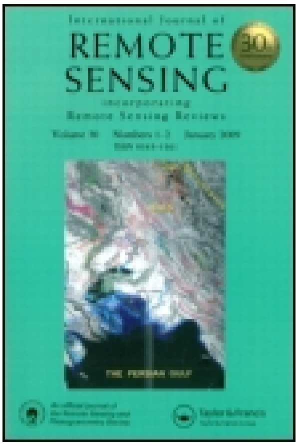

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A piece-wise approach to removing the nonlinear and irregular stripes in MODIS data

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A piece-wise approach to removing the nonlinear and irregular stripes in MODIS data

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As a result of imaging acquisition conditions, Moderate Resolution Imaging Spectroradiometer (MODIS) imagery suffers from nonlinear and irregular striping. The nonlinear stripes are those whose degradation parameters change with the ground objects, and the irregular stripes are those in which only some of the pixels are contaminated. These kinds of stripes result in great difficulties for conventional statistical destriping methods. To deal with these problems effectively, we propose a piece-wise destriping method. This approach divides the recognized defective rows into different portions by the local statistical and mean curve information. The destriping is then performed in each portion, based on the different correction coefficients, with a neighbouring normal row as a reference. Experimental results demonstrate that the proposed algorithm can effectively destripe MODIS data.

1. Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a cross-track scanning radiometer that uses a double-sided scanning mirror to view on-board calibrators and the earth (Rakwatin, and Takeuchi, and Yasuoka 2009). Many bands of MODIS images contain periodic and/or random stripes, which is a very common problem for instruments based on a sensor array (Di Bisceglie et al. 2009). Stripes lead to significant radiometric uncertainties in reflectance and radiance data. Hence, without correction, stripes will create problems in higher-level remote sensing products such as the normalized difference vegetation index, land surface temperature, etc.

MODIS data are affected by three kinds of striping noise: detector-to-detector stripes, mirror-side stripes, and noisy stripes (Rakwatin, and Takeuchi, and Yasuoka 2007). In this article, we are concerned with the removal of detector-to-detector stripes, which are mainly caused by inaccurate calibration of the relative gain and offset of each detector. Another reason for detector-to-detector stripes is that photomultipliers are nonlinear and have a response which depends on their exposure history (Rakwatin, and Takeuchi, and Yasuoka 2007).

In the literature, various methods have been explored to remove striping noise in remotely sensed images. The common destriping methods can be divided into several categories. The first category is the frequency domain methods. Due to its periodic characteristic, striping noise can be extracted by frequency information using spectral analysis and removed with an adequate low-pass filter or finite impulse response filter in the Fourier domain. This approach was first researched by Srinivasan and White (1988), and has since been adopted and improved

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*Corresponding author. Email: shenhf@whu.edu.cn by various different researchers (Crippen 1989; Pan and Chang 1992; Simpson, Gobat, and Frouin 1995). Instead of the employment of the Fourier transform, Yang, Menzel, and Frey (2003) removed the stripes in MODIS images using wavelet shrinkage.

Another category is the statistical destriping methods, which examine the distribution of digital numbers for each sensor and adjust these distributions to a reference distribution. This type of approach assumes that the distribution of each detector is valid, even though the gain and offset are significantly distorted. The typical statistical destriping methods are moment matching (Gadallah, Csillag, and Smith 2000), histogram matching (Horn and Woodham 1979), and the equalization method (Corsini, Diani, and Walzel 2000; Antonelli et al. 2004). Inspired by these methods, Rakwatin, and Takeuchi, and Yasuoka (2007) proposed an improved histogram matching method for the removal of stripes in MODIS data.

The variational methods (Shen and Zhang 2009; Bouali and Ladjal 2011; Yuan, Zhang and Shen 2012, 2013) are a class of destriping algorithms which have been the subject of recent discussion, and they have been successfully applied to the destriping of MODIS data (Shen and Zhang 2009; Bouali and Ladjal 2011). These methods repair the striped remote sensing images by introducing regularization methods into the calculation of the image solution model, and obtain the desired image by employing an optimization method. This class of algorithms can effectively make use of the neighbouring pixels as an *a priori* constraint of the image, and have produced desirable results.

