

Solar photospheric velocities measured in space: A comparison between SO/PHI-HRT and SDO/HMI

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ABSTRACT

The Polarimetric and Helioseismic Imager (SO/PHI) on board Solar Orbiter is a spectropolarimeter scanning the Fe I line at 617.3 nm, providing data of the solar photosphere. The same line is sampled by the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO) and many other ground-based instruments. In this paper our aim is to assess the consistency between the line-of-sight (LoS) velocity measurements from the two instruments. Reliable measurements of upflows and downflows from SO/PHI are crucial and unique when Solar Orbiter is facing the far side of the Sun. Also, a combination of measurements from two vantage points to study horizontal flows must rely on consistent observations. For this purpose, we compare the LoS velocity measured by SO/PHI's High Resolution Telescope (SO/PHI-HRT) and SDO/HMI on 29 March 2023, when Solar Orbiter was crossing the Sun–Earth line at a distance of 0.39 au from the Sun. Because such co-alignments are rare, this configuration offered an almost unique opportunity to directly compare data products from the two telescopes. The data are aligned and remapped to allow a pixel-by-pixel comparison of the whole time series of 4 hours. Temporal and spatial variations are considered for a direct combination of the measurements. The LoS velocity distributions are evaluated and a clear linear relation is found between the two instruments with a slope of 0.96 and a correlation of 92%. We find that the signals form at similar heights, with a separation of 9 ± 12 km, which is larger than previous estimates. A close-up look at the penumbra of a sunspot and its Evershed flow is presented. We conclude that the signals inferred by SO/PHI-HRT and SDO/HMI show very good agreement and high correlation when instrumental effects and large-scale velocities on the Sun are properly accounted for.

Key words. space vehicles: instruments – Sun: photosphere – sunspots

1. Introduction

The Polarimetric and Helioseismic Imager (SO/PHI, Solanki et al. 2020) on board Solar Orbiter (Müller et al. 2020) is the first spectropolarimetric imager to observe the Sun from a vantage point lying outside the Sun–Earth line. Two telescopes are part of the instrument, the Full Disk Telescope (SO/PHI-FDT) and the High Resolution Telescope (SO/PHI-HRT, Gandorfer et al. 2018), which both provide measurements of the photospheric magnetic field vector, continuum intensity, and line-of-sight (LoS) velocity in the solar photosphere. Only a few other satellites have instruments capable of retrieving these photospheric quantities, such as the Spectropolarimeter instrument (SP, Lites et al. 2013) of the Solar Optical Telescope (SOT, Tsuneta et al. 2008) on board Hinode (Kosugi et al. 2007), the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory (SDO/HMI, Schou et al. 2012; Pesnell et al. 2012), and the Full-Disk Vector MagnetoGraph on board the Advanced

Space-Based Solar Observatory (ASO-S/FMG, Bai et al. 2024; Gan et al. 2023).

Despite the clear advantages of satellite observations, such as the absence of the disturbance from the Earth's atmosphere and the capability of uninterrupted data acquisition, many challenges have to be faced to achieve consistent data reduction. In the case of SO/PHI the highly eccentric orbit and low telemetry periods when the spacecraft is at more than 1 au from Earth, make the SO/PHI data reduction considerably more challenging. On the other hand, SO/PHI can for the very first time measure the photospheric properties of the Sun from different viewpoints than Earth-bound observatories (Müller et al. 2020). This unique orbit opens the possibility for novel scientific applications, such as building fast synoptic maps of the LoS magnetic field (Loeschl et al. 2024b,a) or direct combination of intensity and magnetic field data in stereoscopic configuration (e.g., Valori et al. 2023; Albert et al. 2023; Romero Avila et al. 2024). Comparisons of the magnetic field vector between SO/PHI and SDO/HMI were carried out by Sinjan et al. (2023) and Moreno Vacas et al. (2024) to assess the similarity between the data products of these two instruments. Such inter-instrument comparisons are fundamental for combining data from

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different vantage points, particularly when tracking features on the far side of the Sun as observed from Earth (e.g., [Finley et al. 2025](#)).

The same approach can be applied to the photospheric flows measured by multiple instruments. Dopplergrams are a crucial data product to study the emergence of active regions (e.g., [Lites et al. 1998](#)), waves ([Jess et al. 2023](#)), or the dynamics of the magnetic field in active regions (e.g., [Kazachenko et al. 2015](#)). Providing high quality data comparable to other spectropolarimeters will be a key element for studying the evolution of active regions for more than half of the solar rotation and for disentangling horizontal from vertical flows by combining data from different vantage points.

This work focuses on the comparison of the LoS velocity field measured by SO/PHI-HRT and SDO/HMI. In Section 2 we describe the data used for this work. In Section 3 the method used for the remapping of the data is explained in detail. The results are shown in Section 4 and the discussion and summary are presented in Section 5.

2. Data

The observations analyzed in this work were acquired while Solar Orbiter was in inferior conjunction (along the Sun–Earth line) with Earth on 29 March 2023 during the Solar Orbiter Observing Plan R_SMALL_HRES_HCAD_RS-burst ([Zouganelis et al. 2020](#)). This orbital configuration gave us the opportunity to have Earth-bound and Solar Orbiter instruments observing the Sun from an almost identical viewing angle. Here we focus on the comparison of SO/PHI-HRT and SDO/HMI. Both telescopes scan the Fe I absorption line at 617.3 nm with the same angular resolution, although this translates to different spatial resolutions on the photosphere due to the different distances of the telescopes from the Sun, which varies greatly along Solar Orbiter’s orbit. Information about the observation employed in this paper can be found in Table 1, such as the time of the acquisition, the NOAA number of the observed sunspot, cadence, pixel scale, and the position of the spacecraft. More information about the technical comparison between the two telescopes is provided in [Sinjan et al. \(2023\)](#).

An overview of the data is shown in Fig. 1. The top panels display the continuum intensity and LoS velocity as measured by SO/PHI-HRT, the bottom panel depicts the LoS magnetic field as seen from both instruments, with the SO/PHI-HRT field of view (FoV) indicated by the yellow box in the SDO/HMI magnetogram. All the panels are shown in the respective detector frame, which means that the SO/PHI-HRT y -axis is roughly aligned with the north–south direction and SDO/HMI is rotated by approximately 180° (as shown by the arrows in the bottom panels). The data products chosen for this comparison are the 45 s cadence data products of SDO/HMI based on the technique developed for the Michelson Doppler Imager (MDI-like technique, [Couvidat et al. 2016](#); [Scherrer et al. 1995](#)) and the newly improved standard results of the SO/PHI-HRT pipeline ([Sinjan et al. 2022](#); [Kahil et al. 2022](#); [Bailén et al. 2024](#)), which is now also correcting for residual stray light, based on the inversion of the radiative transfer equations (RTEs) in Milne–Eddington approximation with the MILOS code ([Orozco Suárez & Del Toro Iniesta 2007](#)). This data product became the standard data product in most recent data releases¹ (for more details, see [Sinjan et al. 2026](#)).

