Automatic data analysis for the Sky Brightness Monitor

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ABSTRACT
The Sky Brightness Monitor (SBM) is an important instrument for measuring the brightness level for the sky condition, which is a critical parameter when judging a site for solar coronal observations. In this paper, we present an automatic method for processing SBM data in large quantities. This method can separate the regions of the Sun and the nearby sky, as well as recognizing the regions of the supporting arms in the field of view. These processes are implemented on the data acquired by more than one SBM instrument during our site survey project in western China. Applying the result from our processes, an analysis has been carried out for the assessment of the scattered-light levels by the instrument. These results are considerably significant for further investigations and studies, notably to derive a series of other atmospheric parameters, such as extinctions, aerosol content and precipitable water vapour content, that are important for candidate sites. Our processes also provide a possible way for full-disc solar telescopes to track the Sun without an extra guiding system.

Key words: atmospheric effects – methods: data analysis – site testing – telescopes – surveys – Sun: general.

1 INTRODUCTION
The sky brightness is a critical parameter when judging a site’s potential for direct coronal observations. Because of the large difference in the brightness of the solar disc and its nearby sky (halo), it is difficult to achieve accurate and direct measurements of the sky brightness during day time. Until the Lyot coronagraph was invented (Lyot 1930, 1939), the corona could only be observed during total solar eclipses. Since then, a photometer has been constructed by Evans (1948) to measure the sky brightness near the Sun. The Evans Sky Photometer (ESP) has been used for a long time at various solar observatories (Garcia & Yasukawa 1983; Labonte 2003). A modern Sky Brightness Monitor (SBM) has been developed for the Advanced Technology Solar Telescope (ATST) site survey project, which can image the solar disc and the nearby sky simultaneously at 450, 530, 890 and 940 nm (Lin & Penn 2004; Penn et al. 2004). In addition, the SBM data can yield information about the extinction, the aerosols, and the precipitable water vapour content of the atmosphere.

To meet future requirements in the development of the Chinese Giant Solar Telescope (CGST) and large-aperture coronagraph projects, our SBM has been designed and developed following the same idea as Lin & Penn (2004), that is, it is one fundamental tool (Liu et al. 2012b). These SBMs are implemented for the site survey project in Western China (Liu and Zhao 2013) and have already been applied at many different candidate sites (Liu et al. 2011, 2012a,b). The optical configuration of one SBM consists of an external occulter, an objective lens, a neutral density filter on the objective lens and four bandpass filters (Lin & Penn 2004). Generally, the original images acquired by the SBM are not intuitive and concise for direct further analysis. Moreover, the absence of an autoguide system to serve the equatorial tracking system might mean that the positions of the solar disc in the SBM images cannot be determined. Wen et al. (2012) have studied and compared possible methods for determining the center of the solar disc in the SBM data. However, some parameters in their method have to be determined according to the experience. Furthermore, the regions that are invalid for calculating the sky brightness have been excluded manually in previous work (Liu et al. 2012b). With the rapid progress of our site survey project, the accumulation of huge amounts of data urgently requires an efficient, accurate and fully automated processing approach to deal with the SBM data.

For this purpose, we have developed a method for automatically processing SBM data, which allows us to separate the regions of the Sun and the nearby sky as well as permitting us to automatically recognize the regions of the supporting arms. In the next section, we describe the main adopted technologies for our procedure. In

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Section 3, we present the data reduction in detail. In Section 4, we apply our procedure to a set of SBM data and we analyse the scattered light based on the results of our procedure. Our conclusions are presented and highlighted in Section 5.

2 MAIN TECHNOLOGIES

SBM instruments can simultaneously image the Sun and its nearby sky regions. The data are useful for directly deducing the normalized sky brightness, which is a critical parameter when investigating coronagraph sites. Fig. 1 shows a typical SBM image taken at Gaomeigu Station. Near the centre of the image, the attenuated solar disc and the projection of the ND4 – nominal optical density of 4 – filter are shown. The bright ring is caused by the diffraction at the edge of the ND4 filter, while the three narrow strips are from the projections of the supporting arms of the ND4 filter.

