Modelling the effect of Meridional Flows in Time-Distance Helioseismology: Born vs. Ray approximation

Vincent Böning[1,2], Markus Roth[1], Jason Jackiewicz[2], Shukur Kholikov[3]

[1]Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany
[2]Department of Astronomy, New Mexico State University, Las Cruces, NM, USA
[3]National Solar Observatory, Tucson, AZ, USA

KIS Kiepenheuer-Institut für Sonnenphysik

Abstract

Accurate meridional flow measurements are important for understanding the solar dynamo. Recent inversions for meridional flows have not yet reached a consensus on the nature of the meridional flow in depths greater than about 0.9 solar radii. In time-distance helioseismology, current modelling of the solar interior for meridional flow inversions is performed using ray kernels, which assume that waves propagate along infinitely thin ray paths. The Born approximation may constitute a more accurate approach as it models the first order perturbation to the wave field in the whole solar interior. We present the current status of an undergoing validation of a recently developed model for computing spherical Born approximation sensitivity functions suitable for inferring meridional flows. In addition, we compare Born and ray approximations using flow models.

Born Approximation in Spherical Geometry (Böning et al., 2016)

In time-distance helioseismology of solar interior flows, the Born approximation assumes a first order perturbation of the solar interior wave field due to a flow field. A Born kernel $\mathbf{K}$ samples a 3D region in the solar interior of diameter comparable to the travel distance and models the effect of the flow field $\mathbf{v}(\mathbf{r})$ on the travel time of a wave packet in this region. $\delta\tau = \iiint \mathbf{K}(\mathbf{r}) \cdot \mathbf{v}(\mathbf{r})\, \mathrm{d}^3\mathbf{r}$, where $\delta\tau$ is the perturbation to the travel time.

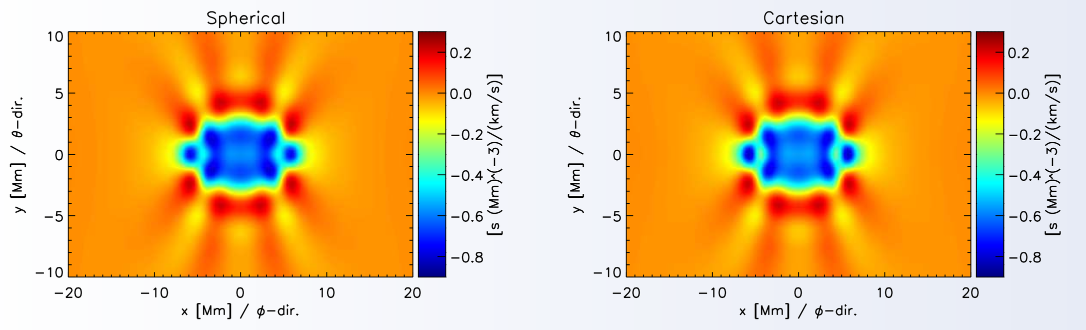
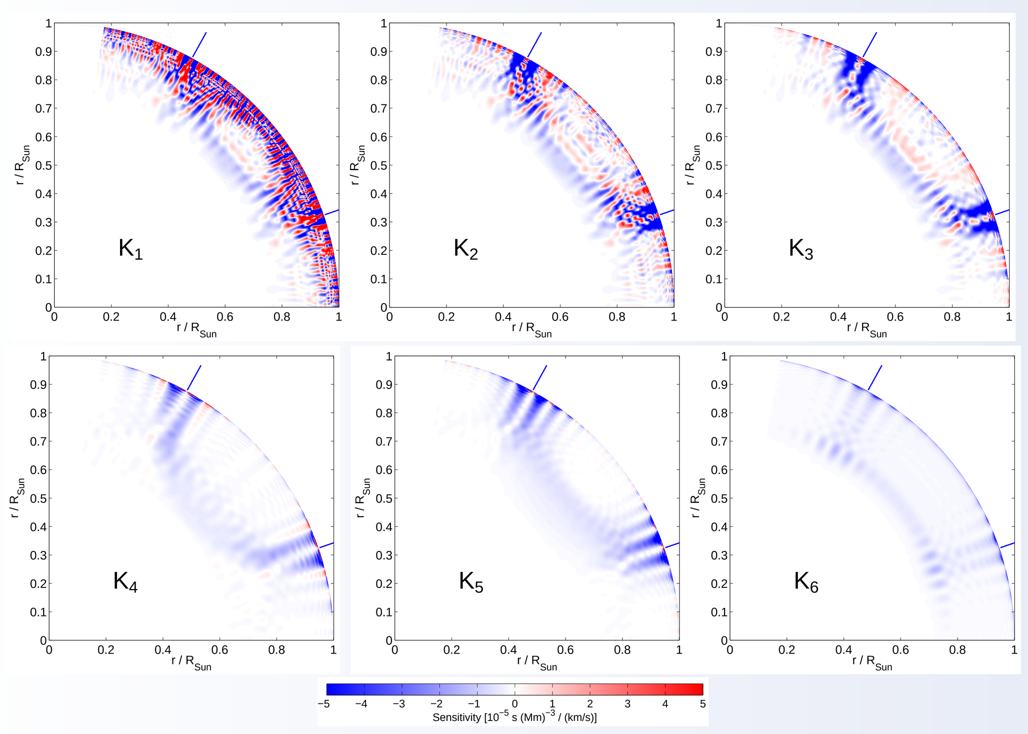