We post-processed the SO/PHI-HRT data with the method described in [Calchetti et al. \(2023\)](#), which mainly consisted

¹ Fifth SO/PHI-HRT data release notes.

Table 1. Details of the observations.

	SO/PHI-HRT	SDO/HMI
Time	2023-03-29, 11:40-15:40 UT	
NOAA number	13262	
μ value	0.96	
Cadence	60 s	45 s
Angular separation	2.3°	
Sun distance	0.39 au	1 au
Pixel scale	143 km/px	362 km/px

Notes. The μ value is defined as the cosine of the heliocentric angle of the center of the field of view. The pixel scale is defined as at disk center.

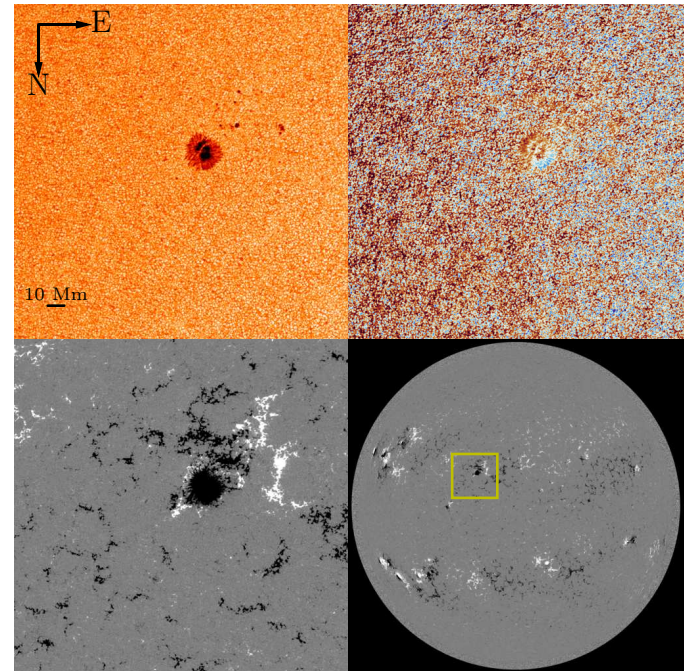


Fig. 1. Top left panel: Intensity continuum as measured by SO/PHI-HRT. A 10 Mm scale is given as reference. Top right panel: LoS velocity as measured by SO/PHI-HRT. Bottom left panel: LoS magnetic field as measured by SO/PHI-HRT. Bottom right panel: LoS magnetic field as measured by SDO/HMI. The yellow box shows the SO/PHI-HRT FoV. The black arrows in the top left panel indicate the solar north (N) and east (E). We note that all the panels of this figure are shown in the SDO/HMI detector frame.

of aligning the whole time series and temporally interpolating each frame of the Stokes vector to the same observing time. For consistency, instead of a linear interpolation we used an apodized normalized *sinc* function. The choice was motivated by using a similar function to that in the SDO/HMI pipeline ([Martínez Oliveros et al. 2011](#)), even though no significant dependence is found of the results presented in this work on the employed interpolation scheme.

3. Remapping and alignment

An accurate alignment of the whole time series is needed for a pixel-by-pixel comparison. The procedure described below is applied to every SO/PHI-HRT observation (240 in total), which is then associated with the closest SDO/HMI dataset in time.

Differences in light travel times are also considered when selecting the SDO/HMI dataset.

First, the World Coordinate System (WCS) of SO/PHI-HRT is updated to compensate for three as-yet-unaccounted-for contributions to the nominal spacecraft pointing: the tracking of the image stabilization system, the translation of the field of view (FoV) due to the change in the focus position, and the pointing inaccuracy of the spacecraft itself. Other residuals coming from small variations in the instrument bore-sight are also compensated for. The alignment is achieved via cross-correlation between the continuum intensity maps of SO/PHI-HRT and SDO/HMI; the latter are remapped on the SO/PHI-HRT detector frame. This procedure is repeated iteratively while updating the WCS information to account for the misalignment found with the cross-correlation until the obtained shift is smaller than a hundredth of a pixel.

Second, we compensated for geometrical distortions in the SO/PHI-HRT FoV. This step starts by cropping the SDO/HMI time series to the desired FoV (see the yellow box in Fig. 1) and by tracking the sunspot in the center of the FoV at the Carrington rotation rate, similar to the *mtrack* module in the SDO/HMI pipeline. We then destretched the SO/PHI-HRT LoS magnetic field map, remapped onto the cropped SDO/HMI detector frame, with respect to the corresponding SDO/HMI magnetogram. The pixel-by-pixel shifts obtained by this destretching algorithm were then applied in the algorithm that remaps SO/PHI-HRT onto the SDO/HMI detector frame with a cubic interpolation. This procedure can be applied only when the angular separation of the two instruments is close to 0° , where differences in viewing geometry are minimized, and it is necessary to remove any residual geometrical distortion in the FoV.

Finally, before remapping the SO/PHI-HRT LoS velocity on the SDO/HMI image plane, we convolved the SO/PHI-HRT Dopplergram with the SDO/HMI theoretical point spread function (PSF) and removed the LoS photospheric large-scale velocity components (LSCs) in the data, including solar differential rotation, spacecraft velocity, meridional flow, convective blueshift, and gravitational redshift (see Schuck et al. 2016; Castellanos Durán et al. 2021, for details). The LSCs are also removed from the SDO/HMI Dopplergrams. More information on the equations used for the LSCs are given in Appendix A. The final result consists of 240 SO/PHI-HRT Dopplergrams of 440×440 pixels remapped onto the SDO/HMI detector frame. We refer to this time series from now on as remapped SO/PHI-HRT. The cadence of this time series is still 60 s, but the SDO/HMI time series has an irregular cadence in order to always consider the closest dataset in time taking into consideration the difference in light travel time. Basically, since we consider the 45 s nominal SDO/HMI cadence, we excluded one of every four datasets. As a consequence, the time difference between the SO/PHI-HRT and SDO/HMI Dopplergrams repetitively cycle between approximately 20, 5, and 10 s.

4. Results

Different types of comparisons are reported in this section. Taking advantage of the subpixel accuracy in the alignment of the time series, we studied the differences between velocities measured by the two instruments in space, time, and in the Fourier space on a pixel-by-pixel basis. Such studies are possible only with an accurate alignment of the data, as described in Sect. 3, which is crucial in order to reveal both global and localized discrepancies in the data.

