MOAT FLOW IN THE VICINITY OF SUNSPOTS FOR VARIOUS PENUMBRAL CONFIGURATIONS

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Received 2007 December 18; accepted 2008 February 5

ABSTRACT

High-resolution time series of sunspots have been obtained with the Swedish 1 m Solar Telescope between 2003 and 2006 at different locations on the solar disk. Proper motions in seven different active regions have been studied. The analysis was performed by applying local correlation tracking to every series of sunspots, each of them more than 40 minutes long. The sunspots’ shapes include a different variety of penumbral configurations. We report on the systematic behavior of the large-scale outflows surrounding the sunspots, commonly known as moat flows, that are essentially present only when preceded by a penumbra not tangential but perpendicular to the sunspot border. We present one case for which this rule appears not to be confirmed. We speculate that the magnetic neutral line, which is located in the vicinity of the anomalous region, might be responsible for blocking the outflow. These new results confirm the systematic and strong relation between the moat flows and the existence of penumbrae. A comparative statistical study between moats and standard granulation is also performed.

Subject headings: Sun: granulation — Sun: photosphere — sunspots

1. INTRODUCTION

The Sun’s strong magnetic behavior is clearly revealed through its most prominent visible manifestation, the sunspots. The newest generation of solar telescopes and the latest restoration techniques have greatly increased the spatial resolution of the images and therefore the variety of details and tiny structures in and around sunspots that can be resolved. Nevertheless, it is still not well understood how these structures form, evolve, and affect the photosphere surrounding them. Many approaches have been made in this direction, such as the identification of small magnetic elements called “moving magnetic features” (MMFs) traveling radially outward while immersed in an annullar cell around the sunspot of strong radial outflows known as a “moat” (Sheeley 1972; Harvey & Harvey 1973). For a recent overview of the literature on MMFs see the introduction of Hagenaar & Shine (2008). The averaged moat flow thus defines an organized horizontal flow pattern that ends quite abruptly at a distance that can be comparable to supergranular sizes or even larger. Sobotka & Roudier (2007) study the characteristics and temporal evolution of moats at two heights in the atmosphere for a large sample of sunspots with different sizes, shapes, and evolutive stage. A similar work studying the properties of moats was previously performed by Brickhouse & Labonte (1988). The averaged moat flow velocity reported ranges from $\sim$0.4 to $\sim$1 km s$^{-1}$.

New findings (Sainz Dalda & Martínez Pillet 2005) have shown that the penumbral filaments extend beyond the sunspot boundary entering the region dominated by the moat flow where the MMF activity is detected. Thus, the temporal average of magnetograms has unveiled the existence of moat filaments: horizontal, filamentary structures coming from the penumbra and reaching the photospheric network as an extension of penumbral filaments. Moreover, some MMFs have been found (Sainz Dalda & Martínez Pillet 2005; Ravindra 2006) starting just inside the sunspot boundary in its way out from the sunspot. Kubo et al. (2007) have established a relationship between the vertical components (spines) of the magnetic field in the so-called uncombed structure of the penumbra and MMFs observed in moat regions.

In a recent letter, Vargas Domínguez et al. (2007) studied the moat flow in a complex active region. They found that no outflow was detected in the granulation next to umbral cores that lack penumbrae. Outflows were only found in the granulation regions adjacent to the penumbrae in the direction following the penumbral filaments. Granulation regions located next to penumbral sides parallel to the direction of the filaments show no moat flow.

The aim of the present work is to extend the study by Vargas Domínguez et al. (2007) to a larger sample of cases, that is, to establish whether this moat-penumbra relation is systematically found in other active regions and how the granular convective pattern surrounding sunspots behaves. In doing so, we have used several high-quality time series observed at high spatial resolution. A total of seven different sunspot series have been processed and analyzed. The sample includes sunspots with different penumbral configurations, varying from well-developed penumbrae to rudimentary penumbral morphologies. The paper describes first in § 2 how the observations were performed and the restoration technique used to correct for atmospheric aberrations. Once the time series are ready to analyze, § 3 presents some calculations and statistics of proper motions of structures surrounding the sample sunspots. We finally discuss the results and future work in § 4.

2. OBSERVATIONS AND DATA PROCESSING

The observations were obtained with the Swedish 1 m Solar Telescope (SST; Scharmer et al. 2003a) on La Palma between 2003 and 2006. All observations benefited from the use of the
SST adaptive optics system (Scharmer et al. 2003b) that minimized the degrading effects of seeing. Image postprocessing techniques were applied to increase the homogeneity in the quality of the time series and to enhance the image quality over the whole field of view (FOV). For the 2003 data set we applied multiframe blind deconvolution (MFBD) using the implementation developed by Löfdahl (2002). The MFBD code was succeeded by the multi-object multiframe blind deconvolution code (MOMFBD; Van Noort et al. 2005), which employs multiple objects and phase diversity. MOMFBD was applied to the data sets after 2003. For all the time series we present in this paper, the seeing conditions were generally very good and sometimes excellent. A large fraction of the restored images in the different time series approach the diffraction limit of the telescope.

