

Multi-height probing of horizontal flows in solar photosphere using high-resolution spectropolarimetry

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Main points

- Can concurrent spectropolarimetric imaging in two magnetically sensitive optical spectral lines **that probe two different layers of the solar atmosphere** help constrain the depth variation of horizontal flows?
- Optical flow methods aim to infer horizontal velocities in the solar atmosphere from the temporal changes of the maps of the intensity or the magnetic field in the low/mid photosphere.
- The motivation for using spectral lines lies in their sensitivity to different depths in the solar atmosphere.
- The monochromatic absorption coefficient of the solar plasma increases rapidly with wavelength toward the line center → different formation heights for radiation observed at the continuum and line wavelengths.

Data

- 31 three-dimensional cubes containing the spatial variation of T , p , velocity vector $\mathbf{v}_0$ and the magnetic field vector $\mathbf{B}$ calculated using MURaM code.
- For the synthesis of SUNRISE/TuMag observations the emergent I was calculated at every pixel in the direction of the disk center for a range of wavelengths containing the lines Fe I 525.0 nm and Mg I b2 using SNAP1.

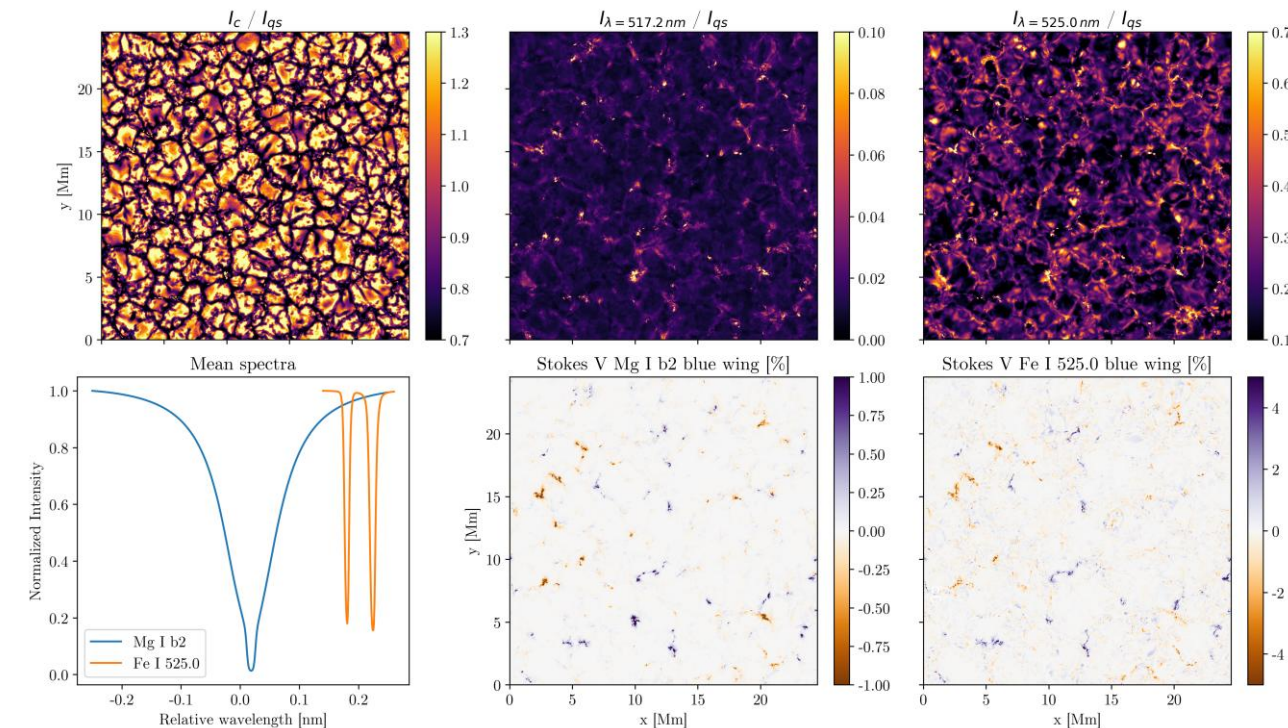


Figure 1. Synthetic observables calculated for the first snapshot in the series – continuum image at 517.2 nm, nominal line cores of the Mg I b2 line and Fe I 525.0 nm line, spatially averaged spectra of the considered spectral lines (Fe I lines are shifted for clarity), circular polarization in the wings of the Mg I line and Fe I line.

