Approximate vs. purely numerical approaches for full waveform modeling of global Earth structure

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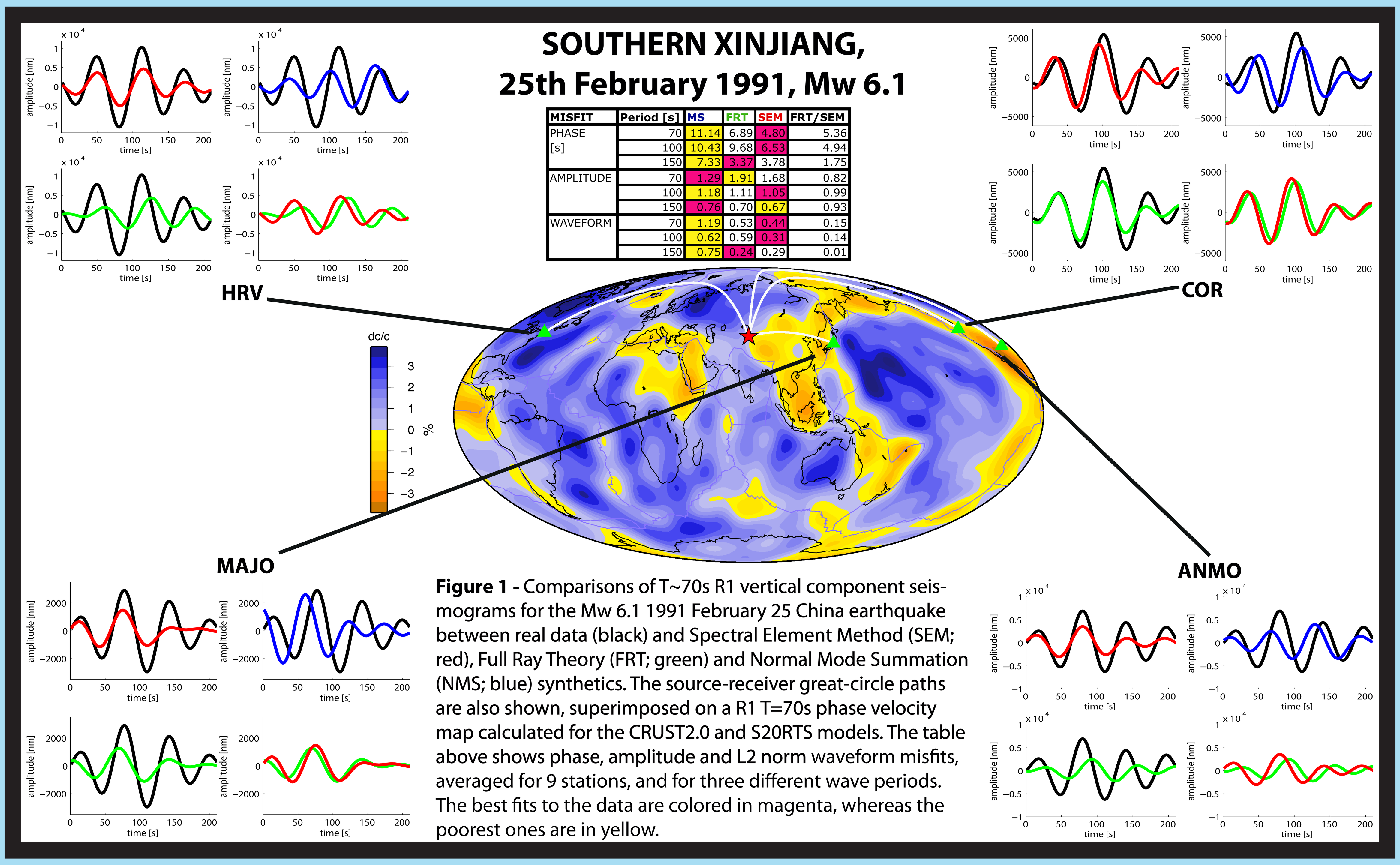
Introduction and aim of the work

In order to enhance global tomographic models, we need to explore the full richness of seismic waveforms and to use accurate seismic wave propagation theories. While for spherically symmetric 1-D Earth models, exact, fast methods such as normal mode summation (e.g., Gilbert, 1971) can be used, for the laterally varying 3-D Earth seismologists have traditionally relied on approximate methods such as the great-circle approximation (e.g., Woodhouse and Dziewonski, 1984). Other approximate, but more accurate forward modeling techniques have also been developed, such as the full ray theory approach (e.g., Ferreira and Woodhouse, 2007) and the Born approximation (e.g., Capdeville, 2005). However, these have not yet been fully explored in global tomography applications. More accurate purely numerical methods, such as the Spectral Element Method (e.g., Komatitsch et al., 2002), are also now available, but their computational cost is still prohibitive for global tomography applications, which typically involve inversions of hundreds of thousands of waveforms.