After image restoration, we applied standard techniques to the time series including correction for the diurnal field rotation, rigid alignment, and destretching to correct for seeing-induced image warping. A $p$-mode filter was also applied to the series (threshold phase velocity $4 \text{ km s}^{-1}$).

Table 1 presents details for the different active region targets, and Table 2 gives some details on the restored time series. Below we provide more detailed information on the different data sets.

### 2.1. S1: AR 440, 2003 August 22

An interference filter centered at the continuum at 436.4 nm (FWHM 1.1 nm) was used. In the remainder, this filter will be referred to as the “G-cont” filter. Every 25 s, the three highest contrast images were selected and stored to disk. These three images were used for MFBD processing. This sunspot is shown in Figure 1.

### 2.2. S2: AR 608, 2004 May 10

An interference filter centered at the G band at 430.5 nm (FWHM 1.2 nm) was used. In the remainder, this filter will be referred to as the “G-band” filter. This observation involved two cameras set up as a phase-diversity pair: one in focus and one slightly out of focus. Twenty exposures from each camera, acquired over the course of 7.5 s, were used for MOMFBD processing. During processing of the time series, a few bad-quality images, suffering from too much blurring, were dropped. The exposure time was 11 ms. This sunspot is shown in Figure 2.

### 2.3. S3: AR 662, 2004 August 20

This time series was observed with the G-cont filter. The MOMFBD processing was performed using 10 exposures (acquired during 7 s) from a phase-diversity pair of cameras. For the central part of the FOV, centered on the sunspot, the MOMFBD processing was extended to involve a G-band phase-diversity pair of cameras. After MOMFBD restoration, the best-quality image from three subsequent images was selected for further processing of the time series. The exposure time was 11.3 ms. This sunspot is shown in Figure 3.

### 2.4. S4: AR 662, 2004 August 21

This time series was processed in a manner similar to S3. After MOMFBD restorations, the worst 14% of the images were dropped from the time series. This sunspot is shown in Figure 4.

| Name  | Number of Images | Cadence (s) | Duration (min:s) |
|-------|-----------------|-------------|------------------|
| S1    | 128             | 24.7        | 52:47            |
| S2    | 376             | 7.5         | 47:10            |
| S3    | 144             | 19.8        | 47:20            |
| S4    | 344             | 8.0         | 45:57            |
| S5    | 240             | 10.1        | 40:12            |
| S6    | 556             | 8.7         | 80:3             |
| S7    | 124             | 19.7        | 40:26            |

**Table 2.** Restored Sunspot Time Series

**Fig. 1.—** Sunspot S1. Map of the horizontal velocities inside the moat with deprojected magnitudes $>0.3 \text{ km s}^{-1}$. The sunspot exhibits a well-developed penumbra in the lower region. The moat flow is clearly found in the same region following the penumbra filamentary direction and in no other region surrounding the sunspot. The coordinates are expressed in arcseconds. The black bar at (0, 0) represents $1.5 \text{ km s}^{-1}$ for the projected velocities in all the flow maps hereafter. A peculiar region is shown with a white square.
2.5. S5: AR 789, 2005 July 13

For this time series, MFBD processing was applied to 18 subsequent G-band images, acquired during 10 s. Images that were too blurred, and when the AO system was not actively compensating, were dropped from the MFBD sets. This sunspot is shown in Figure 5.

2.6. S6: AR 813, 2005 October 4

This time series was observed with an interference filter centered on the spectral region between Ca K and Ca H at 395.4 nm (FWHM 1.0 nm). For the MOMFBD processing, 20 exposures (acquired during 8.3 s) from a phase-diversity pair of cameras were used. In addition, simultaneous exposures from two other cameras were used for the restoration: one equipped with a narrowband filter centered in the Ca H wing at 396.5 nm and one equipped with a narrowband filter centered on the Ca H core (396.8 nm). The exposure time was 11 ms. This sunspot is shown in Figure 6.

2.7. S7: AR 893, 2006 June 10

This time series was observed with an interference filter centered at 630.2 nm (FWHM 0.8 nm). This is the prefilter for the Lockheed SOUP filter. MOMFBD processing was applied to 400 exposures obtained during 19 s. The restorations included images from a phase-diversity pair of cameras with the wideband filter and narrowband SOUP exposures in the Fe i 630.2 nm spectral line. This sunspot is shown in Figure 7.

