3D Seismic Wave Simulations of Mantle Heterogeneity and Shear Wave Splitting Phases

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1. Background and Motivations

Background:

Seismic anisotropy

- -Evidence in crust, upper mantle, transition zone, top of lower mantle, lowermost mantle, inner core
- -Shear Wave Splitting is a powerful technique and widely used, specifically for the D" layer
  - Ray theoretical approximations are commonly used

Previous work on full waveform modeling of SKS and SKKS shear wave splitting:

- -*Lin et al., 2014* – normal mode summations 1D PREM, shallow earthquake sources
- -*Tesoniero et al., 2020* – axisymmetric spectral-element method (AxiSEM3D), 1D PREM
- -*e.g., Sieminski et al., 2008* – spectral-element method (SPECFEM3D_GLOBE), 1D PREM, calculation of adjoint kernels, theory
- -**Previous work**: only 1D mantle models have been considered with singular event depths

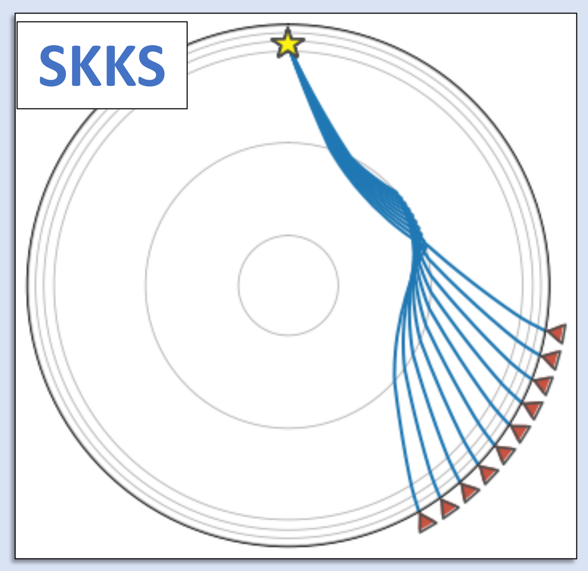
Major Questions:

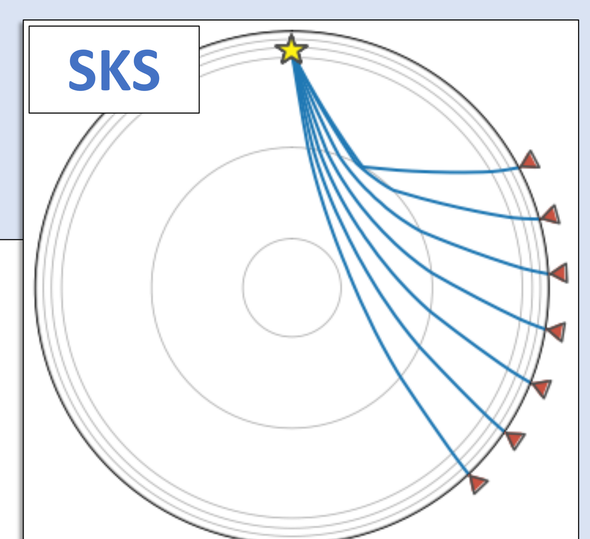
Do 3D crustal and mantle heterogeneity affect shear wave splitting?

How does source depth and location affect waveforms?

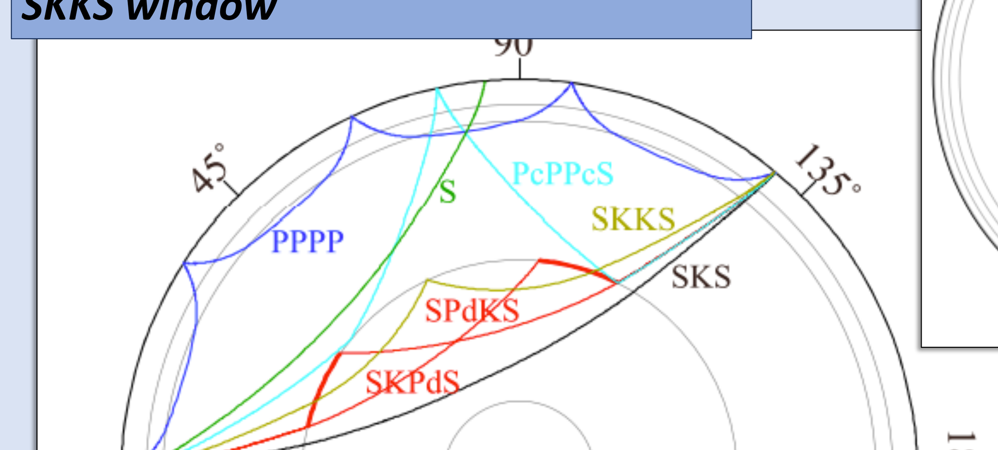
Goals:

1. Capture full complexity of wave propagation in shear wave splitting
2. Assess quality of ray theoretical measurements and modeling





Many interfering phases in SKS and SKKS window



Lin et al., 2014

3. Future Work and Conclusions

-Moving beyond ray theoretical approximations may be needed to better understand the sources of splitting, especially for D" layer where there are fewer measurements and accurate measurements are needed.

-Ray theoretical approximations to shear wave splitting may be challenging for several event depths and distances (see attached figure of preferred distance ranges for SKS and SKKS). Figure shows ideal distance ranges based on event depth where there are no strong apparent interfering phases on the radial or transverse components.

-In the future we will explore other phases, like PKS, S, ScS, Sdiff, and PcS, continue calculating data-sensitivity kernels, and adding azimuthal anisotropy.

2. Methods and Results

Methods

-Simulations conducted with SPECFEM3D_GLOBE (Komatitsch & Tromp, 2002a,b)

-NEX (number of elements on each side of a chunk, 6 total chunks for the globe) = 480

-600 or 864 CPUs (Expanse and Stampede2 HPC Systems)

9s seismograms (dominant f of an SKS ~ 12s)

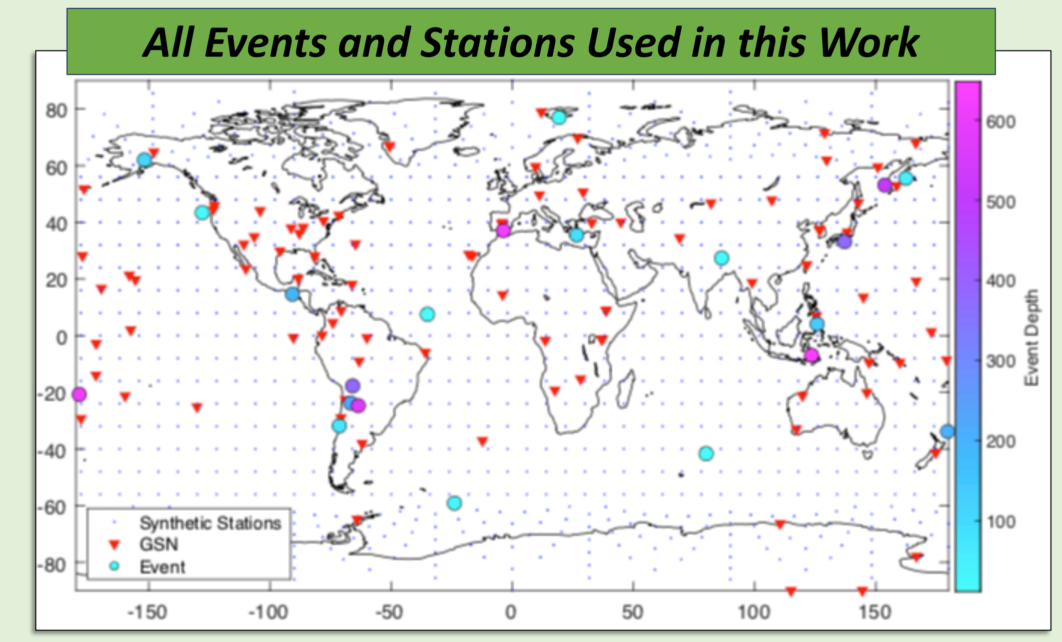
Models:

1D Models: PREM (isotropic: Dziewonski and Anderson, 1981) and 1D Averaged Crust

3D Models: S40RTS (Ritsema et al., 2011; CRUST 2.0: Bassin et al., 2000), GLAD-M15 (Bozdag et al., 2016)

No azimuthal anisotropy included yet

All Events and Stations Used in this Work



Results 1: 1D vs. 3D Mantle/Crustal Models

Overall, there are significant differences between 1D and 3D mantle models on the SKS and SKKS waveforms (fig. 1A), when using shallow events and 3D crustal models. We calculated synthetics for several background models and event depths (e.g., 12 km deep event fig. 1A). We compared the S40RTS synthetics with PREM by calculating cross correlations (fig. 1B). Overall, we see largest cross correlation differences when using shallow events and the 3D crustal model.

