

Application of coherent structure tracking to solar Doppler maps to determine horizontal velocity fields at the Sun's surface

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ABSTRACT

Context. Coherent structure tracking (CST) is a technique for determining solar surface horizontal flows at high spatial and temporal resolution by tracking the proper motion of granules. This technique has traditionally been applied to solar intensity images in the continuum, which clearly depict granular patterns. However, solar granulation is also visible in Dopplergrams.

Aims. We show that CST can be applied to solar Dopplergrams to derive solar surface horizontal velocity fields with the same level of confidence as those determined by CST on intensity images.

Methods. We applied CST to continuum intensity images and Dopplergrams obtained from SDO/HMI and from a numerical simulation of granulation. We compared the resulting solar surface horizontal velocity fields and their derivatives (namely, the horizontal divergence and the vertical component of the vorticity) for different time windows.

Results. Pearson's linear global correlation coefficient (GCC) between horizontal velocity fields determined from CST on Doppler and on intensity images of a relatively less active Sun is about 73% for a 30-minute time average, while the corresponding local correlation coefficient (LCC) near the disk center is about 80%. For the divergence of the horizontal velocity field, we obtain a GCC of 72% and a near-disk-center LCC of 84%. The curl of the horizontal velocity field is noisier and exhibits somewhat reduced GCC and LCC. These coefficients increase with an increasing time window. We observe a similar trend for Spearman's and Kendall's rank-order correlation coefficients, although their values are somewhat smaller. The different correlation coefficients slightly decrease for a magnetically more active Sun with sunspots or emerging pores in plage regions. We obtain a high correlation between the horizontal flows derived by applying CST to intensity and vertical velocity maps from a numerical simulation.

Key words. Sun: granulation – Sun: photosphere

1. Introduction

Most solar phenomena occurring in the solar atmosphere are the result of interplay between solar surface flows and magnetic fields anchored in the convection zone. Hence, it is crucial to understand and determine the nature of solar surface flows from small to large scales. Although Doppler measurements provide a direct determination of the line-of-sight component of plasma velocity on the Sun, indirect methods are needed to determine the transverse component. Many techniques exist to measure this transverse or horizontal component of solar surface flows, such as local correlation tracking (LCT; November 1986), feature tracking (Strous 1994, 1995), time-distance helioseismology (Duvall et al. 1993), Fourier local correlation tracking (FLCT; Fisher & Welsch 2008), and DeepVel (Asensio Ramos et al. 2017). Coherent structure tracking (CST; Roudier et al. 2012) is a method that tracks the proper motions of solar granules to determine surface horizontal flows. In CST, solar granules are used as passive scalars to follow the underlying plasma motions (see Roudier et al. 1999; Rieutord et al. 2007; Roudier et al. 2012; Rincon et al. 2017; Roudier et al. 2018, for more details on CST technique). This technique can be used to study short- to long-term flows (such as solar differential rotation and meridional circulation) on the surface of the Sun (Mahajan et al. 2024).

It is important to note that the different flow methods mentioned above (except time-distance helioseismology, which uses consecutive Dopplergrams) determine solar surface horizontal flows using consecutive continuum images of the Sun. Thus, they give an estimate of the optical flows at the solar surface and may not represent the actual solar plasma motions. Several studies in the literature have therefore focused on comparing the horizontal velocities derived from these flow methods with the actual plasma velocities obtained from state-of-the-art magnetohydrodynamic simulations (see e.g., Rieutord et al. 2001; Verma et al. 2013; DeGrave et al. 2014; Louis et al. 2015; Asensio Ramos et al. 2017; Tremblay et al. 2018). Rieutord et al. (2001) show that granules can statistically trace large-scale flows (at mesogranular and supergranular scales) but systematically underestimate the actual velocities. They show that the horizontal velocities determined by CST underestimate the actual plasma velocities by roughly a factor of two (see Fig. 4 of Rieutord et al. 2001). Verma et al. (2013) show that the horizontal velocities determined by LCT are roughly three times underestimated. We note that while CST follows individual granules, LCT uses a spatial window that includes both granules and intergranular lanes. Thus, LCT measurements are affected by the width of the spatial window (see e.g., Verma et al. 2013; Louis et al. 2015). Louis et al. (2015) show that the horizontal velocities retrieved from LCT lack the fine structure observed in the simulated data, although there is general morphological agreement between the two. Tremblay et al. (2018) show

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that DeepVel reproduces horizontal velocities at subgranular and granular scales very well and is second only to FLCT at meso-granular and supergranular scales, although it depends on the simulation model used to train the neural network. DeGrave et al. (2014) showed that time-distance helioseismology underestimated solar surface horizontal flows. Despite this systematic underestimation of flow velocities by different flow techniques, no other method is available for an accurate and exact determination of actual solar plasma motions at all scales. Therefore, underestimation of flow velocities also persists in the present paper using CST on Doppler maps.

As mentioned above, the CST technique is traditionally applied to time sequences of solar intensity images in the continuum, such as those provided every 45 s by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012; Schou et al. 2012) onboard the Solar Dynamics Observatory (SDO; Pesnell et al. 2012, hereafter SDO/HMI). In this technique, velocities are measured by following the trajectory of each granule (a coherent structure) over the course of its lifetime, defined as the time between its birth and death. The measured horizontal velocities and Doppler velocities from SDO/HMI Dopplergrams are then corrected for satellite motion, limb effects (namely, limbshift correction applied to Doppler velocities to account for geometry-induced errors) and the tilt of the solar rotation axis with respect to the observer (see Appendix A of Rincon et al. 2017). In this way, CST provides the solar surface velocity field (V_x , V_y) in a Cartesian coordinate system, where x and y lie in the plane of the sky, with x increasing toward solar west (i.e., parallel to the direction of solar rotation) and y increasing toward solar north, while z is directed toward the observer along the line of sight. The horizontal velocity fields (V_x , V_y) are then combined with the line-of-sight velocity field V_z determined from SDO/HMI Dopplergrams to construct the photospheric full vector velocity field in spherical coordinates (Roudier et al. 2013; Rincon et al. 2017). Horizontal flow fields from CST have a spatial resolution of 2.5 Mm and a temporal resolution of 30 min.

In this paper, we show that the CST technique can be applied to Dopplergrams¹ to determine V_x and V_y , since the solar granulation pattern is also visible in Dopplergrams. For this purpose, we consider Dopplergrams obtained from SDO/HMI as well as from a numerical simulation of solar granulation. Using global and local correlation coefficients, such as Pearson's linear correlation and Spearman's and Kendall's rank correlation statistics, we compare the surface flow fields obtained by applying CST to intensity and Doppler maps. The comparison is also made for the horizontal divergence and vertical component of the curl of the flow field. We also present these comparisons using the pixel-by-pixel similarity measure given by the mean squared error. For our comparison, we consider three time-averaging windows of 30, 60, and 120 min.