Comparatively speaking, the most direct destriping techniques are the frequency domain methods, but they always result in obvious smoothing and ringing artefacts. The variational methods produce good results in terms of both the quantitative and qualitative evaluation; however, the high computational cost makes them inappropriate for batch data processing. The statistical destriping methods are the most widely utilized because they have a better balance between efficacy and efficiency; however, they produce desirable results only when the stripes are regular and the degradation is linear.

In several bands of MODIS data, however, there are nonlinear and irregular stripes. The nonlinear stripes are those whose degradation parameters change with the ground objects, and the irregular stripes are those in which only some of the pixels are contaminated. The traditional statistical destriping approaches cannot effectively remove such irregular and nonlinear stripes. In view of this, this letter proposes a piece-wise statistical destriping approach to deal with nonlinear and irregular stripes in MODIS data. Considering the causes and characteristics of nonlinear and irregular stripes, a combined piece-wise strategy that considers the local statistical and mean curve information is proposed, and the defective rows are processed using local correction coefficients in each portion. The proposed method is quantitatively evaluated using two metrics: the inverse coefficient of variation (ICV) and the ratio of noise reduction (NR).

2. The destriping algorithm

2.1. The moment matching destriping method

The common causes of stripes are the differences between forward and reverse scanning, the variations in calibrations across the sensor array in multisensory instruments, and dropped lines during scanning (Fuan and Chen 2008). Statistical algorithms are the most widely used approach for the elimination of common stripes in remotely sensed images. The moment matching method and the histogram method are the typical representative methods. According to analyses of experimental results in MODIS data (Shen and Zhang 2009), the performances of moment matching and histogram matching are similar.

However, moment matching is more easily implemented than histogram matching, and is therefore employed as the basis of the destriping method in this article.

Moment matching assumes that sensors differ only in gain and offset, and that there is a linear relationship between them (Gadallah, Csillag, and Smith 2000). This approach is achieved by examining the distribution for each sensor, and adjusting these distributions to a reference distribution. It is calculated as

$$Z_{x,y} = (g_{x,y} - B_x)/A_x, \tag{1}$$

where $g_{x,y}$ and $z_{x,y}$ denote the values before and after the destriping at location (x, y), respectively, and A_x and B_x are the corresponding relative gain and offset parameters of the x line. According to the assumption of moment matching, the relative gain and offset parameters are calculated by the following formula:

$$\begin{cases} A_x = \dfrac{\sigma_x}{\sigma_r} \\ B_x = \mu_x - \mu_r \dfrac{\sigma_x}{\sigma_r} \end{cases}, \tag{2}$$

where μ_x and σ_x are the mean and standard deviation of the striped line, and μ_r and σ_r are the corresponding mean and standard deviation of the reference line.

A_x and B_x in the conventional moment matching method are considered as a constant over a given scan line. This implies that the stripes are removed by means of an additional calibration procedure of the relative gains and offsets of the noisy detectors. However, in several of the bands of MODIS there are nonlinear and irregular stripes, as shown in Figure 1. Figures 1(*a*) and (*c*) contain nonlinear stripes, in which the degradation parameters change with the complexity of the ground objects. Figures 1(*b*) and (*d*) show irregular stripes which only contaminate some of the pixels in the defective lines. Irregular stripes are often caused by unstable detectors when the sensitivity varies in a part of the scan (Jung et al. 2010). The conventional destriping methods such as moment matching and the other statistical methods cannot effectively eliminate these kinds of stripes.

2.2. *The proposed piece-wise destriping method*

As described above, the different degradation levels in the different locations of the nonlinear and irregular stripes lead to the ineffectiveness of the traditional destriping methods. In order to remove the nonlinear and irregular stripes in MODIS data, we propose a piece-wise destriping method. The basic idea of the proposed method is to divide a stripe line into different portions, and to then implement a statistical destriping method, e.g. moment matching, on each portion. It is clear that if the piece-wise procedure is able to produce sub-rows which have similar internal degradation levels, desirable destriping results should be ensured. In order to remove the two kinds of stripes shown in Figure 1, the piece-wise procedure is divided into two parts.