Figure 1: Comparison of travel-time sensitivity functions for zonal flows, K_ϕ (left, spherical code, from Böning et al., 2016) and K_x (right, Cartesian code of Birch & Gizon, 2007). The two observation points are located on the equator ($y = 0$) at $x = \pm 5$ Mm.



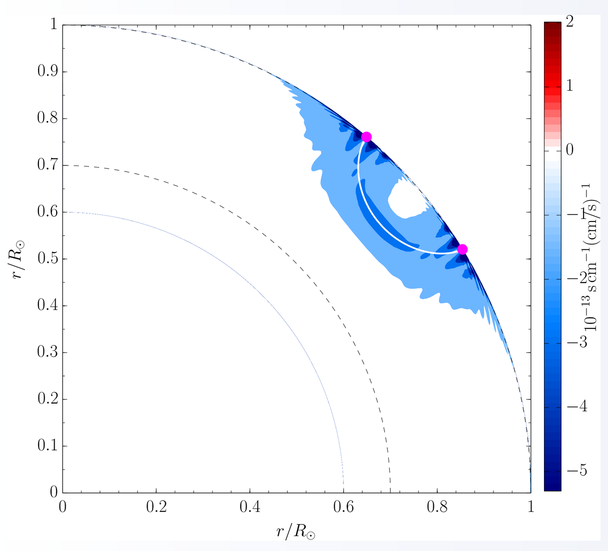
Kernel	Filter	mean l
K_1	$l \leq 170$	84
K_2	$l \leq 99$	49
K_3	$l \leq 79$	39
K_4	$l \leq 49$	24
K_5	Gaussian	45
K_6	phase-speed	46

Figure 2: Vertical cuts at the central meridian through example travel-time sensitivity functions for meridional flow, K_θ, for a travel distance of $\Delta = 42°$. The locations of the observation points are marked with blue bars.

Conclusions:

(1) The extension from Cartesian to Spherical Geometry was successful.
(2) A Cartesian model for computing Born kernels (see Gizon & Birch, 2002 and Birch & Gizon, 2007) was successfully extended to spherical geometry.
(3) The kernels show a significant dependence on the choice of data analysis filter employed.
(4) We choose to apply a phase-speed filter as was done by Jackiewicz et al. (2015), see K_6 in Figure 2.

Kernels: Born vs. Ray Approximation



In the ray approximation, sound waves are assumed to travel along infinitely thin ray paths, which (possibly as a bundle) are used to model travel times. $\delta\tau = 2\int_\Gamma \frac{\mathbf{n}(s)\cdot\mathbf{v}(s)}{c_s^2}\, \mathrm{d}s$, where Γ is the ray path.