The brightness of the sky within a few solar radii away from the solar centre at a good coronal site is expected to be below $10^{-5} \times I_0$, where $I_0$ is the intensity of the solar disc (Lin & Penn 2004). It is convenient to measure the sky brightness with millionths of $I_0$. In order to extract the regions of the solar disc and the Sun’s nearby sky, it is necessary to accurately determine the solar radius and the position of the solar centre in the image. Because the region of the Sun’s nearby sky on the image contains the projections of the supporting arms, which must be excluded in the calculation, accurate positions of these projections are also needed for each image. In our procedure, there are mainly three technologies used to achieve the separation of these regions: image binarization with Otsu’s method, image matching with cross-correlation and image fitting using the least-squares method.

In digital image processing, Otsu’s method is usually used to automatically perform clustering-based image binarization. The algorithm assumes that the image contains two classes of pixels corresponding to two peaks on its histogram (foreground and background). The optimum threshold to separate these two classes is calculated by minimizing their combined spread (intra-class variance) (Otsu 1979).

In Otsu’s method, the intra-class variance (the variance within the class) is defined as a weighted sum of variances of the two classes:

$$
\sigma^2(T) = \omega_1(T)\sigma_1^2(T) + \omega_2(T)\sigma_2^2(T).
$$

(1)

Here, $\omega_i$ are the probabilities of the two classes separated by a threshold $T$ and $\sigma_i^2$ are variances of these classes.

In this step, the image is rescaled to an eight-bit image and the normalized histogram is calculated. Then, we test all the possible thresholds $T$ from 0 to 255 to calculate the intra-class variances and to find the desired $T$ in the 256 thresholds. Finally, the actual threshold for the origin image is obtained by inverse scaling mapping. For example, the application of Otsu’s method on a white light solar image would locate the boundary with high accuracy (Fig. 2). In our procedure, Otsu’s method is mainly used to detect the edge of the SBM image.

Correlation techniques are predominately used for template matching in image processing (Gonzalez & Woods 2002). If we want to determine whether an image $f(x, y)$ contains a particular object or region of interest, we let $h(x, y)$ be that object or region (template). Then, if there is a match, the correlation of the two functions will be maximum at the location where $h(x, y)$ finds a correspondence in $f(x, y)$.

The cross-correlation of two continuous functions $f$ and $h$ is defined as

$$
f(t) \ast h(t) = \int_{-\infty}^{\infty} f^*(\tau)h(t + \tau) d\tau,
$$

(2)

where the asterisk denotes the complex conjugate of $f$. If $f$ and $h$ are real valued functions, this formula shifts the function $h$ along $x$-axis and $y$-axis and calculates the integral of their product at each position. When the functions match, the value of $f \ast h$ is maximized. This is because when peaks (or troughs) are aligned, they make a large contribution to the integral. With complex valued functions $f$ and $h$, taking the conjugate of $h$ ensures that aligned peaks (or aligned troughs) with imaginary components will contribute positively to the integral. Therefore, we can use the cross-correlation to find how much $h$ must be shifted to make it identical to $f$. Fig. 3 shows an example to illustrate. In our procedure, cross-correlation is used for edge extracting and to determine the positions of the supporting arms.

The least-squares method is extensively utilized in data fitting. It is a standard approach to the approximate solution of overdetermined systems, in which the number of measurements is more than that of unknown variables. Least-squares means that it minimizes the sum of the squared residuals in our procedure, least-squares is used to fit the circles by the points of the edges of the solar disc and the ND4 filter.

For a circle with the algebraic equation,

$$
F(x_i, y_i, \beta) = a(x_i^2 + y_i^2) + b_1x_i + b_2y_i + c = 0,
$$

(3)

determining the parameters, $\beta = [a, b_1, b_2, c]$, of the algebraic equation in the least-squares sense is called an algebraic fit, while minimizing the sum of the squares of the distances to the centre point

$$
d_i^2 = (\|z - x_i\| - r)^2
$$

(4)

is called a geometric fit. Here, $z$ is the centre coordinate of the circle and $r$ is the radius of the circle (Gander, Golub & Strebel 1994). The sum of the squared residuals of the distance function is obviously a non-linear function. Therefore, we solve this non-linear least-squares problem iteratively with the Gauss–Newton method. Also, the algebraic solution is used as the starting vector for the iteration. An example is shown in Fig. 4. The results of the algebraic and geometric fits are very different. For fitting analysis of data, the algebraic fit only tries to find the curve that minimizes the vertical displacement while the geometric fit tries to minimize the orthogonal distance. On this account, the geometric fit is sometimes called...
3 DESCRIPTION OF THE DATA REDUCTION

