AN AUTOMATED PROCEDURE FOR MEASUREMENT OF
PROMINENCE TRANSVERSE VELOCITIES

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ABSTRACT

A computer algorithm to measure transverse velocities (proper motion) in prominences has been developed. The algorithm is based on local cross correlation. We present the method and discuss its usefulness and optimization, and examples of prominence velocity maps are shown.

1. Introduction.

The interpretation of apparent displacements of intensity structures in prominences in terms of "velocities" or mass or energy transport is not straightforward. Nevertheless these motions provide a direct and commonly used means of determining the "evolution" of a prominence. The detailed mapping of such an evolution seems likely to be an important ingredient in the process of trying to understand the dynamics taking place in prominences, and through it the correct interpretation of the intensity displacements themselves.

Fine structure within quiescent prominences typically exhibit speeds of 5-10 km/s (Tandberg-Hanssen 1974, Schmieder 1989), but have been seen to reach 80 km/s (Engvold 1979). The quantification of the displacements of structures as shown qualitatively in a time lapse movie may be carried out by eye, but is a tedious process of comparing images and recognizing structures and it is inevitably subjective. In the present study we attempt to use computer image processing using local cross correlation techniques to quantify the prominence motions. Local cross correlation techniques have been developed during recent years (Dunn and November 1985, November 1986, November and Simon 1988, Title et al 1986, von der Lühe 1983, Andreassen et al 1985, Darvann 1986) and have been used for measurement of proper motion of granulation (Title et al 1987, Simon et al 1989, November 1988, November 1989, Brandt et al 1988, Darvann 1988), for measurement of seeing distortion (Darvann et al 1987, Karud 1988), for flows in sunspot penumbrae (November et al 1987) and for destretching of white light flare and granulation images (Wiborg 1989). Very recently the technique has successfully been applied to show the flows inside sunspot umbrae (Zirin 1989), and has been shown to be able to measure motions in the chromospheric network (Yi 1989, Chung 1989). Our version of the correlation technique is applicable to timeseries of prominence images, and provides an accurate, well defined and automated means of quantifying proper motions in prominences. In the following we describe the technique and its merits and limitations.
2. The Algorithm.

Cross correlation algorithms applied to granulation images are described in detail by von der Lühe (1983) and by Novembre (1986). The correlation functions may be computed directly or by use of the Fast Fourier Transform. The computationally simplest correlation algorithm computes the un-normalized Local Cross Correlation Function (LCCF) which may be written as

$$LCCF(z,y) = \sum_u \sum_v f(z,y) \cdot g(z+u,y+v) \cdot w$$

where \( f \) is a reference image sampled at time \( t \), \( g \) is an image sampling the same scene as \( f \) at a later time \( t + \Delta t \) (\( \Delta t \) defines the correlation time) and \( w \) is a sampling window defining the effective size of \( g \). The summation is carried out over spatial shifts of \( g \) relative to \( f \) by an amount of \( u \) pixels in the x-direction and of \( v \) pixels in the y-direction. The result is a cross correlation array with dimension \( u \times v \) where the position of maximum determines the best fit of \( g \) relative to \( f \) in the neighbourhood of \( (x,y) \) as defined by \( w \). It is straightforward to apply [1] to granulation images provided \( \Delta t \) is shorter than the granulation evolution time and \( w \) is large enough to contain a few granules.

Prominence images show much steeper intensity gradients and a wider range of size of fine structure than granulation images. We find that [1] often fails when applied to prominence images and is applicable only in regions of the prominence where there is sufficient fine structure, and when no large scale intensity gradient is present across the sampling window. The bias of the computed shifts due to large scale gradients may be reduced by replacing [1] by the Local Absolute Difference Function defined by

$$LADF(z,y) = \sum_u \sum_v \left| f(z,y) - g(z+u,y+v) \cdot w \right|$$

as pointed out by Karud (1988). Even this approach fails (unless the sampling window is allowed to be unreasonably large) as is demonstrated in Figure 1a. In the figure the LADF has been computed using a pair of images sampled 120 s apart and is shown for some locations in the prominence. The method has failed in those cases where there is no well defined minimum in the LADF array. (In the figure the absolute difference arrays are shown inverted.)

