DETECTION AND RESTORATION OF NON-RADIAL VARIATION OVER FULL-DISK SOLAR IMAGES

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ABSTRACT

Full-disk solar images are provided by many solar telescopes around the world. However, the observed images show Non-Radial Variation (NRV) over the disk. In this paper, we propose algorithms for detecting distortions and restoring these images. For detecting NRV, the cross-correlation coefficients matrix of radial profiles is calculated and the minimum value in the matrix is defined as the Index of Non-radial Variation (INV). This index has been utilized to evaluate the H α images of GONG, and systemic variations of different instruments are obtained. For obtaining the NRV's image, a Multi-level Morphological Filter (MMF) is designed to eliminate structures produced by solar activities over the solar surface. Comparing with the median filter, the proposed filter is a better choice. The experimental results show that the effect of our automatic detection and restoration methods is significant for getting a flat and high contrast full-disk image. For investigating the effect of our method on solar features, structural similarity (SSIM) index is utilized. The high SSIM indices (close to 1) of solar features show that the details of the structures remain after NRV restoring.

Key words : techniques: image processing — methods: data analysis — Sun: general

1. INTRODUCTION

Daily full-disk solar images are provided by many ground-base solar telescopes around the world in several wavelengths. For example, there are nine H α full-disk solar instruments in Global High Resolution H α Network (GHN, for details, visit the site: http://swrl.njit.edu/ghn_web/), and six in Global Oscillation Network Group (GONG, for details, visit the site: <http://gong.nso.edu/>). Weather permitting, these telescopes capture a large number of images in every day. Many pre-processing techniques have been developed for the standardization of full-disk solar images from different observatories. The main purpose of these techniques is to obtain flat and high contrast full-disk images (Preminger et al. 2001) for automated further solar activities detection and segmentation (Veronig et al. 2000; Benkhalil et al. 2003; Zharkov et al. 2005). Raw solar images are unsuitable for immediate processing due to variations of background intensity over the solar disk (Bornmann et al. 1996; Walton et al. 1998).

Generally, two important pre-processing steps must be taken, which are calibration and limb fitting. Calibration includes dark and flat-field correction. The

dark field can be obtained by exploring with the CCD covered, and the flat-field is usually obtained by the Kuhn-Lin method (Kuhn et al. 1991; Denker et al. 1999). The basic idea of the Kuhn-Lin method is to compute horizontal and vertical derivatives of the logarithm of the gain function from multiple shifted full-disk images, and to solve the pixel gain function for various displacement vectors by an iterative least-square algorithm. The solar atmosphere's line-on-sight thickness that changes from disk center to limb leads to limb-darkening in visible emission or limb-brightening in UV emission. Usually, radial limb fitting includes the following steps: (Denker et al. 1999; Zharkova et al. 2003; Zharkov et al. 2005):

- 1) Centering the full-disk images
- 2) Translating the full-disk images from Cartesian coordinates to polar coordinates
- 3) Obtaining an average radial profile by computing the median value at each radial position, and using polynomial fit and wider smoothing kernels to flatten the part of the profile at disk center
- 4) Replacing each row by the average radial profile and translating back to Cartesian coordinates to yield a two-dimensional smoothed "Quiet Sun" image
- 5) Subtracting the background images from the full-

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disk image and obtaining the contrast image.

This procedure works very well if high quality flat-field could be obtained, and the vignetting non-uniformities of the filters and CCD responses can be successfully eliminated. Unfortunately, this condition cannot always be satisfied. Usually, a flat-field is taken at the beginning of each day's observation and applied for all images of that day. Vignetting and optical path misalignments caused by tube flexure cannot be corrected totally by a single flat-field because they are related to solar celestial coordinates. Clouds in the Earth's atmosphere change almost every minute and make irregular large-scale shadows over the full-disk image. Multiple full-disk images are not very easily obtained for the Kuhn-Lin method, and a bad flat-field can be worse than no flat-field at all. As a result, the high contrast image obtained by removing radial limb-darkening profile is not very flat. There is large scale Non-Radial Variation (NRV) over the image. Fig. 1a shows an original image, which looks quite good, but the image after removing center to limb variations, Fig. 1b, shows the NRV clearly.

In order to automatically segment and measure very long or large solar activities such as filaments or plages, these NRV should be automatically detected and removed. Therefore, we develop a method to process NRV in these images. The layout of the paper is as follows. The automatic algorithm for detecting NRV is presented in Section 2. The filter design for obtaining the NRV's image is detailed in Section 3. The experimental results are shown in Section 4. The effect of this method on the solar features is inspected in Section 5. Finally, the conclusions are given in Section 6.