In this study we investigate the accuracy of the Full Ray Theory (FRT) approach compared to the Spectral Element Method (SEM), as part of a project aimed at finding optimal forward modeling schemes for global tomography. Specifically, our main questions are:

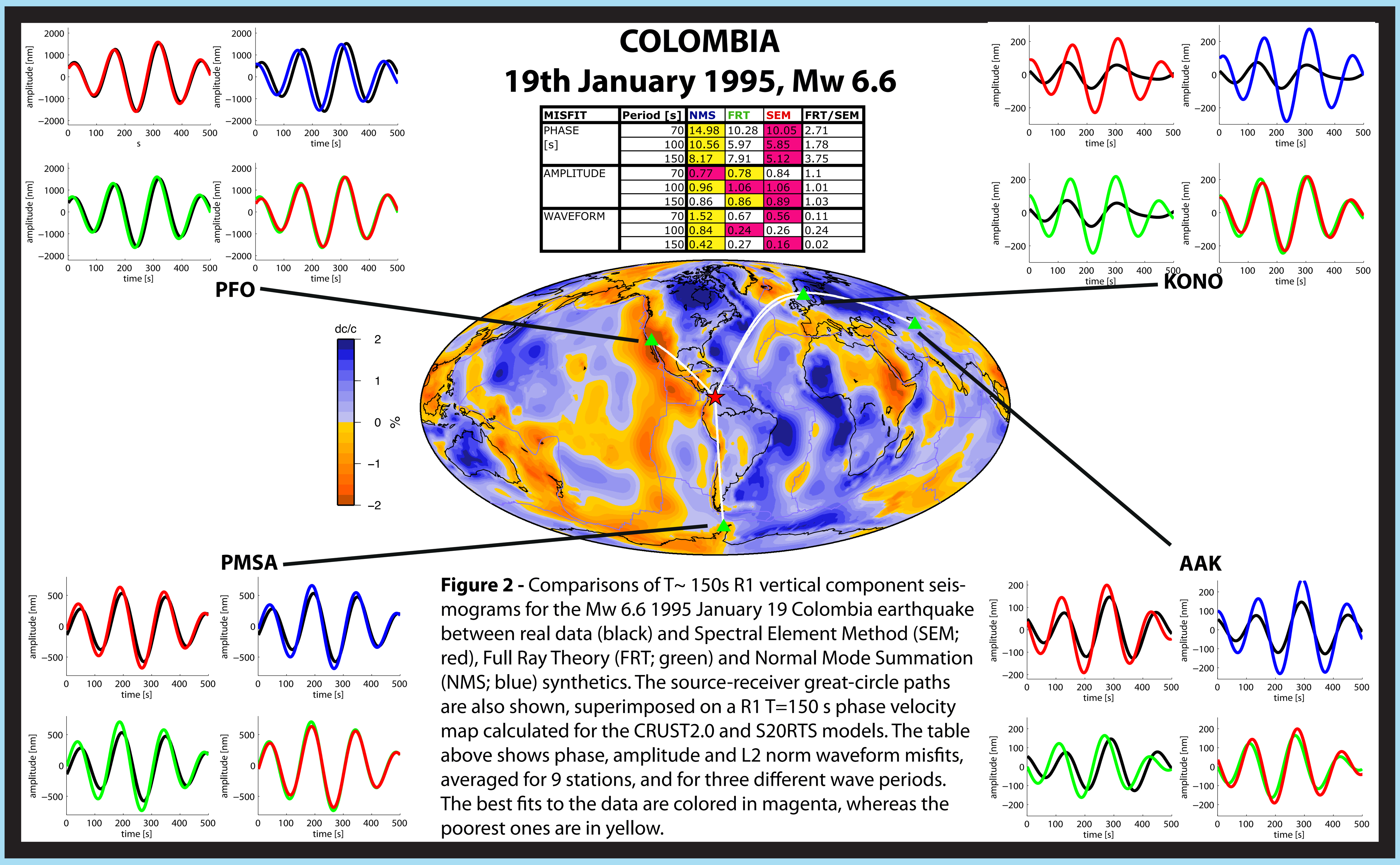
1. Is it necessary to use highly accurate but computationally expensive numerical methods (e.g., SEM) in global tomography, or can we use faster, approximate techniques (e.g., FRT, Born, a hybrid scheme)?

2. Which method is most appropriate to investigate different Earth mantle properties (e.g., seismic speeds, anisotropy, attenuation)?