3. DATA ANALYSIS

The high quality, stability, and long duration of the restored sunspot series enable us to follow the dynamics of the plasma around the sunspots. We have computed proper-motion velocity fields (horizontal velocities) employing the local correlation tracking (LCT) technique (November & Simon 1988, using the implementation of Molowny-Horas & Yi 1994). A Gaussian tracking window of FWHM 1.0" suitable for mainly tracking granules has been used for the entire series. The method produces a sequence of map pairs, each one describing, within a short time interval (tens of milliseconds), the horizontal velocity components $-x$ and $-y$ along the FOV. These maps of components have been averaged over 5 and 10 minute periods and also over the respective total duration of every sunspot series (more than 40 minutes in all cases). From the averaged maps of velocity components, the distribution of velocity magnitudes over the FOV (flow map) has been easily derived.
It is well documented in the literature that LCT techniques in general produce some systematic errors in the determination of displacements (see November & Simon 1988, Fig. 13). Their significance depends on several factors like the width of the tracking window in relation to the size of the elements used as motion tracers and the presence of large-intensity gradients in the images. Also, the nature of the interpolation algorithm to fix the position of the correlation maximum with subpixel accuracy may play a role. The LCT method typically underestimates the velocity fields. Tests performed by the authors of the LCT code we are employing in this work lead to the conclusion that in the worst cases this underestimate can amount to 20%–30% (Yi 1992; Molowny-Horas 1994). Even so, this drawback does not change the main conclusions of the present paper since we are not interested in fixing absolute values of velocities but rather in the detection of large-scale regularly organized flows around the sunspots in comparison with those typically found in a normal granulation field. In both cases we use the solar granules as the tracers of motion and the same size for the tracking window so that in case of some bias it will affect both velocity fields similarly.

**Fig. 4.** Sunspot S4. Map of the horizontal velocities inside the moat with deprojected magnitudes $>0.3$ km s$^{-1}$. The figure corresponds to a sunspot with two distinct penumbrae, one tangential to the umbra and the other coming out radially from the right part of the umbra. The moat flow continues as prolongations of the last one. The coordinates are expressed in arcseconds. A peculiar region is shown with a white square.

**Fig. 5.** Sunspot S5. Map of the horizontal velocities inside the moat with deprojected magnitudes $>0.3$ km s$^{-1}$. This sunspot presents very distinct areas with and without penumbrae. The penumbral distributions follow radial directions coming out from the umbra. Moat flows are organized radially as the penumbra. The coordinates are expressed in arcseconds. A peculiar region is shown with a white square.

**Fig. 6.** Sunspot S6. Map of the horizontal velocities inside the moat with deprojected magnitudes $>0.3$ km s$^{-1}$. This sunspot exhibits penumbrae on the right and upper sides. The penumbra on the right is mostly tangential to the sunspot border. In the upper penumbra we identified the moat flow as the prolongation of the penumbral filaments as expected. The coordinates are expressed in arcseconds. A peculiar region is shown with a white square.

**Fig. 7.** Sunspot S7. Map of the horizontal velocities surrounding the sunspot with deprojected magnitudes $>0.3$ km s$^{-1}$. The sunspot includes a well-developed penumbra but also an empty region with no penumbra. Looking at the large flows, they completely disappear in the emptied areas with no penumbra. The white contours outline the moat regions. The coordinates are expressed in arcseconds.
The sample of sunspots studied in this paper includes a variety of heliocentric positions on the solar disk as shown in Table 1 (with $\mu = \cos \theta$, where $\theta$ is the heliocentric angle). Away from solar disk center, the measured proper motions are in fact projections of the real horizontal velocities in the sunspot plane onto the plane perpendicular to the line of sight (LOS). Thus, to evaluate the real horizontal velocities we have deprojected the velocities obtained from the LCT technique to a plane tangent to the solar surface at the center of the sunspot.

In Figure 8 we consider the orthogonal coordinate system $SX$, $SY$, $SZ$ (the sunspot system [SS]) with the $SZ$-axis perpendicular to the plane tangent to the solar surface at the sunspot location and the $SX$-axis tangent to the meridian of the solar sphere at this location. The figure also shows the coordinate system $X$, $Y$, $Z$ (the observing system [OS]) with a common origin, the $Z$-axis coinciding with the LOS and the $X$-axis pointing to the axis crossing the Sun center in a direction parallel to the LOS. Note that the axes $X$, $SX$, $Z$, and $SZ$ are coplanar and $SY$ and $Y$ are collinear. The real horizontal velocities, $v(v', \phi)$, are contained in the ($SX$, $SY$) plane, whereas we observe their projections $v'(v', \phi')$, in the ($X$, $Y$) plane. Calculations based on Figure 8 lead to the following relationships (eqs. [1] and [2]) between the magnitudes $v$ and $v'$, and the azimuths $\phi$ and $\phi'$, that will allow us to deproject our observations:

$$v'^2 = v^2 (\sin^2 \phi + \cos^2 \phi \cos^2 \theta),$$

$$\tan \phi' = \frac{\tan \phi}{\cos \theta}. \quad (2)$$

Since the $X$- and $Y$-axes do not necessarily coincide with our natural reference system (i.e., the edges of the CCD frame), the measurement of the projected azimuths, $\phi'$, requires the knowledge of the orientation of our FOV with respect to the $X$-axis that points to the solar disk center.

