The Size of Penumbral Filaments

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Motivation

Magnetic fields on the sun manifest in a large variety of scales and intensities, the huge (~20 Mm) and dark sunspots being only the most prominent features. Still the filamentary structure of the outer part of those sunspots, the so-called penumbra, is a constant source of open questions. One of those questions is the actual size of the filaments. While observations with moderate resolution seem to indicate an average size of 0.35×2 arcsec^2 [6], observations of the net circular polarization in broadband wavelength ranges require a large variation of the inclination angle along the line of sight that can be explained by filaments that are only a few km in diameter [3]. Evidence for that small structures might be detectable by looking at the powerspectrum of the azimuthal intensity variations in the penumbra [4]. The authors claim to find a flat powerspectrum, compatible with structures far smaller than the resolution limit of the telescope.

Observations

Observing structures that are at or close to the resolution limit of the telescope are always strongly influenced by the earth atmosphere ("seeing"), and a thorough removal of all artifical effects is crucial for trustable results. Apart from being located on an excellent site, the Dutch Open Telescope (DOT, [2]) uses the speckle masking method to eliminate the atmospheric wavefront distortions and therefore is the ideal tool for this kind of observations.

For this investigation, I choose two observation series of sunspots, taken on September 20, 1999 (NOAA 8704, 150 min) and April 1, 2001 (NOAA 9407, 60 min). The image scales are 0.08"/pixel and 0.07"pixel, respectively, thus fully sampling the theoretical resolution limit of the telescope of 0.2" at the observed wavelength (430 nm, G-band).

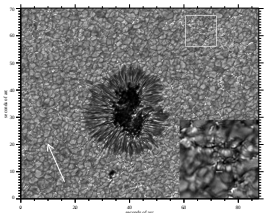


Figure 1: Sunspot NOAA 9407, observed with the DOT on April 1, 2001. The arrow indicates the direction towards disk center. The inset is a magnification of the marked area, demonstrating the resolution of the image. The white line is one arc second long, corresponding to 725km on the solar surface.

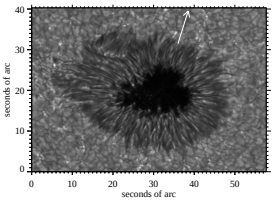
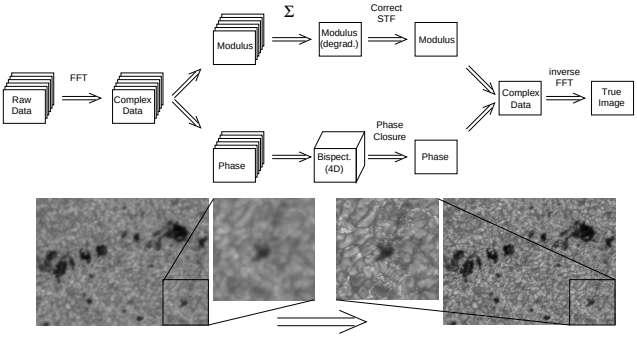


Figure 2: Sunspot NOAA 8704, observed with the Dutch Open Telescope (DOT) on September 20, 1999

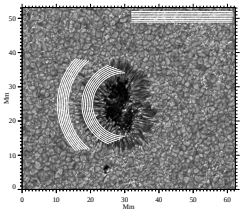
Basic data reduction



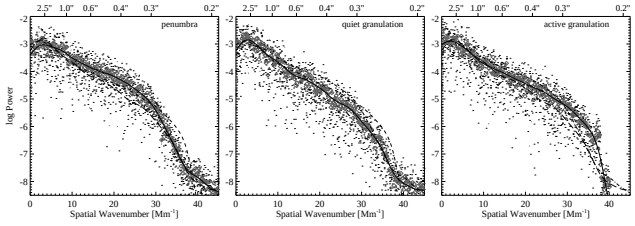
This is a diagram that explains the speckle masking procedure: Data are taken in bursts of typically 100 images, sampling the atmospheric distortions (the object may not change during a burst, which restricts the available time). The images are transformed to Fourier representation, and are split into phase and modulus. From the phases the bispectrum is computed, which basically contains the phase gradients. It is integrated in a phase closure algorithm that recovers the true phase spectrum of the object. The modulus is just summed and corrected by a degradation function that is computed from a statistical model of the atmosphere [1]. Combining phase and modulus again and transforming back to spatial domain reveals the undistorted image. With our current equipment (camera, computers) each burst is around 256 MB in size and takes 90 minutes to reconstruct.