2. Data

2.1. Numerical simulation

Following Roudier et al. (2020, see also Roudier et al. 2019), we used the first two-hour sequence from the full 27-hour sequence of (synthetic white light) emergent intensity and vertical velocity (V_z) fields produced by a 3D magnetoconvection simulation

of solar granulation (Stein & Nordlund 1998; Stein et al. 2009, see also the review by Stein 2012). We used this sequence at continuum optical depth unity (that is, $z = 0$ Mm). The simulation data cube has dimensions of 1008×1008 pixels in the horizontal (x, y) plane, with a pixel size of 79.26 km and a time step (time cadence) of $\Delta t = 60$ s. Since CST is custom-made for SDO/HMI intensity images, which have a pixel size of $0''.5$, we rebinned the simulation data to $0''.5$ to allow application of CST.

2.2. Observations

We used data from SDO/HMI. More specifically, we used full-disk continuum images of the solar photosphere near the Fe I 6173 Å absorption line and line-of-sight velocity maps (Dopplergrams) observed by SDO/HMI on 29 December 2022, 28–29 May 2023. The data from 29 December 2022 correspond to a relatively less active Sun (with only a few spots at higher latitudes, somewhat closer to the limb), while those from 28 and 29 May 2023 correspond to a magnetically more active Sun with two large sunspots close to the equator and a plage region showing emerging spots near the equator, respectively. We chose these datasets to verify the suitability of using CST on Doppler maps to determine horizontal flow fields, compared to using CST on intensity images. These data are recorded by SDO/HMI every 45 s with a pixel scale of $0''.5$. We applied the CST algorithm to these data sets for the first 30, 60, and 120 min to derive horizontal velocity fields and their derivatives, such as the horizontal divergence $D = \partial_x V_x + \partial_y V_y$ and the vertical component of vorticity $\zeta = \partial_x V_y - \partial_y V_x$. For 29 May 2023 data, we applied the CST algorithm to the first ten hours of the observed data to understand the nature of horizontal surface flows in the plage region with emerging spots or pores.

3. Comparison of horizontal surface flows from CST applied to intensity and Doppler maps

In this section, we compare horizontal flow fields and their derivatives determined by applying the CST technique to intensity images and Doppler maps. We note that the application of CST to Doppler maps does not require any modification of the CST algorithm. We used Dopplergrams as input instead of the intensity images. While CST applied to intensity images requires processing Doppler maps to obtain line-of-sight velocities to construct the full three-dimensional velocity vector, CST applied to Doppler maps avoids processing intensity images and thus reduces data storage and computing time involved in processing intensity images in the CST step². As mentioned in Section 2 we applied the CST technique to three temporal sequences of data from a numerical simulation of granulation and from SDO/HMI observations.

In addition to presenting a visual comparison of the horizontal flow fields obtained by CST on intensity and Doppler maps, we also present a more quantitative comparison using Pearson's linear correlation coefficient and the rank-order correlations such as Spearman's and Kendall's rank correlation coefficients. The Pearson linear correlation coefficient is defined as

$$C_{ab} = \frac{\sum_{i=1}^n (a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\left[\sum_{i=1}^n (a_i - \bar{a})^2\right] \left[\sum_{i=1}^n (b_i - \bar{b})^2\right]}}, \quad (1)$$

¹ In this context, we note that Roudier et al. (2019) show that LCT can be applied to Doppler maps obtained from simulation or observations to determine horizontal velocity fields that are in very good agreement with those obtained by applying LCT to intensity images.

² For the CST code and for more details on the CST method, see the CST manual available at <https://idoc.osups.universite-paris-saclay.fr/medoc/tools/cst-codes/>

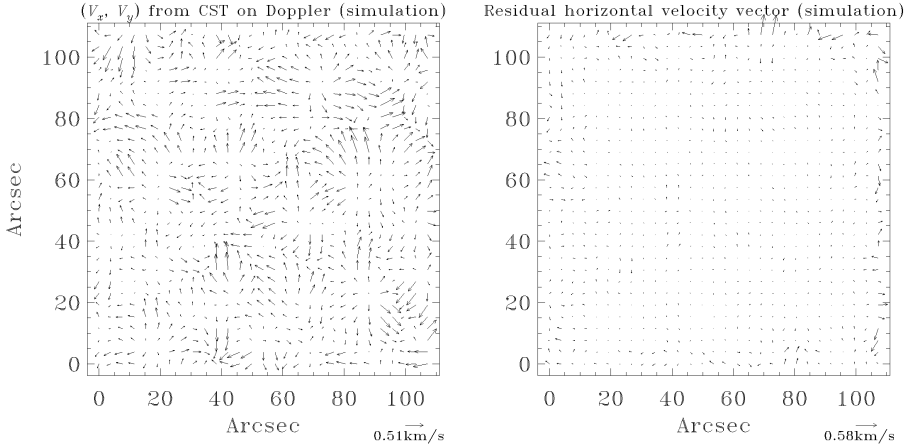


Fig. 1. Left : horizontal velocity vector (V_x, V_y) determined by applying CST to a vertical velocity (V_z) map from a numerical simulation of granulation. Right : residual vector between horizontal velocities obtained by applying the CST to intensity and vertical velocity map from simulation. We use a temporal window of 30 min. The arrow in the bottom-right corner of each panel shows the length of the maximum horizontal velocity vector in the left panel and of the maximum residual vector in the right panel. Although they are of similar magnitude, the residual vector is considerably smaller almost everywhere except near the edges.

Table 1. Pearson’s linear, Spearman’s rank-order, and Kendall’s rank-order correlation coefficients between flow quantities determined from CST applied to intensity and vertical velocity (V_z) maps of a numerical simulation of granulation.

Flow quantity	Pearson’s linear correlation coefficient			Spearman’s rank-order correlation coefficient			Kendall’s rank-order correlation coefficient		
	(30 min)	(60 min)	(120 min)	(30 min)	(60 min)	(120 min)	(30 min)	(60 min)	(120 min)
V_x	0.934	0.962	0.989	0.930	0.957	0.989	0.805	0.844	0.938
V_y	0.915	0.959	0.980	0.917	0.960	0.984	0.786	0.850	0.924
V_{amp}	0.880	0.921	0.961	0.876	0.926	0.965	0.721	0.779	0.887
Divergence D	0.892	0.947	0.975	0.904	0.950	0.978	0.765	0.823	0.903
Curl ζ	0.820	0.871	0.949	0.821	0.875	0.955	0.663	0.714	0.856

Notes. These coefficients are given for 30, 60, and 120 min temporal windows.

where n is the size of the sample, a_i, b_i are the individual sample points, and $\bar{a}$ and $\bar{b}$ represent their respective means.