### 3.1. Flowsmaps for Different Penumbral Configurations

As mentioned above, for every sunspot series, the map of horizontal velocities averaged over the whole time series is evaluated. In order to coherently detect the moats and compare the statistics (§ 3.3) in all active regions of our sample, we have deprojected the observed velocity vectors onto the sunspot plane as described above. Overlaying the observed images, we construct maps showing in the granulation field only those projected velocity vectors having deprojected magnitudes above a certain threshold. In these maps, extensive organized outflows coming out from the sunspots can easily be identified so that we can outline masks delimiting in a qualitative way the area of the moats for the purpose of statistical calculations and graphical representation. We have fixed the mentioned threshold to $\sim 0.3 \text{ km s}^{-1}$ as the best compromise to define the limits of the moats. This value should not be understood as an absolute (universal) velocity threshold to define moats in general. As we have mentioned before, the particular method used here to measure the displacements may underestimate the velocity magnitudes. Moreover, outside the moat one can easily find velocities larger than that. The point is that this particular threshold makes in our case more evident the existence of a well-organized radial outflow around the sunspots in comparison with the rest of the FOV.

Lower values (even zero) for the threshold do not extend the areas of organized flows around the sunspots but produce maps with a very dense and noisy (exploding granules everywhere) representation of arrows where the outline of the frontiers of the moats becomes more difficult. Figures 1–2, the upper panel of Figure 3, and Figures 4–6 show, within the moats, only those velocity vectors with deprojected magnitudes above $0.3 \text{ km s}^{-1}$. In Figure 7 we extend this representation to the entire granulation field showing that large velocities are also present outside the moat. These velocities are generally grouped and associated with exploding granules. Our sunspot sample includes different penumbral configurations as a key factor to establish the moat-penumbra relation in a robust way.

First we focus on granulation regions that display moat flows. Close inspection of Figures 1–2, the upper panel of Figure 3, and Figures 4–7 reveals that the velocity vectors in the moats are oriented following the direction of the penumbral filaments. We observe that in all cases the moat flow direction lines up with penumbral filaments that are oriented radially with respect to the sunspot center. Nevertheless, the completeness of the velocity vectors (density of arrows) in the flow maps depends on the threshold previously imposed, as expected. This can be seen in Figure 5, where the left-hand side penumbra does not seem to be strictly associated with large flows in the granulation region. However, this penumbral part has in fact an associated moat flow similar to the other penumbral regions that is not visible in the representation since the magnitude of the velocities is slightly lower than the threshold of $0.3 \text{ km s}^{-1}$.

Next we consider granulation regions close to the sunspots that do not display moat flows. All sunspots of our sample, except S3, have parts of the umbral core in direct contact with granulation regions without intervening penumbrae. In all these granulation regions we do not detect systematic large-scale outflows that fulfill our criteria for moat flows. This supports the conclusion that umbral core boundaries with no penumbra do not display moat flows.

![Figure 8](image-url)
Finally, there are also granulation regions in the vicinity of penumbras that lack significant moat flows. To study these cases in more detail we mark peculiar regions of interest in Figures 1, 4, 5, and 6 with rectangular white boxes. These regions are represented as closeups in Figure 9. In the three upper panels, the penumbral filaments display significant curvature such that they are not radially oriented with respect to the sunspot center but extend in a direction tangential to the sunspot border (as marked with black lines in the overview images of Figs. 1, 4, and 6). The lower panel of Figure 9 shows a penumbral extending radially from the umbra. The surrounding photosphere exhibits moat flows only in the direction of the penumbral filaments (also see Fig. 5). These four examples lead to the conclusion that moat flows are not found in directions transverse to the penumbral filaments.

In a few cases we found small pores in the vicinity of penumbral in a region where we would expect moat flows. Such cases are seen around coordinates (19, 29) in Figure 1 and coordinates (29, 11) in Figure 6. For these regions the measured proper motions are less reliable since we have a FWHM = 1.0" tracking window acting on a region of only a few arcseconds (~2–3) between the pore and penumbra. Another possibility is that the pores themselves are somehow blocking the large outflows changing the expected behavior. In the case presented in Figure 6 the most plausable explanation for the absence of moats is the presence of a neutral line close to coordinates (29, 11) as we describe in § 3.2.

