Coupling Interior and Atmosphere through Active Regions

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1. INTRODUCTION

- The Sun's interior oscillations, the *p*-modes, are normally trapped in a subsurface cavity, but behave very differently when they encounter an active region. The magnetic field turns them into a complex mixture of fast, slow, and Alfvén waves through two different mode conversion processes. They then partially escape into the solar atmosphere and partially reflect to rejoin the internal wave field, with profound consequences for the local seismology. We present results, from Cally & Moradi (2013; *MNRAS*, 435, 2589), of simulations that show substantial "travel time" shifts that depend on magnetic field inclination and orientation, and are closely related to escaping acoustic and Alfvénic wave fluxes.

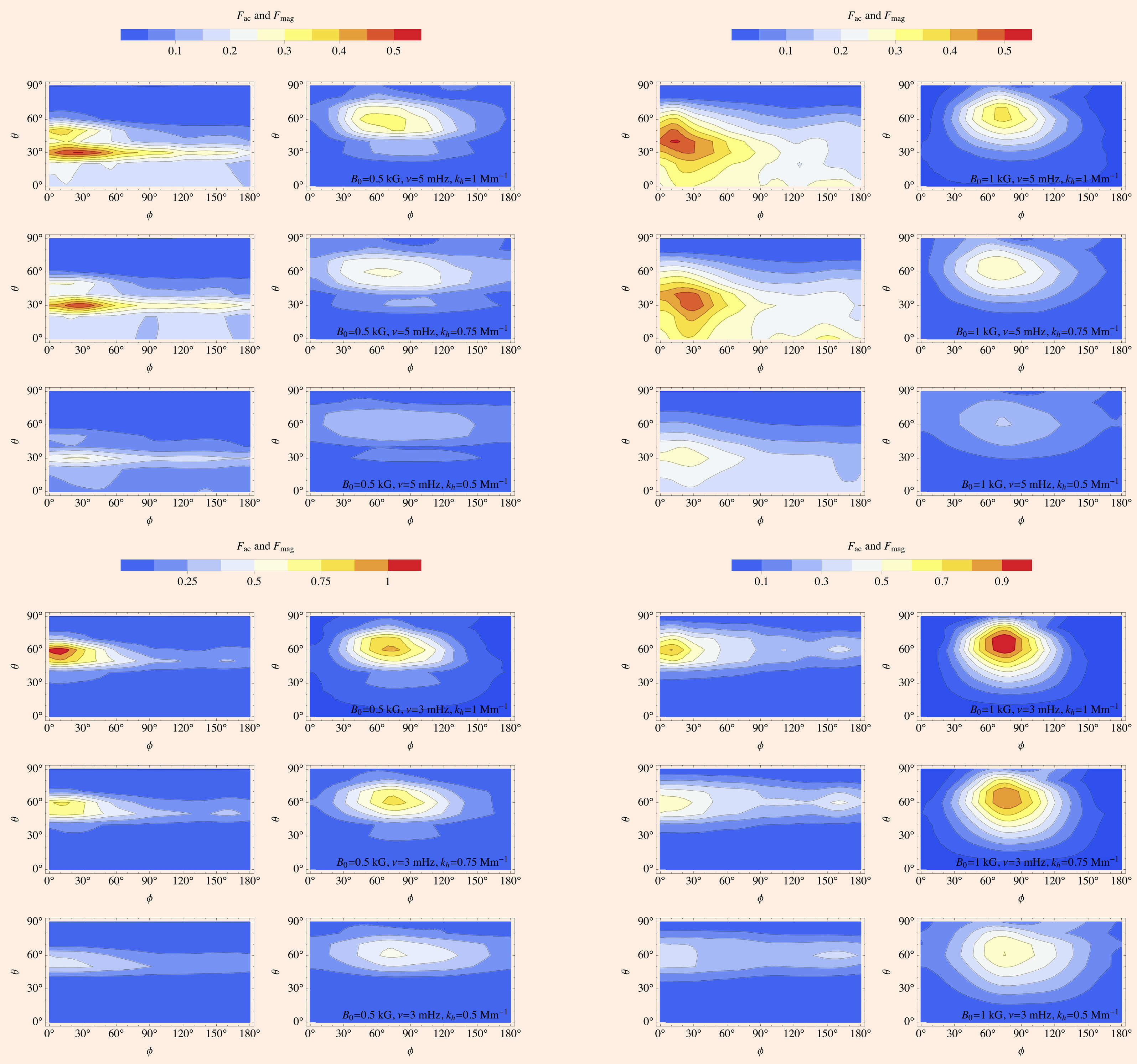
2. NUMERICAL MODELLING

- We employ the 3-D linearised MHD wave propagation code SPARC (Hanasoge, 2007; PhD thesis) for the simulations. Our computational box spans 26.53 Mm in z (covering heights $-25 \le z \le 1.53$ Mm, with nz = 265, the vertical grid spacing varies from several hundred km deeper within, to tens of km in the near-surface layers) and 140 Mm in x and y (with nx = ny = 128 evenly spaced grid points providing a horizontal resolution of 1.09 Mm/pixel).
- The background (thermodynamic) model consists of a convectively stabilised quiet-Sun solar model. In conjunction with this quiet-Sun model, we employ uniform B_0 = 0.5 and 1 kG magnetic fields inclined at θ from the vertical. The field inclination is varied from 0° to 90°, in 10° increments.
