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Evaluation of a method for the resolution improvement of near-limb solar images(*)

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Summary. — We present a methodology, based on the correction for the limb darkening and the use of a directionally sensitive operator the "MadMax", for the image processing of observations obtained near the solar limb. Our image processing method substantially enhances near-limb observations and permits an insight into the studies of the very fine chromospheric structures, over higher-resolution images. Space/time images produced from filtergrams processed with our method indicate that polar surges and spicules are probably related to different physical mechanisms.

PACS 96.60.Na – Chromosphere and chromosphere-corona transition; spicules.
PACS 95.75.Mn – Image processing (including source extraction).
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Achieving high resolution near the extreme limb to analyze the chromospheric structure is a challenge: not only subarcsecond features should be imaged, but a good temporal and spectral resolution is needed to understand dynamic phenomena. Apart from low angular resolution the contrast of near-limb solar images is degraded by the effect of limb darkening. Observers that want to be able to distinguish the over-limb fine structure should overexpose images, which results in loosing the detail of near-limb features. We use an image processing method for the correction of near-limb observations that allows the simultaneous observation of both near-limb and over-limb structures and improves the visibility of fine structures. The method is based on the combination of a method for the correction of limb darkening with a method for the enhancement of the contrast of fine structures. In this work we present the procedure that we follow for the enhancement

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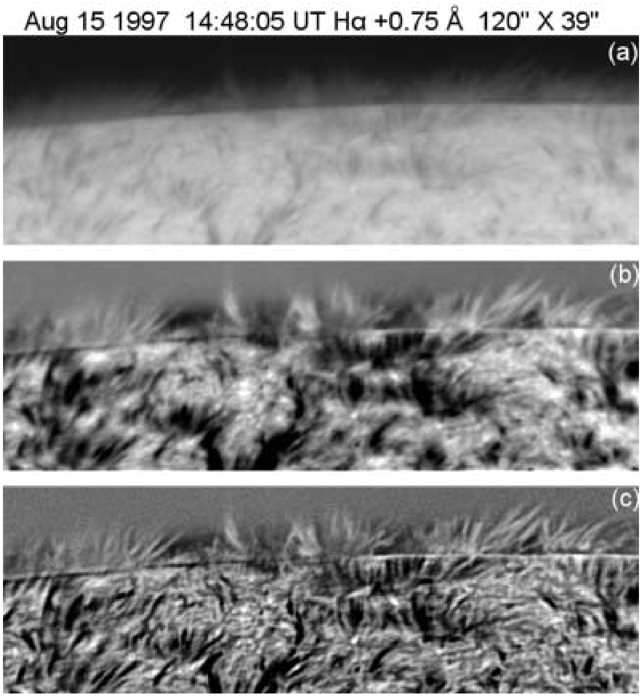

Fig. 1. – Single image of a near-limb region observed on August 15, 1997 from the DST of NSO SPO, in Hα +0.75 Å; (a) original image, (b) the same image corrected for limb darkening, (c) further enhanced using the Madmax operator.

of near-limb chromospheric observations and we show processed images demonstrating the improvement achieved. We further show some examples of various applications of the method.