In our case, a and b can represent $V_x, V_y, V_{\text{amp}} = \sqrt{V_x^2 + V_y^2}$, horizontal divergence D , or curl ζ obtained by applying CST to intensity and Doppler maps, respectively. Spearman’s rank correlation coefficient between data sets a_i and b_i is simply Pearson’s correlation between the rank values of the two data sets. Unlike Pearson’s correlation, which measures linear relationships between two datasets, Spearman’s rank correlation measures monotonic relationships between the datasets (irrespective of whether they are linear or not). In other words, it indicates the correlation between the two sets of ranks. Like Spearman’s rank correlation, Kendall’s rank correlation also measures monotonic relationships between two datasets, but its calculation is based on concordant and discordant pairs. More specifically, Kendall’s rank correlation coefficient is the ratio of the difference between the number of concordant and discordant pairs and the total number of pairs. Here, a pair (a_i, b_i) and (a_j, b_j) is said to be concordant if the ordering of (a_i, a_j) and (b_i, b_j) agrees (i.e., if either both $a_i > a_j$ and $b_i > b_j$ hold or both $a_i < a_j$ and $b_i < b_j$ hold); otherwise, the pair is said to be discordant. Clearly, the computing time for Kendall’s rank coefficient increases with sample size n . Hence, it is usually computed for smaller datasets. Furthermore, to measure image similarity pixel by pixel, we also computed the mean squared error (MSE), defined as

$$\text{MSE}_{ab} = \frac{1}{n} \sum_{i=1}^n (a_i - b_i)^2. \quad (2)$$

3.1. Comparison using simulation data

Using numerical simulations, Rieutord et al. (2001) showed that horizontal velocity fields derived by tracking the proper motion of granules are highly correlated with the actual plasma velocity fields at the mesogranular and supergranular scales, although a systematic underestimation of actual flows persists. For this purpose, they applied both CST and LCT to the intensity images from a numerical simulation and compared the resulting horizontal velocities with the actual flow velocities. They showed that the results from both techniques broadly agree with the numerical simulation. Hence, we focus here on comparing the horizontal velocities obtained by applying CST to intensity and vertical velocity maps derived from a numerical simulation (see Sect. 2.1). We recall that the time cadence of the numerical simulation is 60 s and we considered the first two hours of the simulated data. The left panel of Figure 1 shows the horizontal velocity vector obtained by applying CST to the vertical velocity (V_z) derived from this numerical simulation. We considered a temporal window of 30 min. The right panel of Figure 1 shows the residual velocity vector, defined as the difference between the horizontal velocity vectors obtained by applying CST to intensity images and to vertical velocity maps from the simulation. This clearly shows that the flows obtained by both methods are highly similar except at the very edge, particularly the right edge. However, these differences decrease with an increasing temporal window. This is clear from the Pearson’s linear, Spearman’s, and Kendall’s rank correlation coefficients presented in Table 1 for different flow quantities. We also computed the MSE (see Eq. (2)) for all flow quantities and for the three time windows. We obtained a maximum MSE of 0.0044 for divergence D with

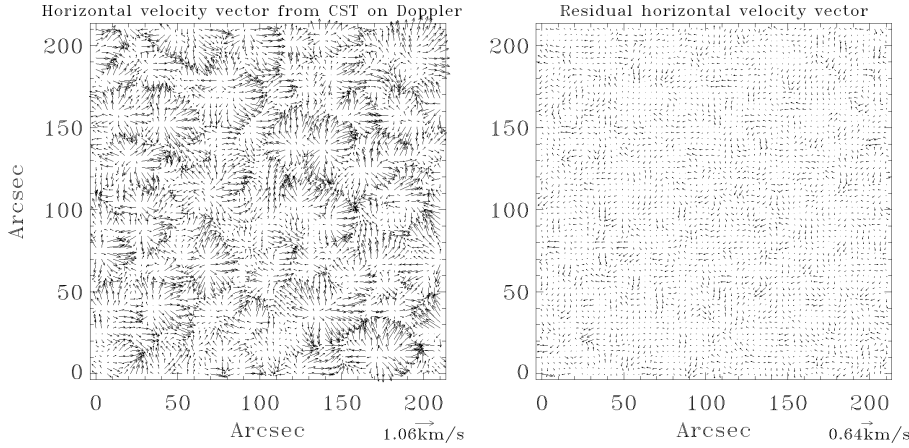


Fig. 2. Left: horizontal velocity vector (V_x , V_y) determined by applying CST to Dopplergrams from 29 December 2022 SDO/HMI observations is shown for a region near the disk center and for a temporal window of 30 min. Right: residual vector between the horizontal velocities obtained by applying the CST to intensity and Doppler maps from these observations is shown for the same region and time window as in the left panel. The arrow in the bottom-right corner of both the panels shows the length of the maximum horizontal velocity vector in the left panel and of the maximum residual vector in the right panel.

Table 2. Pearson’s linear and Spearman’s rank-order GCC for different flow quantities with 30, 60, and 120 min averaging.

Flow quantity	Pearson’s linear GCC			Spearman’s rank-order GCC		
	(30 min)	(60 min)	(120 min)	(30 min)	(60 min)	(120 min)
V_x	0.717	0.807	0.861	0.665	0.757	0.819
V_y	0.704	0.791	0.845	0.647	0.733	0.795
V_{amp}	0.762	0.822	0.860	0.840	0.875	0.899
Divergence D	0.720	0.824	0.893	0.638	0.742	0.820
Curl ζ	0.464	0.586	0.695	0.420	0.526	0.626

Notes. Relatively less active Sun observations from SDO/HMI on 29 December 2022 are considered.

Table 3. Pearson’s linear, Spearman’s rank-order and Kendall’s rank-order LCC near the disk center for different flow quantities with the 30, 60, and 120 min averaging.

Flow quantity	Pearson’s linear LCC			Spearman’s rank-order LCC			Kendall’s rank-order LCC		
	(30 min)	(60 min)	(120 min)	(30 min)	(60 min)	(120 min)	(30 min)	(60 min)	(120 min)
V_x	0.858	0.919	0.952	0.858	0.918	0.952	0.666	0.749	0.807
V_y	0.859	0.920	0.952	0.853	0.915	0.948	0.664	0.747	0.804
V_{amp}	0.674	0.785	0.851	0.650	0.769	0.839	0.461	0.570	0.643
Divergence D	0.839	0.913	0.947	0.828	0.905	0.945	0.635	0.733	0.796
Curl ζ	0.585	0.707	0.789	0.561	0.684	0.768	0.392	0.496	0.574

Notes. We computed the LCC using a 210×210 arcsec window near the disk center. Relatively less active Sun observations from SDO/HMI on 29 December 2022 are considered.

a 30 min time window, and a minimum MSE of 0.0003 for V_x with a 120 min time window. Clearly MSE is quite small and it indicates a higher similarity.

3.2. Comparison using observational data

We first applied CST to the relatively less active Sun data from 29 December 2022. We show the horizontal velocity vector obtained by applying the CST to Dopplergrams in the left panel of Figure 2. It covers a region of 210×210 arcsec near the disk center. We considered a temporal window of 30 min. The similarity between the flows obtained by applying CST to intensity images and Dopplergrams can be clearly inferred from the residual velocity vector shown in the right panel of Figure 2. Tables 2 and 3 show a quantitative comparison based on the different correlation coefficients.

Table 2 displays the global correlation coefficient (GCC) obtained for different flow quantities using the 30, 60, and 120 min time averages. For the GCC calculation, the sample size n

(see e.g., Eq. (1)) corresponds to the full solar disk observed by SDO/HMI, namely 4096×4096 pixels with a pixel scale of $0''.5$. However, because CST provides horizontal velocity fields on a spatial scale of 2.5 Mm (about seven SDO/HMI pixels), n for the GCC would be 586×586 pixels, where one pixel corresponds to $3''.5$. The GCC increases with an increasing time window for both Pearson’s linear and Spearman’s rank-order correlations (see Table 2). For all flow quantities except the curl, the GCC is reasonably high, indicating a very good correlation between CST applied to intensity images and to Doppler maps. For flow velocities V_x , V_y , and V_{amp} , we obtain an average Pearson’s linear GCC of about 73% for a 30 min time window, which increases to 81% and 86% for 60 and 120 min time windows, respectively. The horizontal divergence D also exhibits a good correlation. However, the curl ζ , being noisier, exhibits a reduced correlation that nevertheless increases with an increasing time window. Spearman’s rank-order GCC for different flow quantities exhibits a similar trend to the corresponding Pearson’s linear GCC, although its values are slightly smaller.

