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Inversion of the two-point velocity correlations on the Sun's surface

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Helioseismology and Applications

Context

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$$v = v_0 + V$$

where v_0 is the deterministic mean part of the velocity and V the fluctuating (turbulent) part.

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- Supposing that the turbulent part is horizontally spatially homogeneous, the two-point velocity correlations can be written as

$$R_{ij}(\mathbf{d}, z_1, z_2) = \langle V_i(\mathbf{x}, z_1) V_j(\mathbf{x} + \mathbf{d}, z_2) \rangle.$$

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- Aim: recover R_{ij} from SDO/HMI observations.

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Inversion possibilities

$$\tau^{\boldsymbol{\Delta}}(\mathbf{x}) = \int_V \mathbf{K}^{\boldsymbol{\Delta}}(\mathbf{x}' - \mathbf{x}, z) \cdot v(\mathbf{x}', z) d^2\mathbf{x}' dz + \Lambda^{\boldsymbol{\Delta}\boldsymbol{\Delta}'}(\mathbf{x}')$$

$$\tau_1, ..., \tau_N \xrightarrow{\text{Standard inversion}} v_1, ..., v_N$$

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$\tau_1, \ldots, \tau_N$ —— Standard inversion ——> $v_1, \ldots, v_N$

$v_1, \ldots, v_N$ —— Covariance ——> R_{ij}

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Advantage: We know how to do it!

Drawback: Costly! Requires N inversions then averaging

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$v_1, \dots, v_N$ —— Covariance ——→ R_{ij}

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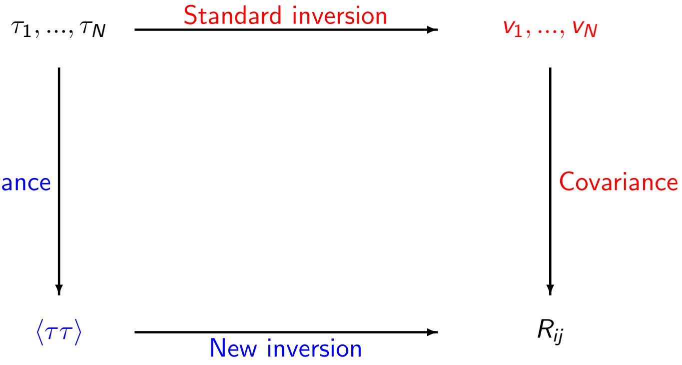

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Advantage: Only one inversion required. Should be fast! Improve the signal-to-noise ratio

Drawback: We need kernels, a noise model

$\tau_1, ..., \tau_N$ —Standard inversion→ $v_1, ..., v_N$

$\tau_1, ..., \tau_N$ —Covariance→ $\langle \tau\tau \rangle$

$v_1, ..., v_N$ —Covariance→ R_{ij}

$\langle \tau\tau \rangle$ —New inversion→ R_{ij}

Relation between products of travel times and two-points velocity correlations

- Relation between travel times and velocity

$$\tau^{\mathbf{\Delta}}(\mathbf{x}) = \int_V \mathbf{K}^{\mathbf{\Delta}}(\mathbf{x}' - \mathbf{x}, z) \cdot v(\mathbf{x}', z) d^2\mathbf{x}' dz + \Lambda^{\mathbf{\Delta}\mathbf{\Delta}'}(\mathbf{x}')$$

where $\Lambda^{\mathbf{\Delta}\mathbf{\Delta}'}(\mathbf{x}') = Cov[\tau^{\mathbf{\Delta}}(\mathbf{x}), \tau^{\mathbf{\Delta}'}(\mathbf{x} + \mathbf{x}')]$.