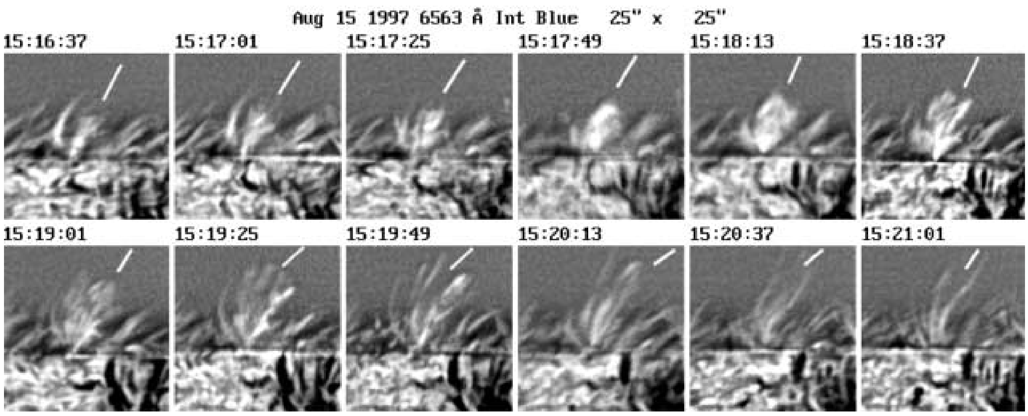

Fig. 2. – Images at Hα −0.75 Å showing the appearance and development of a “bush” of spicules.

2. – Image processing method

The raw images are corrected for dark current and flat field. We furthermore normalize images computing the average intensity over the whole image (excluding the sky) and dividing the intensity of each pixel by this value in order to compensate for changes of sky transparency when using time series and/or images taken at different wavelengths.

In order to correct the images for the limb darkening of both the photosphere and the chromosphere (including the part above the photospheric limb) and enhance their spatial resolution, we first determine the position of the center of the solar disk and the solar radius, fitting a circle to the limb. The precision of the fitting is better than half a pixel.

Our data contain only part of the solar disk. Thus, in order to determine the position of the limb, we first compute a gradient of the image in radial direction. Subsequently we take lines across the limb and determine the inflection point of the limb. Finally using an iteration procedure we fit a perfect circle to limb points.

After having determined the center of the solar disk and the solar radius, we compute the average intensity along circular arcs parallel to the solar limb with half a pixel step. We get this way the limb darkening profile as a function of the distance from the disk center. The limb darkening profile computed this way is a continuous function except at the limits of the solar disk. Subsequently we compute the distance of each point of the image from the center of the solar disk and subtract from its intensity the corresponding limb darkening intensity.

We further enhance the fine structures applying a version of Madmax, a directionally sensitive operator originally developed by Koutchmy [1], in order to process optically thin coronal features. For each pixel the maximum of the secondary derivatives in all directions around the pixel is computed. The procedure is repeated with different pixel steps (distances from the original pixel). Subsequently the sum of the maximum value of the secondary derivatives for each step size multiplied by a weight is computed at each position. The weight depends on the scale of the fine structures that is desirable to enhance. Finally the sum is added to the original intensity of the pixel. The new intensity of each pixel is computed using the following formula:

$$N(I) = I + aM(\mathrm{SD1}(I)) + bM(\mathrm{SD2}(I)) + cM(\mathrm{SD3}(I))\,, \qquad (1)$$

where M selects the maximum absolute values of the secondary derivatives computed in eight equally spaced directions, around each pixel; SD is an operator for the computation of the secondary derivative. SD1, SD2, ... represent the computation of derivatives with different sampling, while a, b and c are weights depending on the characteristic scale of the structures in the image that one would like to restore. In general they depend on the smearing due to the instrument and earth atmosphere and finally on the spectral disturbances and on the noise present in each image. In order to determine the values of a, b and c that give the best results, we compute the distribution of the fine structures' width taking image slices vertically along characteristic features (like spicules, mottles, fibrils). Subsequently we compute the average of the most probable values and take the weights so that a corresponds to the most probable value, b to the most probable value plus $\sigma/2$ and so for. Although the technique substantially restores the spatial details of fine structures, we use the original images, *e.g.*, to deduce velocity. We performed a number of tests applying the Madmax enhancement technique to a variety of solar images (spot areas, active regions, quiet regions near disk and near limb, filaments and