Potential impacts: if waveforms are significantly affected by 3D crustal structures, so may shear wave splitting

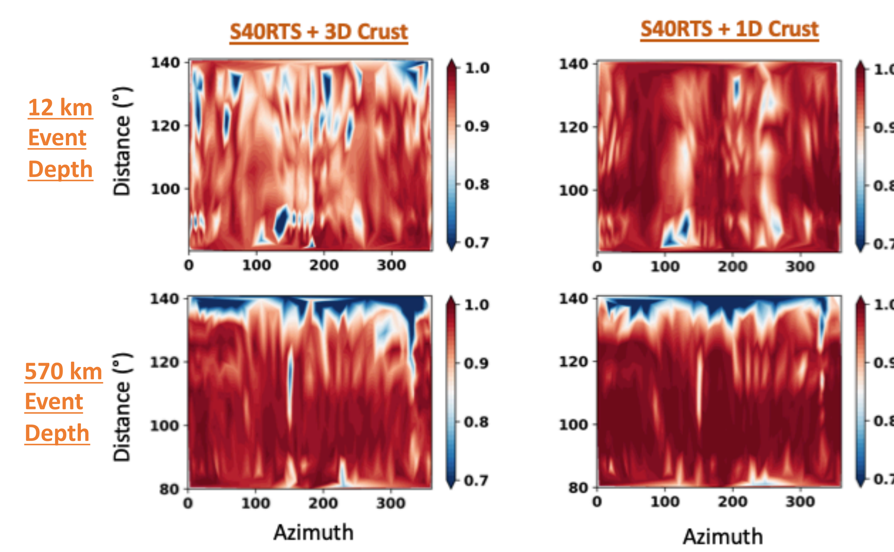
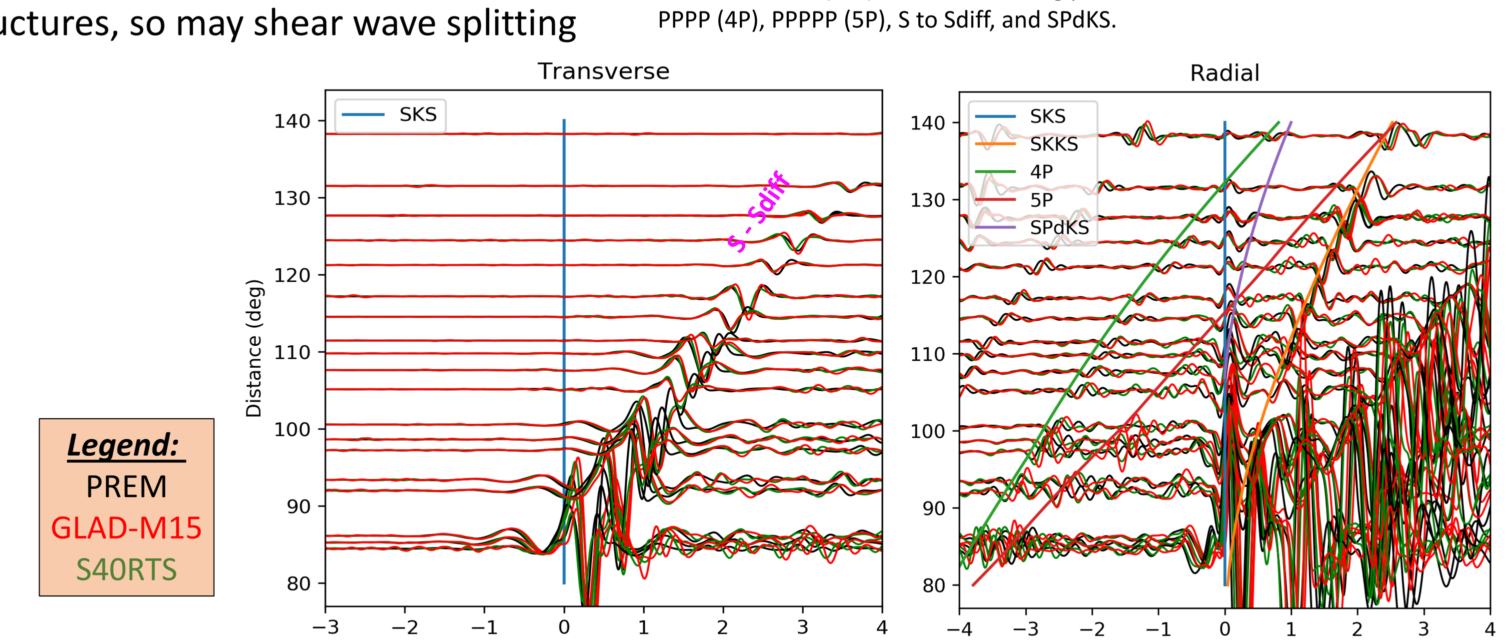