A tremendous improvement of the performance of the algorithm is found if the intensity images are converted to gradient images (derivative of the intensity), i.e. the images \( f \) and \( g \) in [2] are replaced by \( f' \) and \( g' \) where

$$f' = \frac{\Delta f}{\Delta x} + \frac{\Delta f}{\Delta y} \quad \text{and} \quad g' = \frac{\Delta g}{\Delta x} + \frac{\Delta g}{\Delta y}$$

An example of a gradient image is shown in Figure 1b. With such a preprocessing of the images the algorithm performs quite satisfactorily as may be seen from the LADF arrays shown in Fig 1b, they show well-defined minima everywhere in the prominence. Sub-pixel accuracy in locating the minimum in the LADF array is necessary, and may be achieved by fitting a second order polynomial to the array. We have found that the use of a six-point interpolation formula fitting a paraboloid provides sufficient accuracy, as demonstrated by the results of an accuracy test shown in Figure 2. The test is carried out on pairs of images having known relative shifts. An image was digitized repeatedly with the microdensitometer, each time adding a small shift.
of 1/10 of a pixel in x and y. Figure 2 demonstrates the capability of the algorithm to reproduce the true shifts across the prominence using a sampling window size of 8x8 arcseconds. The measured shift divided by the true shift +/- RMS is plotted against the true shift. The test was carried out for three different regions of the prominence: a) the "edge" of the prominence where it meets the dark background, b) the "body" or central part of the prominence and c) the lower part of the prominence including parts of the limb. The algorithm applied to the limb part is seen to reproduce the true shift very accurately while the error is larger at the edge.

Figure 1. Plots of the Local Absolute Difference Function arrays (here shown inverted) at some locations in the prominence image showing qualitatively the improved performance of the LADF algorithm when applied to gradient images (b) instead of the intensity images (a). The LADF arrays to the right in the figure have been computed at the locations shown to the left. Inner square boxes show the size of the 8x8 arcsecond window that has been applied, outer boxes represent the total area covered when moving the window 4 pixels in all directions.
The differences in performance seen in the different parts of the prominence reflects the fact that the algorithm as applied to a particular type of fine structure gives rise to a typical shape of the LADF array which may or may not be well fitted by the six-point paraboloid formula. On the average the algorithm is seen to reproduce the true shifts to about 30% as determined by the RMS, which corresponds to a 0.3 pixel error bar on a shift of 1 pixel.

Figure 2. Results of an accuracy test of the LADF algorithm performed on pairs of prominence gradient images having a known relative shift. The accuracy of the algorithm varies with the position in the prominence (see the text). The black squares in the image to the lower right show the location and size of the areas used for alignment of images as described in section 4.

Properties like lifetime, contrast, size and amount of fine structure change from prominence to prominence and usually within each prominence. It is therefore useful to change parameters in the LADF algorithm depending on the position in the prominence. The two most important parameters are the window size \( w \) and the correlation time \( \Delta t \). In our algorithm computation of the LADF is repeated automatically with a larger \( w \) and a larger shift \((u \text{ and } v)\) whenever a well defined minimum in the LADF is not found.

The choice of \( \Delta t \) needs to be adjusted according to the evolutionary timescale of the particular prominence under study. It needs to be short enough so that shape and position of structures within the sampling window have not been changing too much. At the same time it should be as long as possible in order for displacements in the prominence to be significant compared to the noise due to seeing distortion. Seeing noise is large in a single displacement map but is efficiently reduced by averaging several maps. It is even more efficient to average the LADF arrays before determining the displacements (November and Simon 1988). The LADF arrays that are computed from bad seeing images have low contrast and contribute less to the average.

The number of LADF arrays needed to build up a reliable velocity map depends on the seeing, but for a given dataset the number will be a minimum for the best choice of the correlation time \( \Delta t \). Figure 3 demonstrates how the quality of the velocity map improves when more LADF arrays are being averaged. For this computation a timeseries of images (of Aug. 2, 1989) was divided in two interlaced timeseries (frame rate 15/min). We computed a velocity map from each of the timeseries and may use the amount of difference between these two independent maps to estimate the noise in the maps. With a \( \Delta t \) of 120 s  the correlation coefficient between the independent maps is 0.92 after averaging 50 LADF arrays in time (corresponding to 200 s). Figure 4 shows two independent velocity maps. Averaging the arrays for a longer time than 200 s does not increase the correlation coefficient any further; a noise level due to the seeing and evolution of the fine structure has been reached.