We also considered the local correlation coefficient (LCC) and studied its variation across the full disk of the relatively less active Sun. Figure A.1 shows Pearson's linear LCC for the different flow quantities obtained using 30 min (panels (a)), 60 min (panels (b)), and 120 min (panels (c)) time window. To compute the LCC, we divided the 586×586 pixels into spatial windows of 20×20 pixels, such that n (see Eq. (1)) for LCC is given by the latter. We recall that one pixel after application of CST corresponds to $3''.5$. As with Pearson's linear GCC (see Table 2), the LCC also increases with an increasing time window and the curl of the horizontal flows exhibit a lower LCC than the other flow quantities.

For a given time window, Pearson's linear LCC decreases near the limb, which is an edge or projection effect. At high latitudes and longitudes (close to the limb), the granules in intensity images are grouped, and therefore segmentation near the limb does not isolate individual granules due to curvature near the limb. As a result, the proper motion of the individual granules in intensity cannot be measured near the limb. This is referred to as an edge or projection effect. Moreover, because of the center-to-limb variation in intensity, near the limb we sample granules in the higher layers than at the disk center, so that the granules exhibit less contrast and appear blurred or faded. In contrast, in Dopplergrams at the disk center, the Doppler velocity represents the vertical velocity inside the granule, and close to the limb it represents the horizontal velocity inside of the granule (granule expansion). Hence, between the disk center and the limb, the Doppler signal of a granule is a mixture of these two components (namely the vertical and horizontal velocities within the granule). Thus, when we go from the disk center to the limb, the correlation between CST on intensity and Doppler is affected. Nevertheless, with Doppler, close to the limb, we always follow the same entities (more horizontal granule expansion), which helps to measure the horizontal velocities V_x and V_y on the Sun (and subsequently V_r , V_ϕ , V_θ ; see e.g., Roudier et al. 2013). For the above reasons, the LCC also becomes negative in some regions close to the limb, indicating anti-correlation. To better visualize this, whenever the LCC is negative, we set it to -1 irrespective of its actual value. As a result, regions where the LCC is negative appear as black squares in Fig. A.1. Thus, the grayscale gradations shown in this figure are restricted to positive LCC values.

Fig. A.1 clearly demonstrates that CST applied to full-disk Doppler maps produces flow fields similar to those derived from intensity (though with slight differences). This approach is useful for determining large-scale flows such as differential rotation and meridional circulation when long time sequences of data need to be processed (see Sect. 4 for a discussion of computational requirement for CST on Doppler and intensity images). Previous studies have applied CST to full-disk intensity images from SDO/HMI to derive large-scale flows (see e.g., Roudier et al. 2018; Mahajan et al. 2024; Upton et al. 2024). Studies have also applied other optical flow techniques, such as LCT and self-supervised optical flow methods, to full-disk observations to determine large-scale flows (see Löptien et al. 2017; Li et al. 2023).

Table 3 lists the Pearson's linear, Spearman's, and Kendall's rank-order LCC values for different flow quantities, computed using a 210×210 arcsec window near the disk center (similar to that considered for Figure 2). As expected, Pearson's linear and Spearman's rank-order LCC near the disk center are larger than the corresponding GCC (compare Tables 2 and 3). For the curl of the flow field, both the Pearson's and Spearman's LCC values near the disk center are also higher than the corresponding

GCC values. Since the computation time for Kendall's rank-order correlation increases significantly with sample size n , we only computed it for the near-disk-center region (see Table 3). Furthermore, for V_x , V_y , and V_{amp} together, we obtain an average near-disk-center Pearson's linear LCC of about 80% for 30 min time averaging, which then increases to 87% and 92%, respectively, for 60 and 120 min time averaging, respectively. Both rank-order LCCs are slightly smaller than Pearson's linear LCC, but they increase with an increasing time window in the same manner. For the MSE (see Eq. (2)), we obtain a maximum value of 0.027 for V_y with a 30 min time window and a minimum value of 0.0058 for curl ζ with a 120 min time window.

The left panels of Figure 3 show histograms of the amplitude of the horizontal velocity field, V_{amp} , obtained by applying CST to intensity images and Dopplergrams. We also present histograms of the scalar product of horizontal velocities obtained from CST on intensity and Doppler maps, namely

$$\hat{V}^{\text{Int}} \cdot \hat{V}^{\text{Dop}} = \frac{V_x^{\text{Int}} V_x^{\text{Dop}} + V_y^{\text{Int}} V_y^{\text{Dop}}}{V_{\text{amp}}^{\text{Int}} V_{\text{amp}}^{\text{Dop}}}, \quad (3)$$

where the superscripts "Int" and "Dop" indicate that the corresponding velocity is obtained by applying CST to intensity and Dopplergrams, respectively. The right panels of Figure 3 show histograms of the difference in V_{amp} obtained by the two methods. We used a bin size of 0.025 km/s for the velocity amplitudes and 0.025 for the scalar product. Again, we show histograms for 30, 60, and 120 min time-averaging windows. The high degree of similarity between the histograms obtained by the two methods (as indicated by the blue and red lines) is clearly visible in panels a, c, and e, which shows that the velocity amplitudes are accurately determined by CST applied to Dopplergrams. This is also evident from the velocity-amplitude-difference histogram, where the differences are confined to small velocity amplitude. This is expected because the identification of granules in segmented intensity data and in Dopplergrams could be slightly different, giving some incertitude on the location of each granule's center of gravity. The granule area identified by CST on Doppler can also differ from that identified in intensity images. Velocities higher than 0.3 km/s show good agreement. A similar behavior to that observed for V_{amp} is also seen for V_x and V_y individually (figure not shown). Furthermore, the histogram of the scalar product (see the magenta line in panels a, c, and e) is confined to cosine values of the angle between $\hat{V}^{\text{Int}}$ and $\hat{V}^{\text{Dop}}$ in the range 0.8–1, indicating that horizontal velocity directions are also well recovered. However, the scalar product histogram exhibits two peaks, whereas we expect only one peak around unity. The second peak around 0.8 could be due to the fact that between the disk center and the limb, Doppler measures both vertical and horizontal component of flow velocity, while CST on intensity measures only the horizontal component. Nevertheless, from all studies presented so far, we conclude that CST can be applied to Doppler maps of the relatively less active Sun to derive horizontal flows.