For the nonlinear stripes, the employment of constant correction coefficients over a scanning line, which is based on the traditional statistical methods, can remove the stripes in heterogeneous regions, but this approach always leads to uncompleted or over-corrected results in homogeneous regions. Hence, our motivation is to distinguish the heterogeneous regions from the homogeneous regions before the statistical destriping. To do this, a local activity indicator is needed. In general, this can be standard deviation, structure tensor, or any

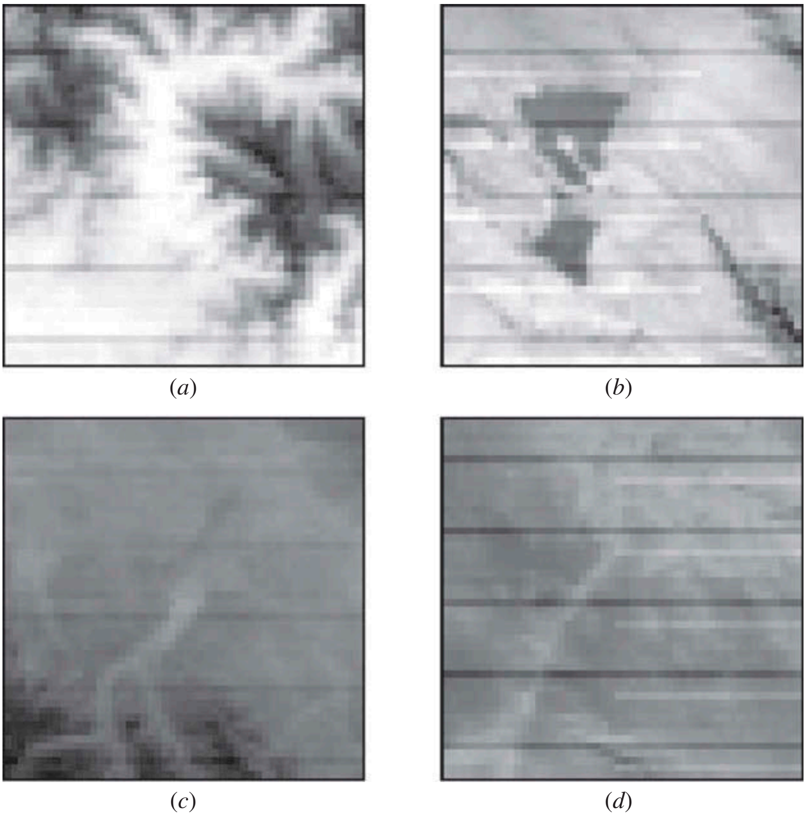
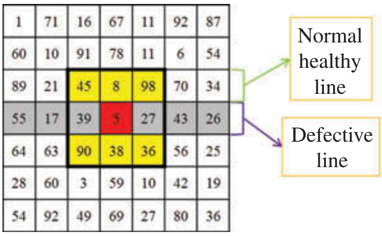


Figure 1. Typical nonlinear and irregular stripes in MODIS data. (*a*)–(*b*) Aqua MODIS band 30, and (*c*)–(*d*) Aqua MODIS band 27.

other similar metric. With regard to both efficiency and accuracy, the standard deviation metric is employed here. The steps involved in the piece-wise method are as follows.

(1) Define a rectangular region $S_1 = N_1 \times N_1$ for each contaminated pixel, on the premise that the contaminated pixel is in the centre.
(2) Calculate the standard deviation of the valid pixels in the determined window, using the normal pixels. As shown in Figure 2, the values of 45, 8, 98, 90, 38 and 36 represent the digital numbers of the normal pixels which are used to compute the standard deviation.
(3) If the standard deviation of a contaminated pixel is higher than a threshold T, this contaminated pixel is labelled as heterogeneous, and *vice versa*. Thus, a striped line can be divided into a certain number of connected sub-portions, with the attribute of heterogeneous or homogeneous.

Using the above method, the irregular lines cannot always be properly processed. Here, we propose to undertake a further process using the statistical information of the defective line and an adjacent normal line. Figure 3 shows the mean information profiles of a defective line and an adjacent normal line. We can see that the brightness of the defective irregular line fluctuates up and down around the adjacent normal line. The



1	71	16	67	11	92	87
60	10	91	78	11	6	54
89	21	45	8	98	70	34
55	17	39	5	27	43	26
64	63	90	38	36	56	25
28	60	3	59	10	42	19
54	92	49	69	27	80	36

Figure 2. Example of a rectangular region of a contaminated RS image.

