Solar Image Enhancement Method Based on Histogram Specification (Postprint)

Authors: Wang Rui, Xu Zhi, Yang Lei, Ji Kaifan

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Abstract

Solar images encompass various activity phenomena of diverse scales, structures, and brightness levels, all of which constitute research targets in observational solar physics. These activity phenomena frequently cause excessive dynamic range in image display, resulting in the concealment of faint detailed structures. For ground-based telescopes, the influence of Earth' s atmosphere on observational data also leads to a degradation of overall image contrast. These factors are detrimental to the intuitive discovery of solar activity phenomena or structural features of interest from images. To address these issues, the histogram specification method is employed to process several types of observational target images commonly encountered in observational solar physics (solar extreme-ultraviolet images, solar photospheric sunspot images, chromospheric active region images, and chromospheric prominence images), achieving display contrast enhancement for these images through histogram forms such as Rayleigh distribution, double Gaussian distribution, and triple Rayleigh mixture distribution. The processing effectiveness of this method is demonstrated through the processing of extreme-ultraviolet solar images from the space telescope SDO and chromospheric and photospheric images from the 1m New Vacuum Solar Telescope (NVST). The results indicate that the method can effectively enhance the visibility of various types of solar activity phenomena, facilitating the discovery of activity phenomena of interest during the initial stages of research.

Full Text

Solar Image Enhancement Based on Histogram Specification

Wang Rui[1],[2], Xu Zhi[1], Yang Lei[1], Ji Kaifan[1] [1]Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: Solar images contain various active phenomena with different scales, structures, and brightness levels, all of which are targets of observational solar physics research. These phenomena often cause excessive dynamic range in image display, resulting in the concealment of faint structural details. For ground-based telescopes, atmospheric effects further reduce overall image contrast. These factors hinder intuitive identification of solar activity phenomena or structural features from the images. To address these issues, we apply histogram specification to several common observational targets in solar physics (solar EUV images, photospheric sunspot images, chromospheric active region images, and chromospheric prominence images). We employ Rayleigh distribution, double-Gaussian distribution, and triple-Rayleigh mixture distribution histograms to enhance display contrast for these image types. The method' s effectiveness is demonstrated through processing of EUV images from the Solar Dynamics Observatory (SDO) and chromospheric/photospheric images from the 1-meter New Vacuum Solar Telescope (NVST). Results show that this method effectively improves the visibility of various solar activity phenomena, facilitating the discovery of interesting features during initial research stages.

Keywords: Solar image; Histogram specification; Image enhancement

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1 Histogram Specification Theory and Algorithm Implementation

According to classical histogram specification theory, the intensity of an original image is considered a continuous random variable distributed over the interval [0, L], represented by a probability density function (PDF) with a cumulative distribution function (CDF). If the specified histogram has probability density function and cumulative distribution function, the histogram specification process requires finding a monotonically increasing function that satisfies, meaning the area under the probability density histogram below corresponding intensity values must be equal.

In actual digital images, pixel intensity values are discrete, and their probability density function is represented by the frequency of each intensity value in the image (the normalized histogram), with summation replacing integral transformation. Histogram specification is achieved by matching the input image' s CDF to the target CDF. The implementation process consists of four steps:

(1) Compute the normalized histogram of the input image:

where is the th intensity value, is the number of pixels with that intensity, and is the total number of pixels in the input image.

(2) Compute the cumulative distribution function CDFi of the input image:

(3) Compute the cumulative distribution function CDFh of the target histogram:

where is the normalized target histogram and is the th intensity value.

(4) Derive the mapping function M from CDFi and CDFh, which then provides the input image intensity values corresponding to each target histogram intensity value. The mapping relationship implementation process is illustrated in Figure 1 Figure 1: see original paper.

S1: On the CDFh curve, locate the cumulative distribution value CDFh(zj) corresponding to intensity zj.
S2: Sequentially compare the cumulative distribution values of the CDFi curve from 0 to 1 with CDFh(zj) until the cumulative distribution value CDFi(rk+1) corresponding to the (k+1)th intensity value first exceeds the target cumulative distribution value CDFh(zj). This identifies the approximate value of the target cumulative distribution in the input CDF as CDFi().
S3: Determine the input image intensity value corresponding to the CDFi() value.