The findings described above suggest a link between the moat flows and the Evershed flows in penumbrae. We come back to this relation in § 4.

3.2. Neutral Lines Affecting the Flow Behavior

Only one of the sunspots we study displays a complete regular and well-developed penumbra completely surrounding the umbral core. Figure 3 shows the flow map calculated for this active region, plotting the horizontal velocities surrounding the sunspot with deprojected magnitudes >0.3 km s\(^{-1}\). Large outflows are not found in part of the right side of the upper panel of Figure 3 (square).

Following the findings of § 3.1, we would expect to find a moat flow in this region. The penumbral filaments are oriented radially from the umbral core, which suggest the presence of a moat flow in the granulation region in the direct vicinity. Even with a lower velocity threshold, no moat flow can be discerned in this region. Nevertheless, when comparing with the magnetogram (see Fig. 3, bottom), we found an inversion in magnetic polarity just outside the right border of the sunspot: the magnetogram displays positive polarity (in white) for the sunspot but negative polarity for the small magnetic elements and pore just outside the penumbra. The reversal of polarity (or neutral line) is confined to a narrow region that roughly coincides with the sunspot border. The absence of large outflows following this penumbra is suggestively related to the presence of this neutral line that might somehow be acting as a blocking agent for the moat flow in this region. The position of the neutral line measured by LOS magnetograms is generally influenced by the location of the sunspot (θ angle). In this case, since the sunspot is very close to the disk center, we can claim a reliable determination of the neutral line.

For the sunspot in Figure 6 there is also a neutral line crossing all along the right border of the sunspot from top to bottom around coordinates (20, 28) to (28, 11), respectively (see De Pontieu et al. 2007, Fig. 2). The penumbral filaments extend from the umbra to the right and seem to bend, being forced to follow the direction of the neutral line as they approach it. The sheared configuration of this penumbra is arranged so that the penumbral filaments end up along directions parallel to the sunspot border. Moat flows are then not found beyond this sort of penumbral configuration, as mentioned in § 3.1. A similar case was also found by Vargas Domı´nguez et al. (2007) in a complex 6-configuration active region. For that active region the authors found a strong sheared neutral line crossing a penumbral border where a moat flow was expected to follow the penumbral filaments direction but actually not detected. More observations of complex active regions with neutral lines present in the vicinity of penumbrae are needed to firmly establish the relation between the absence of moat flows and magnetic neutral lines.
and reduce the noise in our calculations. This enables us to improve the statistics of the velocity magnitudes for a time series, we would finally obtain eight maps of 5 minutes or four maps of 10 minutes. We then compute maps every 5 minutes (or 10 minutes) up to complete the total duration of the series (i.e., when having 40 minutes of duration for a time series, we would finally obtain eight maps of 5 minutes or four maps of 10 minutes). This enables us to improve the statistics of the velocity magnitudes and reduce the noise in our calculations.

In this section the statistics of time-averaged horizontal velocity fields in moats are performed. For the sake of comparison, the velocity statistics in quiet granulation areas has also been computed. To that aim, boxes (∼9 × 9 arcsec²) in regions of less-magnetized (quiet) granulation and far from the moat flows have been manually selected in every FOV. Table 3 summarizes the statistical properties of the deprojected magnitudes of horizontal velocity fields within both moat masks and selected granular boxes. Here we again remark that because of the possible underestimation of the displacements by using LCT, we intend to perform not an absolute but a comparative statistical study between moat regions, where we find radially organized outflows and quiet granulation regions far from the sunspots.

For each sunspot of our sample three velocity magnitude maps result from averaging over different time periods, namely, 5 minutes, 10 minutes, and the whole duration of the corresponding time series. Table 3 shows that in most cases the mean velocity magnitude in moats is greater than in granulation. In a few cases and only for averages in short time periods (5 and 10 minutes), we find similar values in both or even slightly lower velocities in moats. However, when averaging over a long time period, the difference of mean velocities in moats and granulation is in all cases positive and more conspicuous than for short time period averages (see Table 3, col. [10]). A similar behavior is obtained for the rms parameter (see Table 3, col. [9]).

The maximum velocity values are also systematically larger in moats than in granulation. The described statistical behavior is expected since for short time averaging periods, of the order of the granulation lifetime (5–16 minutes; see Hirzberger et al. 1999 and references therein), the proper motions of the granulation structures compete in magnitude with the velocity of large-scale flows. However, averaging velocity components over long time periods results in local velocity cancellations in short-lived structures while steady motions at large spatial scales prevail. So moats can be considered as a long-term and large-scale phenomenon where the mean velocity exceeds that of quiet granulation by ∼30%.