Figure 3: Comparison of Born (shaded 2D-structure) and ray kernels (ray path depicted in white) for an exemplary travel distance of $\Delta = 18°$.

Conclusion: Born kernels sample considerably larger regions in the solar interior compared to ray kernels.

Forward Travel-Times: Born vs. Ray vs. Simulated Data

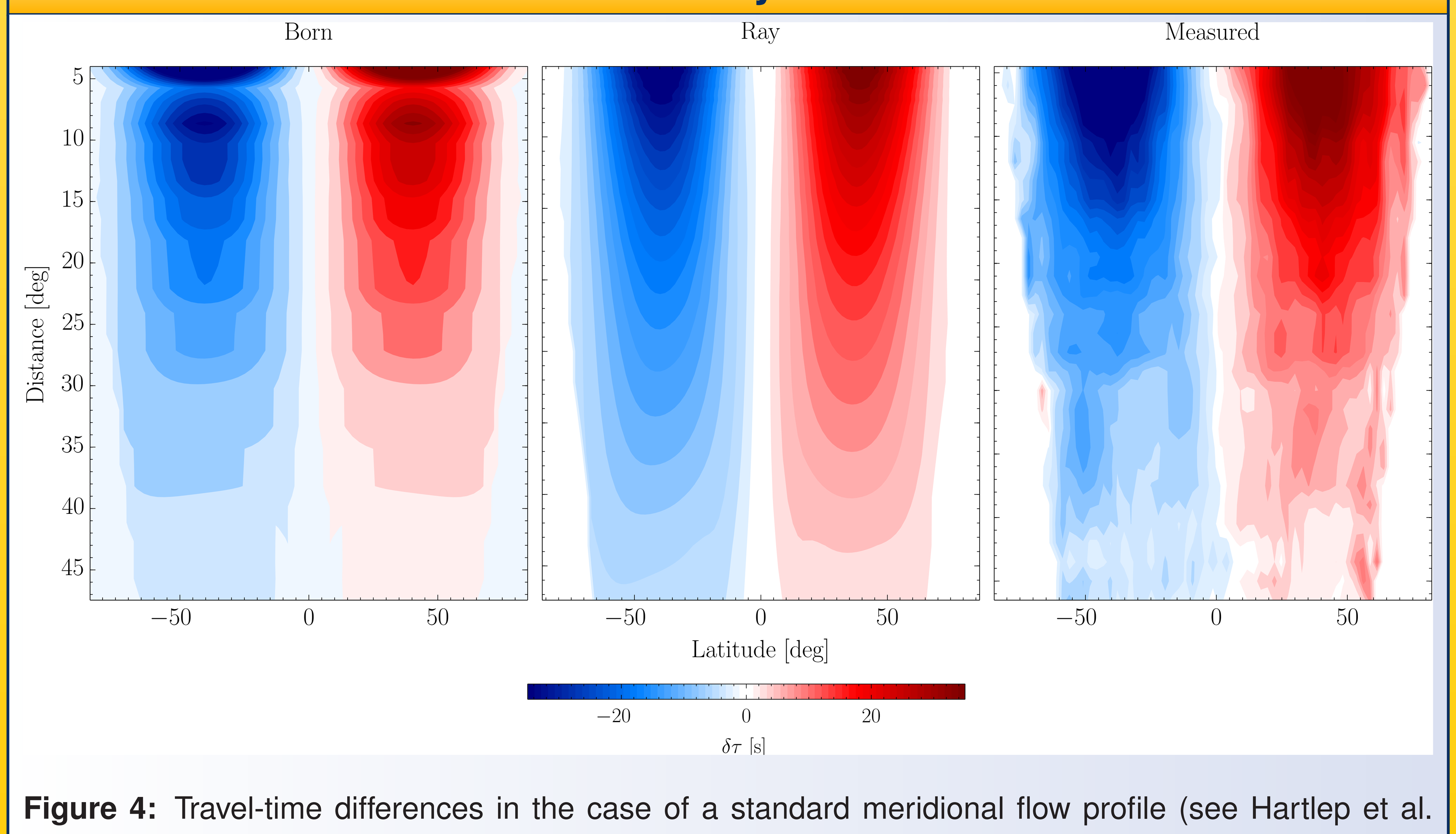


Figure 4: Travel-time differences in the case of a standard meridional flow profile (see Hartlep et al. (2013) and target flow in Figure 5). We compare the forward-modelled travel times using Born (left) and ray kernels (middle) to measurements (right) obtained by Jackiewicz et al. (2015) from artificial helioseismic data simulated by Hartlep et al. (2013).

Conclusion: Travel times from both Born and ray kernels generally match the pattern observed in measured travel times.

SOLA Inversion Tests using Born Kernels

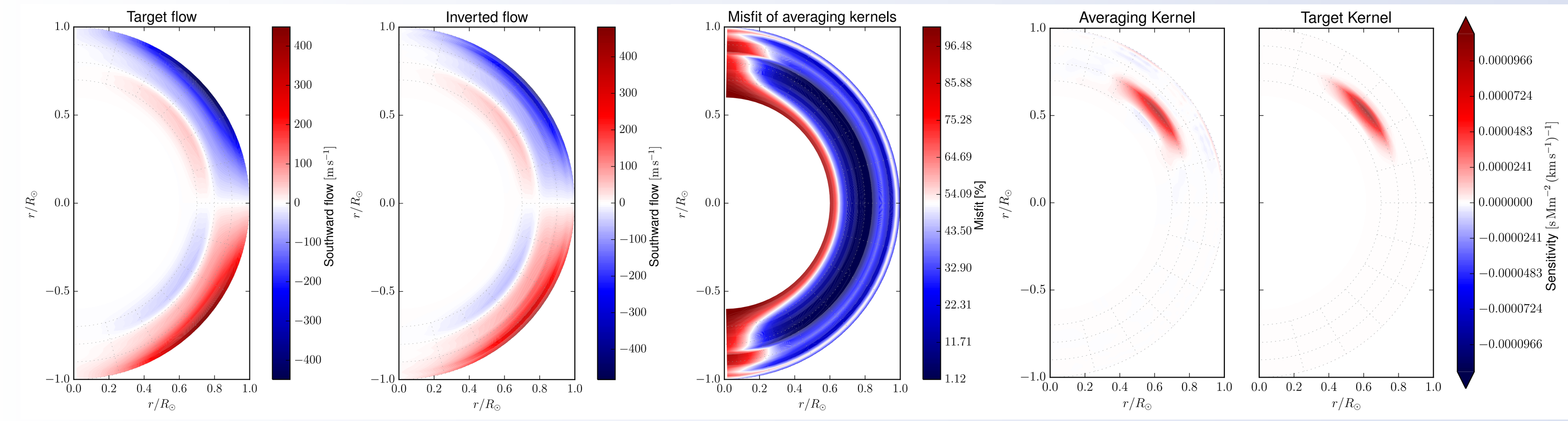


Figure 5: Test inversion of forward travel times (see Figure 4, left panel) using the SOLA method (Jackiewicz et al., 2012). From left to right: Target flows, inversion results, misfit, and comparison between averaging and target kernels.