MISFIT	Period [s]	MS	FRT	SEM	FRT/SEM
PHASE [s]	70	11.14	6.89	4.80	5.36
	100	10.43	9.68	6.53	4.94
	150	7.33	3.37	3.78	1.75
AMPLITUDE	70	1.29	1.91	1.68	0.82
	100	1.18	1.11	1.05	0.99
	150	0.76	0.70	0.67	0.93
WAVEFORM	70	1.19	0.53	0.44	0.15
	100	0.62	0.59	0.31	0.14
	150	0.75	0.24	0.29	0.01

Figure 1 - Comparisons of T~70s R1 vertical component seismograms for the Mw 6.1 1991 February 25 China earthquake between real data (black) and Spectral Element Method (SEM; red), Full Ray Theory (FRT; green) and Normal Mode Summation (NMS; blue) synthetics. The source-receiver great-circle paths are also shown, superimposed on a R1 T=70s phase velocity map calculated for the CRUST2.0 and S20RTS models. The table above shows phase, amplitude and L2 norm waveform misfits, averaged for 9 stations, and for three different wave periods. The best fits to the data are colored in magenta, whereas the poorest ones are in yellow.



MISFIT	Period [s]	NMS	FRT	SEM	FRT/SEM
PHASE [s]	70	14.98	10.28	10.05	2.71
	100	10.56	5.97	5.85	1.78
	150	8.17	7.91	5.12	3.75
AMPLITUDE	70	0.77	0.78	0.84	1.1
	100	0.96	1.06	1.06	1.01
	150	0.86	0.86	0.89	1.03
WAVEFORM	70	1.52	0.67	0.56	0.11
	100	0.84	0.24	0.26	0.24
	150	0.42	0.27	0.16	0.02

Figure 2 - Comparisons of T~ 150s R1 vertical component seismograms for the Mw 6.6 1995 January 19 Colombia earthquake between real data (black) and Spectral Element Method (SEM; red), Full Ray Theory (FRT; green) and Normal Mode Summation (NMS; blue) synthetics. The source-receiver great-circle paths are also shown, superimposed on a R1 T=150 s phase velocity map calculated for the CRUST2.0 and S20RTS models. The table above shows phase, amplitude and L2 norm waveform misfits, averaged for 9 stations, and for three different wave periods. The best fits to the data are colored in magenta, whereas the poorest ones are in yellow.

Method

We calculate phase, amplitude and L2-norm waveform misfits between vertical component minor-arc Rayleigh wave data and synthetic seismograms for two earthquakes in China and in Colombia. The phase and amplitude misfits are calculated using a least-squares algorithm that finds the optimal phase shift (in s) and amplitude factor that brings the synthetics into agreement with the data, and the L2-norm waveform misfits are given by the formula $\mathbf{m^2=(s-d)^2/d^Td}$.

We calculate data misfits for T=70s, T=100s and T=150s waveforms and for three types of synthetics: (i) Normal mode summation (NMS) for the 1D PREM model (Dziewonski and Anderson, 1981); (ii) SEM; and (iii) FRT for the CRUST2.0 (Bassin et al., 2000) model combined with S20RTS (Ritsema et al., 1999). Moreover, we also calculate misfits between SEM and FRT synthetics.

Preliminary results

Figures 1 and 2 show that the SEM and FRT simulations generally lead to a better data fit than NMS, with the 1-D PREM mode summation synthetics leading to the poorest fit to the phase data, as expected.

As for the amplitudes, the 3-D Earth simulations (SEM or FRT) do not lead to a systematic improvement in the data fit, probably due to limitations in the 3-D Earth models used and/or to unmodelled 3-D attenuation effect. However, these preliminary results need to be carefully verified by using a larger number of earthquakes and stations to carry out significant statistical comparisons.

Moreover, we need to ensure that exactly the same Earth models are used in the SEM and FRT calculations, which is presently not the case, as the crustal model CRUST2.0 is implemented slightly differently in the two algorithms. We are currently extracting depth profiles on a 2x2 degree surface grid while running the SEM simulations (Fig. 3), which will then be used as input models for the FRT calculations, and thus ensure that exactly the same Earth models are used.

We also plan to carry out comparisons of synthetics calculated for a variety of mantle and crust models with various levels of heterogeneity and complexity.

Conclusions

In this work we compared real seismograms with Full Ray Theory (FRT) and Spectral Element Method (SEM) synthetics, as part of an ongoing project aimed at finding optimal forward modeling schemes for global waveform tomography.

Our preliminary results suggest that:

1. Overall the SEM synthetics fit the phase data better than FRT, but there is a relatively good agreement with FRT synthetics. Depending on the level of accuracy desired, the faster approximate FRT approach may be suitable for waveform tomography.

