Global azimuthal anisotropic phase velocity maps for higher modes of Love and Rayleigh waves

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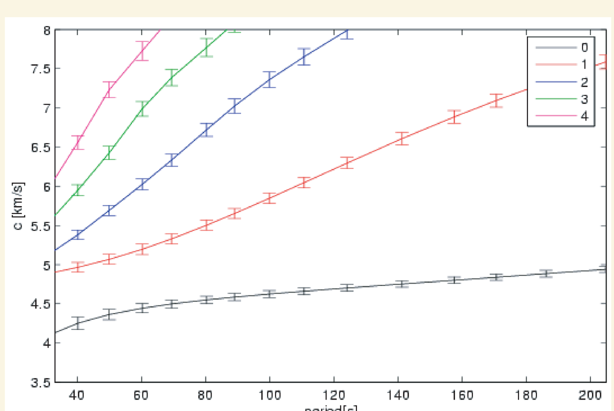
Introduction

It is well established that the Earth's uppermost mantle is anisotropic, but there are no clear indications of anisotropy in the deeper parts of the mantle. Surface waves are well suited to observe anisotropy since they carry information about radial and azimuthal anisotropy. Fundamental mode surface waves, for commonly used periods up to 200s, are sensitive to the first few hundred kilometers and therefore do not provide information on anisotropy below. Higher mode surface waves have sensitivities that extend to and beyond the transition zone and should thus give insight about azimuthal anisotropy at greater depths. We construct azimuthal anisotropic phase velocity maps for fundamental and higher mode Rayleigh and Love waves using phase velocity measurements for fundamental and higher mode surface waves (Visser et al., 2007). Following Trampert & Woodhouse (2003), we determine the optimum relative weighting for anisotropy prior to inversion.

Data

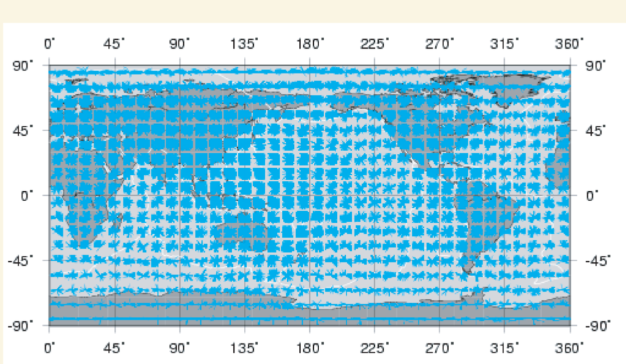
We measured higher mode phase velocity measurements of seismograms of the GDSN and GEOSCOPE networks from 1994-2004 using a model space search approach (Visser et al., 2007). The seismograms are separated in different frequency and time windows to be able to measure both the fundamental as well as the higher mode phase velocities. We performed a non-linear waveform inversion for a 1-D shear wave velocity model. This model allows us to compute phase velocities for each higher mode and at each period. Since we use a model space search approach we obtain an ensemble of models and we can compute the standard deviations. For one seismogram, we obtain a dispersion curve such as the figure below.



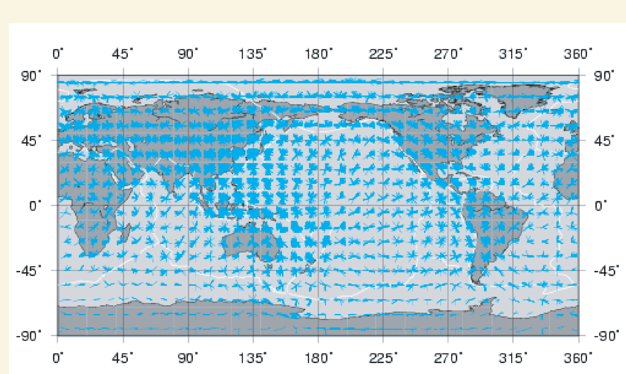
Dispersion curve for a single seismogram with corresponding uncertainty

We obtain phase velocity measurements for the fundamental and higher modes as well as the corresponding uncertainties.