The mapping function M between input image intensity and specified output image intensity obtained through this process can be expressed as:

Figure 1(b) shows the input-output image intensity curve of the final mapping function M. Applying this mapping relationship to the input image achieves histogram specification.

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2 Histogram Specification for Solar Images

Solar atmospheric activity phenomena are diverse (e.g., photospheric granulation, penumbral filaments, chromospheric filament structures, chromospheric magnetic loops, brightening phenomena, coronal loops, flare eruptions). These phenomena primarily involve photospheric sunspot images, chromospheric active region images, chromospheric prominence images, and solar EUV images in observational solar data. This section describes how appropriate histogram forms can be used to specify these data types, thereby enhancing the visibility of corresponding activity phenomena.

2.1 Histogram Specification for Solar EUV and Chromospheric Active Region Images

For solar EUV images and high-resolution chromospheric active region images, the intensity histogram distribution characteristics resemble a Rayleigh distribution. We employ a simple Rayleigh distribution for specification to improve image contrast. The Rayleigh distribution histogram formulation is:

where L is the intensity level count of the specified histogram; k is an adjustable expansion factor in the interval [0,1]. Adjusting k stretches the histogram width, thereby regulating the dynamic range of the output image display. Larger k values produce greater dynamic range.

2.2 Histogram Specification for Photospheric Sunspot Images

For high-resolution photospheric sunspot images, the image intensity histogram consists of two components (exhibiting a bimodal distribution): low-intensity sunspot regions and high-intensity granulation regions. Based on this characteristic, we apply double-Gaussian distribution specification to highlight penumbral filament structures and umbral dots while also enhancing granulation contrast. The double-Gaussian distribution histogram formulation is:

where the first term (left term) is the primary Gaussian term, primarily adjusting intensity values for the photospheric granulation region; the second term (right term) is the secondary Gaussian term, primarily adjusting intensity values for the photospheric sunspot region. L is the intensity level count of the specified histogram; k is the variance adjustment coefficient for the primary Gaussian term in the interval [0,1], which modifies the half-width of the primary Gaussian distribution to achieve satisfactory enhancement effects. A and A are the peak gains of the two Gaussian terms, proportional to the square root of the total pixel count in each intensity region of the original image, with, where Si is the total number of pixels in each intensity region, N is the total number of pixels in the input image, pg is the specified histogram, and bz is the bin size of the output histogram intensity levels. and represent estimates of the mean intensity of the granulation and sunspot regions in the original image (as in Equation (7)), while is an estimate of the intensity variance of the sunspot region (as in Equation (8)).

Mean intensity of the original histogram (i.e., image intensity mean):

Intensity variance of the histogram (i.e., image intensity variance):

where represents the th intensity value and is its frequency in the image.

To compute these parameters, the original image intensity must first be segmented into granulation and sunspot regions based on the intensity histogram. Otsu' s method, a commonly used automatic threshold selection technique, is notable for its simplicity and stability. In Otsu' s method, threshold t divides image intensity into foreground and background classes, with representing interclass variance. The optimal threshold t is obtained by maximizing inter-class variance. We apply this method to divide the original image intensity into sunspot and granulation regions using threshold t, then calculate distribution parameters for each segmented region.

2.3 Histogram Specification for Chromospheric Prominence Images

For high-resolution chromospheric prominence observations, image intensity clearly consists of three components (exhibiting a trimodal distribution): high-intensity chromospheric disk regions, intermediate-intensity spicule regions at the solar limb, and low-intensity prominence and dark background regions outside the solar disk. For this characteristic, we propose using a triple-Rayleigh mixture distribution for specification to highlight prominence structures while preserving chromospheric structural details to some extent. The triple-Rayleigh mixture distribution histogram formulation is:

where Ai are the peak gains of each Rayleigh distribution, proportional to the square root of the total pixel count in each intensity region of the original image, calculated using the same method as for double-Gaussian peak gains; zthi are the starting intensity values for each Rayleigh distribution; are the intensity variances of each region in the input image (as in Equation (8)); is the average intensity variance; and ki are adjustable expansion coefficients for each Rayleigh distribution in the interval [0,1], used to regulate display contrast for each image component.