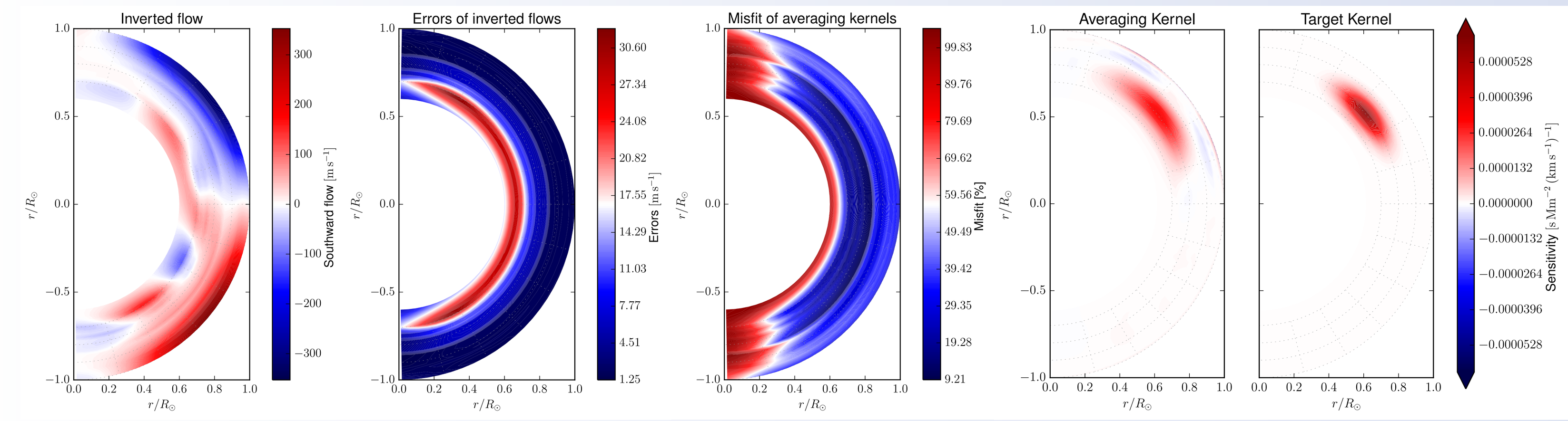


Figure 6: Test inversion of measured travel times (see Figure 4, right panel). From left to right: Inversion results, errors, misfit, and comparison between averaging and target kernels. For the target flows, see Figure 5.

Conclusions:

(1) A test inversion of noiseless forward travel times (see left panel of Figure 4) can well reproduce the target meridional flow profile.
(2) A test inversion using noisy measured travel times from the simulation (see right panel of Figure 4) reproduces the target meridional flow profile well in depths up to $0.8R_\odot$.
(3) The deeper smaller-magnitude return flow below $0.8R_\odot$ can partly be recovered by the inversion of noisy travel times.
(4) Improvements are still possible in the choice of regularization parameters as a function of latitude and depth in order to better recover the deep return flow in the inversion of noisy travel times.