The positions of the solar disc in a time sequence are crucial parameters for the sky brightness calculations. Because of the actual operation of the instrument, the solar image centre is usually shifted around the centre of the ND4 filter. Because the two ND2 filters are fixed on the supporting arms, the position of the centre and the projection size of the filters are also important parameters for the calculations.

3.1 Data selection

In actual observations, there can be a large amount of data that are mistakenly collected because of observational constraints. Because the SBM is a portable measurement designed for field observations, the weather conditions have a great influence on the acquired images. Moreover, in the absence of a guiding system and a
Figure 3. A simple illustration of image correlation, constructed following example 4.41 of Gonzalez & Woods (2002). (a) is the image and (b) is the template. (c) shows the cross-correlation between (a) and (b), and (d) is the horizontal profile line through the highest value in (c).

high-precision tracking system, the SBM often gathers bad images in which the Sun moves out of the field of view. Hence, a data selection program must be performed prior to any further calculations.

There are mainly two types of bad data in observations, which are represented in Fig. 5. Fig. 5(a) represents a bad image covered by clouds and Fig. 5(b) shows a bad image that is saturated. We use an operation on experiential thresholds to recognize these situations. Binary operations are applied to the images according to the thresholds by Otsu’s method and a 0.999 maximum, respectively. Then, the areas of the binarization images are calculated. Because Otsu’s threshold separates two typical classes of pixels optimally and these two classes are much more difficult to be distinguished under the influence of the clouds, the areas from Otsu’s threshold will be very large. Also, if the image is saturated, there will be too many pixels with values identical to the maximum. Hence, the area from the 0.999 maximum threshold will be too large. We note that these two criteria are not independent. For example, when the weather is very cloudy, the image will be saturated over a large area, and the binarization images based on Otsu’s threshold and the 0.999 maximum threshold are nearly the same.

We also take into account some other ordinary situations (e.g. when the Sun is totally out of the field of view). Our data selection procedure is very effective at removing these data automatically. This has been verified based on all the SBM data, collected in 2013,
length of the SBM, we can gain the theoretical size of the solar diameter on the image. By taking into account the size of the CCD element, we finally obtain the solar diameter in pixels. Then, the template for cross-correlation can be constructed. Indeed, a ring with a width of five pixels is constructed and adopted as the template instead of a simplified circle template. The results are shown in Fig. 7. The image and template are padded to avoid wraparound error. The maximum of the resulting correlation image highlights the displacement with which the template should be shifted. According to this recovered displacement and the size of the template, the edge of the solar disc can be extracted from the image reported in Fig. 6. Afterwards, by applying the least-squares approach we fit the circle using the edge points of the solar disc to accurately estimate the coordinates of the solar centre and radius. Similar procedures are performed on the edge of the ND4 filter.

For the solar disc analyses, the cross-correlation technique might give the wrong displacement. In some situations, there is so much scattered light between the solar disc and the inner edge of the ND4 filter (diffraction ring) that the thresholding image from Otsu’s method might give ambiguous edges. Consequently, when the template is shifted to the position where the scattered light is evident, the correlation coefficient is significantly amplified. To overcome this, we proceed by calculating the convolution of the correlation image and the corresponding Laplacian kernel function. It turns out that the correlation maximum of the defective correlation image is effectively reduced after convolution. It is noted that in the case of the ND4 filters, there is no similar problem found.

3.3 Locating the position of the supporting arms

Considering that the regions of the projections of the supporting arms cannot be used for sky brightness calculations, we need to remove these regions. For this purpose, we test the cross-correlation technique to locate the position of the supporting arms. However, it cannot be applied directly because the template with invariable characteristics is hardly to be constructed. Moreover, as long as the supporting arms are fixed on the ND4 filter, we can use the centre of the ND4 filter as the pole to expand the image in the polar coordinate system. As shown in Fig. 8, an annular region from the diffraction ring is isolated and expanded. The expanded image reveals a clear distinctive feature, namely, three parallel strips 120° away from each other.