2. AUTOMATIC DETECTION OF NRV

GONG's images are collected once per minute (Harvey et al. 2011). Although the dark, smear, and flat-field corrected, the NRV probably exists. Thus, before using these images, we need to detect the images whether has such problem automatically.

The perfect profile lines of the "Quiet Sun" should symmetrically pass through the center of the sun, and their shapes should be identical. They will overlap if drawn together. Consequently, if there is no NRV in the image, the cross-correlation coefficients between the radial profiles in random angles of a full-disk solar image should be very close to 1. The bigger the distortion, the lower the coefficient. Accordingly, we define the minimum value in the correlation coefficients matrix as the Index of Non-radial Variation (INV) to evaluate the NRV over the full-disk image.

The automatic detection of NRV consists of five main steps:

- 1) Centering the full-disk image and translating the full-disk image from Cartesian coordinates to polar coordinates. This step is the same as in the standard method of removing limb-darkening

- 2) Splitting the image in polar coordinates evenly along the angle axis to four quadrants, and each quadrant covers 90 degrees

- 3) Computing the regional average radial profile by computing the median value at each radial position in each quadrant, which represents the average radial variations in this quadrant

- 4) Calculating the pairwise cross-correlation coefficients of four regional average radial profile

- 5) Picking the minimum value in the matrix as the INV, which indicates the maximum difference between two quadrants

The correlation coefficients matrix of Fig. 1a is shown in Table 1.

Table 1.
Correlation coefficients matrix

	Quadr- ant I	Quadr- ant II	Quadr- ant III	Quadr- ant IV
Quadrant I	1	0.96	0.99	0.98
Quadrant II	0.96	1	0.96	0.91
Quadrant III	0.99	0.96	1	0.97
Quadrant IV	0.98	0.91	0.97	1

In this case, the INV, which is the minimum value of this matrix, is 0.91. It is produced between quadrant II and IV. It means that the trends of profiles at these two quadrants of full-disk are not exactly the same, and implies that there is NRV over this full-disk solar image. We also carefully check other images that have low INV manually and confirm that using INV can identify the NRV effectively.

We apply this approach to evaluate the NRVs of GONG's H α full-disk images. Fig. 3 shows the INVs of the images obtained by the Observatorio del Teide in the Canary Islands on January 1, 2013 (Fig. 3a) and the Learmonth Solar Observatory in Western Australia on January 5, 2013 (Fig. 3b).

The INV of Fig. 3a are mutually consistent and very close to 1 during that day, and the minimum and the maximum were between 0.975 and 0.986. This implies that the whole observation, including telescope, CCD and weather conditions, was very stable, and there was little NRV over these images. On the contrary, Fig. 3b shows the INV decreased systematically over time in one day's observation. The amplitude was between 0.521 and 0.956, which implies that the NRV was increasing from the beginning to the end of this observation. This issue can be explained by the fact that the flat-field was obtained at the beginning of daily observation and applied to correct the whole day's images. The accumulative errors in the flat-field correction grew along with time.

Besides these two, we also measure the INVs of four

Fig. 1.— A typical full-disk solar image which has the NRV; (a) is the original image which is obtained by the GONG $H\alpha$ telescope of the High Altitude Observatory at Mauna Loa in Hawaii, USA at 02:14:14 UT on March 8, 2013; (b) the NRV is visible after removing limb-darkening.

Fig. 2.— (a) shows the image of Fig. 1a that has been transformed into polar coordinates, and split evenly in every 90 degrees along the angle axis, (b) shows the four quadrants' average radial profiles. If there was no NRV on the full-disk, these four profiles should be same and overlapped.

other GONG' stations. The INV of the Big Bear Solar Observatory in California, USA was between 0.836 and 0.981 on January 3, 2013, the Udaipur Solar Observatory in India was between 0.896 and 0.983 on January 2, 2013 and the Cerro Tololo Interamerican Observatory in Chile was between 0.906 and 0.979 on January 4, 2013. The instrument at the High Altitude Observatory at Mauna Loa in Hawaii, USA showed the biggest systematic variation, which was between 0.245 and 0.972 on February 2, 2013.

3. DESIGNING THE FILTER

Besides limb-darkening, NRV should be also removed before automatically analyzing the feature struc-

ture over the full-disk; otherwise they will be misunderstood by further processing. To extract the NRV, we must separate them from the full-disk image that is covered by solar activities. Consequently, the key technique is to design a low-pass image filter for getting the large-scale NRV background.