Methods

- The frequently used method for tracking features and estimating velocities is *Fourier Local Correlation Tracking* (FLCT). FLCT calculates the relative displacement vector in the xy plane between two images that makes the patterns of the two features best match each other.
- Relative displacement/time interval during which it occurred = velocity!** FLCT (FWHM = {300, 600} km, $dt = 30s$) applied to track T and B_z at different optical depths ($\log \tau_{500} = \{-1, -2, -3, -4\}$) in an atmosphere simulated using the MURaM code.
- Inferred the horizontal distribution of B_z from synthetic observations (inversions), applied FLCT to the time sequence of these magnetograms and compared with original $\mathbf{v}_0(\mathbf{h})$ velocities.

Results

- Tracking B_z yields horizontal velocities, $\mathbf{v}_p$, that, **after appropriate temporal and spatial averaging, excellently agree with the horizontal component of the simulated velocities**, both calculated at constant $\log \tau_{500}$ surfaces, up to the temperature minimum ($\log \tau_{500} = -3$). For T **this breaks down** at the $\log \tau_{500} = -2$.
- The agreement between divergence is significantly poorer than for the individual comparison of the v_x and v_y components. Additional Gaussian smoothing is necessary to improve correlation!

	FWHM[km]	$\log \tau_{500} = -1$		$\log \tau_{500} = -2$		$\log \tau_{500} = -3$		$\log \tau_{500} = -4$	
		r_{v_x}	r_{v_y}	r_{v_x}	r_{v_y}	r_{v_x}	r_{v_y}	r_{v_x}	r_{v_y}
T	600	0.72	0.73	0.38	0.41	-0.05	-0.06	0.03	0.04
	300	0.64	0.65	0.33	0.35	0.05	0.05	0.11	0.12
B_z	600	0.90	0.90	0.87	0.88	0.86	0.85	0.87	0.88
	300	0.91	0.91	0.90	0.90	0.86	0.85	0.85	0.86

Table 1. Pearson's correlation coefficients between simulation velocities and FLCT velocities recovered from temperature and B_z at $\log \tau_{500} = \{-1, -2, -3, -4\}$, respectively. Correlations are shown only for filtered simulation velocities. **Benchmark case based on MURaM simulations, for the reference.**