- Waves are stochastically excited (at z = −0.16 Mm) in our computational box via the introduction of a forcing term in the vertical momentum equation such that a solar-like power spectral distribution is obtained. The horizontal boundaries of the computational box are periodic, while the vertical boundaries are absorbent (PMLs). We simulate for 12 hours, but conduct our analyses on the last 8.5 hours of each run.
- As random stochastic wave sources are used, Fourier filtering is applied to each relevant simulated physical quantity in order isolate selected horizontal wavenumbers, wave propagation directions and frequencies. To do this we apply Gaussian ball filters in wavevector space, centred at particular horizontal wavevectors k_h (for the cases we studied k_h = 1, 0.75 and 0.5 Mm^{-1} with $\delta k_h = 0.2\ \mathrm{Mm}^{-1}$), oriented at angle ϕ (where 0° ≤ ϕ ≤ 180°, in 5° increments) from the x-direction, in combination with standard Gaussian frequency filters centred at ν = 3 and 5 mHz, with δν = 0.5 mHz.

3. RESULTS

- The resultant filtered data cubes are analysed in two ways. First, the acoustic (slow) and magnetic (Alfvén) wave energy fluxes are calculated at z = 1.2 Mm (just below the PML layer) and plotted as contoured functions of field inclination for ν = 3 and 5 mHz. The fast wave is evanescent, and so contributes no flux. Similarly, time-distance travel time perturbations relative to quiet Sun are also plotted against θ and ϕ.