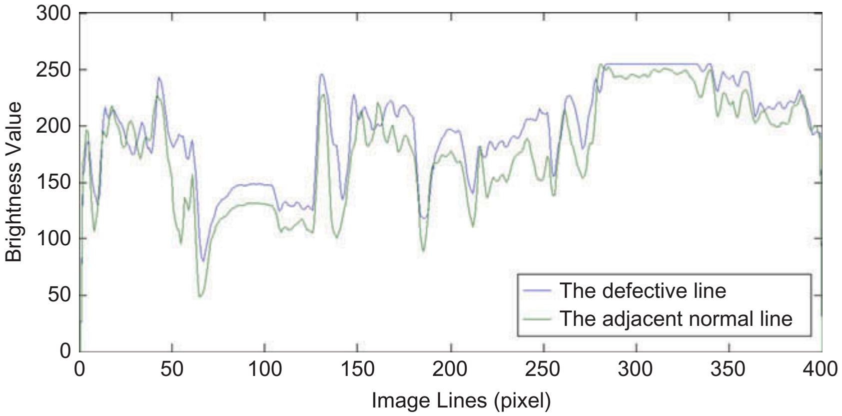


Figure 3. Characteristics of a defective line and adjacent normal line.

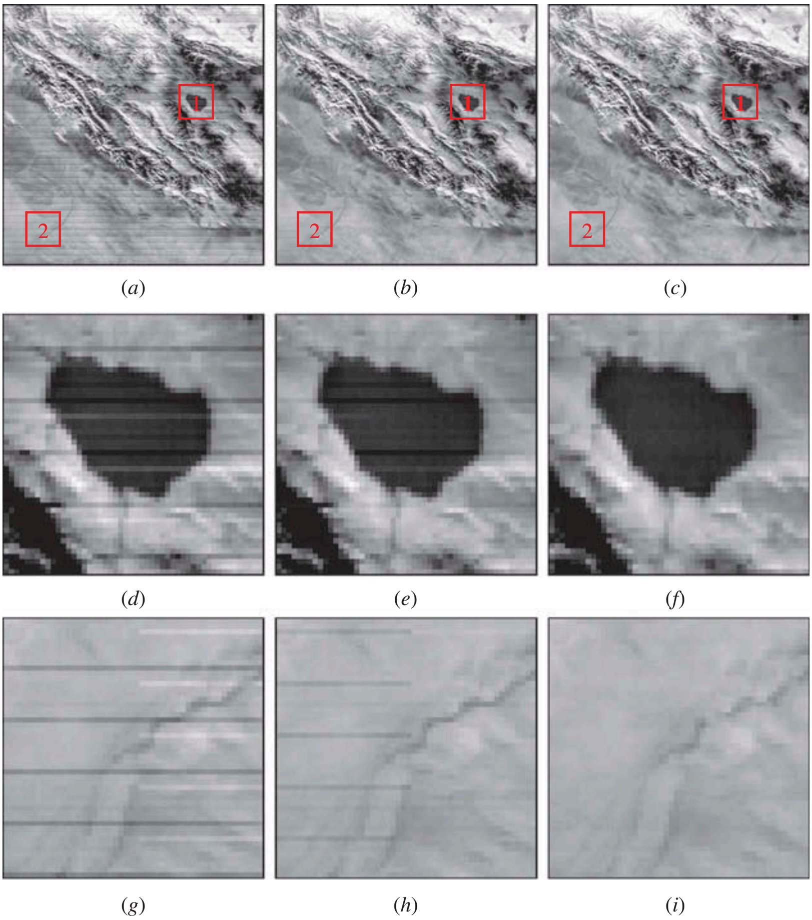
intersection points of the mean information lines are employed here as cut-off points to accomplish the piece-wise process. The piece-wise algorithm is operated as follows.

(1) Define a rectangular region $S_2 = 1 \times N_2$ for each contaminated pixel in the defective line and normal pixel in the adjacent reference line.
(2) Calculate the mean value in the sub-window along the defective line and the adjacent reference line. For each pixel position, compute the difference of the two means and judge whether the difference is greater than 0 or not.
(3) According to the difference judgment, record the intersection points of the two lines. Regard the intersection points as the cut-off points to divide the image into different portions.