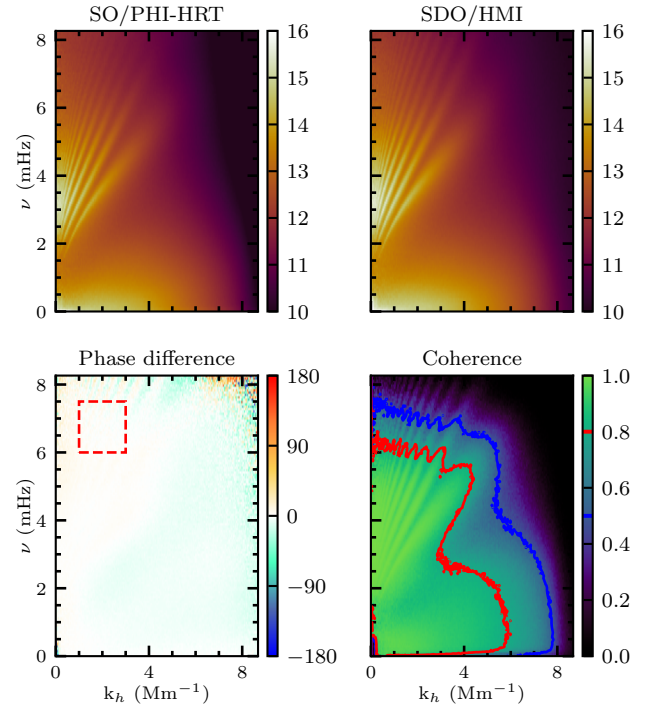


Fig. 2. k - ω diagrams. Top left panel: Power spectrum of the remapped SO/PHI-HRT time series (units: m^2/s^2). Top right panel: Power spectrum of the SDO/HMI time series interpolated to 60 s cadence (units: m^2/s^2). Bottom left panel: Phase difference between SO/PHI-HRT and SDO/HMI (units: degrees). The red dashed box shows the area used to compute the height difference between the two signals. Bottom right panel: Coherence spectrum between the two signals. The blue and red contours show the 50% and 80% coherence, respectively.

A mask excluding 50 pixels at the edges of the FoV is applied to avoid missing SO/PHI-HRT data caused by the alignment and remapping of the time series. In addition, we examine the sunspot penumbra region in more detail.

4.1. Fourier space

The comparison between two time series in the Fourier space can be addressed by means of the k - ω diagrams (see Jafarzadeh et al. 2025 for a description of this method). The best accuracy is attained by using two time series with the same spatial resolution, cadence, and size. The SDO/HMI time series constructed for our study has an irregular cadence, which had to be corrected for this analysis (see Section 3). To do that, we reduced the full 45 s cadence SDO/HMI observation to the 60 s SO/PHI-HRT cadence by removing the highest frequencies in Fourier space, keeping the same starting and ending time of the original series, which means that there is still a (constant) time difference of 20.5 s with respect to the SO/PHI-HRT time series. This resampled time series was not used for the pixel-by-pixel comparison to avoid any spurious result that might have been generated by this procedure.

The power spectra of the remapped SO/PHI-HRT and SDO/HMI time series and their phase difference and coherence spectrum are shown in Fig. 2. The phase difference was corrected for the time difference between the two time series. The coherence spectrum shows the linear relation between two signals and it is not affected by their amplitude (Vigesh et al. 2017). The

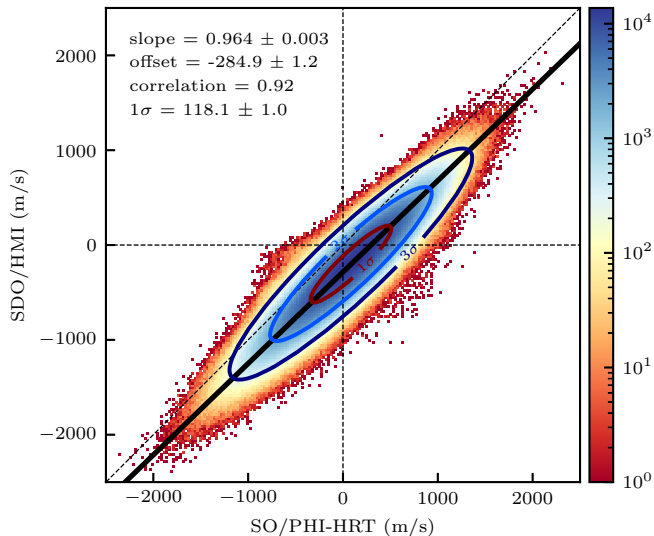


Fig. 3. Scatter plot distribution of the velocity field values as measured by the remapped SO/PHI-HRT (x -axis) and SDO/HMI (y -axis). The color scale shows the number of points in each bin on a logarithmic scale. The black line shows an orthogonal least-squares linear fit to the data points, while the contours depict the results of a 2D Gaussian distribution fit. The slope and offset obtained by the linear fit, the Pearson correlation coefficient, and the 1σ spread of the Gaussian fit are indicated in the top left corner of the figure. The uncertainties represent one standard deviation estimated using the bootstrap method with 500 subsamples.

first thing to note is the similarity between the power spectra of the two instruments, which is made more evident by the diagrams showing the phase difference and the coherence between the two time series. The phase difference remains consistently close to 0° across most of the domain, while the coherence spectrum shows very high values (above 80%) along the p-modes and f-mode ridges and in the internal gravity waves and granulation regime. The phase difference diagrams can be used to estimate the average height difference between the two signals (see equations (2) and (3) in Vesa et al. 2023). We selected the area of the diagram where the waves have real vertical wave numbers, which means that they propagate and they are not evanescent (as when the vertical wave number is imaginary). We can then restrict our choice only to vertically propagating waves by considering only small horizontal wave numbers (see the red dashed box in the bottom right panel in Fig. 2). We assume the cut-off frequency, buoyancy frequency, and sound speed to be equal to 5.4 mHz, 4.9 mHz, and 7 km/s, respectively. We find that the SO/PHI-HRT signal forms approximately 9 km above SDO/HMI, with a broad distribution between -10 and 30 km. Previous result by Schou et al. (2023) suggested a formation height of ~ 156 km for SDO/HMI and ~ 158 km above the solar surface for SO/PHI obtained with the help of a MURaM simulation. This result was obtained by retrieving the velocity through the MDI-like algorithm also for SO/PHI, so we would expect the signals to be closer than those addressed in that work.