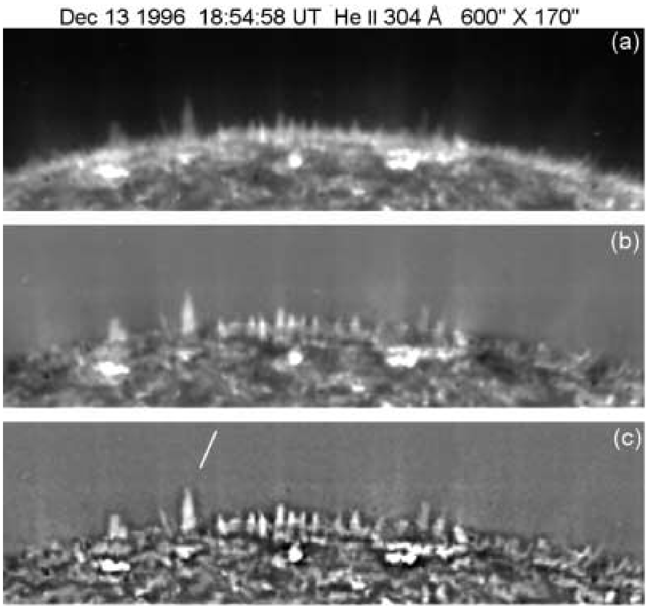

Fig. 3. – He II 304 Å images obtained on December 13, 1996 from EIT on board SOHO (ESA-NASA); (a) original image, (b) the same image corrected for limb darkening, (c) further enhanced using the Madmax operator.

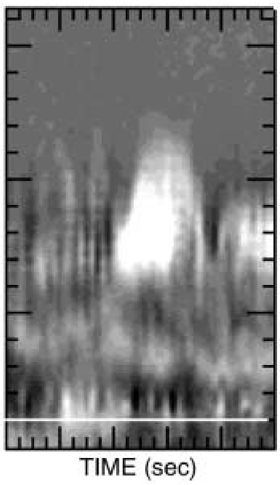

Fig. 4. – "Space/time slices" image at Hα center, to illustrate the light curve of a characteristic example of a spicule; the x-axis corresponds to the time and the y-axis to the height. Tick marks in the x-axis correspond to 60 s and tick marks in the y-axis correspond to $1.3''$.

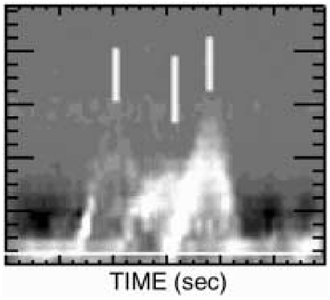

Fig. 5. – "Space/time slices" image at He II 304 Å (EIT/SOHO), showing the light curve of a characteristic example of a polar surge (marked with a white line in fig. 3); the x-axis corresponds to the time and the y-axis to the height. Tick marks in the x-axis correspond to 160 s and tick marks in the y-axis correspond to 6.5″(both the spatial and time scales are different from the image of fig. 4). Three subsequent ejections of material can be observed.

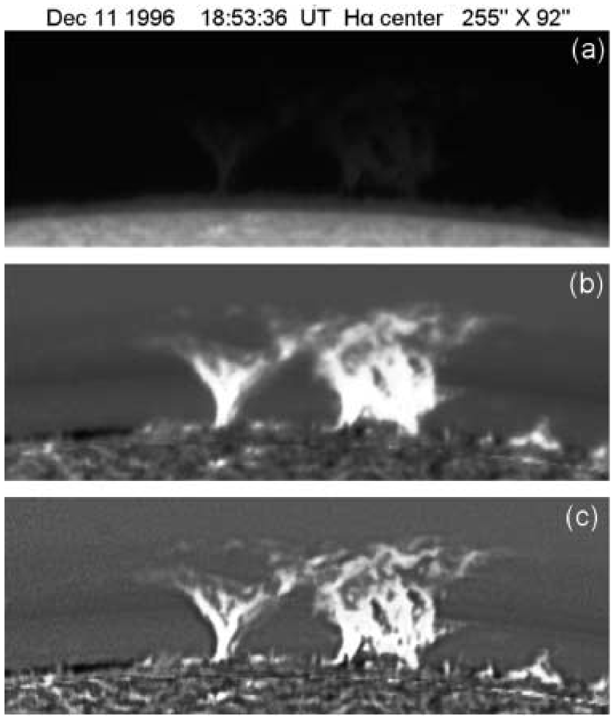

Fig. 6. – Hα center image, large FOV, showing tree-like prominences; (a) original image, (b) corrected for limb darkening, (c) further enhanced using the Madmax operator. The images were obtained on December 11 1996 near the solar limb (S42.4, E90.2).

prominences). We compared visually the processed images with the original ones in order to ensure that there is *no artifacts* introduced. The technique behaves quite well, except in case that the original image suffers from high additive noise (salt and pepper). In that case before the application of the technique a median filtering is necessary.