Azimuthal coverage



Fundamental mode Rayleigh
63,628 measurements (best case)



Fifth higher mode Love
8,514 measurements (worst case)

Azimuthal anisotropy

In a slightly anisotropic medium:

$$\frac{dc}{c_0}(\omega,\psi) = \alpha_0(\omega) + \alpha_1(\omega)cos(2\psi) + \alpha_2(\omega)sin(2\psi) + \alpha_3(\omega)cos(4\psi) + \alpha_4(\omega)sin(4\psi)$$

We can write this as a classical inverse problem: $\mathbf{d} = \mathbf{Gm}$

Solving the cost function: $C = (\mathbf{d}-\mathbf{Gm})^T \mathbf{C}_d^{-1}(\mathbf{d}-\mathbf{Gm}) + \mathbf{m}^T \mathbf{C}_m^{-1}\mathbf{m}$

We know the data covariance (given by the standard deviations on the data), but not the model covariance. We partition the model covariance as follows

$$(C_{m_0})_{jj} = \frac{1}{\lambda}\frac{1}{[l(l+1)]^2}$$

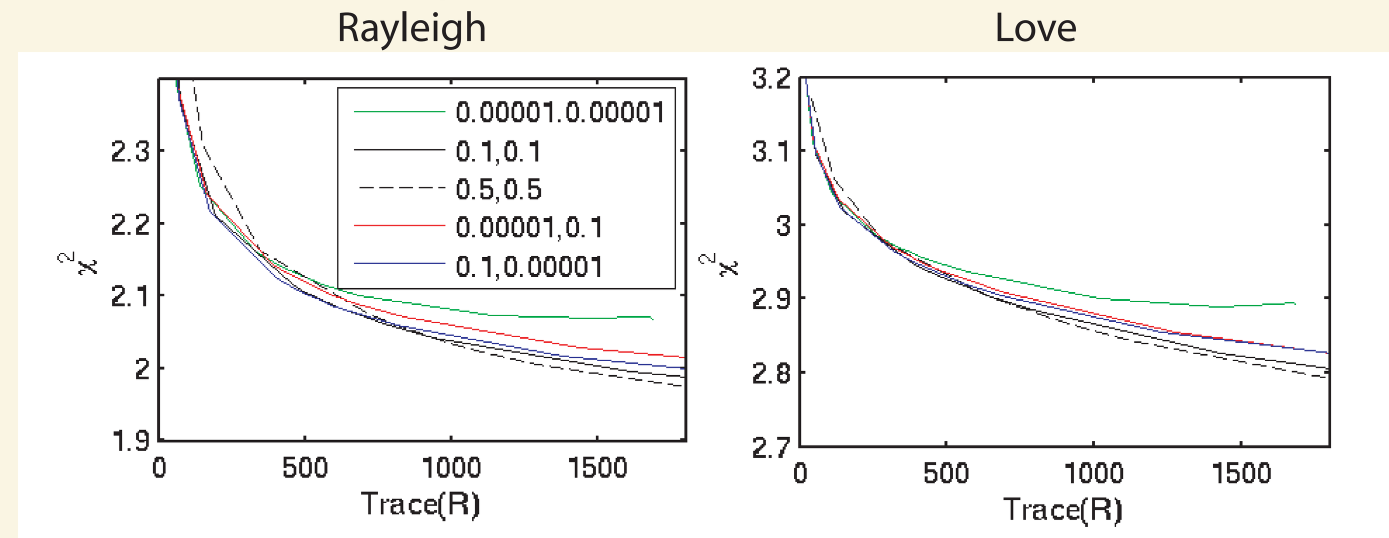
$$(C_{m_2})_{jj} = \frac{\theta_2}{\lambda}\frac{1}{[l(l+1)]^2}$$

$$(C_{m_4})_{jj} = \frac{\theta_4}{\lambda}\frac{1}{[l(l+1)]^2}$$

λ is an overall smoothing parameter
θ_2 and θ_4 determine the scaling relation between the isotropic and anisotropic terms. (θ_2,θ_4 = 0,0) means that we do not allow any anisotropy.

Do we need anisotropy to explain the phase velocity measurements?

Results for different scaling relations between the isotropic and anisotropic terms (θ_2,θ_4).



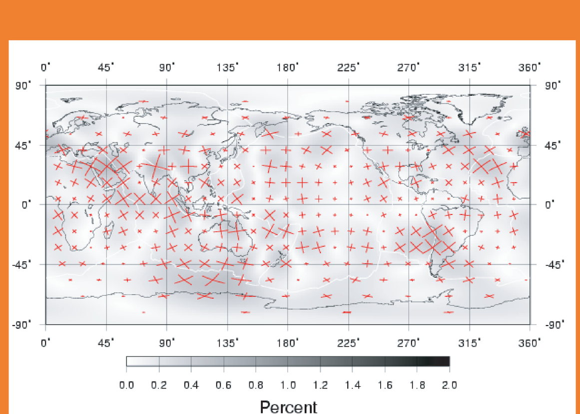
misfit curves for different scaling relations as a function of the trace of the resolution matrix

