Increasing the Fine Structure Visibility of the \textit{Hinode} SOT Ca II H Filtergrams

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Abstract We present an image processing technique, the improved OMC filter (also called Madmax), which selects maxima of convexities of intensity modulations of an image. The filter computes second derivatives of the image in multiple directions around each pixel. It is shown to be efficient for pattern recognition, and bright hair-like or small anisotropic features can be enhanced. The filter is tested on artificially generated images, and the effect of a different number of directions in which the second derivatives are calculated is evaluated. Ca II H line images of spicules and prominences obtained with \textit{Hinode}/SOT are also used to illustrate its efficiency on real data. It is shown how to make the choice of the sensitive parameters to be used in improving the image visibility.

Keywords Automatic tracing · Image processing

1. Introduction

Modern observations of the solar chromosphere in the Ca II H line using the Solar Optical Telescope (SOT) of \textit{Hinode} (Tsuneta et al., 2008; Suematsu et al., 2008; Shimizu et al.,...
and also in a wide range of other optical lines such as Hα and Hβ, and the infrared triplet lines of Ca II, as well as in UV and EUV lines, exhibit a myriad of thin and highly dynamical features usually called limb spicules. They can reach heights of 4000 – 10000 km before fading out or falling back towards the solar surface. Their smallest widths are only 100–200 km (we loosely use the term diameter in discussing the spicule thickness, just because it is convenient to assume that the cross section is nearly circular, in the approximation of a magnetic flux tube; see the discussion in Veselovsky, Triskova, and Koutchmy (1994)).

Tavabi, Koutchmy, and Ajabshirzadeh (2011) statistically analyzed spicules observed with Hinode/SOT starting from the 1 Mm height above the limb and found that indeed spicules show a whole range of diameters and time variations, including “interacting spicules”.

Almost all spicules seen at the largest heights fade out and/or tend to show lower contrast above the background than the near-limb spicules. Therefore, image processing techniques which enhance the contrast of these faint structures are required to study them. In this paper, we will propose one of such techniques.

2. Proposed Algorithm

The 2D Wiener filter is an optimal filter in terms of the mean square error. In other words, it minimizes the overall mean square error in the process of filtering and noise smoothing. The algorithm we discuss here is based on the application of a pixel-wise adaptive operator which computes the maxima of convexities of intensity variations in several directions around each pixel, which is shown to be efficient for pattern recognition. We also recall the spatial filter which was advocated in the reference book (Rosenfeld and Kak, 1976) on image processing which is based on the use of the 2D Laplacian (rather noisy) operator.

The most frequently used method for increasing the visibility of small-scale features is the unsharp masking or its variant using the wavelet transform. This method can be understood as a convolution with the derivative of a 2D Gaussian function which enhances the visibility of thin structures. This is equivalent to a 2D Fourier filtering and has been very useful for evaluating eclipse images of the solar corona in white light as demonstrated in November and Koutchmy (1996). There exist a large number of numerical and automated codes, specialized either for the case of curvilinear features (Ajabshirzadeh, Tavabi, and Koutchmy, 2008; Aschwanden et al., 2008; Biskri et al., 2010). However, there is no general pattern-tracing code which has a superior performance in all kinds of data and features. Therefore, for a particular data set and structure the method needs to be adapted to the particular morphological properties of a given data set. We should also note that manual tracing is not suitable when a very large population of similar structures needs to be analyzed.

In this context, another operator we prefer, one of a more general purpose, is the multidirectional (4, 8, 16, . . . ) maximum gradient operator, OMC (Operator of Maximum Convexities). OMC was first introduced by Koutchmy and Koutchmy (1989) in order to increase the visibility and contrast of solar structures with relative immunity against noise. This operator has later been called and nicknamed “Madmax”. It has been repeatedly shown that this operator works successfully for improving the visibility of coronal filtergrams; see excellent examples in Takeda et al. (2000), Suematsu et al. (2008), and more recently in Anan et al. (2010) and Tavabi, Koutchmy, and Ajabshirzadeh (2011).

This algorithm is briefly summarized below, for eight directions as a basic feature: It could be expanded to more radial directions (November and Koutchmy, 1996; Christopoulou, Georgakilas, and Koutchmy, 2001).