Fig. 1B. Cross correlation of SKS window comparing PREM and S40RTS over all distance ranges and azimuths for two different event depths and two different models: S40RTS with a 3D crust (CRUST 2.0) and a 1D average crust. Colors represent cross correlations.

Fig. 1A. Global synthetics of SKS, comparing PREM (black), S40RTS (green), and GLAD-M15 (red). Other interfering phases are noted, such as SKKS, PPPP (4P), PPPPP (5P), S to Sdiff, and SPdKS.



Results 2: Interfering Phases and event depth considerations

Energy = $\frac{1}{L}\sum|u(t)|$

u(t) = amplitude, L = length of window

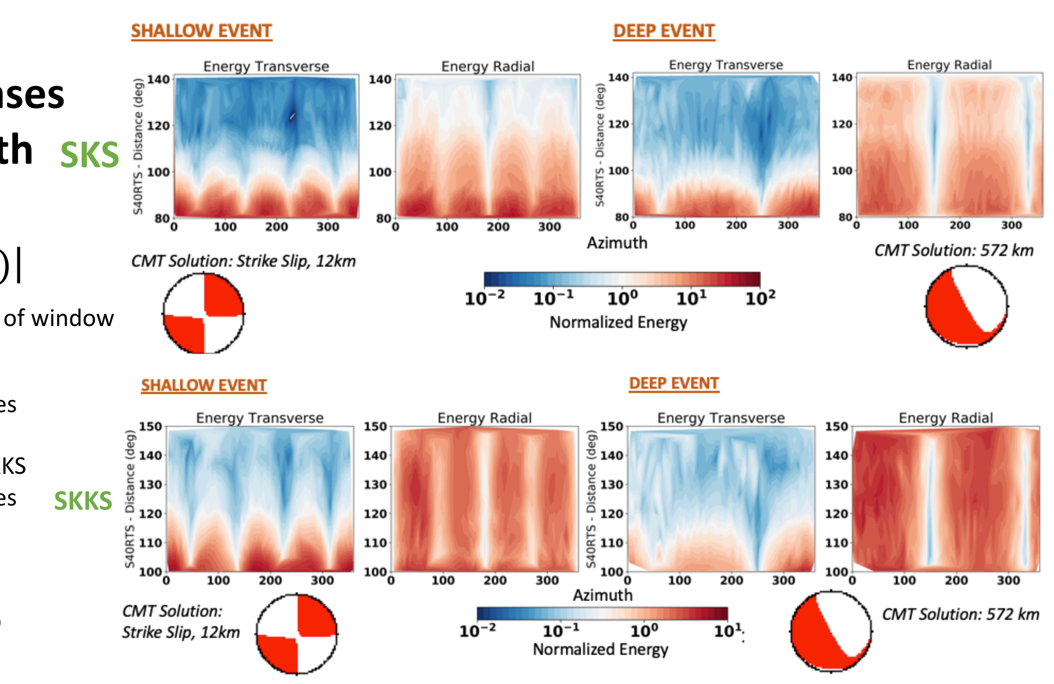


Fig. 2A. This figure illustrates the energy (see equation above) over the SKS and SKKS windows for all arc distances and azimuths for S40RTS (GLAD-M15 and PREM are similar) for two different events (a shallow and deep event).