To determine parameters for each Rayleigh distribution term, the original image intensity must first be segmented. Here, we use the extended multi-threshold Otsu method to perform two-threshold segmentation on the original intensity histogram, dividing it into three parts: chromospheric disk (high-intensity) region, chromospheric limb spicule (intermediate-intensity) region, and prominence/dark background (low-intensity) region. The basic approach involves setting two thresholds t and t to divide the original image into three classes. The intensity threshold interval is divided into, and the optimal threshold combination is found in threshold space that maximizes inter-class variance, where and represent the probability and mean of each class, respectively.

Figure 2 [Figure 2: see original paper] presents a detailed flowchart of our histogram specification program. After intensity histogram specification, the original image intensity is redistributed and then linearly mapped to a 256-level grayscale image for display. This expands the overall display dynamic range and enhances visibility across grayscale regions. It should be emphasized that histogram specification for solar images constitutes a nonlinear intensity transformation. The processed images serve to help researchers intuitively discover interesting activity phenomena during initial research stages; contrast-enhanced images are not directly used for subsequent quantitative scientific calculations and analysis.

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3 Results Analysis and Discussion

Solar coronal EUV images contain various atmospheric activity phenomena and structures, such as solar active regions, filament channels near different brightening regions, and magnetic loops. Figure 3 [Figure 3: see original paper] compares processing results and corresponding histograms for AIA 171 Å images from the space-based solar telescope. Figure 3(a) shows the original image, where the presence of locally bright flare regions prevents display of details in other dark regions. This is reflected in the histogram (Figure 3d), where most intensity values are concentrated in the low-intensity region with a small distribution in the high-intensity region, causing details concentrated in low-intensity regions to be hidden. Figures 3(b) and 3(e) show the image and histogram after logarithmic processing using an image processing package. The logarithmically processed image shows significant improvement, with dark details and coronal loops clearly visible, but overall grayscale contrast is insufficient, and details of the filament structure below the loops are not prominent. Figures 3(c) and 3(f) show the image and histogram after processing with our method, where the standard deviation =424.4 is obtained from the intensity distribution of the original image (Figure a), and the expansion factor k=0.82 expands the dynamic range of the output image histogram. The histogram shows that pixels with intermediate intensity values are expanded, significantly improving image contrast. Coronal loop structures are enhanced while filament structure details are also appropriately enhanced. Figure 4 [Figure 4: see original paper] compares processing results and corresponding histograms for AIA 304 Å images of the same region, where we similarly applied Rayleigh distribution histogram specification to this band. Figures 4(a) and 4(d) show the original image and histogram, where the overall image display is too dark. Figures 4(b) and 4(e) show the image and histogram after logarithmic processing. Although dark structures are significantly brightened, contrast is insufficient for observing low-intensity structures like filaments. Figures 4(c) and 4(f) show the image and histogram after Rayleigh distribution histogram specification, where the original image standard deviation =271.4 and output image expansion factor k=0.64. Compared with simple logarithmic processing, our method significantly improves both image contrast and details, making active region filament loop structures more clearly visible. This helps researchers clearly observe details of solar coronal magnetic loops and chromospheric active region filaments and their footpoint structures.

In high-resolution chromospheric observation research, studying the structure and evolution of active region filaments and the dynamic characteristics of prominences are important topics in observational solar physics. Figure 5 [Figure 5: see original paper] presents results of Rayleigh histogram specification applied to H chromospheric active region images from the 1-meter New Vacuum Solar Telescope (NVST), compared with intensity thresholding used in NVST data processing. Figures 5(a) and 5(d) show the original image and intensity histogram, where the overall image is too dark for observation and analysis. Figures 5(b) and 5(e) show the image and histogram after intensity thresholding, where image brightness is overall enhanced and filament details are clearly visible, but saturation occurs in the active region portion. Figures 5(c) and 5(f) show the image and histogram after our method, where the original image intensity standard deviation =3540.7 and output image expansion factor k=0.79. The results show that filament details are clearly visible without causing saturation in locally bright regions, and overall image display contrast is significantly improved.