Linear filters are very important tools used extensively in digital image processing, and offer satisfactory performance in a variety of applications. However, the intensities of solar activities are unpredictable, and their statistical distributions are definitely non-Gaussian. For example, sunspots or flares look like "impulsive noise" on the "Quiet Sun". Therefore, linear techniques are not suitable for filtering these signals. Wang et al. (2008) applied Fourier low-frequency

Fig. 3.— The systematic INVs of the Observatorio del Teide in the Canary Islands on January 1, 2013 (Fig. 3a) and the Learmonth Solar Observatory in Western Australia on January 5, 2013 (Fig. 3b).

passing filter to obtain the pattern in full-disk vector magnetograms, and “pollution” of small magnetic structures during the Fourier transformation was still shown by the filtering results. On the other hand, the development of nonlinear image filter techniques has made significant advances. Unlike filtering by linear filtering, nonlinear filtering uses neighboring pixels according to a nonlinear law. A classical example of them is the median filter, which is based on order statistics and has robustness properties in suppressing impulsive noise (Pitas et al. 1992). At the Paris-Meudon observatory, both large and small windows of median filtering and two thresholds were utilized to estimate the large-scale variations (Fuller et al. 2004, 2005).

Morphological filter is another family of nonlinear image processing techniques, which are nonlinear signal transformations that locally modify geometric features of signals (Vincent et al. 1994; Parvati et al. 2009). Their basic operations include dilation, erosion, opening, and closing, as introduced by Matheron (Matheron et al. 1975) and Serra (Serra et al. 1982). A set-theoretical method for image analysis, mathematical morphology, is the foundation of morphological processing. Mathematically, the gray-scale dilation and erosion of f by structuring element b , denoted $f \oplus b$ and $f \ominus b$ are defined as

$$f \oplus b(x, y) = \max\{f(x-x', y-y') + b(x'+y') | (x', y') \in D_b\} \quad (1)$$

and

$$f \ominus b(x, y) = \min\{f(x-x', y-y') - b(x'+y') | (x', y') \in D_b\} \quad (2)$$

where D_b is the domain of b , and $f(x, y)$ is assumed to equal $-\infty$ outside the domain of f (Gonzalez et al. 2009).

The opening and closing of image f by b , denoted $f \circ b$ and $f \bullet b$, are erosion followed by dilation and

dilation followed by erosion

$$f \circ b(x, y) = (f \ominus b) \oplus b \quad (3)$$

and

$$f \bullet b(x, y) = (f \oplus b) \ominus b \quad (4)$$

A morphological filter compounds operations like opening and closing. Two standard morphological filters are the *open-closing* filter (opening followed by closing) and the *close-opening* filter (closing followed by opening). Both of them are transformations with special structuring elements and locally adapt the element shape based on the image, and therefore have nice filtering capabilities. In practice, gray-scale filter is performed using flat structuring elements with disks, squares, hexagons, octagons, etc. Compared with the median filter, the *open-closing* (or the *close-opening*) filter behaves similarly for suppressing impulse noise, and requires less computational time. In addition, it can separate positive and negative noise, whereas the median cannot (Maragos et al. 1987a,b). The applications of morphological filters in image processing and analysis are numerous, such as digital image filtering, image enhancement, image segment, and edge detection.

Fig. 4 shows a 1-D signal, which is obtained from the horizon profile of a solar image, and its large-scale smoothed versions with median and morphological filters of *close-opening* and *open-closing*. We can see that: (1) the results of median filtering are bounded by that of *open-closing* and *close-opening* filtering; (2) the contrast from the minimum to maximum values of the morphological filtering result are lower than that of median filtering; (3) the morphological filtering shows some small “steps”, and the variations of median filtering result are smooth.

Based on our studies and experiments, we design a Multi-level Morphological Filter (MMF) to smooth the

Fig. 4.— The 1-D signal, which is obtained from the horizon profile of a solar image, and its large-scale smoothed versions with median filter and morphological filters of *close-opening* and *open-closing*.

Fig. 5.— The test solar full-disk image and the subarea of $1300'' \times 1300''$.

solar full-disk image. The basic principle includes: filtering with small-scale windows before with large-scale window; averaging the result of *open-closing* and *close-opening* filtering; polishing the small “steps”. The following is the details of the algorithm:

- 1) Setting the morphological filter structure element with a quarter of filtering window width
- 2) Filtering the original image I_0 by *open-closing* and *close-opening* separately, then averaging them to create I_1
- 3) Repeating the above steps 1 and 2 to create image I_2 , but using a half of filtering window width instead of a quarter of it and I_1 instead of I_0
- 4) Repeating step 3 to create I_3 , but using the full window width to filter I_2
- 5) Filtering I_3 by moving-average with the filtering window

The objective of the filter is to eliminate structures of the solar activities, and only leave the large-scale NRV. Therefore, the filtered image should be as flat as possible on the solar feature scale; otherwise, the

residuals from solar features will remain in the NRV image.