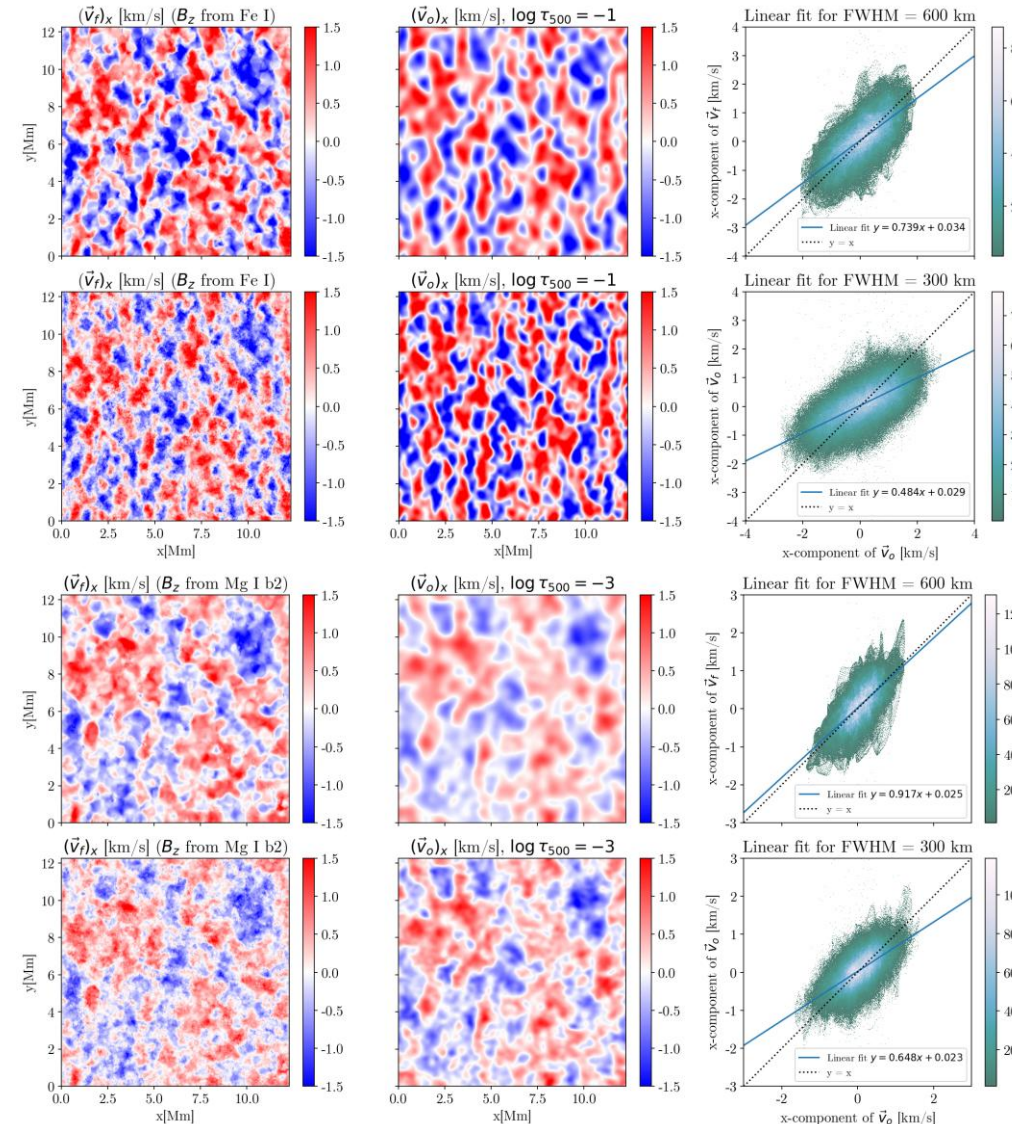


Figure 2. Comparison of the inferred and the original x -component velocity for FWHM = {300, 600} km using B_z from inversion of Fe I 525.0; bottom – B_z from inversion of Mg I b2. Left column represents FLCT velocity averaged over 15 minutes, middle column smoothed original velocity averaged over 15 minutes and right column linear fit between the two.

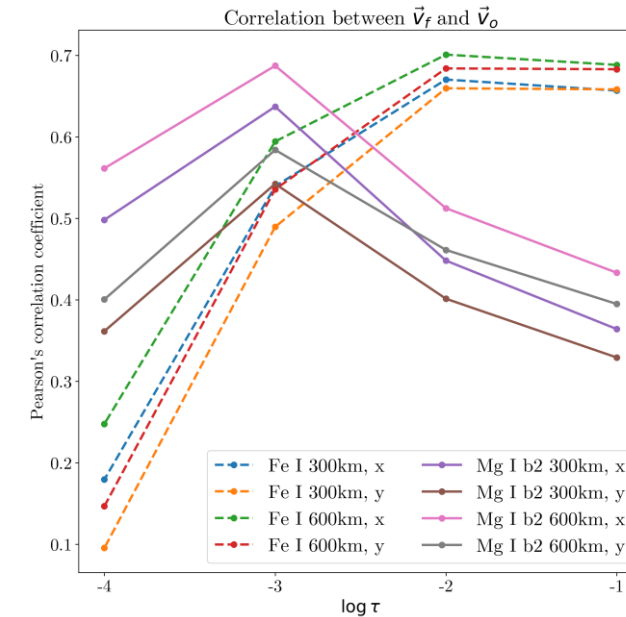


Figure 3. Pearson's correlation coefficient between FLCT-inferred velocities ($\mathbf{v}_p$) from synthetic line observations and original velocities ($\mathbf{v}_0$) at different $\log \tau_{500}$ -s.

Div.	FWHM[km]	$\log \tau_{500} = -1$	$\log \tau_{500} = -2$	$\log \tau_{500} = -3$	$\log \tau_{500} = -4$
Fe	600	0.62	0.62	0.51	-0.05
	300	0.64	0.65	0.48	-0.08
Mg	600	0.29	0.34	0.46	0.21
	300	0.27	0.33	0.47	0.20

Table 2. Pearson correlation coefficient for divergence of FLCT and simulated velocities. The FLCT velocities are recovered from B_z inferred either from Milne-Eddington inversion of Fe I 525.0 nm or from the WFA approximation using the Mg I b2 line and simulation velocities at $\log \tau_{500} = \{-1, -2, -3, -4\}$, after applying an additional Gaussian filter of $\sigma = 200$ km. Correlation is shown only for filtered simulation velocities.

Conclusions

- Our results indicate that high spatial resolution spectropolarimetric imaging in strong solar spectral lines can yield meaningful information on the horizontal plasma velocities over a range of atmospheric heights!
- This is extremely important in the advent of novel instruments for solar observations like SUNRISE III/TuMag, DKIST/VTF, SST/MiHI, and SST/HeSP.
- However, the FLCT technique performs significantly worse when calculating the horizontal divergence of the velocity, yielding correlation coefficients of 0.6 or less.

Future work

Application of physics-based method DAVE4VM, which solves the induction equation, and AI-based DeepVel, which can in principle infer horizontal velocities at multiple heights to spectral line data.

Acknowledgements

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