Figure 4. An example of least-squares fitting. The dot-dashed line represents the algebraic fitting and the solid line represents the geometric fit.

Figure 5. (a) represents the bad image covered by clouds. (b) represents the bad image, clearly saturated.
Figure 6. (a) is the enhanced image, which is the logarithm of the initial image. (b) is the gradient of image (a) by the Sobel operator. (c) is the binarized image based on the threshold from (b). (d) is the eroded image of (c) using the morphological method. Hereafter, the grey levels of the binarized images are inverted for display.

Figure 7. (a) is the padded edge image. (b) is the padded template. (c) is the cross-correlation between (a) and (b). (d) is the superimposed image of (a)–(c).
It is worth noting that, for convenience, we inverse the values of the expanded image. Because the projections of the supporting arms in the expanded images are relatively fixed and parallel, a two-column template can work well enough. Moreover, the sky brightness is not uniform at the angular direction, and the template constructed adopting two Gaussian functions is more suitable than using three Gaussian functions. Because we are concerned only with the positions of the supporting arms in the angular direction, the template does not need to be designed too high. With regards to the efficiency, we eventually adopt a template consisting of two Gaussian functions aligned with their maximums at a distance of 120° and with a width of 32 pixels. The results are illustrated in Fig. 9.

The SBM measures the solar disc and sky brightness at four wavelengths: 450, 530 and 890 nm and at the water vapour absorption band of 940 nm. The data acquisition system is collecting images at four wave bands in the sequence of wavelengths. The scattered light of the sky might be found to be weaker than that of the supporting arms, especially in some cases when the sky brightness is too weak. An example is depicted in Fig. 10. In this situation, the images at 890 and 940 nm will present different characteristics from those at 450 and 530 nm. Thus, the above template is not always suitable
Figure 10. The expanding sky regions at different wavelengths. The parabolic regions are the annular regions out of the image constructed by interpolating with the points on the edge.

Figure 11. (a) shows an image of the SBM, and (b) is the mask. (c) is the product of (a) and (b). (d) shows the solar disc and the sky regions.
for all four wave bands. The SBM requires approximately a few tens of seconds to acquire a set of data that contains four images at different wavelengths. The positions of the supporting arms are not significantly changing in a given data set. For each data set, our procedure consists of computing the positions from 450 nm, adopting the cross-correlation method and then applying them on the other three wavelengths.

### 3.4 Calculation of the sky brightness

The sky brightness is usually measured as

\[
S = \frac{I_{\text{sky}}}{I_{\text{sun}}},
\]

where \(I_{\text{sky}}\) is the average intensity at the region several solar radii away from the solar disc and \(I_{\text{sun}}\) is the true intensity at the centre of the solar disc before it is weakened by the ND4 filter. We note that the scattered light of the SBM is not included in equation (5) and that the scattered light is discussed in the next section. In our measurement, the region corresponding to \(I_{\text{sky}}\) is between 5.0 and 7.0 solar radii, excluding the projections of the supporting arms. For this purpose, we construct a mask based on the angular coordinates of the positions and the central coordinates of the ND4 filter. Then, the mask is multiplied by the image from the SBM. Next, we remove the region out of 7.0 solar radii and in 5.0 solar radii from the masked image, according to the fitting position of the solar centre and solar radius. The results are reported in Fig. 11.

The solar intensity \(I_{\text{sun}}\) is usually computed in two ways: a central solar intensity is computed within 0.1 \(R_{\text{sun}}\), or a mean solar intensity is computed using all pixels out to 1 \(R_{\text{sun}}\) (Penn et al. 2004). Generally, the first way has been adopted in previous works (Lin & Penn 2004; Penn et al. 2004; Liu et al. 2012b). However, the solar centre in the image does not necessary coincide with the physical centre of the Sun. This is mainly because the tube of the SBM is not always perfectly parallel to the light ray during observations. The observers must adjust the position of the SBM after tracking the Sun for a period of time, which is about 30 min to 2 h, based on the desired alignment accuracy. Here, we stress once again that the portability of the device is of great importance and we should avoid spending too much time on the alignment issue in a site survey. As a consequence, the mean solar intensity near the disc centre might seem to change sharply with time. In order to avoid this possible inconsistency, we adopt the intensity at the centroid of the solar disc in the image for the sky brightness calculations.