Matching the Power Spectrum

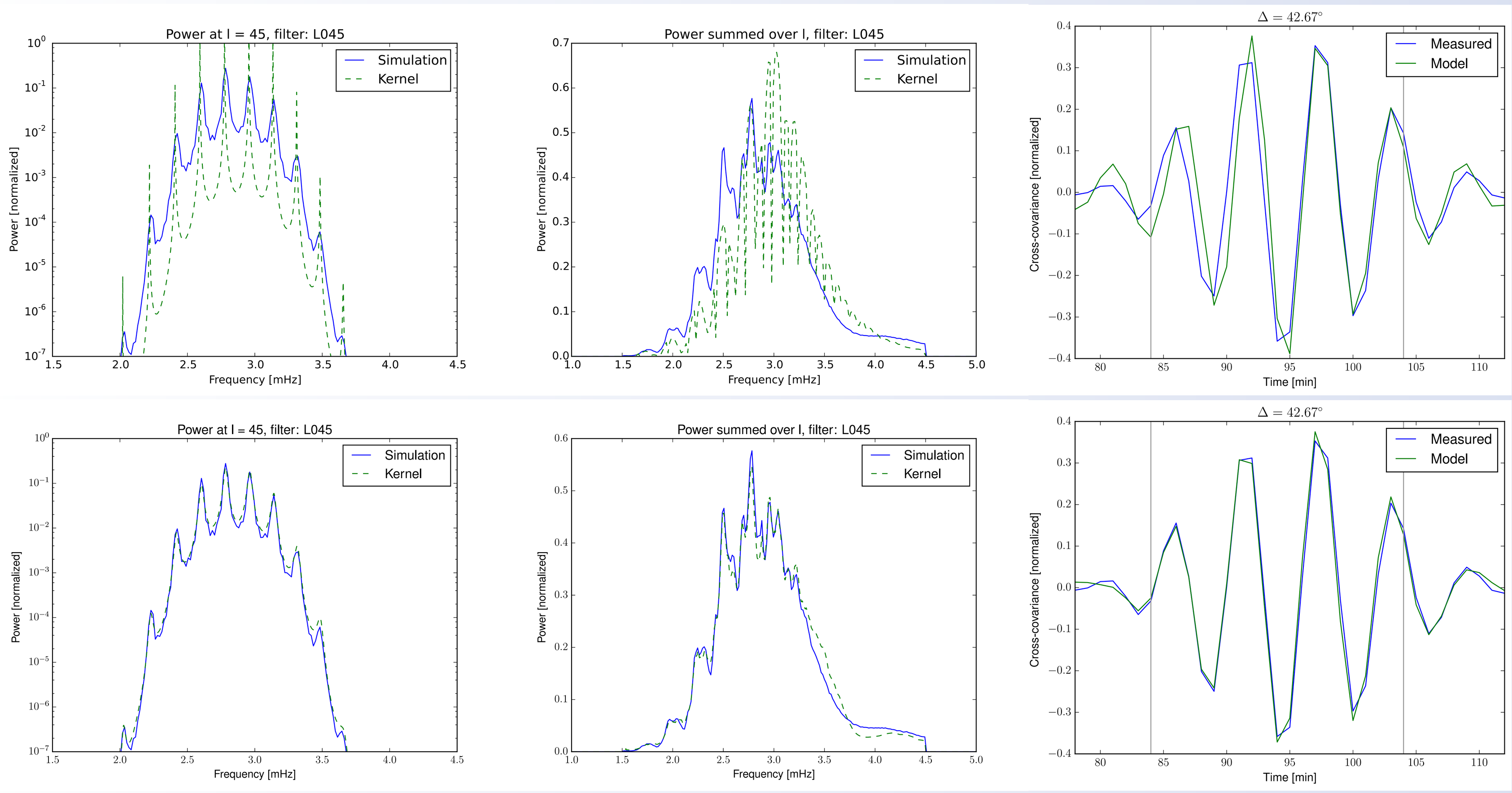


Figure 7: Match of Born approximation model power spectra and cross-covariances to simulated data, for a first guess (top) and in a fine-tuned case (bottom). Shown is an example case relevant for measuring deep flows.

Conclusion: Fine-tuning the match of the zero-order power model spectrum for computing Born kernels to the observed power spectrum results in a considerably better match in the reference cross-covariance.

Summary

(1) Using the Born approximation for inferring deep solar meridional flow looks like a promising technique compared to the ray approximation.
(2) Forward-modelled travel times from the Born approximation match well the observed pattern in measured travel times from simulated artificial data.
(3) When doing inversions of meridional flow using Born kernels, it is in principle possible to recover the target flow profile. Improvements can still be achieved in the case of noisy travel times for deep flows.

References

Birch, A. C., & Gizon, L. 2007, Astronomische Nachrichten, 328, 228
Böning, V. G. A., Roth, M., Zima, W., Birch, A. C., & Gizon, L. 2016, *Astrophys. J.*, 824, 49
Gizon, L., & Birch, A. C. 2002, *Astrophys. J.*, 571, 966
Hartlep, T., Zhao, J., Kosovichev, A. G., & Mansour, N. N. 2013, *Astrophys. J.*, 762, 132
Jackiewicz, J., Birch, A. C., Gizon, L., et al. 2012, *Solar Phys.*, 276, 19
Jackiewicz, J., Serebryanskiy, A., & Kholikov, S. 2015, *Astrophys. J.*, 805, 133

Acknowledgements: The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 307117. This work was supported by the SOLARNET project (www.solarnet-east.eu), funded by the European Commission's FP7 Capacities Programme under the Grant Agreement 312495. This work has been supported by an NSF Career award to New Mexico State University.

erc European Research Council
Established by the European Commission

Contact: Vincent Böning, vboening@kis.uni-freiburg.de