Let $u[x, y]$ be a matrix of measured intensity. The operator $M$ applying to $u[x, y]$ is introduced as
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\[
M\left( u \begin{bmatrix} x \\ y \end{bmatrix} \right) = \alpha M_8 \left( u \begin{bmatrix} x \\ y \end{bmatrix} \right) + \beta E_2 \left( M_8 \left( S_2 \left( u \begin{bmatrix} x \\ y \end{bmatrix} \right) \right) \right) + \gamma E_4 \left( M_8 \left( S_2 \left( S_2 \left( u \begin{bmatrix} x \\ y \end{bmatrix} \right) \right) \right) \right) + \cdots,
\]

where

\[
M_8 = \max(\nabla^2_k),
\]

and \( \nabla^2_k \) means the second order difference operator in the \( k \)-direction defined by angles 0, 45, 90, \ldots, \( S_2 \) is the operator which averages every two rows and columns. \( E_2 \) and \( E_4 \) are the operators which expand a matrix by bilinear interpolation with the row and column expansion factors of 2 and 4, respectively. The coefficients \( \alpha, \beta, \text{and} \gamma \) are some weights, following Koutchmy and Koutchmy (1989).

The most important operator is \( M_8 \), which amplifies convex points. Therefore, its main effect is to find the direction of quasi-discontinuities, \textit{i.e.}, the locations where there is an abrupt change in image intensity. Note that \( M_8 \) is shift-invariant but it is NOT a morphological filter (see Coster and Chermant, 1985) due to its non linear property. It is less sensitive to noise; see Koutchmy and Koutchmy (1989) for a comparison with other methods regarding the sensitivity to noise.

3. Test Results

The OMC filter has been applied to a test image (Figure 1A), which is made of artificially generated 2D texture lines blurred by a Gaussian mask mimicking an isotropic point spread function (PSF) supposed to reproduce the effect of finite resolution. The width (full width at half maximum, FWHM) of the Gaussian blurring function is selected to be about 2.5 times the width of the average value of the finest line thickness (see Figure 1B).

The result of applying the operator on the blurred test image is shown in Figures 1C–1E. Figure 1C has been reconstructed using the second derivative spatial filter in four directions (up, down, left, and right). This method is suitable for edge detection, but the finest features are almost removed and a lot of them are definitely lost.

Figures 1D and 1E show the results of the filters using second derivatives in 8 and 16 directions, respectively. The filter with eight directions performs well and almost all threads (parallel ones and crossing ones) are clearly seen, but at the very location of crossing features, an artificial effect causes a discontinuity along the threads.

Figure 1E shows an even better performance when the number of directions has been increased to 16. Artificial discontinuities are almost removed and the OMC operator works more optimally; the obtained image has a high resemblance to the original unblurred image. However, more computer resources are needed and this should be considered when processing a long sequence of images.

4. Applications and Discussion

Next, we will apply the OMC filter to Ca II H images obtained with \textit{Hinode}/SOT. We have selected some “Level-0” images from the \textit{Hinode} database, and first processed the images using the IDL routine \texttt{fg_prep}, which is a part of the \textit{Hinode} tree of SolarSoftware. This produces Level-1 images corrected for pixel shifts, dark current and flat-field non-uniformity.
Figure 1 Original test image with textures (A), the corresponding blurred image (B) representing the result of finite resolution observations, and the reconstructed images (C–E) using the OMC filter for three different steps of tiling (4, 8, and 16 directions in calculating second derivatives).

For each filtergram in the data set. Of course, the background subtraction procedure is not perfect, and residual non-spicule emission may be present in the background-subtracted images.

Figure 2 shows the results of OMC filter applied to an image of Ca II H at the limb. The right-hand-side two frames show the results of applying the filters with second derivatives in 8 and 16 directions, respectively. A large-scale jet (a surge) is ejected from among several
underlying small loops and spicules. The jet consists of many long parallel threads, which are evidenced only after applying the OMC operator.

The next example is a limb prominence (Figure 3). According to Figure 3, under the presence of a large noise, some additional wavelet filtering can help to reduce its influence and increase the contrast of the smallest features.