4.2. Distributions

As a second assessment of the similarity of the SDO/HMI and SO/PHI-HRT Dopplergrams, a scatter plot of the remapped SO/PHI-HRT and the non-interpolated SDO/HMI time series is shown in Fig. 3. Only the datasets with time difference of 5 s

were selected for plotting in this figure because the width of the distribution is affected by the time discrepancy. The colors correspond to the number of points inside a specific bin in logarithmic scale. Two functions have been fit to this distribution: a linear function and a 2D Gaussian distribution. The linear fit shows a clear correspondence between the data, with a slope of 0.964 ± 0.003 , a correlation coefficient of 92%, and an offset of -284.9 ± 1.2 m/s. The Gaussian distribution indicates the spread between the two signals, which is 118.1 ± 1.0 m/s at 1σ . The uncertainties are estimated with the bootstrap method by repeating the fitting on 500 random subsamples. The bootstrap was performed by randomly partitioning the data into individual subsets (i.e., sampling without replacement). Consequently, every data point appears in only one of the subsamples, and their union is the full original set of values. We also determined the mean of the distribution, which provides information on the offset of the zero point between both time series. The average of the distribution for SDO/HMI is at -224 m/s, whereas the SO/PHI-HRT mean value is at 64 m/s. Discussing the absolute calibration of these instruments is a challenge that goes beyond the scope of this work, but it is a point that needs to be mentioned. In the SDO/HMI case, the reference velocity can be set in many ways available in the literature (e.g., Mathew et al. 2003; Grigor'ev et al. 2011; Okamoto et al. 2009; de la Cruz Rodríguez et al. 2011; Welsch et al. 2013), including simply setting the mean signal at the center of the Sun to zero (after the removal of all the LSCs). The same approach is not always possible for SO/PHI-HRT, due to its smaller FoV and the fact that it often points such that the solar disk center does not lie in its FoV.

To investigate the presence of any temporal dependence, we repeated the analysis described above for each of the 240 frames separately. Figure 4 shows a selection of fit parameters as a function of time. The uncertainties were estimated with the bootstrap method by repeating the fitting on 80 random subsamples. The top panel displays the results of the linear fit on each of the 240 observation pairs of frames. The blue points show the slope and the orange points the offset obtained by the linear fit. We can clearly distinguish a linear trend through the 4 hours of observation in which both values evolve toward a value closer to 1. The middle panel depicts the coordinates of the average of the Gaussian distribution. The left axis (in green, x coordinates of the center of the distribution) corresponds to the mean values of each dataset of the remapped SO/PHI-HRT; the right coordinates (in red, y coordinates of the center of the distribution) correspond to SDO/HMI. The range of the two y -axes is the same for both coordinates, meaning that the relative variation with time of both values is directly comparable. In this case, the SDO/HMI values do not show any significant variation with time, while the remapped SO/PHI-HRT values go from 70 to 55 m/s. The bottom panel shows the root mean square (rms) of the remapped SO/PHI-HRT (purple) and SDO/HMI (brown) time series, which is used to quantify the amplitudes measured by the instruments. The two axes in this case are exactly the same for both distributions. The remapped SO/PHI-HRT rms is overall higher than SDO/HMI, as expected, because the slope of the linear fit shown in Fig. 3 is smaller than one. On the other hand, we see a decrease in the rms in SO/PHI-HRT of ~ 5 m/s and an increase in SDO/HMI of ~ 10 m/s, which is also consistent with the increase in the slope in time.

In a further step we look at the spatial variation of the results of the linear fit. For that, the FoV was divided into square regions of 8×8 pixels and we performed a linear fit in each of these regions through the whole time series. We also computed the

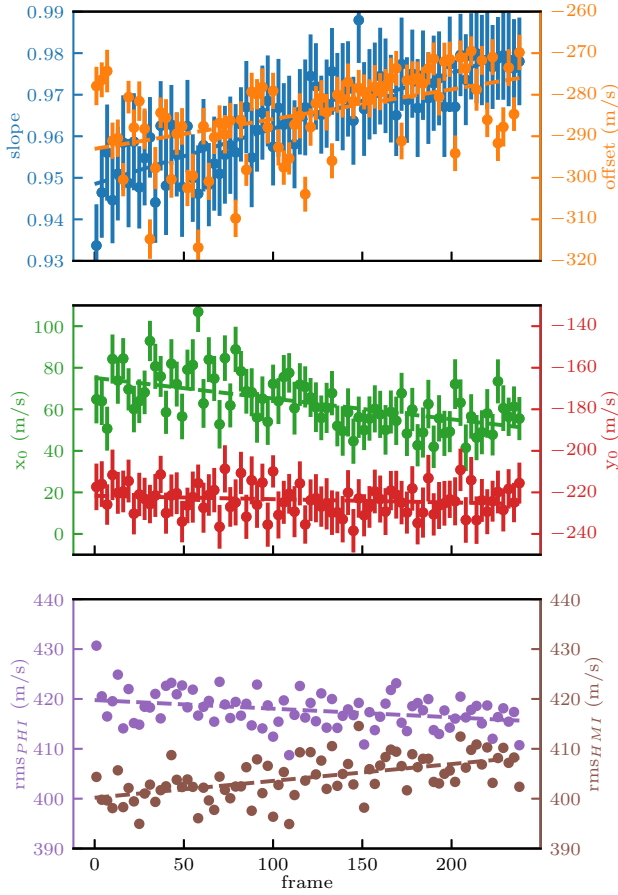


Fig. 4. Temporal variation of the fitting results. The dots represent the results of the fits obtained frame by frame, whereas the dashed lines show the linear trends of these results. The error bars represent one standard deviation estimated using the bootstrap method with 80 subsamples used for the fitting. Top panel: Slope (left axis, blue) and offset (right axis, orange) obtained by the linear fit. Middle panel: x_0 (left axis, green) and y_0 (right axis, red) coordinates of the mean of the 2D Gaussian distribution. Bottom panel: Root mean square (rms) of the remapped SO/PHI-HRT (left axis, purple) and of the SDO/HMI (right axis, brown) time series.

averaged correlation between the two time series in each subregion. The results are shown in Fig. 5. The top panel shows the spatial-distribution of the correlation, which is overall very high with a mean value of 93%. Lower values are found especially within the sunspot umbra, where the correlation drops to 70-80%. Many factors lead to this low correlation including the low intensity signal, the large line splitting due to the strong magnetic field that can become as large as the total wavelength range in the line that is scanned, the low velocity in the umbra, the few measured wavelength points within the line (which are different for SDO/HMI and SO/PHI), and different algorithms to retrieve the velocity signal, all contribute to the low correlations between the two instruments within the umbrae (see Sect. 5).