Although there existed a speckle reconstructed observation series of NOAA 8704, I decided to use a much longer time series of the same spot later on the same day that only used frame selection to store only the very best image of every 20 second period. To correct those images for seeing influence, they have been destretched using polynomial warping. By computing the average radial powerspectrum and comparing that to the one of the speckle recionstructed observations from a few hours earlier, a correction function was computed and applied.

Results 1: Flat or not?



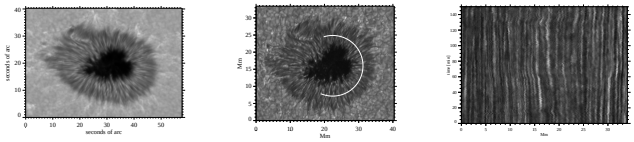
To answer the question whether the true powerspectrum of the penumbral intensity variations is flat and/or compatible with a structure size much smaller than the resolution limit of the telescope, I selected one image from the April 1 data. It is the one that had been taken during the best seeing conditions (Fried parameter $r_0 = 10$ cm). The image was corrected for geometric distortions due to the position on the solar disk. In this destretched image, a total of 21 cuts have been placed, 7 in the penumbra, 7 in the moat that does not contain a substantial amount of fluxtubes, and 7 in an active area with a lot of fluxtubes.



The above figure shows the powerspectra of the intensity variations along the selected cuts. Dots are the single values, diamonds represent the average at each frequency point, the lines are smoothed fits. In each plot, the PS of the other regions are shown also for comparison. This clearly shows:

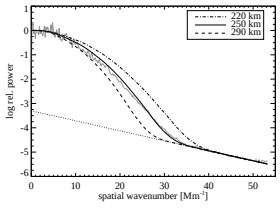
- None of the powerspectra is flat.
- The penumbral powerspectrum has more power in the mid-range (1–0.3 arcsec) as compared to the quiet granulation.
- The active region powerspectra show substantially higher power in the high frequency range than both granular and penumbral PS. The sharp cut-off at 40 Mm^{-1} is due to the resolution limit of the telescope and indicates a structure size below that limit.

Results 2: How thick are you?



The September 20 data spanned a total of 150 min and thus allowed to look at the temporal evolution. The first image above shows the **average of all 450 images**. It is amazing how much structure still is visible in the penumbra. This supports a model by [5] that explains the observed intensity and flow patterns as the rise of magnetic fluxtubes through the whole penumbra.

Concerning the powerspectra of the intensity variations, a different approach was used: Only one azimuthal cut has been put in the center of the penumbra, and the temporal change of the intensities along this cut have been evaluated. As before, the averaged powerspectrum shows a fall-off towards high frequencies and drops to zero before the noise level is reached. To understand this shape, one can set up a simple model: just assume a **gaussian intensity profile** for the cross-section of the filaments and some **distribution function** for placing them. The observed powerspectrum is then the product of the PS of the gaussian and the PS of the distribution function. Assuming a random distribution yields a constant function for the latter, and the observed PS should basically resemble the PS of the single filament. The plot shows the observed PS together with three computed PS for different widths of the gaussian. This method is very sensitive to the width and allows to settle the value down to 250 km.



- The filaments really extend through the whole penumbra, the observable features are local brightenings within this structure.
- The typical size (width) of a penumbral filament is 250 km, or 0.34 arcsec. We are therefore resolving most of the penumbral structure with current high-resolution ground-based observations (speckle, adaptive optics).

References

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[6] M. Sobotka. Sunspots seen at high spatial resolution. In *ASP Conf. Ser. 118: 1st Advances in Solar Physics Euroconference. Advances in Physics of Sunspots*, pages 155+, 1997.

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Links

DOT: http://dot.astro.uu.nl/
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