# SENSITIVITY OF SOLAR F-MODE TRAVEL TIMES TO INTERNAL FLOWS


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## INTRODUCTION

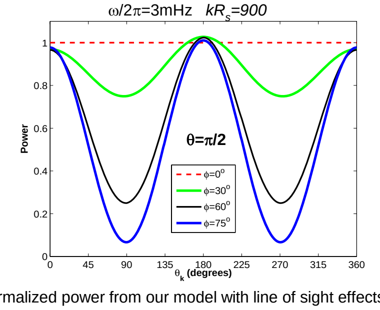
We compute f-model travel-time sensitivity kernels for flows for time-distance helioseismology. In the computation, we take into account two systematic effects: the projection of the velocity vector onto the **line of sight**, and the **foreshortening**. These corrections are necessary before any attempt at data inversions are made, in order to make the whole computation consistent.

Flow kernels are functions which give the sensitivity of travel-time measurements of f modes to small amplitude, two-dimensional, and spatially varying flows. We are interested in travel time differences between waves traveling from one point to another. The kernels are calculated from an approximate solar model, which uses the Born approximation in estimating the scattering of waves from flow perturbations.

In the following, we present the effects of the line of sight and the foreshortening on the **model power spectrum** and on the **flow kernels**, calculated for a constant density model.

## LINE OF SIGHT

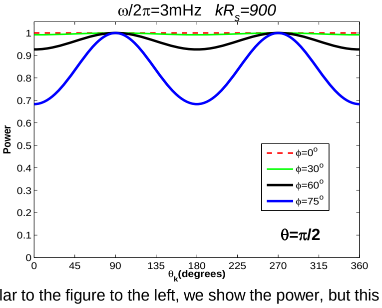
We calculate kernels on a local region of the sun that is approximated to be plane-parallel and tangent to the sphere. The line of sight is only coincident with the normal of this plane at solar disk center. Each local plane is associated with particular values of the spherical-polar angles ($\phi$,$\theta$), measured from the central meridian and the north pole respectively.



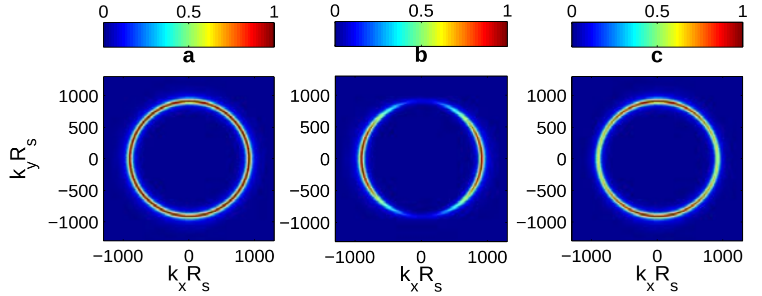

The normalized power from our model with line of sight effects included, plotted as a function of the direction of ***k***, along the equator at the longitudes shown. The power is greatly reduced along the $\boldsymbol{k_y}$ direction as the limb is approached, and unchanged in the $\boldsymbol{k_x}$ direction.

## FORESHORTENING

Foreshortening is the reduction toward the limb of the spatial resolution as measured on the sun. We correct for this in the calculation of the kernels by applying a filter function that is an approximation to a foreshortened pixel. This function depends on the location on the solar disk. In this manner, the kernels should then be suitable for inversions of local regions away from disk center.



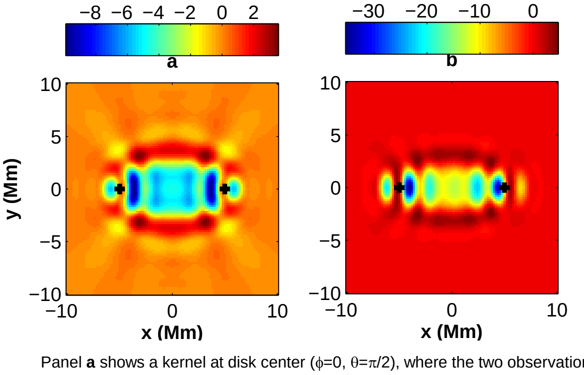

Similar to the figure to the left, we show the power, but this time only foreshortening effects are included (line of sight effects neglected). Note how the power is reduced instead along the $\boldsymbol{k_x}$ direction, which is ***90º*** out of phase with the line of sight effect.



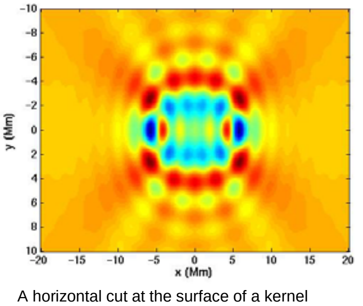

Three model f-mode power spectra cuts at constant angular frequency $\omega/2\pi$=3 mHz. Panel **a** ($\phi$=0, $\theta=\pi/2$) shows the spectrum at disk center, which is symmetric. Panel **b** ($\phi=\pi/4$, $\theta=\pi/2$) is the power with the **line of sight effects only** included. Panel **c** is also at ($\phi=\pi/4$, $\theta=\pi/2$) , with **foreshortening effects only**. This figure re-enforces the result of the top 2 figures, in that the power minima are seen to be out of phase. Note that the line of sight contribution to the reduction of the power is always of greater magnitude than that due to the foreshortening.

## KERNELS

The flow kernels to the right are computed in an analogous manner to the kernels in Gizon & Birch (2002). The two observation points used in the cross-correlation are given by crosses. It is important to note that the kernels depend on (1) where we are on the solar disk, and (2) the orientation of the observation points. Also, these two kernels have the same integral over space, which for a constant flow would give the same travel time difference.




Panel **a** shows a kernel at disk center ($\phi$=0, $\theta=\pi/2$), where the two observation points lie on the equator. Panel **b** shows a kernel at ($\phi=\pi/3$, $\theta=\pi/2$) on the equator, and takes into account the foreshortening and line of sight effects. It is clear that line of sight effects have a non-trivial effect on these sensitivity kernels.




A horizontal cut at the surface of a kernel calculated from the full 3-dimensional model of Birch *et al*. (2004), without any of the corrections mentioned above taken into account. Please see one of the authors for a full explanation of this calculation.


**Reference**: Gizon L., and Birch A.C., 2002, ApJ 571, 966.

**Reference**: Birch A.C., Kosovichev A.G., and Duvall T.L.., 2004, ApJ 608, 580.