Finally, the two piece-wise procedures described above are combined by adding the two series of cut-off points together. Thus, each stripe line can be divided into different portions. The method proposed in this letter assumes that each portion can be corrected by a constant coefficient using a traditional statistical method. To get the suitable correction coefficients, the adjacent normal line should also be divided by the same cut-off points. The moment matching method is then employed as the destriping method after the piece-wise procedure.

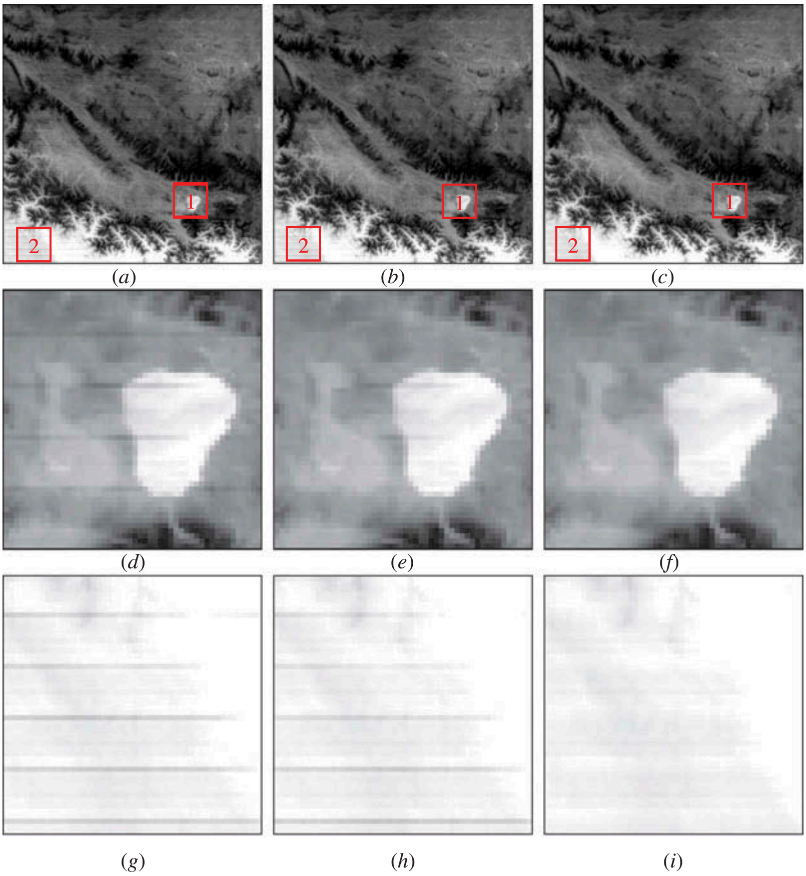
3. Experimental results

In this section, the experimental results of Aqua MODIS data with nonlinear and irregular stripes are presented. Since the stripes are periodic, their positions were determined manually in the first scanning swath of the image. The first image is shown in Figure 4(*a*), which was acquired on 31 December 2009 (band 27). In order to validate the proposed method, the traditional moment matching is employed for comparison, and the destriped result is shown in Figure 4(*b*). Figure 4(*c*) is the resulting image of the proposed method. For the convenience of visual comparison, two detailed regions are cropped and shown in Figures 4(*d*)–(*f*) and Figures 4(*g*)–(*i*), respectively. In Figure 4(*d*), there are nonlinear strips whose degradations change along the line, especially between the lake and the land. In the result of the moment matching method (Figure 4(*e*)), therefore, there are still obvious stripes in the lake. In the second region of Figure 4(*g*), there are periodic irregular stripes. Specifically, the left portions are normal and the right portions are defective. Using the moment matching method, the defective portions are properly corrected, but the normal portions suffer a re-degradation, as shown in Figure 4(*h*). From Figures 4(*f*) and (*i*), it can be seen that the proposed method provides much better destriping results, from the visual perspective, for both cases. Another similar experiment is shown in Figure 5, in which the original image was



(*a*) (*b*) (*c*)
(*d*) (*e*) (*f*)
(*g*) (*h*) (*i*)

Figure 4. Destriping results of Aqua MODIS band 30. (*a*) Original image. (*b*) Moment matching. (*c*) Proposed piece-wise destriping with $T = 12$, $S_1 = 3 \times 3$, $S_2 = 1 \times 3$. (*d*)–(*f*) Detailed regions with marker 1 in (*a*)–(*c*), respectively. (*g*)–(*i*) Detailed regions with marker 2 in (*a*)–(*c*), respectively.