### 4 RESULTS AND ANALYSIS

In this section, we highlight our analysis and approach, based on the techniques described in the previous sections and applied to the data set acquired on 2013 October 23, at Namco Lake in Tibet. Our procedure takes approximately 4 h to automatically process the 10,422 results in the data set with a normal PC with a dual-core processor (Intel Core i3-2350M CPU at 2.30 GHz). The results are exported in a table-format output containing the wave bands, recording time, sky brightness and solar zenith angle. These output results can subsequently be used for the evaluation of a series of important physical parameters. A short-list sample of the results is given in Table 1. Note that these raw data are not listed sequentially in time. Because of the recording time, sorting the results by Julian date counts is an effective and necessary step for further calculations.

During the coronagraph site survey, the performance of the SBM instruments in long-time field work might cause unexpected parameter changes, such as increased scattered light levels for different wave bands. Thus, it is necessary to calibrate the scattered light levels frequently. According to Martinez-Pillet, Ruis-Cobo & Vazquez (1990), the normalized sky brightness including a constant instrumental scattered light can be expressed as

\[
\frac{I_{\text{sky}}}{I_{\text{sun}}} = \phi, M + B,
\]

where \(\phi\) is the atmospheric scattering function, \(B\) is an instrumental constant that depends on the wavelength and \(M\) is the airmass. Following Lin & Penn (2004), the airmass column can be calculated as a function of zenith angle under the uniform curved atmospheric model:

\[
M = -R \cos Z + \sqrt{R^2 \cos^2 Z + 2Rt + t^2}.
\]

Here, \(Z\) denotes the zenith angle, \(R\) is the sum of the altitude and the radius of the Earth and \(t\) is the thickness of the atmosphere. Then we can obtain

\[
S(Z) = B - \alpha R \cos Z + \alpha \sqrt{R^2 \cos^2 Z + 2Rt + t^2}.
\]

Therefore, we can fit the measured sky brightness \(S(Z)\) as a function of \(Z\) to equation (8), in which \(B, \alpha\) and \(t\) are three free parameters in the fitting algorithm.

Fig. 12 displays the variations of the sky brightness measured with time in all four wavelengths throughout the course of a day. The fact that the measured sky brightness in the morning and afternoon, with the same zenith angles, cannot overlap with each other, implies that the atmospheric conditions are not stable throughout the day.

| No. | Passband | Sky brightness | Recording time (UT) | Zenith angle (°) |
|-----|----------|----------------|---------------------|------------------|
| 0   | Blue     | 35.7           | 2013-10-23T01:37:53 | 74.879           |
| 1   | Green    | 39.1           | 2013-10-23T01:37:50 | 74.889           |
| 2   | Water    | 62.4           | 2013-10-23T01:37:55 | 74.872           |
| 3   | Red      | 61.3           | 2013-10-23T01:37:45 | 74.905           |
| 4   | Blue     | 37.8           | 2013-10-23T01:38:02 | 74.850           |
| 5   | Green    | 42.4           | 2013-10-23T01:37:59 | 74.859           |
| 6   | Water    | 66.2           | 2013-10-23T01:38:04 | 74.843           |
| 7   | Red      | 63.5           | 2013-10-23T01:37:57 | 74.866           |
| ... | ...      | ...            | ...                 | ...              |
| 5121 | Blue   | 13.6           | 2013-10-23T07:08:30 | 45.859           |
| 5122 | Green  | 16.9           | 2013-10-23T07:08:27 | 45.855           |
| 5123 | Water  | 38.8           | 2013-10-23T07:08:32 | 45.862           |
| 5124 | Red    | 41.5           | 2013-10-23T07:08:25 | 45.852           |
| 5125 | Blue   | 13.4           | 2013-10-23T07:08:39 | 45.873           |
| 5126 | Green  | 17.0           | 2013-10-23T07:08:36 | 45.868           |
| 5127 | Water  | 38.7           | 2013-10-23T07:08:41 | 45.876           |
| 5128 | Red    | 40.0           | 2013-10-23T07:08:34 | 45.865           |
| ... | ...     | ...            | ...                 | ...              |
| 10414 | Blue  | 18.0           | 2013-10-23T04:30:26 | 47.058           |
| 10415 | Green | 22.1           | 2013-10-23T04:30:23 | 47.063           |
| 10416 | Water | 44.4           | 2013-10-23T04:30:28 | 47.054           |
| 10417 | Red   | 45.2           | 2013-10-23T04:30:21 | 47.066           |
| 10418 | Blue  | 18.1           | 2013-10-23T04:30:35 | 47.042           |
| 10419 | Green | 21.8           | 2013-10-23T04:30:32 | 47.047           |
| 10420 | Water | 45.0           | 2013-10-23T04:30:37 | 47.038           |
| 10421 | Red   | 44.8           | 2013-10-23T04:30:30 | 47.051           |
Lin & Penn (2004) did not suggest using this kind of data to fit the model. However, to obtain the fitted sky brightness we decide on adopting only the data during the morning (i.e. the first half of the observations with better sky condition). The calibration parameters of the scattered light are 2.06, 5.13, 30.26 and 28.06 millionths for the blue, green, red and water vapour bandpasses, respectively, obviously higher than those values reported by Liu et al. (2012b). The increased scattered light levels indicate that the black coating material inside the SBM tube should have been seriously faded after long-term sunshine and exposure to high-energy radiation in a high-altitude environment. This problem can be resolved by coating the SBM tube regularly in the factory. The coefficients of the ND2 filters show few changes because we have tested them annually. Fig. 13 shows the variations of the sky brightness with the local time at Namco Lake before and after the calibration of the scattered light.