In high-resolution photospheric observation research, analyzing dynamic characteristics of sunspot penumbral filaments, such as penumbral waves and twisting motions, is common. Figure 6 [Figure 6: see original paper] compares photospheric sunspot images in the TiO band from NVST before and after double-Gaussian histogram specification. Figures 6(a) and 6(c) show the unenhanced sunspot image and histogram, where penumbral structures are clear but lack sufficient contrast for observation. Figures 6(b) and 6(d) show the image and histogram after double-Gaussian specification, where the red curve (G1, primary Gaussian term) shows the specification curve for granulation intensity, and the green curve (G2, secondary Gaussian term) shows the specification curve for sunspot intensity. The primary Gaussian term has original image intensity standard deviation =2327.8 and mean =30653.2; the secondary Gaussian term has =4439.1 and mean =17269.9; output adjustment coefficient k =0.54; and peak gains are A =26089.7 and A =1657.28. Figure 6(b) shows significantly enhanced display contrast for penumbral filaments, with clearer structures and umbral dots, facilitating observation of umbral dot variations and penumbral filament motions. Simultaneously, double-Gaussian specification enhances granulation display contrast, aiding observation of granulation evolution.

Figure 7 [Figure 7: see original paper] presents original and histogram (Figures 7(a) and 7(d)), intensity-thresholded (Figures 7(b) and 7(e)), and triple-Rayleigh mixture histogram specification processed images and histograms (Figures 7(c) and 7(f)) for an H prominence dataset observed by NVST. Figure 7(f) also shows the profiles of each Rayleigh distribution, where the red curve (Ray1) specifies intensity for dark regions outside the solar disk, the green curve (Ray2) specifies intensity for spicule regions, and the cyan curve (Ray3) specifies intensity for chromospheric disk regions. Peak gains are A =16957.0, A =3001.66, A =6721.95; original intensity standard deviations are =471.26, =1201.0, =1084.9; and output adjustment coefficients are k =0.52, k =0.17, k =0.17. The original image shows excessive contrast between high-intensity disk regions and low-intensity regions outside the disk, preventing clear display of faint prominence structures. After common intensity thresholding used for NVST, prominence structures are somewhat highlighted but disk regions become saturated, and transitional structures between disk and prominence disappear. After our triple-Rayleigh histogram specification, chromospheric disk structures are preserved, and limb chromospheric structures are also retained to some extent, while prominence structures become more clearly visible for observation and analysis.

To quantitatively demonstrate the contrast enhancement effectiveness of our program for various solar images across different bands, we employ several image contrast evaluation parameters to analyze histogram changes before and after processing. We use standard deviation (SDEV), the enhancement measure (EME) proposed in reference [28], and the measure of enhancement by entropy (EMEE) to quantify image contrast changes. Table 1 lists SDEV, EME, and EMEE values before and after processing for SDO AIA 171 Å chromospheric images, AIA 304 Å coronal images, NVST H chromospheric images, NVST TiO photospheric images, and NVST chromospheric prominence images. For AIA 171 Å, AIA 304 Å, H /NVST active region (AR), and H /NVST prominence, the left column shows evaluation parameters for unprocessed images, the middle column for logarithmically processed or intensity-thresholded images, and the right column for images processed with our Rayleigh histogram specification. For TiO/NVST, the left column shows parameters for unprocessed images and the right column for images processed with our double-Gaussian histogram specification. These parameters show that after our processing, image contrast is improved compared to original images and conventional logarithmic or intensity thresholding methods, consistent with conclusions drawn from visual assessment.

This paper employs histogram specification-based image enhancement methods, proposing Rayleigh distribution, double-Gaussian distribution, and triple-Rayleigh mixture distribution histograms to specify several common observational data types in solar physics (solar EUV images, high-resolution chromospheric images, high-resolution photospheric sunspot images, and chromospheric prominence images). This achieves display contrast enhancement for these images, improving visibility of several activity phenomena of interest and facilitating observation and analysis. We also quantitatively analyze and evaluate contrast enhancement effectiveness using parameters such as SDEV, EME, and EMEE. Based on these three parameters, appropriate histogram specification processing of SDO AIA 171 Å and AIA 304 Å EUV images, NVST high-resolution H chromospheric images, and TiO photospheric images yields improved display contrast.

Therefore, after processing with our designed histogram specification program, effective display enhancement can be achieved for different solar phenomena across various bands, helping researchers discover and observe phenomena of interest. However, it should be noted that solar atmospheric activity phenomena are complex. This paper only applies double-Gaussian and (triple) Rayleigh histograms to several common activity phenomena, achieving good results and demonstrating method feasibility. Future research should explore appropriate histogram forms for other activity phenomena and observational conditions to obtain desired effects.

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