![Figure 3. Averaging a number of LADF arrays in time reduces the seeing noise. The correlation coefficient between two independent, interlaced velocity maps is seen to increase up to 0.92 after 3.3 minutes, corresponding to averaging 50 LADF arrays. The three curves represent three different choices of correlation time (time between images used for the comparison); 2, 4, and 8 minutes, favouring the shortest time for this dataset of Aug. 2, 1989.](image)

Figure 4. Example of prominence velocity maps (200s averages) computed from two independent, interlaced timeseries A and B. The x and y components of the velocity is shown separately on a grayscale ranging from black (-5km/s) to white (+5km/s). The correlation coefficient between x-maps is 0.91, between y-maps 0.93.
The number of maps or LADF arrays needed to make a reliable prominence velocity map is smaller than is the case for granulation because velocities are typically larger in prominences.

4. Presentation of Prominence Transverse Velocity Maps.

Prominence transverse velocities have been produced for two different prominences observed with the Vacuum Tower Telescope of National Solar Observatory, Sacramento Peak (NSO/SP). In Figure 5 a velocity map of a prominence of Dec. 12 1988 is presented. The prominence was observed in H\(\beta\) line center with the Universal Birefringent Filter and a CCD camera with a pixel size of 0.51 arcsec. The images were sampled at a rate of 3 per minute. The map is an average of 41 single displacement maps and is accordingly a 14 minute average. The average speed in the map is 1.7 km/s.

Figure 5. 14 minute average velocity map of the Dec. 12, 1988 prominence. The velocity map at the bottom combines the maps of the x and y velocity components shown at the upper right. Center portion of the figure shows the image scale (10 arcsec bars), the size of the sampling window applied, the distribution of the speed in the map (average 1.7 km/s), an error distribution computed from differences between interlaced maps, and a 5 km/s calibration vector. The upper portion of the prominence is very faint.
Figure 6 shows two consecutive velocity maps for a prominence observed on Aug. 2, 1989, this prominence can also be seen in Figures 1 and 2. The prominence was recorded during 40 minutes in Hα on Kodak Technical Pan film at a rate of 30 images per minute and digitized with the NSO/SP Fast Microdensitometer. In this dataset the seeing is better than in the previous set and the pixel size is 0.26 arcsec.

Before computing the maps each image in the timeseries was carefully aligned (one pixel accuracy) relative to an average image using the LADF algorithm and the two windows represented by the black boxes in Figure 2. The areas were chosen because they contain part of the solar limb so that the velocities measured will reflect the motion of the prominence relative to the limb.

Figure 6. Two consecutive 5.3 minute average velocity maps of the Aug. 2, 1989 prominence. Amplitude of the velocity is demonstrated by the 4 km/s vector.
The two velocity maps shown in Figure 6 are made by averaging LADF arrays during 3.3 minutes (50 arrays) but are indeed 5.3 minute averages because of the 2 min correlation time. The two maps are consecutive in time and contain no common images used in the computation but still show considerable amount of similarity. The differences between the two maps represent the evolution of the flow patterns within the prominence after 5.3 minutes. The maps show a very complicated flow pattern with large local changes and also large change during a short time (5.3 min). This is verified by displaying the timeseries of images as a movie. The movie also demonstrates the reason for the relatively small speeds shown by the maps. A lot of fine structures smaller than the spatial extent of the $\approx 4\times4$ arcsec sampling window is seen to exhibit large individual random velocities that have been averaged over the window. The largest speed observed in the movie is estimated to be 60 km/s, (for a bright fine structure $\approx 1$ arcsec in spatial extent, lifetime $\approx 3$ min) while the maximum speed in the maps is about 5 km/s.

5. Conclusion

We have seen that a modified version of a local cross correlation algorithm successfully produces prominence proper motion maps. Velocities are typically averaged over about 5 minutes and are spatially averaged over at least $4\times4$ arcsecond areas. In addition to being able to correlation track prominence images and produce velocity maps the method is directly applicable to destretching of prominence images (local geometric correction for distortion). Destretching of the time series should be carried out before making Dopplergrams from filtergrams or carrying out oscillation analysis at high spatial resolution.

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References

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AUTOMATIZiran POSTUPAK MJERENJA TRANSVERZALNIH BrZINA U PROMINENCIJAMA

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Sacjetak: Razvijen je kompjutorski algoritam za mjerenje transverzalnih brzina (vlastitih gibanja) u prominencijama. Algoritam se temelji na lokalnoj unakrsnoj korelaciji. Prikazuje se metoda, diskutira se njena korisnost i optimalizacija te se daju primjeri karata brzina unutar prominencija.