(*a*) (*b*) (*c*)

(*d*) (*e*) (*f*)

(*g*) (*h*) (*i*)

Figure 5. Destriping results of Aqua MODIS band 27. (*a*) Original image. (*b*) Moment matching. (*c*) Proposed piece-wise destriping $T = 10$, $S_1 = 3 \times 3$, $S_2 = 1 \times 3$. (*d*)–(*f*) Detailed regions with marker 1 in (*a*)–(*c*), respectively. (*g*)–(*i*) Detailed regions with marker 2 in (*a*)–(*c*), respectively.

acquired on 28 December 2003 (band 30). Again, the moment matching method either leads to an incomplete destriping or results in an over-correction in some regions. The advantages of the proposed method are again effectively embodied by the robust removal of the stripes.

Figure 6 shows the mean cross-track profiles of the experimental images and the resulting images in Figures 4(*a*)–(*c*) and Figures 5(*a*)–(*c*). The horizontal axis represents the line number and the vertical axis is the mean of the corresponding line. It can be seen that there are rapid fluctuations in the curves of the original images, due to the existence of the stripes. The fluctuations in Figures 6(*b*) and (*e*) are not completely removed with the moment matching method. Using the proposed method, however, the fluctuations in the profiles are greatly reduced, as shown in Figures 6(*c*) and (*f*). Figure 7 shows the power spectra of the corresponding images. The horizontal axis represents the normalized frequency and the vertical axis represents the averaged power spectrum of all the columns. It can be seen from Figures 7(*b*) and (*e*) that the moment matching algorithm cannot effectively remove the frequency pulse caused by the stripes. In the results of the proposed method in Figures 7(*c*) and (*f*), the pulses have been greatly reduced.

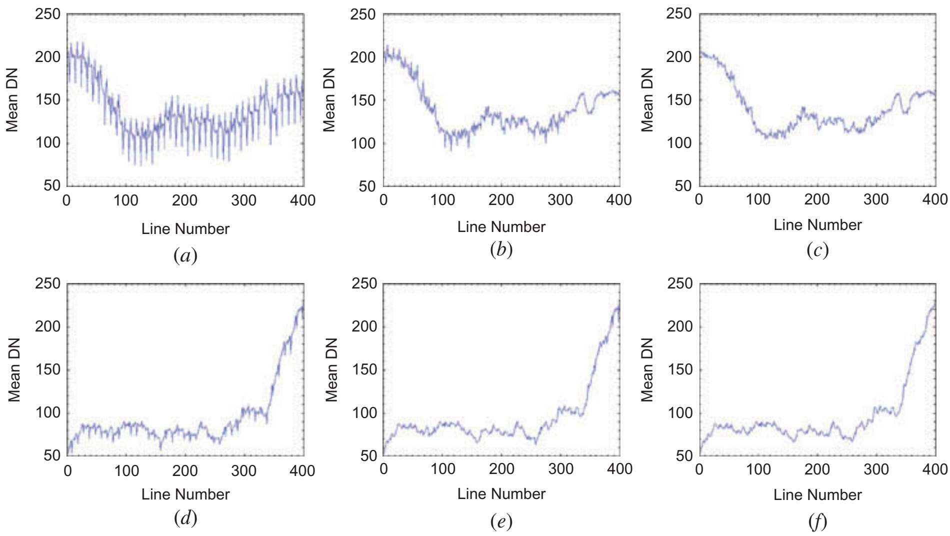


Figure 6. Mean cross-track profiles of Aqua MODIS data. (*a*)–(*c*) Profiles of Figures 4(*a*)–(*c*), respectively. (*d*)–(*f*) Profiles of Figures 5(*a*)–(*c*), respectively.