At the shorter distance ranges of SKS and SKKS, we see significant energy on the transverse component due to S and Sdiff waves for SKS (fig. 2A, top) and SKKS (fig. 2A, bottom). The S wave has a strong influence on polarization deviations from the backazimuth on the SKS waveform (fig. 2B). There can be large backazimuthal deviations due to unwanted transverse component energy up to 105° for SKS and up to 120° for SKKS.

Potential Impacts: Shear wave splitting may have introduced errors if measuring splitting in the 80°-105° for SKS and 100°-120° for SKKS distance ranges

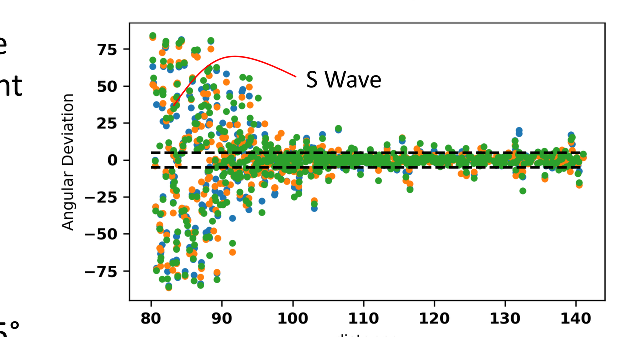


Fig. 2B. This figure illustrates the angular deviation of the particle motion of SKS over the same time window from fig. 2A from the backazimuth. It helps illuminate where the S wave is affecting the SKS waveform.

Results 3: Polarization Deviations from Coriolis Force

S waves are weakly affected by Earth's Coriolis force as it can cause the S wave polarizations to rotate out of plane from the backazimuth (not so much with P waves: see fig. 3A). We show that Coriolis force may affect the polarization of core S waves, which could cause minor errors on the order of 2-3 degrees for north-south propagating paths. For more information on Coriolis force effects on body waves, see Snieder et al. (2015).

Potential Impact: We predict this phenomena won't impact splitting significantly but may be a cause for backazimuthal deviations observed at stations. However, 3D mantle heterogeneities do cause these deviations to increase in some cases up to 5 degrees, which could introduce errors into splitting (fig. 3B).

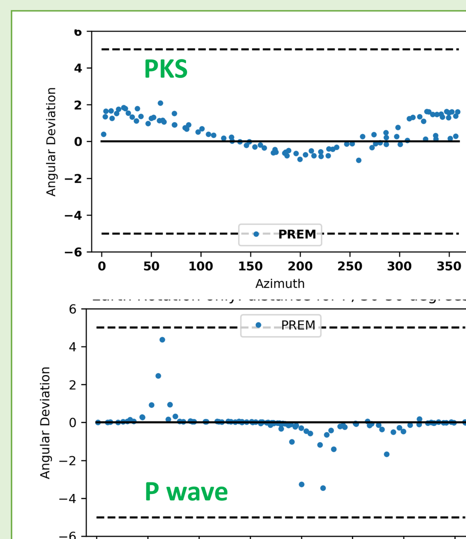
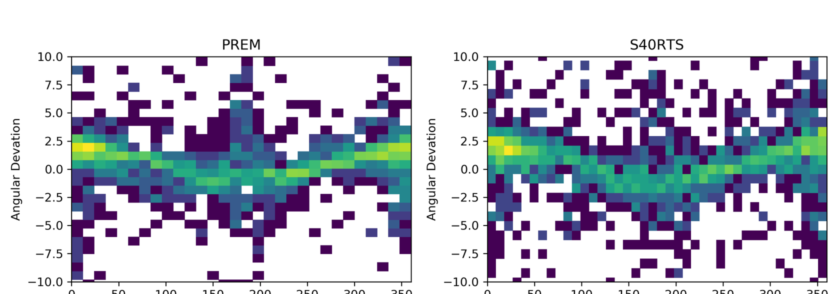


Fig. 3A. Polarization deviations from backazimuth over a narrow window of PKS (top) and a direct P wave (over 30°-50° arc distance range) for PREM. There is an effect of the Coriolis force on S waves, like PKS, but not P waves. Large swings of angular deviations align with the nodal planes of the CMT solution.