Fig. 5 shows a square subarea of a solar disk image, which includes sunspots, filaments, plages and the NRV. The minimum to maximum intensity value has been standardized from 0 to 255. For comparing the performances of removing solar features between MMF and Standard Median Filter (SMF), three indices are applied. They are entropy, peak-to-peak value and standard deviation of the image.

Entropy is a quantity for describing the randomness of an image. The measure is given by

$$E = - \sum_{i=0}^{M-1} p(I_i) \log_2 p(I_i) \quad (5)$$

where M is the number of intensity levels, I_i is the random variable indicating intensity, $p(I_i)$ is the probability of the intensity in an image, and $\log_2$ is the base 2 logarithm. The entropy will be 0 if the image is perfectly uniform, and will increase with increasing variations. The peak-to-peak value is defined by the difference between maximum and minimum intensities in the image, and standard deviation is calculated as the square root of image intensities' variance. The lower values of entropy, peak-to-peak value and standard deviation indicate that the image tends to be flat, and higher values indicate that the image intensity is spread out over a large range of values, which means that the image is non-uniform. The three indices of original image are 5.30, 255 and 10.08, and the measures of filtered image are listed in Table 2.

By same filtering window size, the entropy, peak-to-peak value and standard deviation of the image filtered with MMF are smaller than that with SMF. Thus, MMF removes more small features and leaves behind less residue of solar features in the NRV image than SMF.

Fig. 6 presents the intensities in the subarea indicated in Fig. 5 along three dimensions (Fig. 6a), the filtered image with SMF (Fig. 6b) and MMF (Fig. 6c). All of the filtering window size is 180 arcsec. We can see that the residual solar features in Fig. 6b are brighter than Fig. 6(c), and Fig. 6c is smoother than Fig. 6b.

From the results of Table 2 and Fig. 6, we conclude that the MMF's capacity of filtering the activities over solar disk is higher than SMF's, and MMF is more effective in obtaining the background image of the NRV.

4. EXPERIMENTAL RESULTS OF IMAGE RESTORATION

After obtaining the NRV's image, the distortions in the full-disk image can be corrected. The overall procedure of removing both radial and non-radial variations consists of the following steps:

- 1) Translating the original full-disk image I_0 from Cartesian coordinates to polar coordinates and calcu-

Table 2.

The entropies, peak-to-peak values and standard deviations of the test images which have been filtered with SMF and MMF separately

W_{size} of filter(aresec)	Entropy (SMF)	Entropy (MMF)	Peak-to-Peak Value (SMF)	Peak-to-Peak Value (MMF)	Standard Deviation (SMF)	Standard Deviation (MMF)
30	4.59	4.29	148	69	6.38	5.27
60	4.22	3.96	55	34	4.98	4.46
90	4.07	3.80	42	27	4.57	4.24
120	3.96	3.65	33	16	4.32	3.84
150	3.87	3.58	27	13	4.16	3.78
180	3.78	3.39	21	12	4.03	3.70
210	3.72	3.49	18	12	3.94	3.58
240	3.65	3.40	16	11	3.86	3.55
270	3.61	3.35	15	11	3.79	3.52
300	3.56	3.29	14	11	3.73	3.40

(a)

(b)

(c)

Fig. 6.— (a) is the intensities of original image in three-dimensions, (b) is filtered with SMF and (c) is filtered with MMF.

lating an average radial profile by computing the median value at each radial position and fitting with high-order polynomials

2) Replacing each row by the average radial profile and translating back to Cartesian coordinates to obtain two-dimensional smoothed radial variations image I_b

3) Dividing I_0 by I_b to obtain the residual image I_r , which includes small-scale solar activities and large-scale NRV

4) Filtering I_r with MMF, eliminating solar activities to get a smoothed NRV's image I_s

5) Dividing I_0 by I_s , and subtracting I_b , to obtain the final restoration images.

Fig. 7 shows the restoration steps of three distorted $H\alpha$ full-disk images, which were obtained from GHN instrument of the Big Bear Solar Observatory at 23:00:13

UT on April 5, 2013, GONG instrument of the Big Bear Solar Observatory at 22:03:54 UT on January 1, 2013, and GHN instrument of Yunnan Observatory, China at 2:14:44 UT on March 8, 2013.