The significant fluctuations in ∆(rms) and ∆(mean) (Table 3, cols. [9] and [10]) for the velocity fields averaged over the whole time series deserve a comment and possibly future improved measurements. They could be ascribed to morphological differences in the various cases considered, or they could be related to the particular evolutionary state or magnetic field strength in the various sunspots of our sample. Furthermore, the accuracy in the measurement of θ and ϕ in equations (1) and (2) is crucial for the determination of v. Thus, two sources of inaccuracy are (1) the assumption of constant heliocentric angle θ all along the sunspot area (this has important impact in regions far from the solar disk center) and (2) the determination in our FOV of the direction pointing to the solar disk center that defines the X-axis of the observing coordinate system, i.e., the angular origin for ϕ.

Figure 10 shows the histograms of deprojected velocity magnitudes for averages over the whole time series for sunspots S1 to S7. Thick lines correspond to velocities inside the moats and thin lines to velocities in quiet granulation boxes. In all cases we find the same general trend in both histograms. The thick histograms are globally shifted toward the right with respect to the thin ones. The left wings of the histograms for granulation lie systematically above those of the histograms for moats, and for S1, S2, S3, S4, and S6, both histograms nearly coincide at the farthest left

| SUNSPOT | DURATION (minutes) | Max | rms | Mean | Max | rms | Mean | ∆(rms)* (%) | ∆(Mean)* (%) |
|---------|--------------------|-----|-----|------|-----|-----|------|------------|------------|
| S1      | 5                  | 1048| 174 | 333  | 947 | 157 | 315  | 10.8       | 5.7        |
|         | 10                 | 947 | 162 | 315  | 842 | 157 | 314  | 3.2        | 0.3        |
|         | 55                 | 639 | 137 | 301  | 596 | 123 | 250  | 11.4       | 20.4       |
| S2      | 5                  | 1187| 183 | 329  | 898 | 162 | 307  | 13.0       | 7.1        |
|         | 10                 | 1278| 182 | 327  | 802 | 155 | 300  | 17.4       | 9.0        |
|         | 47                 | 921 | 150 | 303  | 678 | 115 | 249  | 30.4       | 21.7       |
| S3      | 5                  | 1036| 146 | 290  | 870 | 147 | 282  | −0.7       | 2.8        |
|         | 10                 | 868 | 146 | 281  | 671 | 137 | 289  | 6.6        | −2.8       |
| S4      | 47                 | 689 | 126 | 265  | 451 | 101 | 220  | 24.8       | 20.5       |
| S5      | 5                  | 1060| 198 | 411  | 863 | 164 | 362  | 20.7       | 13.5       |
|         | 10                 | 954 | 180 | 379  | 780 | 154 | 348  | 16.9       | 8.9        |
|         | 45                 | 834 | 179 | 365  | 655 | 118 | 262  | 51.7       | 39.3       |
| S6      | 5                  | 999 | 178 | 355  | 968 | 172 | 307  | 3.5        | 15.6       |
|         | 10                 | 972 | 187 | 372  | 1017| 159 | 291  | 17.6       | 27.8       |
|         | 40                 | 802 | 141 | 355  | 545 | 107 | 220  | 31.8       | 61.4       |
| S7      | 5                  | 699 | 129 | 257  | 683 | 130 | 278  | −0.8       | −7.6       |
|         | 10                 | 673 | 131 | 248  | 723 | 136 | 277  | −3.7       | −10.5      |
|         | 40                 | 622 | 125 | 243  | 526 | 104 | 210  | 20.2       | 15.7       |

* ∆(rms) and ∆(mean) stand for increments of the rms and mean values in moats with respect to quiet granulation.

3.3. Statistics of Velocity Fields in Moats versus Quiet Granulation

The maximum velocity values are also systematically larger in moats than in granulation. The described statistical behavior is expected since for short time averaging periods, of the order of the granulation lifetime (5–16 minutes; see Hirzberger et al. 1999 and references therein), the proper motions of the granulation structures compete in magnitude with the velocity of large-scale flows. However, averaging velocity components over long time periods results in local velocity cancellations in short-lived structures while steady motions at large spatial scales prevail. So moats can be considered as a long-term and large-scale phenomenon where the mean velocity exceeds that of quiet granulation by ∼30%.

The significant fluctuations in ∆(rms) and ∆(mean) (Table 3, cols. [9] and [10]) for the velocity fields averaged over the whole time series deserve a comment and possibly future improved measurements. They could be ascribed to morphological differences in the various cases considered, or they could be related to the particular evolutionary state or magnetic field strength in the various sunspots of our sample. Furthermore, the accuracy in the measurement of θ and ϕ in equations (1) and (2) is crucial for the determination of v. Thus, two sources of inaccuracy are (1) the assumption of constant heliocentric angle θ all along the sunspot area (this has important impact in regions far from the solar disk center) and (2) the determination in our FOV of the direction pointing to the solar disk center that defines the X-axis of the observing coordinate system, i.e., the angular origin for ϕ.