Another possible application of our procedure is to guide and track the Sun with high precision, because our methodology can accurately derive the coordinates of the Sun’s centre. Usually, a telescope can track an object using an extra guiding system composed of a tube parallel to the main telescope and an individual CCD imager. For field observations such as our site survey, the portable SBM instruments were not designed to be equipped with an extra guiding system parallel to the main telescope tube. For most guiding systems for solar telescopes with full-disc observing mode, the Sun’s position for tracking is usually derived from the centroid of the solar image. In one test using a white-light solar telescope with an aperture of 100 mm, we found that the centroid of the
Sun could deviate from its position, based on least-squares fitting calculations, by about 50 pixels. In that test, the commercial CCD size is \(5202 \times 3454\) pixels and the data are white-light full-disc solar images with a solar diameter of about 3050 pixels. Moreover, our algorithm is more robust compared with the centroid method, because the fitting does not require all the points of the Sun. When the Sun is partly covered by clouds, our algorithm can give the right results while the centroid method would not. Interestingly, all solar telescopes with the full-disc mode can benefit from our algorithm and they can track the Sun without an extra guiding system.

5 CONCLUSIONS

For the solar site survey data analysis, we have developed one automatic procedure for the SBM instruments. A detailed description of the procedure is presented. The method can calculate the sky brightness, including identifying the solar disc and the sky areas around it as well as the excluded part of the supporting arms. These processes are implemented on our data acquired by different SBM instruments, including those made in China or lent from the US, during the site survey project in Western China. These results are significant and highly encouraging for further future efforts and investigations, particularly in deriving a variety of important physical parameters such as extinctions, aerosol content and precipitable water vapour content. Furthermore, the accurate coordinates for the Sun’s centre derived in our procedure can be applied for tracking the Sun without an extra guiding system. Indeed, we are in a consulting phase with our engineers for a possible near-future practical realization of the project.

A preliminary analysis applying the results has been performed and discussed for the assessment of the levels of the scattered light. When we compare the scattered light levels obtained from this work with those taken 2 yr ago (Liu et al. 2012b), we notice a significant increase in every wavelength. This is probably because of the functional degradation of the dark material coating inside the SBM tube, which has been used after long-term sunshine exposure in the environment of the Tibet plateau. The new results about the scattered light levels will be reported after the tube is coated again in the near future. However, the robotization of our method for SBM data analysis has been tested and confirmed with high speed, based on a large data sample taken in 2013 for various candidate sites, without any artificial intervention, such as changing some parameters according to different SBM instruments or previous weather conditions.

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