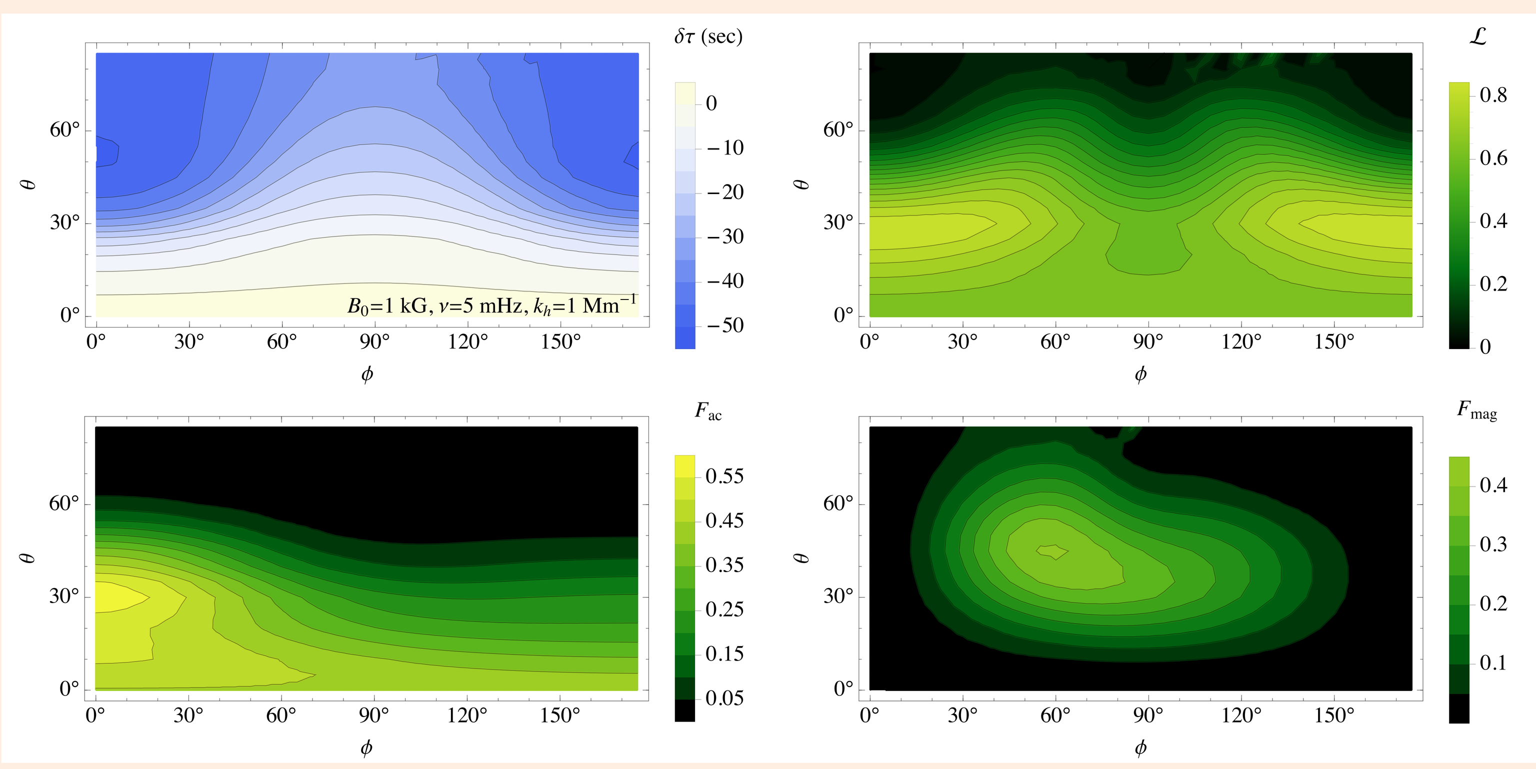
3.1 WAVE ENERGY FLUXES



- Four blocks of vertical wave energy flux plots against field inclination θ and orientation angle ϕ, measured at z = 1.2 Mm. Top left: B_0 = 0.5 kG, ν = 5mHz. Top right: B_0 = 1 kG, ν = 5 mHz. Bottom left: B_0 = 0.5 kG, ν = 3 mHz. Bottom right: B_0 = 1 kG, ν = 3 mHz. Within each block, the first column is the acoustic flux F_{ac} and the second column is the magnetic flux F_{mag}. The three rows in each block are for k_h = 1, 0.75, and 0.5 Mm^{-1} respectively.