2. Our 3-D Earth simulations do not improve the surface wave amplitude data fit compared with 1-D Earth calculations. This suggests that new 3-D elastic and anelastic Earth models are needed to explain surface wave amplitude data.

Future work:

- Use depth profiles extracted from SEM simulations as input models for FRT calculations to ensure that exactly the same Earth models are used in both types of simulations.

- Repeat this exercise for a large number of global earthquakes, stations and various Earth models to carry out meaningful statistical comparisons- to use depth profiles extracted while running the SEM simulations in order to ensure that exactly the same Earth models are used in the SEM and FRT simulations.

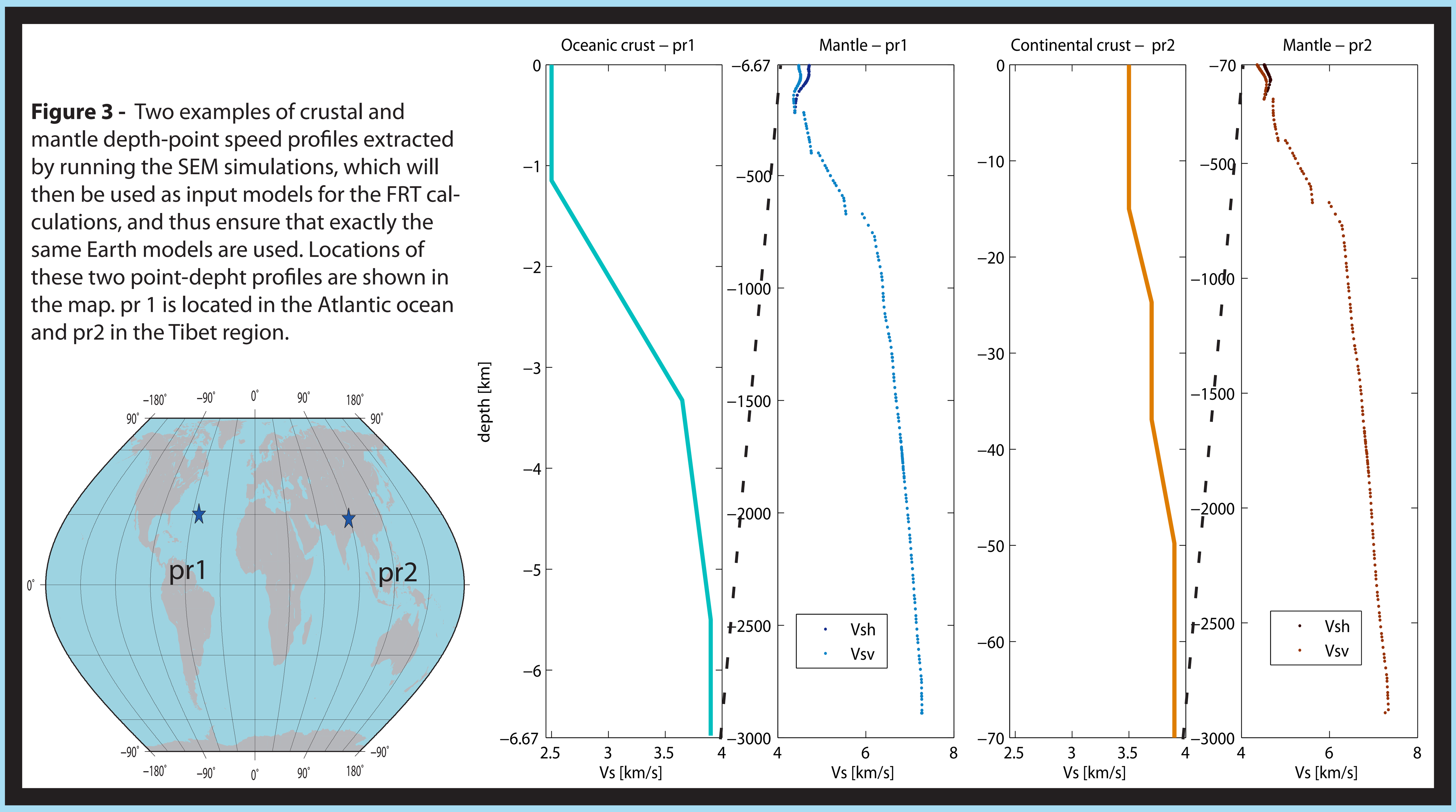


Figure 3 - Two examples of crustal and mantle depth-point speed profiles extracted by running the SEM simulations, which will then be used as input models for the FRT calculations, and thus ensure that exactly the same Earth models are used. Locations of these two point-depht profiles are shown in the map. pr 1 is located in the Atlantic ocean and pr2 in the Tibet region.

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