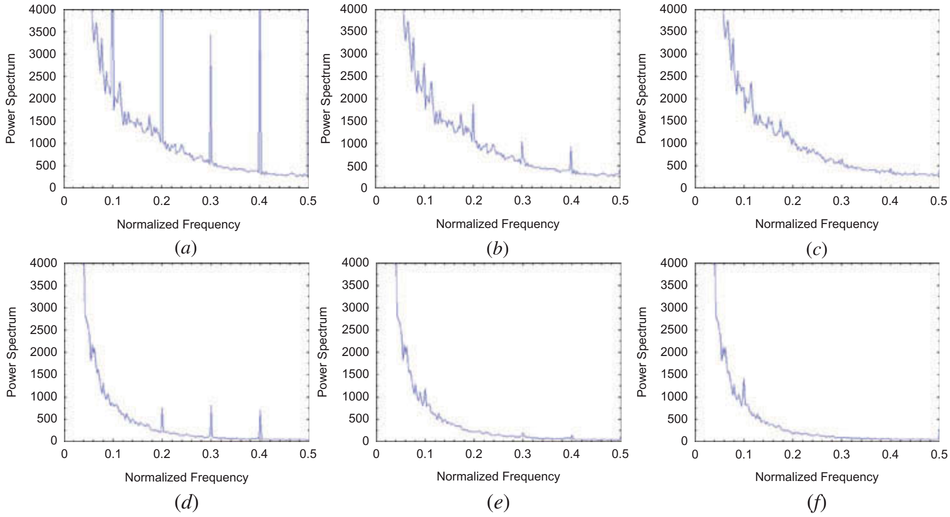


Figure 7. Mean column power spectra of Aqua MODIS data. (*a*)–(*c*) Spectra of Figures 4(*a*)–(*c*), respectively. (*d*)–(*f*) Spectra of Figures 5(*a*)–(*c*), respectively.

For a quantitative measurement, the quality indices of ICV and NR are employed in this letter. ICV is defined as (Rakwatin, Takeuchi, and Yasuoka 2007; Nichol and Vohora 2004; Smith and Curran 2000):

$$\mathrm{ICV} = \frac{R_{\mathrm{a}}}{R_{\mathrm{sd}}}, \tag{3}$$

where the signal response for a homogeneous surface area is calculated by averaging the pixels R_{a} within a window, and the noise component is estimated by calculating the

Table 1. ICV values of the original and destriped MODIS data.

		Sample 1 (ICV)	Sample 2 (ICV)	Sample 3 (ICV)	Sample 4 (ICV)	Sample 5 (ICV)
Aqua Band 27	Original	19.12	18.35	22.32	22.04	19.86
	Moment	27.38	25.62	28.71	28.02	21.17
	Proposed	48.24	42.65	39.11	37.73	42.79
Aqua Band 30	Original	15.81	10.88	12.07	13.57	11.87
	Moment	28.42	24.50	21.42	31.69	21.94
	Proposed	60.78	38.08	28.91	40.61	39.34

Table 2. NR ratios of the original and destriped MODIS data.

	Original	Moment	Proposed
Aqua Band 27	1.00	1.5712	1.6813
Aqua Band 30	1.00	5.2939	7.6779

corresponding standard deviation R_{sd} (Rakwatin, and Takeuchi, and Yasuoka 2007). The ICV index reflects the level of striping noise and should be calculated on the homogeneous regions. In this article, five 10×10 homogeneous regions were selected for the ICV evaluation for each image. The ratio of noise reduction (NR) can be used to evaluate the destriped image in the frequency domain (Rakwatin, Takeuchi, and Yasuoka 2007; Shen and Zhang 2009; Chen et al. 2003). It is calculated by

$$\mathrm{NR} = \frac{N_0}{N_1}, \tag{4}$$

where N_0 and N_1 stand for the power of the frequency components produced by the striping noise in the original image and destriped images, respectively. In general, a robust method should have high values for both metrics. The ICV results and NR results are given in Tables 1 and 2, respectively. Compared to the original images, the results of the moment matching method show a great increase in both metrics. Nevertheless, the proposed algorithm obtains much higher ICV and NR values than the moment matching algorithm, which confirms that the striping noise is eliminated more effectively.

4. Conclusions

This letter presents a new destriping method for the nonlinear and irregular stripes in MODIS data. We combine two corresponding piece-wise algorithms to handle both types of defective lines. The experimental results indicate that the proposed destriping algorithm performs well in terms of both a visual inspection and quantitative evaluation. However, the proposed algorithm requires the selection of a threshold to divide the image into different portions. Therefore, it could be further improved by developing a method for the automatic determination of this threshold.

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