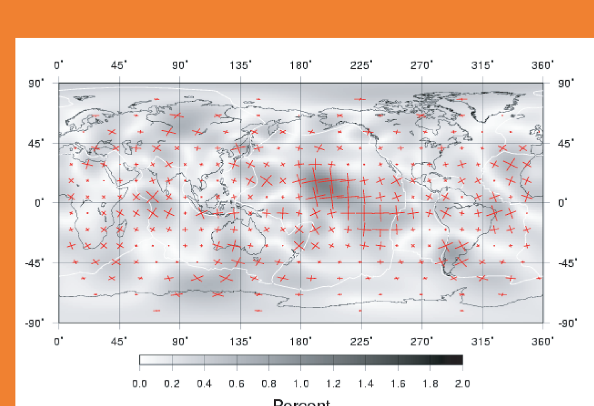
The Ftest tell us whether the difference from one curve to another is significant. At fixed overall damping i.e. trace (R) =1000, a significant difference (99%) is 0.023 (left figure) and 0.044 (right figure). The difference between the green curve (no anisotropy) and all the other curves (anisotropy) is such that we can conclude that we need anisotropy. However, we cannot determine the exact strength of the scaling relation since the difference between the anisotropic curves is too small. We choose (θ_2,θ_4=0.1,0.1) as a conservative measure allowing for both 2ψ and 4ψ anisotropy.

YES we need anisotropy

Results

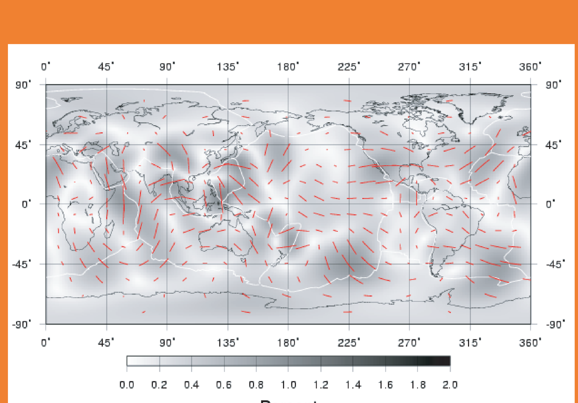
Third higher mode Rayleigh at 78 s and Love at 79s

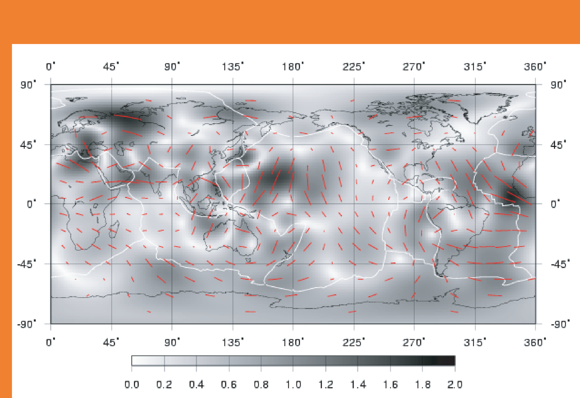




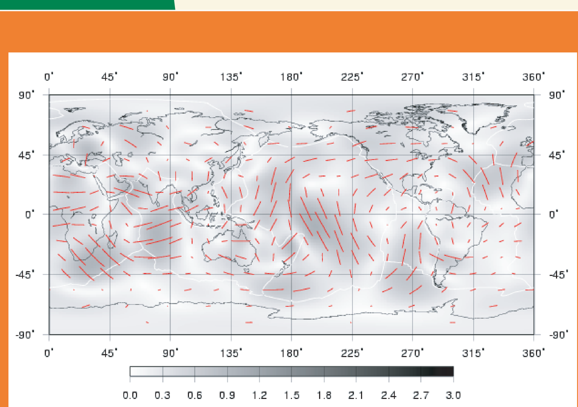
4ψ amplitude Love > 4ψ amplitude Rayleigh (due to sensitivity)

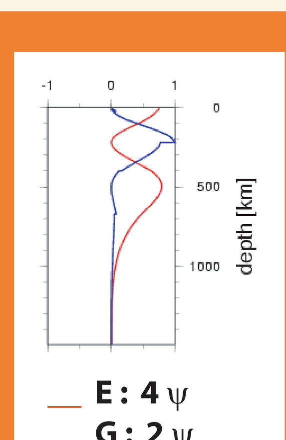
Fourth higher mode Rayleigh at 35s and Love at 35s



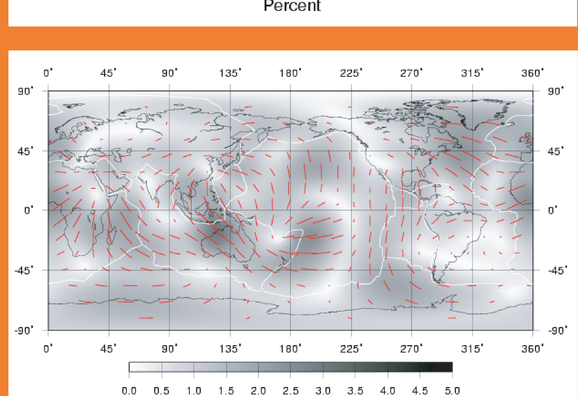


2ψ amplitude Love > 2ψ amplitude Rayleigh (Love has shallower sensitivity=> **shallow anisotropy**?)