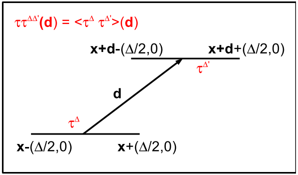
- Similarly, the two-point velocity correlations are linked to a product of travel times

$$\overbrace{\langle \tau^{\mathbf{\Delta}}(\mathbf{x}), \tau^{\mathbf{\Delta}'}(\mathbf{x} + \mathbf{d}) \rangle - \overbrace{\mathbf{\Lambda}^{\mathbf{\Delta}\mathbf{\Delta}'}(\mathbf{d})}^{\text{noise for } \tau}}^{\text{new observables } O^{\mathbf{\Delta}\mathbf{\Delta}'}} =$$

$$\int_{z'} \int_z \underbrace{K_i^{\mathbf{\Delta}}(\mathbf{x}; z) * K_j^{\mathbf{\Delta}'}(\mathbf{x} + \mathbf{d}; z')}_{\text{new kernels } K_{ij}^{\mathbf{\Delta}\mathbf{\Delta}'}} * R_{ij}(\mathbf{d}, z, z') dz dz' + \underbrace{\Gamma^{\mathbf{\Delta}\mathbf{\Delta}'\delta\delta'}(\mathbf{d}, \mathbf{d}')}_{\text{new noise for } \tau^{\mathbf{\Delta}}\tau^{\mathbf{\Delta}'}}$$

where
$\Gamma^{\mathbf{\Delta}\mathbf{\Delta}'\delta\delta'}(\mathbf{d}, \mathbf{d}') = Cov[\langle \tau^{\mathbf{\Delta}}(\mathbf{x}), \tau^{\mathbf{\Delta}'}(\mathbf{x}+\mathbf{d}) \rangle, \langle \tau^{\delta}(\mathbf{x}), \tau^{\delta'}(\mathbf{x}+\mathbf{d}') \rangle]$.

Observations



$$\tau\tau_{xx}(\mathbf{d}) = \frac{1}{V}\int_V \tau^{\mathbf{\Delta}}(\mathbf{x})\tau^{\mathbf{\Delta}'}(\mathbf{x}+\mathbf{d})d\mathbf{x}$$

$$\mathbf{\Lambda}_{xx}(\mathbf{d}) = \frac{1}{V}\int_V n^{\mathbf{\Delta}}(\mathbf{x})n^{\mathbf{\Delta}'}(\mathbf{x}+\mathbf{d})d\mathbf{x}$$

$$\mathbf{O}_{xx}(\mathbf{d}) = \tau\tau^{\mathbf{\Delta\Delta}'}(\mathbf{d}) - \mathbf{\Lambda}^{\mathbf{\Delta\Delta}'}(\mathbf{d})$$

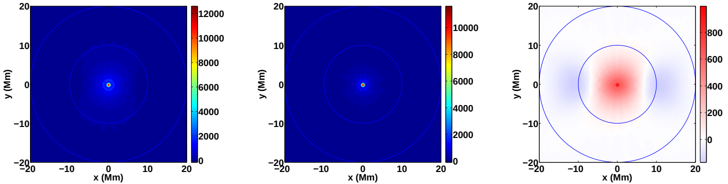


Figure: $\tau\tau_{xx}(\mathbf{d})$ (left), $\mathbf{\Lambda}_{xx}(\mathbf{d})$ (middle) and $\tau\tau_{xx}(\mathbf{d}) - \mathbf{\Lambda}_{xx}(\mathbf{d})$ (right) in s^2 in the real space as a function of $\mathbf{d}$ at a latitude of $+20°$. All units are s^2.

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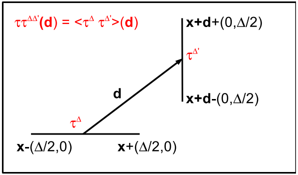

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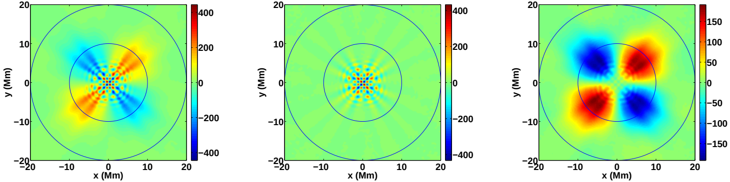

Figure: $\tau\tau_{xy}(\mathbf{d})$ (left), $\mathbf{\Lambda}_{xy}(\mathbf{d})$ (middle) and $\tau\tau_{xy}(\mathbf{d}) - \mathbf{\Lambda}_{xy}(\mathbf{d})$ (right) in s^2 in the real space as a function of $\mathbf{d}$ at a latitude of $+20°$. All units are s^2.