3. – Evaluation of the method

We present results from the application of the method to Hα observations carried out at the R. B. Dunn Solar Telescope (DST) of the Sacramento Peak Observatory using the U.B.F. and to He II 304 observations, obtained with EIT on board SOHO.

Figure 1 shows a near-limb region observed on August 16, 1997, at Hα -0.75 Å and the successive improvement that can be achieved applying the two steps of our method. Figure 2 presents a time sequence of images showing details of the appearance and development of a "bush" of spicules. The feature appears at about 15:16:37 UT as a bundle of flux tubes. Subsequently we observe a brightening lasting from about 15:17:49 to 15:18:37. After the brightening there is an "opening" of the magnetic-field lines that expand and look like a bush of giant spicules.

In fig. 3 we show the improvement that can be achieved to a He II 304 Å image; it was obtained on December 13, 1996 from EIT on board SOHO. Further figs. 4 and 5 show the light curves of a characteristic example of a spicule observed in Hα center and of a polar surge observed in He II 304 Å, respectively. We use the term polar surge to refer to a special class of highly dynamic macrospicules (see [2, 3]). The light curves were produced by adding time slice images (see [4]). They indicate that spicules and polar surges are probably related to different physical mechanisms. The expansion of the spicule appears to take place in two or more stages and the collapse starts from the lower part of the spicule. The motion of its apparent top is best fitted by a ballistic motion with initial velocity of about 40 km s^{-1} and a deceleration of 0.2 km s^{-2} which is lower than the gravitational one. Thus we have to assume either that the material moves on an inclined flux tube with an inclination angle of about 30° (which is not supported by the observations) or that a pure ballistic model is unrealistic and a more complicated scenario is needed (like a ballistic model with continuous injection of material, see [5]). From fig. 5 we observe that in the case of the polar surge three consecutive ejections take place in succession, the third one being the more well defined. The motion of the apparent top of the polar surge is well represented by a parabolic ballistic trajectory with an initial velocity of about 140 km s^{-1} and a deceleration very near that of gravity (0.26 km s^{-2}). We also observe that the central part of the light curve is significantly fainter than the edges, not suggesting a material motion along a flux tube and enhancing the scenario of a ballistic motion. Our results concerning polar surges enhance the conclusions of Wilhelm [6], who found that his observations, using SUMER, were not consistent with any mechanism which requires a field-aligned direction of the macrospicule propagation.

Finally fig. 6 shows an example of an Hα image of a prominence, observed on December 11, 1996. What seems interesting examining images of the lowest parts of the prominence and assuming the feet are not too far beyond the limb, is the apparent *absence* of a connection with a disc feature and the disappearance of the chromospheric connection at a height of say 4000 km (from the classical VAL model the top of the chromosphere is at 2200 km from τ=1). Our image does not present evidence of the "barb" effect, although it might be absorbed by the thick chromosphere situated before, or maybe the true feet of the prominence are situated behind the limb. What we observe is evidence of a kind of quasi-vertical arms/extension like tree-trunk, suggesting the coronal gas is condensing from the hot corona and slowly falling down under the influence of the gravity (because the trunks are radial). More observations processed with our technique, that gives the opportunity to observe details of both the overlimb and the near-limb part of the prominence, will help to better understand the physics of prominences.

Our image processing method substantially enhances near-limb solar observations, helps to see existing details and eventually make measurements in a less noisy environment. It is ideal for studying fine chromospheric structures like spicules, macrospicules, polar surges, surges, fine dark mottles, fibrils as well as the fine structure of prominences.

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