Figure 10 shows the histograms of deprojected velocity magnitudes for averages over the whole time series for sunspots S1 to S7. Thick lines correspond to velocities inside the moats and thin lines to velocities in quiet granulation boxes. In all cases we find the same general trend in both histograms. The thick histograms are globally shifted toward the right with respect to the thin ones. The left wings of the histograms for granulation lie systematically above those of the histograms for moats, and for S1, S2, S3, S4, and S6, both histograms nearly coincide at the farthest left.

3.3. Statistics of Velocity Fields in Moats versus Quiet Granulation

In this section the statistics of time-averaged horizontal velocity fields in moats is performed. For the sake of comparison, the velocity statistics in quiet granulation areas has also been computed. To that aim, boxes (∼9 × 9 arcsec²) in regions of less-magnetized (quiet) granulation and far from the moat flows have been manually selected in every FOV. Table 3 summarizes the statistical properties of the deprojected magnitudes of horizontal velocity fields within both moat masks and selected granular boxes. Here we again remark that because of the possible underestimation of the displacements by using LCT, we intend to perform not an absolute but a comparative statistical study between moat regions, where we find radially organized outflows and quiet granulation regions far from the sunspots.

For each sunspot of our sample three velocity magnitude maps result from averaging over different time periods, namely, 5 minutes, 10 minutes, and the whole duration of the corresponding time series. Table 3 shows that in most cases the mean velocity magnitude in moats is greater than in granulation. In a few cases and only for averages in short time periods (5 and 10 minutes), we find similar values in both or even slightly lower velocities in moats. However, when averaging over a long time period, the difference of mean velocities in moats and granulation is in all cases positive and more conspicuous than for short time period averages (see Table 3, col. [10]). A similar behavior is obtained for the rms parameter (see Table 3, col. [9]).
end. This means that within the moats standard velocity values for quiet granulation are still present but with a lower weight. Such is the case for the fragments of exploding granules that also are swept by large-scale moat flows. At some point, from left to right, both histograms cross each other so that the right wing of the moat histogram surpasses the corresponding quiet granulation wing and extends to larger velocity values (>0.6 km s\(^{-1}\)). This confirms the predominance of large velocities in moats. The intersection point of both histograms corresponds to \(\sim 0.3\) km s\(^{-1}\) in almost all cases (a bit higher in S1, S2, and S4). Interestingly, this value coincides with the threshold empirically selected a priori (§ 3.1) to clearly distinguish the frontiers of the moats, which supports the goodness of the limit value (0.3 km s\(^{-1}\)) chosen to detect moats in our data set.

![Histograms of the velocity magnitudes in moats (thick line) and quiet granulation (thin line), averaging over the whole time series (more than 40 minutes in every case) for sunspots S1 to S7. The vertical and horizontal axes represent the percentages and the velocity magnitudes (km s\(^{-1}\)), respectively.](image)
4. DISCUSSION

Seven time series of sunspots were restored from instrumental and atmospheric aberrations using MFBD and MOMFBD techniques. The high quality of the images allowed us to study proper motions of granules outside the sunspots and measure their time-averaged velocities.

We have extended the study by Vargas Domínguez et al. (2007) to a larger sample of active regions and systematically confirmed their findings:

1. Moat flows are oriented following the direction of the penumbral filaments.

2. In granulation regions found adjacent to an irregular penumbral side parallel to the penumbral filaments moats are absent, or in other words, moats do not develop in the direction transverse to the penumbral filaments. Note that if the moat flows were originated by the blockage of the heat flux from below by the penumbra, one would expect moat flows directed along, but also transverse to, the direction of the penumbral filaments.

3. Umbral core sides with no penumbra do not display moat flows.

Moreover, we include in our sample a case in which a neutral line extends along a penumbral border where we would expect a moat flow continuation. For this sunspot we do not find any moat flow following the direction of the penumbral filaments after crossing the penumbral border where we see a change in magnetic polarity. The same result is found by Vargas Domínguez et al. (2007) in a penumbral portion of a complex active region crossed by a strong sheared neutral line.

All these results indicate a likely connection between the moat flows and flows aligned with penumbral filaments. In a recent work, Cabrera Solana et al. (2006) suggest that the Evershed clouds inside penumbrae propagate to the surrounding moat and then become MMFs after crossing the sunspot border. The MMF displacements trace very well defined paths that can actually be clearly seen when averaging magnetograms in time (Sainz Dalda & Martínez Pillet 2005). Some of these MMFs are seen to start inside the penumbra.