The forward problem

Observations	Kernels			
$\mathbf{O}_{xx}$	$\mathbf{K}_{xx}^{xx}$	$\mathbf{K}_{xx}^{xy}$	$\mathbf{K}_{xx}^{yy}$	$\mathbf{R}_{xx}$
$\mathbf{O}_{xy}$		$\mathbf{K}_{xy}^{xy}$	$\mathbf{K}_{xy}^{yy}$	$\mathbf{R}_{xy}$
$\mathbf{O}_{yy}$			$\mathbf{K}_{yy}^{yy}$	$\mathbf{R}_{yy}$

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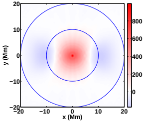
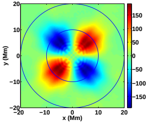
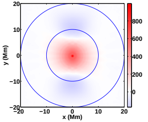
	$\mathbf{K}_{xx}^{xx}$	$\mathbf{K}_{xx}^{xy}$	$\mathbf{K}_{xx}^{yy}$	$\mathbf{R}_{xx}$
		$\mathbf{K}_{xy}^{xy}$	$\mathbf{K}_{xy}^{yy}$	$\mathbf{R}_{xy}$
			$\mathbf{K}_{yy}^{yy}$	$\mathbf{R}_{yy}$

The forward problem

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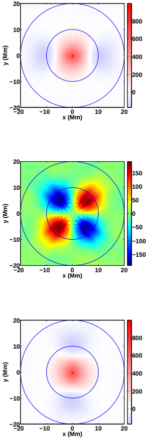
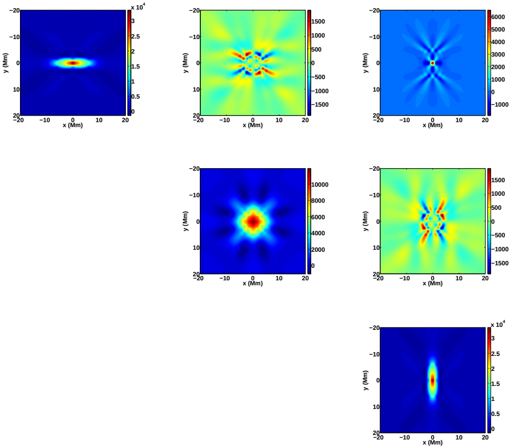
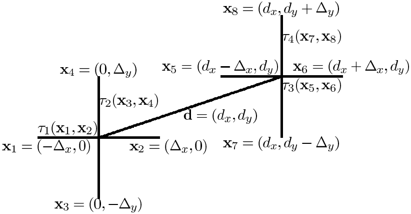
		$\mathbf{R}_{xx}$ $\mathbf{R}_{xy}$ $\mathbf{R}_{yy}$

Covariance matrix for products of travel times

A good approximation of the noise covariance matrix for products of travel times is given by [Fournier 2014]

$$\mathrm{Cov}[\tau_1\tau_2, \tau_3\tau_4] \approx \mathrm{Cov}[\tau_1, \tau_3]\mathrm{Cov}[\tau_2, \tau_4] + \mathrm{Cov}[\tau_1, \tau_4]\mathrm{Cov}[\tau_2, \tau_3].$$



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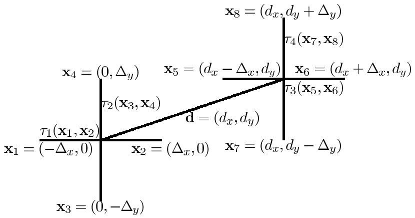

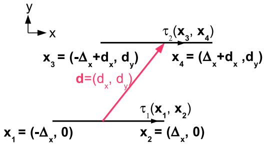

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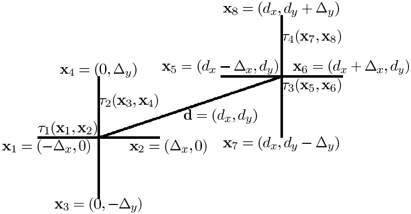

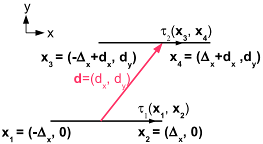

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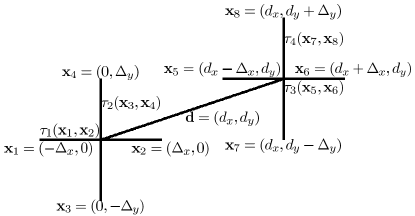