2ψ first higher mode Love at 153s and sensitivity curve

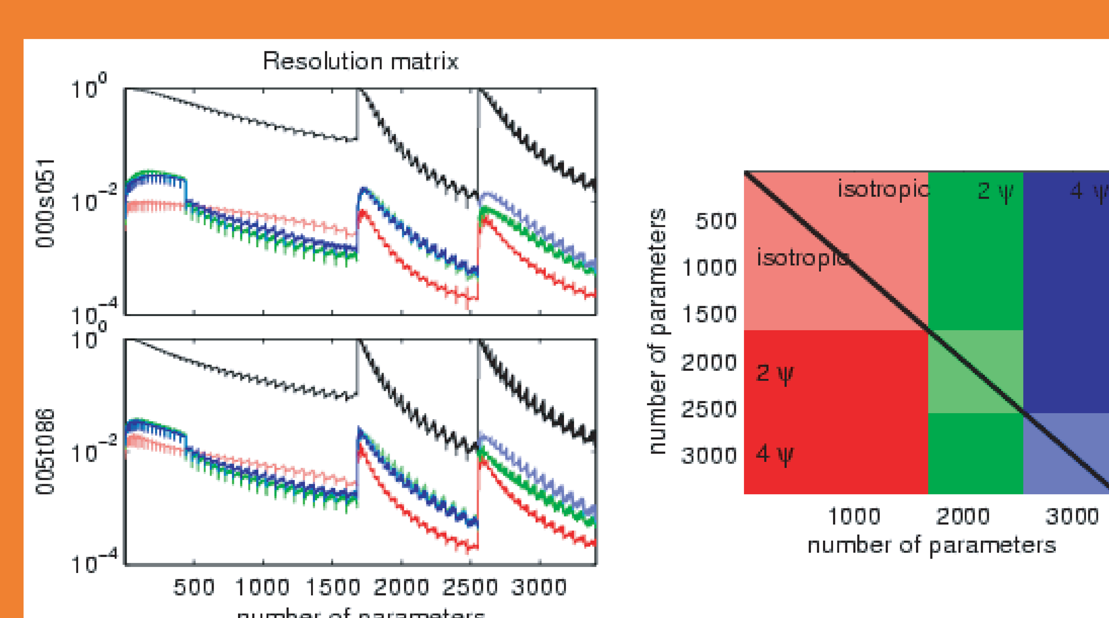


200 - 400 km
(Trampert and van Heijst 2002)

Same long scale wavelength of circulation between 200 and 400 km.

Resolution and Trade-off

Spectral leakage is suppressed by Laplacian damping. The trade-off between the isotropic and anisotropic terms can be investigated using the resolution matrix. The figure shows the resolution matrix for the fundamental mode Rayleigh at 175 s (000s051) and the fifth higher mode Love wave at a period of 56s (005t086).



The rms of peak broadening is indicated by the lighter shades of red, for isotropic, green, for 2ψ and blue for 4ψ. The diagonal of the resolution matrix is shown by the black curve. The rms of the trade-off between isotropic and anisotropic terms is shown by the bright color lines. The amount of trade-off is small for both the fundamental as well as the higher modes.

Concluding remarks

Love and Rayleigh fundamental and higher mode phase velocity measurements need 2ψ and 4ψ anisotropy. For all higher modes at all periods, the Love and Rayleigh 2ψ amplitude is larger than the 4ψ amplitude and the Love 4ψ amplitude is larger than the Rayleigh 4ψ amplitude. This is due to the sensitivity kernels. The Love 2ψ amplitude is larger than the Rayleigh 2ψ amplitude. The sensitivities have similar amplitudes but the Love sensitivity is shallower. Therefore this may indicate a shallow souce of anisotropy. We obtain a good correpondence at long wavelength for the fundamental mode with Trampert and Woodhouse (2003) and for the higher modes with Trampert and van Hejst (2002). Furthermore, we found that the spectral leakage and trade-off between the isotropic and anisotropic terms is small.

References

Trampert, J. & van Heijst, H. J., 2002, Global azimuthal anisotropy in the transition zone, *Science*, 296, 1297-1290

Trampert, J. & Woodhouse, J. H., 2003, Global anisotropic phase velocity maps of fundamental mode surface waves between 40 and 150 seconds, *Geophys. J. Int.*, 122, 675-690.

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