We next considered the application of CST to magnetically active Sun data from 28 May 2023. Here we focus on a field of view of 301×126 arcsec covering the region around two large sunspots near the equator to assess the applicability of CST to Doppler maps around sunspots, while also applying CST to the full Sun intensity and Doppler images. Table 4 lists the different correlation coefficients between horizontal velocities derived from CST on intensity and Doppler maps around the sunspots, for the three different time windows. The different correlation coefficients are smaller than those obtained for

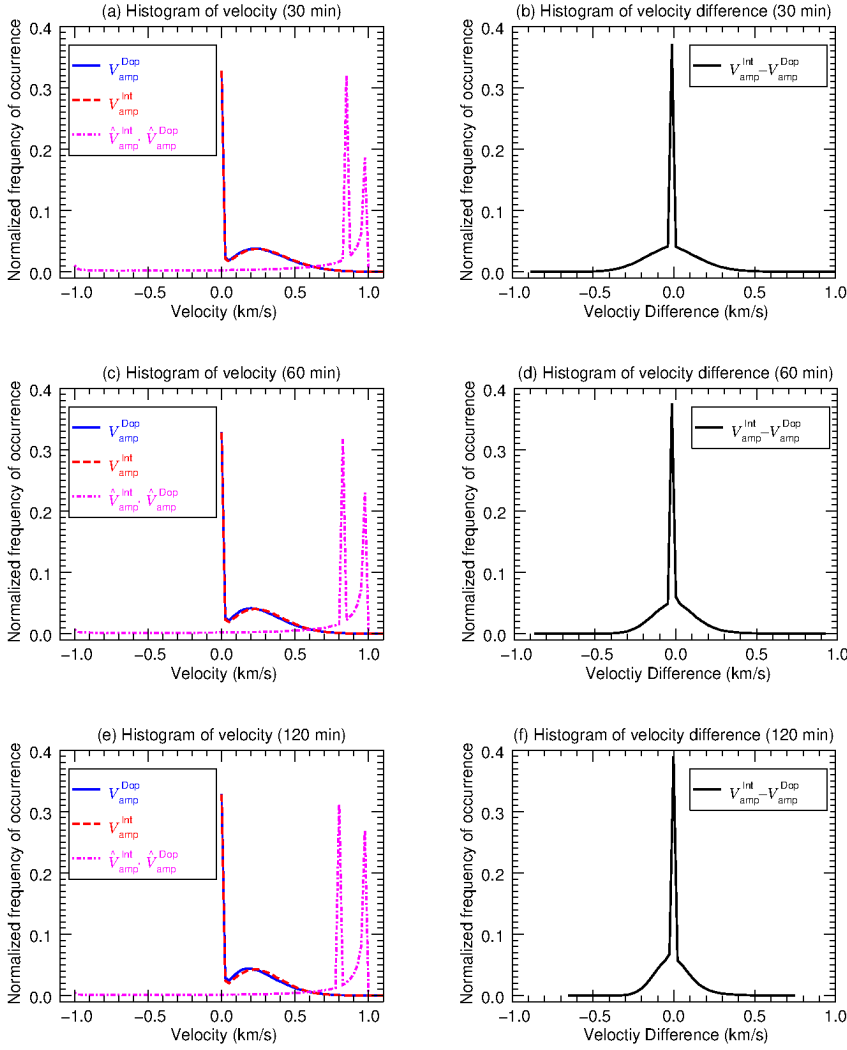


Fig. 3. Histograms of the amplitude of the horizontal velocity field (panels a, c, and e) and the difference in velocity amplitude obtained from CST on intensity and Dopplergrams (panels b, d, and f) for 30 (panels a and b), 60 (panels c and d), and 120 (panels e and f) min time windows. The left panels also show the histograms of the scalar product (see Eq. (3)) between the horizontal velocities obtained from CST on intensity and Doppler maps. In this case, the abscissa represents the cosine of the angle between $\hat{V}^{\text{Int}}$ and $\hat{V}^{\text{Dop}}$, which ranges from -1 to $+1$. In both panels, the superscripts “Int” and “Dop” indicate velocities obtained by applying CST to intensity and Dopplergrams, respectively. In the left panels, the horizontal velocity amplitude V_{amp} is restricted to positive values. Observations of a relatively less active Sun from SDO/HMI on 29 December 2022 are considered.

Table 4. Pearson’s linear, Spearman’s rank-order, and Kendall’s rank-order LCC for different flow quantities obtained with the 30, 60, and 120 min averaging.

Flow quantity	Pearson’s linear LCC			Spearman’s rank-order LCC			Kendall’s rank-order LCC		
	(30 min)	(60 min)	(120 min)	(30 min)	(60 min)	(120 min)	(30 min)	(60 min)	(120 min)
V_x	0.662	0.783	0.855	0.649	0.763	0.834	0.469	0.574	0.651
V_y	0.747	0.839	0.897	0.710	0.804	0.866	0.525	0.617	0.689
V_{amp}	0.519	0.664	0.751	0.460	0.607	0.706	0.319	0.430	0.513
Divergence D	0.679	0.794	0.865	0.665	0.780	0.850	0.479	0.585	0.664
Curl ζ	0.434	0.550	0.653	0.440	0.546	0.640	0.302	0.382	0.459

Notes. We considered a region around sunspots near the equator with a field of view of 301×126 arcsec. We applied CST to magnetically active Sun observations from SDO/HMI on 28 May 2023.

the relatively less active Sun case (compare Tables 3 and 4). This is expected because convection is suppressed within the sunspots and therefore horizontal velocities cannot be detected effectively by tracking granules, especially in the umbra. Furthermore, because the sunspots are not located at the disk center, projection effects exist that can modify the appearance of solar granules in Doppler maps and introduce small differences in the amplitude and direction of the horizontal velocity fields. This is particularly true for CST applied to Doppler maps, because the horizontal velocities are derived by tracking

granular proper motions, unlike the method of Löhner-Böttcher & Schlichenmaier (2013), who directly derived the horizontal velocities from Doppler maps of sunspots located at heliocentric angles of about 50° where the line-of-sight velocities are predominantly horizontal. Thus, while CST on Doppler maps (and even CST on intensity) leads to an underestimation of horizontal velocities in the umbral and penumbral regions of the sunspot, the method of Löhner-Böttcher & Schlichenmaier (2013) does not lead to such underestimation, especially when heliocentric angles are on the order of 50° . Nevertheless, all three correlation