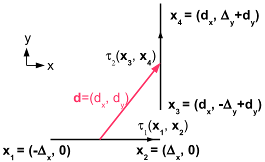

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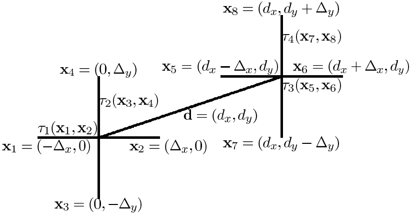
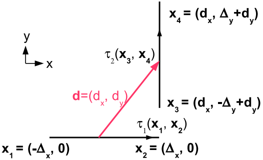
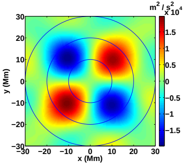




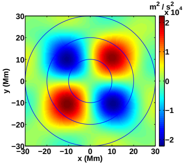
Inversion

$\mathbf{R}_{xy}$

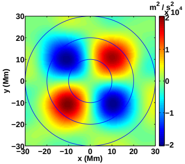
+20°



Equator



-20°



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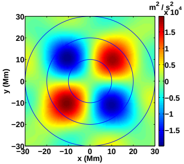

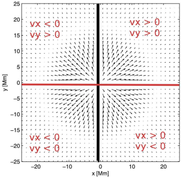

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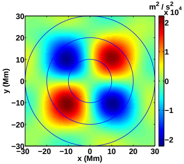

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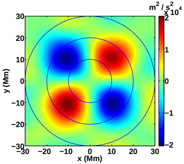

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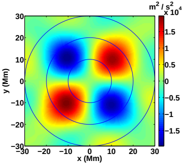
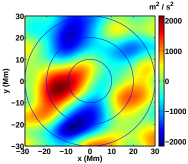
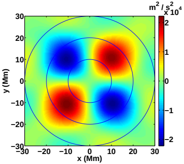
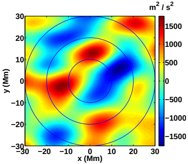
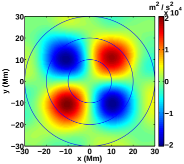
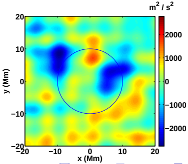
	$\mathbf{R}_{xy}$	non mirror antisymmetric part
$+20°$		
Equator		
-20°		

Additional averaging

- Without rotation $\mathbf{O}_{xy}$ should be mirror antisymmetric

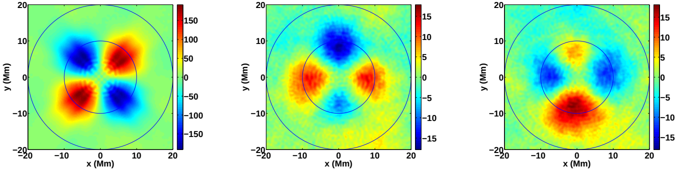


Figure: Observations $\mathbf{O}_{xy}(\mathbf{d})$ (left) and the non mirror antisymmetric part at a latitude of +20°(middle) and -20°(right).

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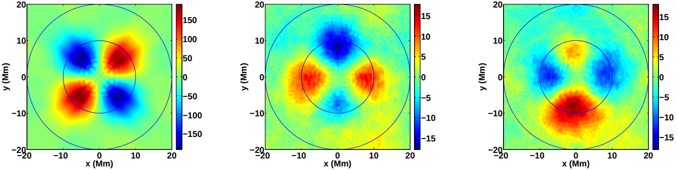

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- With rotation, following [Kitchatinov 1986]

$$\mathbf{O}_{xy}(\mathbf{k}) = \beta\left(\mathbf{O}_{yy}^{(0)}(\mathbf{k}) - \mathbf{O}_{xx}^{(0)}(\mathbf{k})\right) + \beta_{xy}\mathbf{O}_{xy}^{(0)}(\mathbf{k}) + \beta_{yx}\mathbf{O}_{yx}^{(0)}(\mathbf{k})$$