The effect of restoration is significant, and both radial and non-radial variations over the original image are removed. It is worth noting that the average profiles from center to limb in the second row of Fig. 7 seem very different from the standard limb-darkening profile. The reason is that these images were distorted not only angularly but also in a radial direction. Thus, in our restoration algorithm, high-order polynomials (even as high as 6) are applied in fitting the average profile.

Fig. 7.— The top row of images are original I_0 ; the second row are the average profiles from center to limb; the third row are the residual images I_r ; the fourth row are the NRV's images I_s ; the fifth row are the final high contrast images; the bottom row are the average center to limb variation of the high contrast images.

5. THE EFFECT ON THE SOLAR FEATURES

To investigate how our methods affect the solar features over the full-disk, we inspect the images before and after applying our technique. The NRV that has been removed from the full-disk image are large-scale variations, their effects on small structures of solar features in restored image are too small to be observed. Since our algorithm is nonlinear, traditional image quality assessment methods like Peak Signal-to-Noise Ratio (PSNR) and Mean Squared Error (MSE) do not work very well. Therefore, we utilize the structural similarity (SSIM) index (Wang et al. 2004), which is designed to improve on traditional methods, to measure the similarity between the images. The SSIM index considers image degradation in structural information, which is the idea that the pixels have strong inter-dependencies especially when they are spatially close. These dependencies carry important information about the structure of the objects in the image. SSIM has shown to be robust of illumination and contrast changes, and has been used for the purposes of quality assessment of distorted images (Loza et al. 2006, 2007). The measure between two images x and y is:

$$SIMM(x, y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)} \quad (6)$$

where x and y are the two images, μ_x and μ_y are the average intensities of x and y , σ_x^2 and σ_y^2 are the variances, σ_{xy} is the covariance, c_1 and c_2 are the two variables to stabilize the division with weak denominator. The resultant SSIM index is between -1 and 1, and value 1 is only reachable in the case of two identical images.

Two full-disk images which were observed by GONG instruments of the Big Bear Solar Observatory (BBSO) at 22:59:54 UT and the High Altitude Observatory (HAO) at 23:00:14 UT on 2013 April 5 are employed for the inspection. Although the locations of the instruments are different, the observation times of the two images are very close, and the solar activities on the images are identical. Three small features are selected from the full-disk image separately. Each of them covers $240'' \times 240''$ and is shown in Fig. 8.

We measure the SSIM indices of the full-disk and three feature images between before and after applying our method. The results are shown in Table 3.

Both INVs are below 0.7, which means there are NRVs in the full-disk images. The SSIM indices of full-disk are 0.831 for BBSO and 0.741 for HAO respectively, which shows that there are significant differences on large-scale area before and after applying our method. However, the SSIM indices of small features are close to 1 (the minimum is 0.938), which means the structures of solar features are very similar. These results illustrate that our method affect the structures of solar features limitedly and the details of activities are intact after NRV restoring.

6. CONCLUSIONS

In this paper, we propose algorithms for automatic detecting of NRV and restoration of full-disk solar images. The goal of this research is to convert a distorted full-disk image to a flat and high contrast one for further automated solar activities detection and segmentation.

For detecting NRV, the cross-correlation coefficients matrix of different regional profiles is calculated and the minimum value in the matrix is defined as the Index of Non-radial Variation (INV). This index has been utilized to evaluate the NRV of full-disk solar images of GONG, and systemic variations of different instruments are inspected. To restore these distorted images, a Multi-level Morphological Filter (MMF) has been designed that eliminates structures of solar activities over the solar surface and results in a smoothed NRV's image. Three indices including entropy, peak-to-peak value and standard deviation are applied for comparing MMF and SMF. The results indicate that the MMF is a better choice and show that the details of small structures are intact after NRV restoring.

One critical parameter is the filtering window size. If too small a window is selected, the structures of solar activities will be smoothed. Conversely, if a big window is selected, the large-scale variations cannot be removed in the final image. Therefore, the largest size of solar features over the disk as the filtering window size is suggested.

Although our technique exhibits good performance, it must be emphasized that restoring the distorted image with image processing is not the best solution for getting high quality data. In fact, it is the last choice only if we cannot obtain high accuracy observation images directly. Nevertheless, it is useful in some cases, when we cannot control the quality of the observation sufficiently.

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Fig. 8.— Three solar feature images which are selected from the full-disk image.

Table 3.

The SSIM indices of the full-disk and three feature images between before and after applying our method

Observatory	INV	SSIM of Full-disk	SSIM of Feature (a)	SSIM of Feature (b)	SSIM of Feature (c)
BBSO	0.67	0.831	0.986	0.995	0.968
HAO	0.69	0.741	0.981	0.991	0.938

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