The middle and bottom panels show the spatial distribution of the slope and offset of the linear fit. Here a spatial distribution is quite evident, particularly in the case of the offset. The FoV dependence is likely due to calibration residuals, such as an imperfect treatment of the prefilter, etalon cavity correction, or flat correction in SO/PHI-HRT. The spatial variation does not show any correlation with any of the LSCs of either instruments and the amplitude of the signal also does not match with any of

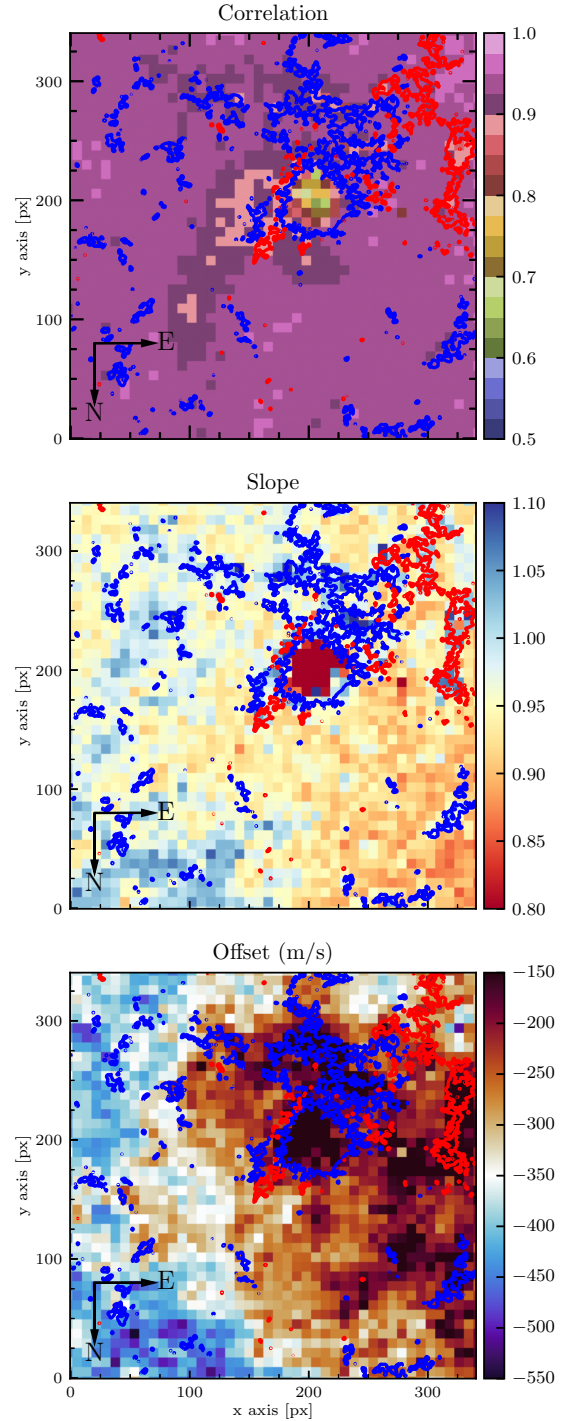


Fig. 5. Spatial dependence of the temporal correlation between the remapped SO/PHI-HRT and SDO/HMI signals (top panel), and of the slope (middle panel) and offset (bottom panel) obtained by the linear fit. The blue and red contours show the -200 and $+200$ G values of the SO/PHI-HRT LoS magnetic field, respectively. The FoV is shown as a yellow box in Fig. 1. The black arrows in each panel indicate the north (N) and east (E) solar limb as in Fig. 1.

the known effects that we compensate for. We note that in the middle panel of Fig. 5 low values of the slope are seen in large parts of the sunspot including parts of the penumbra. This is an artifact of the averaging onto larger pixels, which mixes the low (and uncertain) slope values found in the umbra with the high values in the penumbra (see Sect. 4.3).

4.3. Sunspot penumbra

In this section the penumbra of the sunspot is analyzed in more detail. The penumbra is defined as those pixels with intensity higher than 55% and lower than 89% of the averaged intensity continuum in a nearby quiet Sun area. A reproduction of the scatter plot between the remapped SO/PHI-HRT and the SDO/HMI time series, focusing exclusively on the penumbra and on its Evershed flow (Evershed 1909) is visible in Fig. 6. The contours defining the penumbra boundaries are also visible in the inset. The uncertainties are estimated with the bootstrap method by repeating the fitting on 100 random subsamples. It is evident that the scatter of the points is smaller than in Fig. 3, which can be explained by the smaller FoV considered here (and thus smaller spatial variation) and is well represented by the higher correlation coefficient (95%) with respect to that of the full FoV. The slope obtained by the linear fit (0.928 ± 0.006) is slightly smaller than the one obtained for the whole FoV. Additionally, the offset between the two signals is smaller than that found in Fig. 3. This is expected from the position of the sunspot in the bottom panel of Fig. 5, where it lies in an area where the offset is smaller than the average (as obtained by the linear fit shown in Fig. 3).

After assessing that the velocities measured in the penumbra are comparable to those in the rest of the FoV, the comparison of the spatial dependence of the Evershed flow recorded by the two instruments can be addressed. Therefore, an elliptical polar grid is defined to encompass the whole penumbra and its Evershed flow, which extends slightly beyond the outer edge of the penumbra. The grid is shown as gray lines in the left panel of Fig. 7. The solid gray ellipses show the starting and ending point of the radial distance. The azimuth angle axis is defined starting from the straight solid line in the counterclockwise direction with a 5° step size.

The middle panel of Fig. 7 displays the velocity on the elliptical polar grid. We note that the velocities plotted in this panel are temporal averages over the full 240 frames recorded by the SO/PHI-HRT. The two branches of the Evershed flow are clearly visible in the left and right parts of the plot, which consists of the limb (outlined by the red box) and disk center (blue box) oriented sides of the penumbra, respectively. In order to compare the values obtained by the two instruments, we performed an azimuthal average (along the x -axis) in the red and blue boxes for each time series. The results are shown in the right panel of Fig. 7, where the x -axis represents the radial distance on the elliptical polar grid. The colors are the same as in the middle panel. The crosses show the result obtained with the remapped SO/PHI-HRT and the circles those from SDO/HMI. The curves resulting from the data of the two instruments lie very close to each other until the penumbra–quiet Sun boundary (which lies roughly at a distance of 15 px along the x -axis). An offset, comparable to that shown in Fig. 6, is visible around the peaks of the velocity signals. The asymmetry between the two sides of the penumbra (limb- and disk center-side; e.g., Schlichenmaier et al. 2004) is to be expected. A difference in the flows can also be caused by the asymmetric shape of the sunspot.

5. Discussion

We reported a comparison of the LoS velocity measured by SO/PHI-HRT and SDO/HMI while Solar Orbiter was in inferior conjunction. The data acquired by SO/PHI-HRT were post-processed and remapped onto the SDO/HMI detector frame to allow a pixel-by-pixel comparison. Despite differences in instrumentation, calibration, cadence, and velocity retrieval methods,