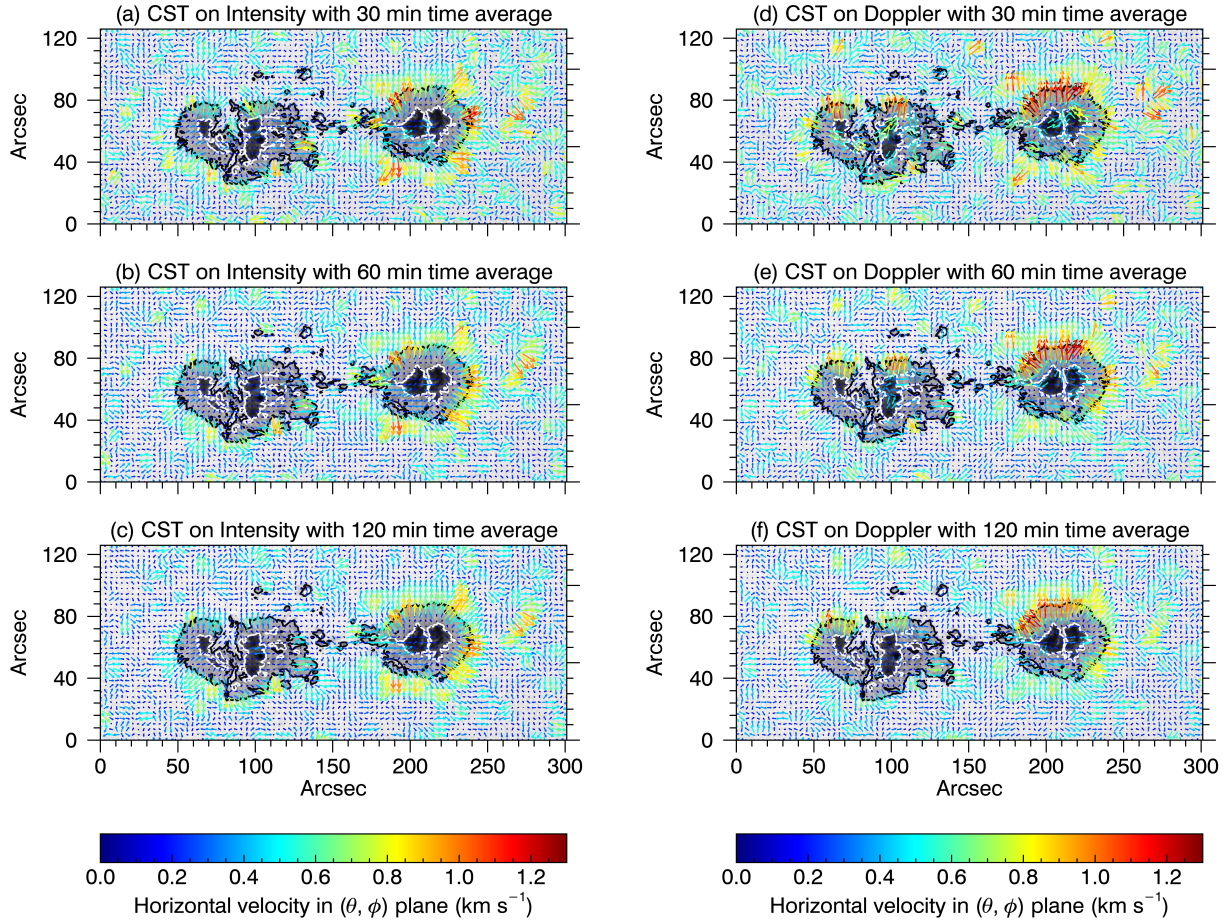


Fig. 4. Horizontal velocity vector (V_ϕ , V_θ) derived by applying CST to intensity (left column) and Doppler (right column) maps observed by SDO/HMI on 28 May 2023. The field of view covers a region around the sunspots near the equator. The top, middle, and bottom rows correspond to 30, 60, and 120 min time averages, respectively. The color and length of the arrows indicate the horizontal velocity according to the spectral scale shown in the color bar. The time-averaged intensity image is displayed in the background. The black and white contours mark the boundaries of the penumbra and umbra, respectively. A moat flow toward the west of leading sunspot is visible.

coefficients increase with an increasing time window, indicating that CST can be applied to Doppler maps around sunspots to derive meaningful horizontal flows for time windows of 60 min or longer. The MSE for the field of view covering the sunspots is also slightly larger than that obtained for the relatively less active Sun case considered previously. More specifically, we obtained a maximum MSE of 0.0492 for V_x with a 30 min time window, and a minimum MSE of 0.0111 for the curl ζ with 120 min time window.

In Figure 4, we compare the horizontal velocities determined by applying CST to intensity and Doppler maps around the sunspot region. Here we plot horizontal velocities in spherical coordinates, namely V_ϕ and V_θ , which represent longitudinal and latitudinal flows, respectively. The transformation of the horizontal velocities V_x and V_y , together with the Doppler velocity, to spherical coordinates (V_r , V_ϕ , V_θ) is described in Section 5 of Roudier et al. (2013). For the reasons already noted above, we find that the differences in horizontal velocities from CST applied to intensity and Doppler are significant mainly within the sunspots and, to a lesser extent (only in amplitude), around the outer boundary of penumbra (the black contour), and these differences decrease with an increasing time window. In general, the amplitude of the horizontal velocity from CST applied to Doppler maps is slightly larger than that determined from CST

applied to intensity. While CST applied to intensity images persistently shows inflows in the umbra and at the inner boundary of the penumbra (see the region in and around the white contour in the left panels of Figure 4) for all three time windows, CST applied to Doppler maps shows this only for time window of 120 min. We see radial outflows around the outer boundary of the penumbra (black contour; except on the eastern side) of the leading sunspot (western one) for all three time windows and for both methods. This represents the moat flow around the leading sunspot (see e.g., Verma et al. 2018). More specifically, the horizontal velocity on the western side of the leading sunspot is directed toward the west. This is expected because the leading sunspot moves more rapidly than the solar rotation, unlike the trailing sunspot. We note that the moat flow is more developed in the leading sunspot than in the trailing sunspot. Using FLCT on a six-year time series of continuum images from SDO/HMI, Löptien et al. (2017) show that large-scale inflows around active regions converge predominantly towards the trailing polarity. This may explain the suppressed moat flow around the trailing polarity observed in Fig. 4. Furthermore, outflows also originate slightly inside the penumbral edge and extend to its periphery in both sunspots, especially on their northern and southern sides. This is seen for all three time windows and for both methods.