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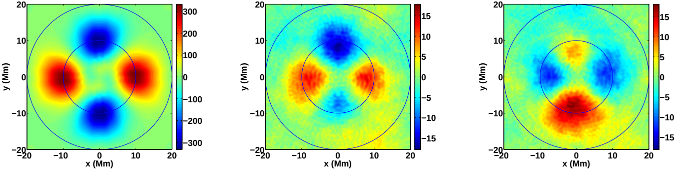

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  where $\mathbf{O}_{ij}^{(0)}(\mathbf{k})$ denotes $\mathbf{O}_{ij}(\mathbf{k})$ in the absence of rotation.
- As $\mathbf{O}_{xy}^{(0)}$ is mirror antisymmetric, we observed a quantity related to $\mathbf{O}_{yy}^{(0)} - \mathbf{O}_{xx}^{(0)}$ as plotted in the mixing length approximation [Rüdiger 2005].

Additional averaging

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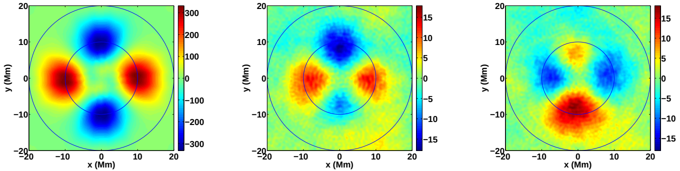

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- As $\mathbf{O}_{xy}^{(0)}$ is mirror antisymmetric, we observed a quantity related to $\mathbf{O}_{yy}^{(0)} - \mathbf{O}_{xx}^{(0)}$ as plotted in the mixing length approximation [Rüdiger 2005].
- The term β contains sin(latitude) which explains the change of sign between -20°and +20°.

Additional averaging

- Without rotation $\mathbf{O}_{xx}$ should be mirror symmetric

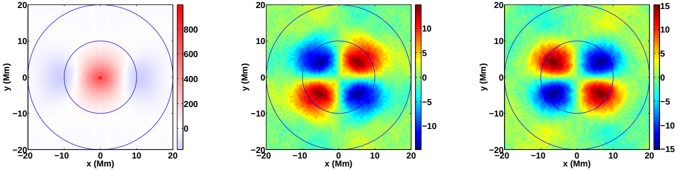

Figure: Observations $\mathbf{O}_{xx}(\mathbf{d})$ (left) and the non mirror symmetric part at a latitude of $+20°$(middle) and -20°(right). All units are s^2.

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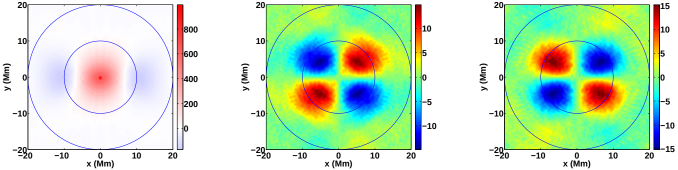

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- With rotation, following [Kitchatinov 1986]

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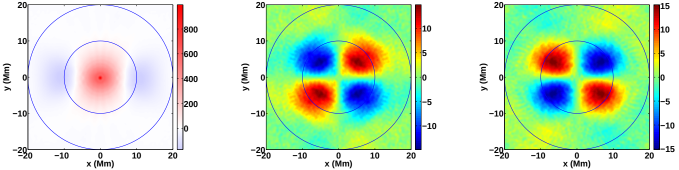

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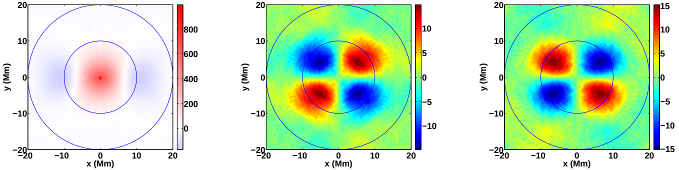

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- We have linked the two-point velocity correlations to products of travel times and derived the forward and noise models. A first inversion showing the concept has been performed.

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- Averaging over angles shows interesting features on the data that can be mainly explained by Kitchatinov and Rüdiger theory of rotating turbulence.
- Inversions with all the data must now be performed in order to have a precise reconstruction and recover the Reynolds stress.