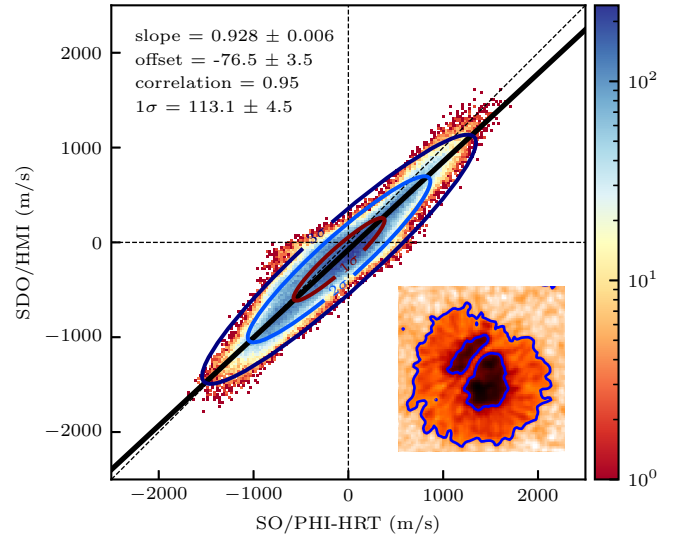


Fig. 6. Scatter plot distribution of the velocity field values as measured by the remapped SO/PHI-HRT (x -axis) and SDO/HMI (y -axis) in the sunspot penumbra. The colors and lines are defined as in Fig. 3. The uncertainties represent one standard deviation estimated using the bootstrap method with 100 subsamples. The image in the lower right quadrant shows a snapshot of the sunspot observed by SDO/HMI oriented as in Fig. 1, and the blue contours define the penumbra boundaries.

the comparison shows an excellent agreement of the LoS velocity signals obtained with these two telescopes. We measured a height difference of 9 ± 12 km between the two time series and obtained a slope of 0.94 for the linear fit of the scatter plot between the two instruments and a correlation coefficient of above 90%. The measured height difference is larger than the result obtained from a MURaM simulation by Schou et al. (2023) and it is possible to estimate the velocity variation due to such a separation. If we consider the conservation of mass from one layer to the other, it holds that

$$\rho_{\text{HMI}} v_{\text{HMI}} = \rho_{\text{PHI}} v_{\text{PHI}}, \quad (1)$$

where ρ is the density at each layer and v is the vertical velocity. A ratio $v_{\text{HMI}}/v_{\text{PHI}}$ of 0.952 for 9 km height separation is obtained by considering the atmospheric densities from the VAL-C model (Vernazza et al. 1981), whereas 6.5 km of separation would be necessary to obtain a ratio of 0.964. Considering the broad distribution of the height separation between the two instruments, it is not possible to address it as the unique cause for having a ratio lower than 1. One more reason is to be found in the bottom panel of Fig. 4, which shows that the rms of the remapped SO/PHI-HRT is always higher than that of SDO/HMI. This is due to the spatial deconvolution of the SO/PHI-HRT PSF including the stray light component during the data reduction, a correction that is not included in the SDO/HMI pipeline, but it can be made available on request. We compare these data with the velocities from SDO/HMI without stray light removed, as we want to compare the standard data products, which are the most likely to be used for studies comparing or combining velocities from the two instruments. One more element that could also contribute is the different sampling of the spectral line. SO/PHI-HRT samples the line in five points with a spectral resolution of 58 000, SDO/HMI in six points with a spectral resolution of 81 000. Stief et al. (2019) showed that the velocity retrieved with different sampling and at different points along the line can substantially affect the measurement. However, a lower spectral resolution reduces the variation in the retrieved velocity near the core of the line (see the

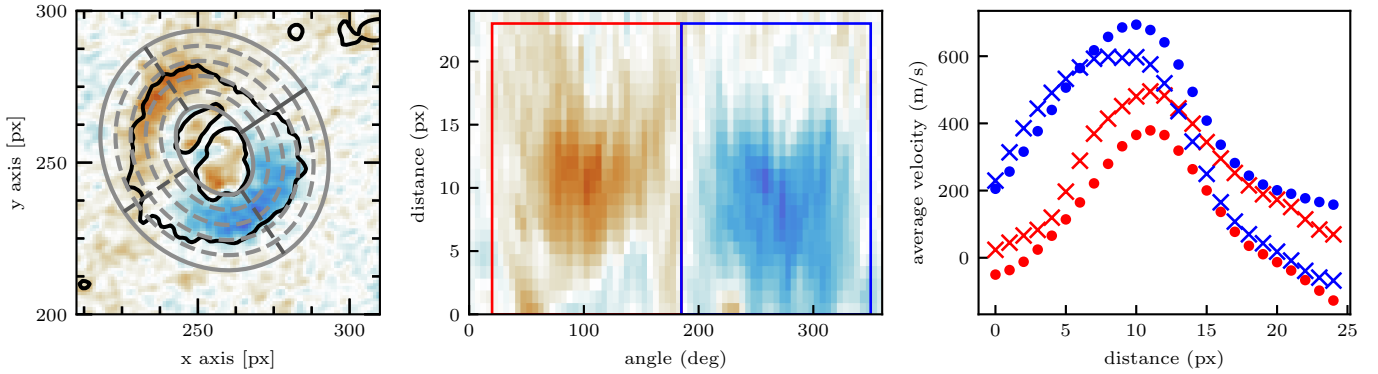


Fig. 7. Left panel: Remapped SO/PHI-HRT LoS velocity signal around the sunspot averaged in time (oriented as in Fig. 1). The black contours are at 55% and 89% of the average continuum intensity. The gray lines show the grid used for the elliptical polar projection of the penumbra. The solid gray ellipses are the starting and ending points of the radial distance axis; the solid straight gray line shows the starting point of the azimuth angle axis (measured counterclockwise). Middle panel: Same signal as shown in the left panel, but represented on the elliptical polar grid displayed in the left panel. The x -axis shows the azimuth; the y -axis shows the radial distance (in pixel) from the innermost ellipse. Right panel: Azimuthal average of the signal within the blue and red boxes of the middle panel. The crosses show the remapped SO/PHI-HRT signal, whereas the points are the SDO/HMI signal. The colors correspond to the boxes shown in the middle panel. The values displayed in blue are multiplied by -1 for easier comparison.

yellow curve in Fig. 5 in Stief et al. 2019 for the SDO/HMI case), meaning that we do not expect this to be the main component of the difference between the two instruments.

The temporal variation of the linear and Gaussian fitting results (presented in Fig. 4) is mostly due to two factors: a variation of ~ 10 m/s in the average distribution of the SO/PHI-HRT velocity field (middle panel) and the opposite variation of the rms of the two instruments (bottom panel). The variation of the average value in SO/PHI-HRT can be caused by the intrinsic sensitivity of the instrument, due to the voltage applied to the etalon, which translates into ~ 17 m/s, and due to the thermal stabilization, which converts into ~ 19 m/s. While the rms increase in SDO/HMI is consistent with the findings of Oba et al. (2020), the slow decrease in SO/PHI-HRT is likely due to the optical quality of the data through the four-hour observation. In particular, a major component can be attributed to the focus of the instrument, which changes with time because of the fast approach of the spacecraft to the Sun and the associated thermal drifts. A possible indication is the presence of the same decrease in the unreconstructed SO/PHI-HRT LoS velocity data and in the intensity contrast in the raw data. These different trends in the two instruments' rms values are responsible for the variation over time of the slope obtained with the linear fit. The increase in the slope up to values close to 1 (and not the opposite behavior) is mostly dependent on the SO/PHI-HRT decrease in rms. It is also important to note that the values of the slope are comparable to those of the ratio of the SDO/HMI to SO/PHI-HRT rms. This can indicate a possible strategy for directly combining the velocities measured by these two instruments when observing from different vantage points.