Fig. 3B. Polarization deviations from backazimuth over a narrow window of SKS for PREM and S40RTS. Four different earthquakes located in the southern hemisphere are combined to see the Coriolis effect.



Results 4: Travel Time Kernels

Overall, we don't see significant differences in travel time kernels between 1D and 3D mantle models, but we can explore interfering phases at different arc distances and event depths. For example, this is an example of a clean signal of SKKS (Figure 4A).

However, with SKS, we can see influences from underside reflections like PPPPP and SPdKS on the P wave kernel. The major differences we see are overall amplitudes of travel time sensitivity.

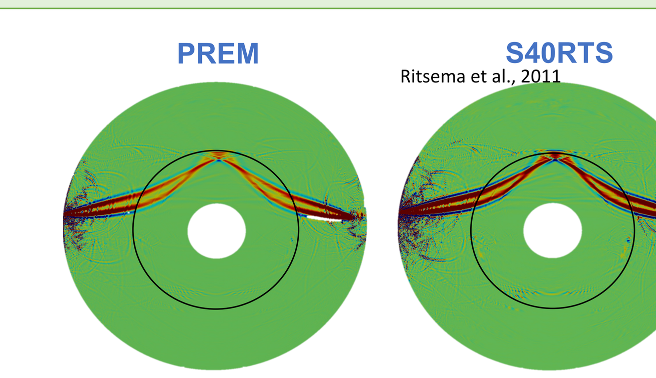
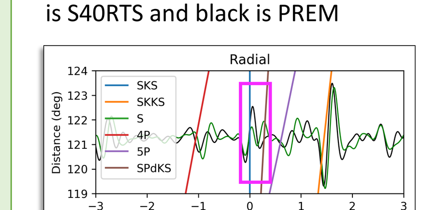
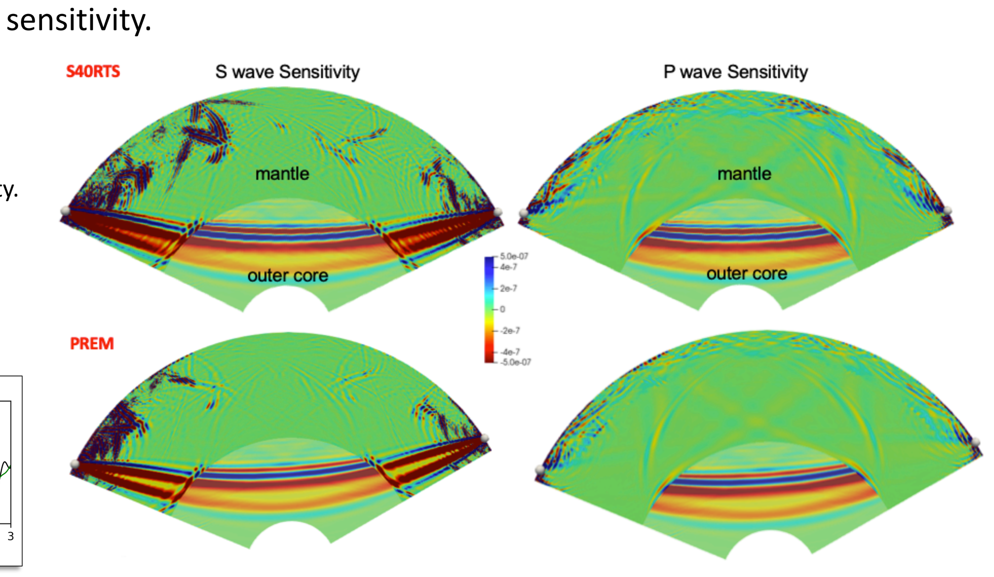


Fig. 4A. Travel time sensitivity kernels for an SKKS, phase for S40RTS and PREM for S wave sensitivity in the mantle and P wave sensitivity in the core.

Fig. 4B. Travel time sensitivity kernels for an SKS, SPdKS and PPPPP phases for S40RTS and PREM for P and S waves sensitivity. The event is shallow at 12km depth at an arc distance of 121° filtered 12-50s. Corresponding seismogram shown below: green is S40RTS and black is PREM





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