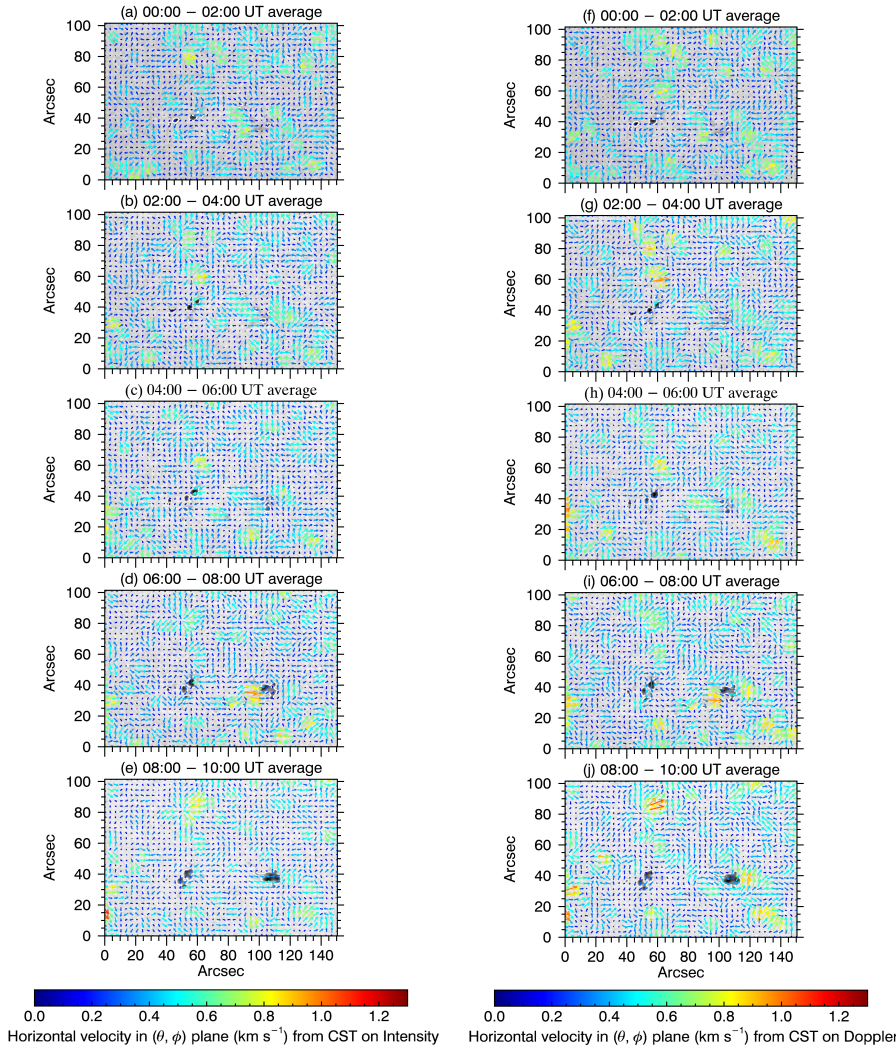


Fig. 5. Horizontal velocity vector (V_ϕ , V_θ) derived by applying CST to intensity (left column) and Doppler (right column) maps observed by SDO/HMI on 29 May 2023. The field of view covers a plage region with emerging pores near the equator. The rows from top to bottom correspond to consecutive 120 min time averages of the first 10 h of observed data. The color and length of the arrows indicate the horizontal velocity according to a spectral scale shown in the color bar. The time-averaged intensity image is displayed in the background. White contours mark the boundaries of the umbrae of the pores.

Finally, we applied the CST algorithm to the first ten hours of SDO/HMI observations on 29 May 2023, which again correspond to a magnetically more active Sun. We focused on surface horizontal flows in a plage region with emerging pores near the equator. For this purpose, we considered a field of view of 151×102 arcsec that covers the plage region. There are two groups of pores in this region (figure not shown), one to the left (east) and the other to the right (west). As time progressed, new pores continuously emerged within the existing group of pores embedded in the plage region and subsequently grew into larger spots. The group of pores to the left remained more or less at the same location for the entire ten hours of observations, while those to the right moved toward the west.

We calculated the correlation coefficients between horizontal velocities derived from the application of CST to intensity and Doppler maps around the plage region for the three time windows, covering the 10-hour evolution of the pores. We find that over the entire evolution of the pores, the correlation coefficients for the different flow quantities and time windows in the plage region are broadly similar to those obtained for the less active Sun case. As in the previously discussed cases, the correlation coefficients increase with an increasing time window. In contrast, the MSE shows greater variation during the evolution of the pores, but remains below 0.055, 0.035, and 0.02 for the 30,

60, and 120 min time windows, respectively. Thus, we conclude that CST can be applied to Doppler maps around a plage region to derive meaningful horizontal flows when the time-averaging window is 60 min or longer.

Figure 5 shows a comparison of horizontal velocities (V_ϕ , V_θ) determined from CST on intensity (left panels) and Doppler (right panels) maps around the plage region for successive 120 min time windows over the ten hours of observations. As in the case of sunspots (see Figure 4), the horizontal velocities obtained from CST applied to Doppler are slightly larger in amplitude than those obtained from CST applied to intensity in the plage region. Kamlah et al. (2023) studied horizontal flows around pores. Consistent with their findings, we find inflows at the boundary (white contour) of the eastern pores. Between the pores, we find horizontal flows from east to west around 75–80 arcsec in the east-west direction and 25–35 arcsec in the north-south direction. Further converging horizontal flows directed towards the west are seen on the left boundary of the west pores. Their amplitude increases as the pores evolve, reaching a maximum for the time average from 6 to 8 UT (see panels d and i) and then decreases (see panels e and j). Clearly, these relatively large-amplitude converging horizontal flows are responsible for the movement of west pores toward the west with time. However, at the right edge of the west pores, we see

horizontal flows pointing more toward the north direction. All of the flow in and around the pores mentioned above are recovered from both CST on intensity and Doppler.

4. Conclusions

Coherent structure tracking (CST) is a tool for determining solar surface dynamics, which is crucial for understanding solar magnetic fields. Since its inception by Roudier et al. (1999) and subsequent developments by Rieutord et al. (2007); Roudier et al. (2012, 2018), CST has traditionally been applied to the intensity images of the Sun obtained in the continuum. In this paper, we apply CST to Dopplergrams for the first time. In particular, we consider Dopplergrams obtained from SDO/HMI and vertical velocity (V_z) maps from a numerical simulation of granulation. We performed a detailed comparison of the horizontal velocity fields determined by applying the CST to intensity and Dopplergrams and/ or vertical velocity maps. For this purpose, we computed Pearson's linear, Spearman's, and Kendall's rank-order correlation coefficients (both global and local), as well as the MSE, to measure image similarity pixel by pixel. We also present histograms of the velocity amplitude, scalar product, and velocity differences between the horizontal velocities obtained from CST applied to intensity images and Dopplergrams. Furthermore, we compared the derivatives of the horizontal fields, namely the divergence and curl.

We show that there is a high degree of similarity between the horizontal fields (in both direction and amplitude) derived by applying CST to intensity images and vertical velocity maps from a numerical simulation. In particular, we obtain a Pearson's linear correlation coefficient of 90% or higher for the horizontal velocities, and 80% or higher for the derivatives of the horizontal fields when a 30 min time averaging is used (see Table 1). Spearman's rank-order correlation coefficient is similar to Pearson's linear correlation coefficient, while Kendall's rank-order correlation is slightly smaller. However, all three correlation coefficients increase with an increasing time-averaging window. Furthermore, the MSE also indicated a high degree of similarity (see Section 3.1), validating the application of CST to vertical velocity maps to derive horizontal flows.

For the SDO/HMI observations, we consider data from 29 December 2022 representing a relatively less active Sun, and data from 28 and 29 May 2023 representing a magnetically more active Sun. For the relatively less active Sun, we obtain a Pearson's linear GCC of 73% and a near-disk-center LCC of 80% for the horizontal velocity fields at 30 min time resolution. The derivatives of the horizontal field, in particular the divergence, also exhibit a similar Pearson's linear correlation coefficient, while the curl, being more noisy, exhibits somewhat reduced correlation coefficient (see Tables 2 and 3 and also Fig. A.1). When we increase the time-averaging window, these correlation coefficients also increase. Spearman's and Kendall's rank-order correlation coefficients exhibit a similar trend but are slightly smaller than Pearson's linear correlation coefficient. The MSE is also smaller in all cases, indicating a high degree of similarity. The correlation coefficients slightly decrease for the magnetically more active Sun with sunspots (see Table 4) or for the plage region with emerging pores, and the MSE is relatively larger. Nevertheless we show that for a magnetically more active Sun, meaningful horizontal flows can be obtained from CST applied to Doppler maps when the time-averaging window is 60 min or longer, while a 30 min time window is sufficient for the relatively less active Sun case.