The spatial correlation and dependence of the linear fitting results are shown in Fig. 5. The correlation map shows very high values through the whole FoV with an average of 93%, with the exception of the sunspot umbra, where the measured LoS velocities are generally lower than in the penumbra or quiet sun. This can be expected by the different algorithms used to retrieve the LoS velocity. SDO/HMI uses the MDI-like method for its LoS observable, whereas in SO/PHI-HRT the LoS velocity field is a result of the RTE inversion. Different algorithms can also retrieve the physical quantities at slightly different heights depending on their response functions. Such a possibility was

not considered in Schou et al. (2023) because the MDI-like algorithm was used for both instruments. The use of different algorithms in the SO/PHI-HRT and SDO/HMI pipelines for the retrieval of the velocities is possibly a further reason for the disagreement between the signals measured by these two instruments.

The slope and offset obtained through the linear fit clearly show a dependence on the FoV. The offset variation is particularly strong in the left to right direction in the SDO/HMI detector frame system. The only physical reason for such a gradient would come from the LSCs, which had already been removed, but perhaps not entirely successfully. More advanced algorithms, such as that presented in Schuck et al. (2016), can be used to improve the LSC correction, but in this work we applied the standard procedure based on well-established models. Another possibility is an instrumental origin of such a variation, which we investigated; however, we could not identify any clear cause due to instrumental properties of SO/PHI-HRT. Several tests using different calibration data have been tried and no significant difference has been observed, such as improved flat fields or different prefilter models. In both instruments, several optical components along the respective optical paths show a FoV variation that needs to be fully and carefully characterized to remove any possible gradients in the two datasets. There is also no clear correlation with any of the LSCs removed from the SO/PHI-HRT data that could cause such a signal, even if the models used for the LSCs can leave residuals in the data (Schuck et al. 2016). Additionally, the amplitude of the variation is much higher than those of the LSCs. It is also worth noting that the convective blueshift signal is highly sensitive to the spatial resolution of the instrument itself, which means that we expect a difference between SO/PHI-HRT and SDO/HMI, but this is not included in this work (see Appendix A). The spatial variation can be treated more easily if the considered FoV is small and the removal of the offset and trends can be addressed with various methods (e.g., Martínez Pillet et al. 1997; Grigor'ev et al. 2011; Welsch et al. 2013), depending on the goal of the study. Such a scenario is clear also in the comparison of the penumbra in Fig. 6. The spread of the distribution is substantially narrower also because of the smaller spread across the FoV and the value of the offset is also considerably closer to 0. On the contrary, the slope is similar to that for the full FoV, indicating the robustness of the

comparison and the weaker dependence on the FoV with respect to other quantities.

As a last result, the Evershed flow within the sunspot penumbra is compared in Fig. 7. The velocity signal displayed on an elliptical polar grid is used to isolate the red- and blueshifted parts of the penumbra. The comparison between SDO/HMI and SO/PHI-HRT, displayed in the right panel of Fig. 7, shows very good agreement between the two instruments within the penumbra boundary, and a small divergence in the quiet Sun comparable to the offset obtained with the linear fit shown in Fig. 6. The difference measured right outside the penumbra does not change significantly along the rotation angle axis, showing a small dependence on such a small FoV. It should be noted that the velocities plotted in blue have to be flipped in sign before this invariance becomes clear. This is in agreement with the result displayed in the bottom panel of Fig. 5, meaning that this difference is due to the general offset between the two instruments. Stated differently, the penumbra itself shows higher velocity and smaller difference with respect to the quiet Sun, which could be due to how MILOS and the MDI-like algorithm retrieve the velocity in different physical conditions. The smaller difference in the penumbra than in the quiet Sun can also explain the smaller spread in Fig. 6 compared to Fig. 3.

6. Conclusion

In summary, the agreement between the LoS velocity data products of SO/PHI-HRT and SDO/HMI has been shown using a variety of analysis methods, providing quantitative supports for applications that combine the data from the two instruments, from tracking of active regions to stereoscopic studies. However, both instruments have calibration residuals that have to be treated with caution. There is not one univocal method for removing the offsets between the instruments without an actual absolute calibration. On the other hand, the difference in the rms can be accounted for considering the dependence on the μ angle (as shown in Oba et al. 2020). Such a procedure can only be applied once the spatial resolution of the two instruments is comparable, as in this work, otherwise a higher spatial resolution will end in a higher velocity contrast (Jess et al. 2023). With such precautions, the data can also be combined pixel-by-pixel to measure 2D flows on the solar surface from different vantage points. The excellent agreement between the instruments, as shown by the high correlation and by the slope consistently close to 1 as obtained by the linear fit on the scatter plot, will then allow the exploitation of the velocity datasets from SO/PHI-HRT and SDO/HMI in multiview configuration.

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Appendix A: Large-scale velocity components

The treatment of the large-scale velocity components (LSCs) in the solar photosphere and their contribution to the LoS velocity field has been extensively treated in many papers (e.g., Schuck et al. 2016; Castellanos Durán et al. 2021). Information about the solar coordinate system can be found in Thompson (2006). Here, for completeness, we summarize the equations used in our analysis. The solar differential rotation is treated according to Hathaway & Rightmire (2011):

$$v_{rot}(\lambda) = (a + b \sin^2 \lambda + c \sin^4 \lambda) \cos \lambda. \quad (\text{A.1})$$

Here λ is the solar latitude in heliographic coordinates and

$$\begin{aligned} a &= 14.437^\circ / \text{day}, \\ b &= -1.48^\circ / \text{day}, \\ c &= -2.99^\circ / \text{day}. \end{aligned} \quad (\text{A.2})$$

The projection along the LoS is given by Schuck et al. (2016)

$$v_{rot}(\lambda) \cdot \hat{\eta}_{LoS} = v_{rot}(\lambda) \left[-\cos B_0 \sin \phi \cos \theta_\rho + (\cos \phi \sin \psi - \sin B_0 \sin \phi \cos \psi) \sin \theta_\rho \right], \quad (\text{A.3})$$

where $\hat{\eta}_{LoS}$ is the LoS vector in helioprojective coordinates, B_0 is the latitude of the center of the solar disk as seen by the observer (solar-B angle), ϕ is the solar longitude in heliographic coordinates (with 0° corresponding to the observer central meridian), θ_ρ is the helioprojective angle, and ψ is the position angle in heliocentric-radial coordinates.