In this paper we also complement the study by Vargas Domínguez et al. (2007) with a statistical analysis describing the differences between velocity fields in moat flows and in less-magnetized solar granulation nearby. In contrast to the granulation, moat flows are well-organized, steady, and large-scale motions. For averages made over more than 40 minutes, the mean velocity in moats (0.3 km s\(^{-1}\)) exceeds that of quiet granulation (∼0.23 km s\(^{-1}\)) by ∼30%, although we obtain a considerable dispersion in the results. Also, the rms of the velocity magnitude is greater in moats by a similar percentage.

The histograms of velocity magnitudes in the moats are broader than those in granulation. The histograms of granulation show conspicuous maxima, most of them ranging from 0.2 to 0.3 km s\(^{-1}\), whereas the histograms of moats present a flatter top. Systematically, the low-velocity wing of the granulation histogram lies above that corresponding to the moat. At some point about 0.3–0.4 km s\(^{-1}\), both histograms cross each other, and the right wing of the moat histogram extends beyond that of the granulation to larger velocity values (>0.6 km s\(^{-1}\)).

We have studied one case of a sunspot penumbra displaying a neutral line all along a sector of the penumbra (Fig. 3). This neutral line is detected at the penumbral boundary but is also emphasized by a large opposite polarity concentration nearby. Interestingly, this penumbral sector shows no moat flow. We interpret this evidence as an indication of the Evershed flow being forced to go into deeper subphotospheric layers at a faster pace than what is normally thought to occur in penumbral regions not associated with neutral lines (Westendorp Plaza et al. 1997). A similar case, but in a sheared neutral line of a δ-spot, was found by Vargas Domínguez et al. (2007).

Although there is increasing evidence linking the moat flows and the Evershed flow along the penumbral filaments, the debate regarding the existence of a moat flow around umbral cores and individual pores is still ongoing. In a recent work, Deng et al. (2007) found that the dividing line between radial inward and outward proper motions in the inner and outer penumbra, respectively, survived the decay phase, suggesting that the moat flow is still detectable after the penumbras disappeared.

Previous works (Sobotka et al. 1999; Roudier et al. 2002) have measured horizontal proper motions in and around pores and have observed a ringlike structure of positive divergence (“rosettas”) around the pores, which is related to a continuous activity of exploding granules. Roudier et al. (2002) identified a very clear inflow around pores that corresponds to the penetration of small granules and granular fragments from the photosphere into the pores, pushed by granular motions originated in the divergence centers around them. They conclude that the motions at the periphery of the pore are substantially and continuously influenced by the external plasma flows deposited by the exploding granules. We interpret the dividing line between radial inward and outward motions, found by Deng et al. (2007) outside the residual pore, as corresponding to the centers of divergence of the exploding granules around the pore. The outward motions these authors described, which are not in the immediate surroundings of the pore but separated by the annular inward motion, would then correspond to the flows coming out from the regular mesh of divergence centers around the pore.

The important questions related to the flows inside and outside sunspots are yet to be studied. In the present work we contribute with a new sample of sunspots observed between 2003 and 2006 in six different observing campaigns. The data sets have been selected on the basis of the seeing quality (sharpness, homogeneity, duration) and the availability of suitable targets: the presence of spots with some form of irregular penumbra. In all of our samples we follow the evolution of the sunspots for more than 40 minutes. Although this only represents a snapshot in the evolution of the sunspots through all their emerging and decaying processes, our sample includes sunspots in different evolutionary stages and penumbral configurations.

New facilities such as the recently launched HINODE satellite can provide long time series of active regions with a constant image quality and enough spatial resolution to provide firm confirmation of the evidences found in this paper. The addition of simultaneous Doppler and magnetogram data to the continuum intensity (or G-band) data sets will enhance our understanding of the link between the Evershed and the moat flows. Needless to say, the study of those stages where penumbrae are just formed or destroyed becomes of extreme importance to validate our findings. Similarly, the results that can be expected in the coming years from local helioseismology, describing the flow patterns in the deeper layers near sunspots, will prove crucial for the establishment of a clear link between these two well-known flow patterns that has thus far not been appreciated.

The Swedish 1 m Solar Telescope is operated on the island of La Palma by the Institute of Solar Physics of the Royal Swedish Academy of Sciences in the Spanish Observatorio del Roque de
los Muchachos of the Instituto de Astrofísica de Canarias. S. Vargas is thankful to A. Sainz Dalda for comments and discussions. Partial support by the Spanish Ministerio de Educación y Ciencia through project ESP2003-07735-C04 and financial support by the European Commission through the SOLAIRE Network (MTRN-CT-2006-035484) are gratefully acknowledged. This research was supported through grants 146467/420 and 159137/V30 of the Research Council of Norway.

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