Here we notice that the optimum number of directions in the OMC filter depends on the spatial resolution of the 2D data and of the size (FWHM) of the structures. Therefore, knowing the instrumental PSF will help to choose the optimum number of directions. For example, the FWHM (or diameter) of a typical chromospheric fine structure is about 0.4 Mm. The pixel size of Hinode/SOT taking the Ca II H line images is 0.054 arcsec (full resolution) or about 40 km on the Sun, and in our image samples the effective resolution is of the order of 120 km (≈ 0°16 arcsec). In such a case there is a difference between using the 8 or 16 directions. The Laplacian operator, using second derivatives in four directions (up-down-left-right) will be enough for detecting the edge of structures, without paying much attention to recovering the unblurred original image. The OMC filter with second derivatives calculated in eight directions gives an unblurred image with more details and a good visibility and enhancement of subtle structures. However, the OMC filter with eight directions is not always the optimum method for all kinds of blurred images. When the image resolution is of the same order as the thinnest structures that we want to consider, the OMC filter with eight directions will not perform successfully around the cross points of two thin
structures. Instead we see a lot of discontinuities near the cross point (Figure 1D). In such a case we should use a higher-order operator (derivatives in 16 directions). For images of lower resolution (or re-binned images to increase the data transformation speed), we may
suggest to apply the OMC filter with 24, 32, or even more directions to avoid any artifact discontinuities in the enhanced image.

Next we will try to resolve structures at the feet of spicules near the solar limb. First we have to anticipate that analyzing the spicule feet is getting increasingly confusing due to the overlapping effect. The overlapping problem can be understood by calculating the effective integration length $L$ along the line of sight tangential to the limb and crossing a point at height $h$. From trigonometry we obtain

$$L^2 + R_0^2 = R_0^2 + 2hR_0 + h^2.$$  

Neglecting $h^2$ as $h \ll R_0$, the double path length (in front and back of the limb) is

$$2L = 2\sqrt{2}R_0h.$$  

A very short chromospheric structure of say $h = 1$ Mm can be seen above the limb if it is within 37 Mm along the line of sight, in front or behind the plane of the sky (see also Zirin, 1988).

In case spicules have an average height of 10 Mm, they would cover a $2 \times 118$ Mm path which is more than a one-third of the solar radius. Therefore they will appear as a rather crowded forest.

Figure 4 shows our attempt to resolve the feet of limb spicules. The arrows at the right-hand-side of the panels are placed exactly at the same height to make the comparison easier. At the bottom of the image processed with the OMC filter, under the limb, two marks are put to help recognize the structures which may come from in front “∧” or from behind “|” the fully opaque photospheric limb. As illustrated in Figure 4, the OMC filter permits us to look, for the first time, at the feet of the spicules closer to the solar limb. It also offers a method to reduce the overlapping effect.

In the original image (Figure 4, top), the roots of chromospheric structures completely disappear under the 1 Mm height above the limb. The decrease in contrast of these structures is produced by the effect of
i) the overlapping of several structures along the line of sight (both the overlap in the emitting structures and absorption by some of them contribute to the confusion), and

ii) the increasing diffuse background when approaching the photospheric limb.

Note that indeed the disk is very bright up to the very limb because the transmission width of the Ca II H filter of Hinode/SOT is broad compared to the width of the Ca II H emission line. Accordingly, in addition to the true diffuse background emission from the chromosphere outside the limb, some parasitic light of instrumental origin is present. Using the images processed with the OMC filter, it is possible to look much deeper towards the photospheric limb, under the 1 Mm height, and see the roots of spicules in front and behind the limb. By looking at the marks | and ∧ in Figure 4 (bottom), approximately half of the roots of spicules situated behind the limb is “progressively” disappearing.

The illustrated example convincingly shows that it should be now possible to improve the hydrostatic homogeneous models of the low chromospheric layers by identifying the root of spicules and characterizing their properties which must be different from the more homogeneous background. This is also illustrated by the movie made using the OMC filter, showing dynamical properties of this layer (Tavabi, Koutchmy, and Ajabshirzadeh, 2011). Further discussion on the apparent small loops very close to the limb and their effect on radiative transfer is left for future publications.

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