We studied the horizontal flows in the region that covers the sunspots and a plage with emerging pores (see Figures 4 and 5). For this purpose, we considered the longitudinal (V_ϕ) and latitudinal (V_θ) flows. We recover moat flows around the leading sunspot from CST applied to Doppler. We further investigated the evolution of horizontal flows in and around the pores and show that relatively large-amplitude horizontal flows are responsible for the westward motion of the western pores. In general, we find that the horizontal flows derived from CST on Doppler are slightly larger in amplitude than those obtained from CST on intensity. This may be due to the fact that SDO/HMI Doppler signals form at a slightly higher height in the photosphere than the SDO/HMI continuum intensity images, as the Doppler signals are derived from Doppler shifts in the Fe I 6173 Å absorption line. Thus, CST on Doppler provides horizontal flows at heights slightly different from those obtained from CST on intensity.

With regard to computational requirements, CST on Dopplergrams completely avoids processing intensity images. This results in considerable savings in data storage, not only for CST applications but also when recording data from space- or ground-based instruments. Furthermore, computing time is also somewhat reduced. More specifically, CST on Dopplergrams leads to about 9.4% saving in CPU time compared to CST on intensity (including both the IDL and FORTRAN parts). The reduction in CST-IDL processing time arises because CST on Doppler only processes Dopplergrams, while CST on intensity processes both continuum intensity images and Dopplergrams (to derive the line-of-sight velocity). With regard to the reduction in computational time in the CST-FORTRAN part, this is related to the fact that CST applied to intensity tends to detect smaller granules more efficiently than in Doppler. The smaller granules seen in the intensity images have Doppler counterparts but with a lower amplitude. This is because smaller granules have a lower vertical velocities and therefore their contrast in Doppler maps is also lower. Since binarization or segmentation of granules (both in intensity and Doppler maps) are based on local derivative and contrast (see Sect. 2.1 of Rieutord et al. 2007), CST applied to Doppler tends to detect fewer small granules than CST applied to intensity images at the disk center. Toward the limb, the further decrease in contrast causes smaller granules to be lost in the CST segmented images, and they are therefore not detected well by CST. For example, for a 30 min time window, CST on full-disk Doppler of a relatively less active Sun detects about 20 000 fewer granules than CST on intensity. This reduced detection decreases the computing time for further operations, such as granule identification and tracking, leading to a saving in CPU time as mentioned above. However, despite this, we show that the detected granules are sufficient to measure horizontal flow fields.

Our studies therefore show that we can apply the CST technique to Dopplergrams to derive horizontal velocity fields on the surface of the Sun with the same level of confidence as CST applied to intensity images. Finally, we emphasize that the main motivation for using CST on Doppler maps is the reduction in memory usage and computational time. This becomes particularly critical when CST is applied to a longer time sequence of data, for example over the solar cycle, to determine the meridional flows.

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Appendix A: LCC across the full-disk of a relatively less active Sun

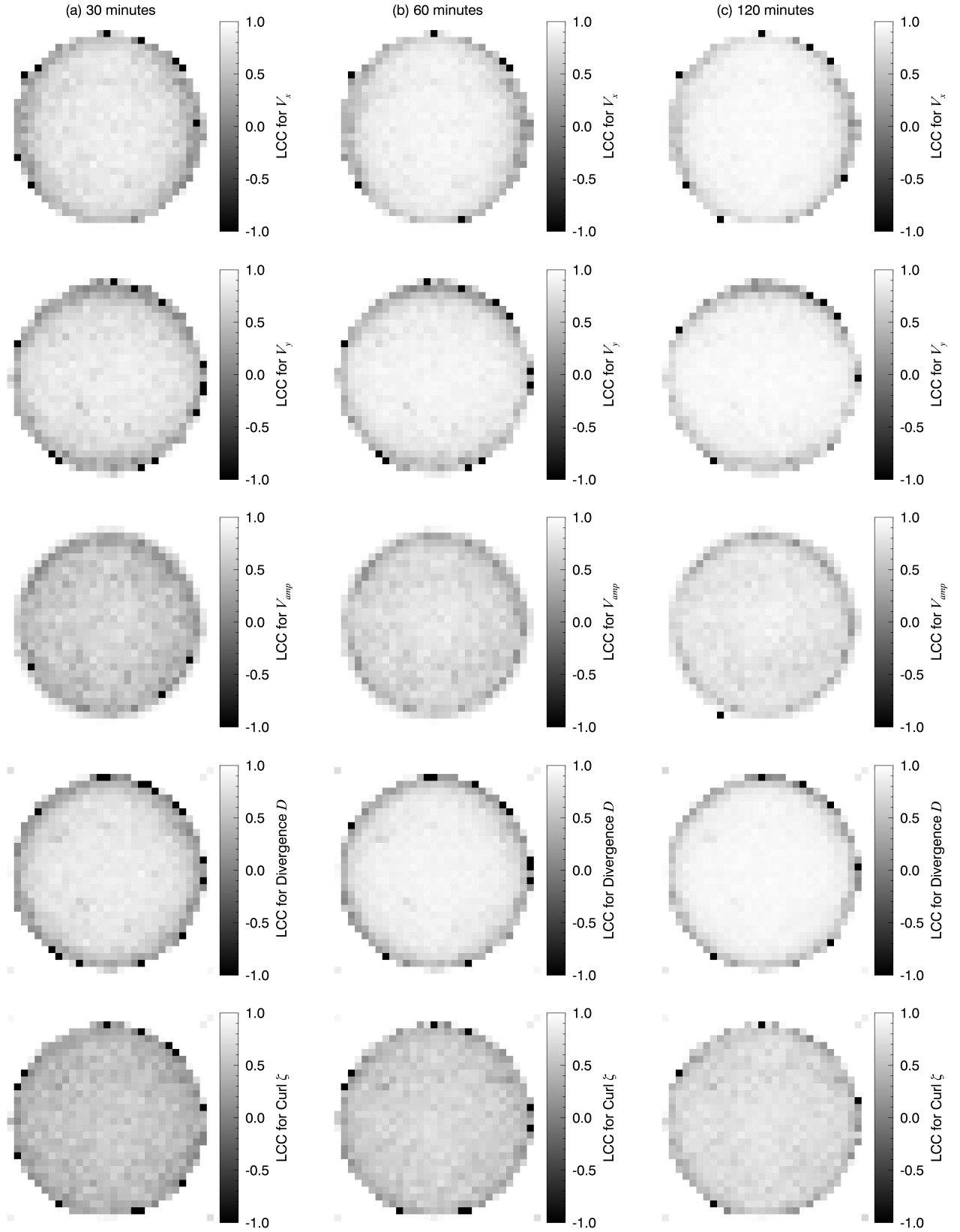


Fig. A.1. Pearson's linear LCC for different flow quantities across the entire disk of the Sun and with the 30 (panels (a)), 60 (panels (b)), and 120 (panels (c)) min averaging. Relatively less active Sun observations from SDO/HMI on 29 December 2022 are considered. Clearly for all the flow quantities the LCC increases with the temporal window for time averaging.