The LoS contribution of the residual spacecraft velocity component is

$$v_{S/C}(\theta_\rho, \psi) = V_W \sin \theta_\rho \sin \psi - V_N \sin \theta_\rho \cos \psi + V_R \cos \theta_\rho, \quad (\text{A.4})$$

where (V_R, V_W, V_N) are the radial, westward, and northward components of the spacecraft velocity, respectively. In the SO/PHI-HRT case, most of the contribution comes from the westward and northward velocities because the etalon can be tuned to compensate for the radial component of the spacecraft velocity. Hence, we also subtract a constant value equal to

$$v_c(\lambda_c) = \frac{\lambda_c - \lambda_0}{\lambda_0} c, \quad (\text{A.5})$$

where λ_c is the SO/PHI-HRT sampled wavelength corresponding to the core of the Fe I line, λ_0 is the rest wavelength, and c is the speed of light.

The meridional flow is also treated according to Hathaway & Rightmire (2011),

$$v_M(\lambda) = (d \sin \lambda + e \sin^3 \lambda) \cos \lambda, \quad (\text{A.6})$$

with

$$d = 29.7 \text{ m/s}; e = -17.7 \text{ m/s}. \quad (\text{A.7})$$

The projection along the line of sight is equivalent to Equation A.4.

The variation from center to limb of the convective blueshift signal is adopted from Castellanos Durán et al. (2021). Despite the dependence of this effect on the spectral resolution (see Stief et al. 2019; Löhner-Böttcher et al. 2019), we are not able to fit the center to limb profile of this effect because SO/PHI-HRT is not a full-disk imager and we do not have continuous observations of the Sun (e.g., as in Löhner-Böttcher & Schlichenmaier

2013). This term is then modeled by Castellanos Durán et al. (2021) as

$$v_{BS}(\mu) = 134 - 1179\mu - 2029\mu^2 + 9112\mu^3 - 10409\mu^4 + 4096\mu^5 \text{ m/s}, \quad (\text{A.8})$$

where $\mu = \cos \theta_\rho$ is the cosine of the helioprojective angle.

The last term is the gravitational redshift. This is a relativistic effect depending on the mass (M_\odot) and radius (R_\odot) of the Sun and on the distance (D) between the observer and the Sun,

$$v_{GRS}(D) = \frac{GM_\odot}{c} \left(\frac{1}{R_\odot} - \frac{1}{D} \right), \quad (\text{A.9})$$

where G is the gravitational constant. The values obtained for the two instruments are 628.8 m/s and 633.3 m/s for SO/PHI-HRT and SDO/HMI, respectively.

Figure A.1 shows all the components for SO/PHI-HRT except for the gravitational redshift which is constant.

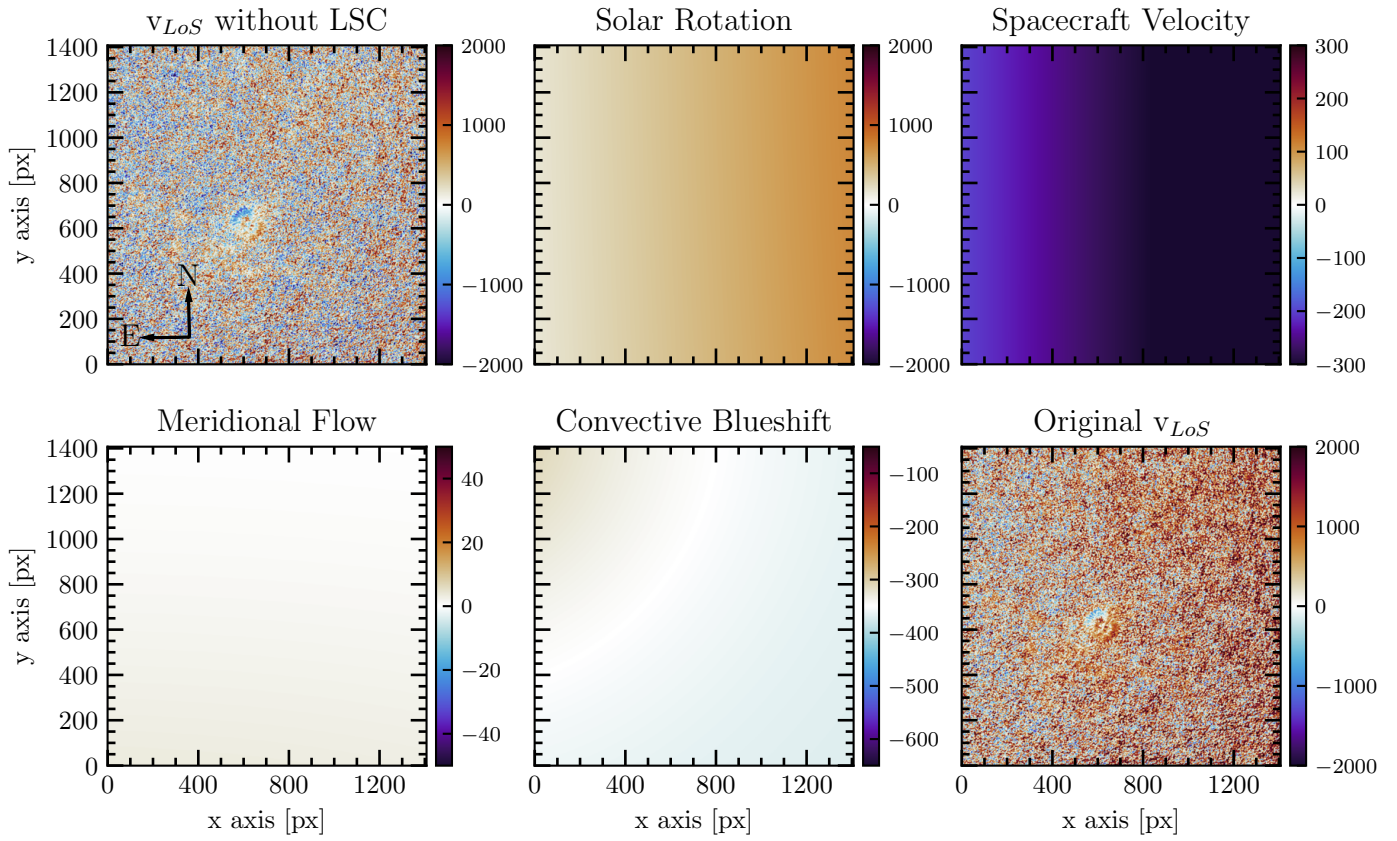


Fig. A.1. Top left panel: SO/PHI-HRT Dopplergram after the removal of the LSCs. The black arrows indicate the north (N) and east (E) solar limb, as in the SO/PHI-HRT detector frame. Top middle panel: Differential solar rotation contribution. Top right panel: Spacecraft velocity residuals. Bottom left panel: Meridional flow contribution. Bottom middle panel: Convective blueshift signal. Bottom right panel: Original SO/PHI-HRT Dopplergram. The units are in m/s in every plot.