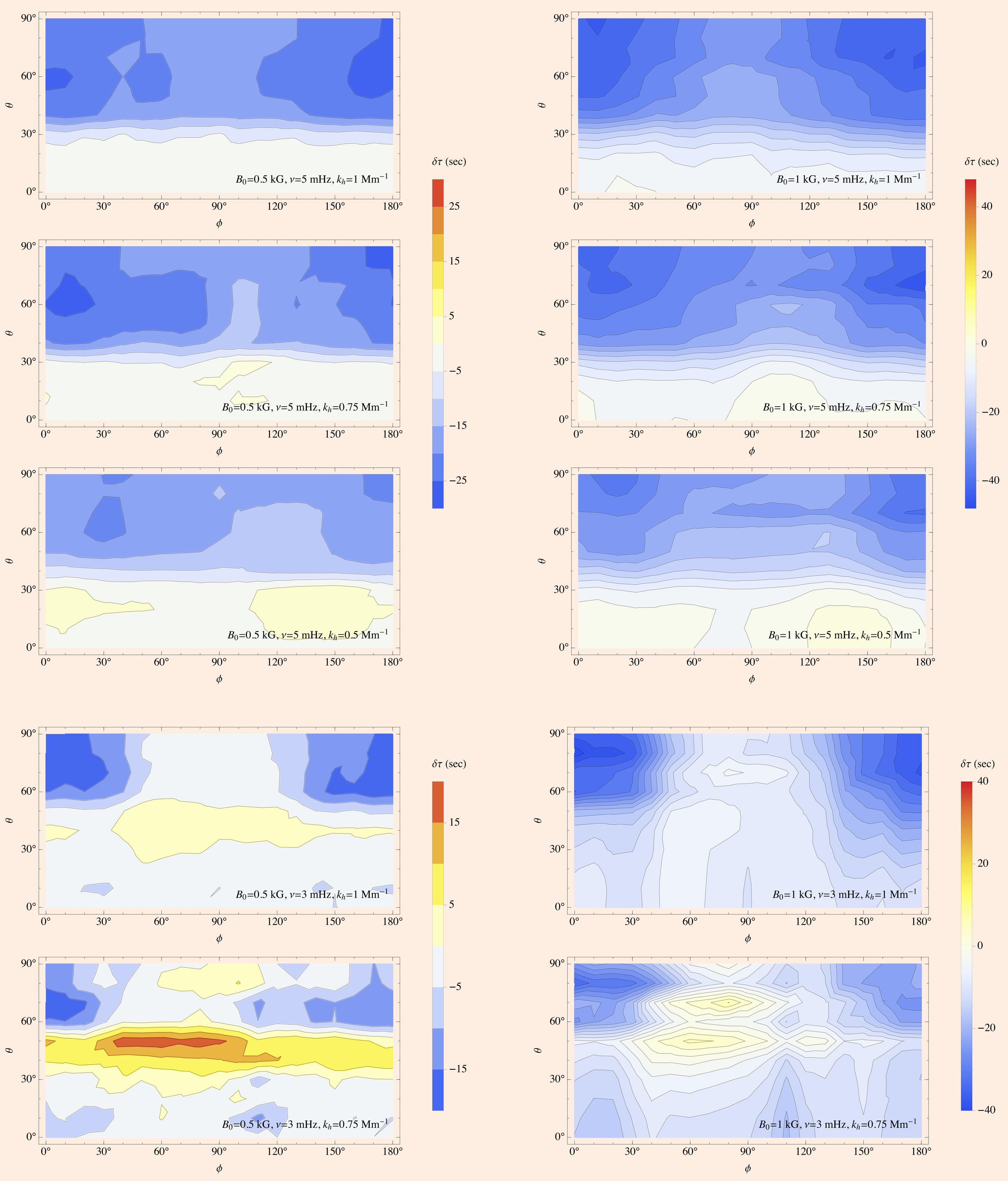
3.3 COMPARISON WITH BVP RESULTS

- Using the ordinary differential equation Boundary Value Problem (BVP) approach of Cally & Goossens (2008; *Sol. Phys.*, 251, 251) and Cally (2009; *MNRAS*, 395, 1309) we can investigate travel time perturbations relative to quiet Sun as well as acoustic and magnetic fluxes for horizontally invariant atmospheres and magnetic fields.
- The figures below apply to the B_0 = 1 kG, ν = 5 mHz, k_h = 1 Mm^{-1} case addressed above, displaying a similar (but cleaner) picture to that obtained from simulation and the time-distance analysis.



- Top left: travel time perturbations. Top right: total fractional losses L from the reflected fast wave at the base of the computational domain relative to that of the original injected monochromatic fast wave. Bottom left: vertical upward acoustic flux at z = 2 Mm (top of the computational domain). Bottom right: vertical upward magnetic flux at z = 2 Mm.

3.2 TIME DISTANCE TRAVEL TIMES



- Four blocks of travel time perturbations δτ against field inclination θ and orientation angle ϕ. Top left: B_0 = 0.5 kG, ν = 5 mHz. Top right: B_0 = 1 kG, ν = 5 mHz. Bottom left: B_0 = 0.5 kG, ν = 3 mHz. Bottom right: B_0 = 1 kG, ν = 3 mHz. All blocks correspond to the flux plots of Section 3.1 on the left. The rows in each block are for k_h = 1, 0.75, and (for 5 mHz only) 0.5 Mm^{-1} respectively.

4. CONCLUSIONS

- At small magnetic field inclination, insufficient to provoke the *cos* θ ramp effect, both fluxes and travel time perturbations relative to quiet Sun are small, suggesting that seismic waves are largely reflected before reaching heights at which they would become involved in mode conversion. In this respect, they do not behave very differently to the quiet Sun case.
- However, once the ramp effect kicks in at larger θ, wave paths extend into the atmosphere and both "travel times" (wave phases) and energy losses become substantial. This is so even at ϕ = 0° and 180°, where Alfvénic losses (essentially) vanish. Further large variations in δτ, now positive, are then correlated with the Alfvénic losses as *sin* ϕ increases.
- In summary, the current simulations suggest that fast-to-slow conversion at the Alfvén-acoustic equipartition level yields large negative travel time shifts, and that subsequent fast-to-Alfvén conversions produce positive shifts superimposed on and therefore partially cancelling the negative shifts. Importantly, δτ displays a very clear directional (ϕ) dependence.
- These results strongly indicate that processes occurring higher up in the atmosphere can significantly affect the core data products of local helioseismology, which could have serious implications for helioseismic inversions of sunspots.