SENSITIVITY KERNELS FOR INTERSTATION CROSS-CORRELATIONS

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INTRODUCTION

For regional surface wave tomography the interstation method is often used. This method relies on the cross-correlation between two seismograms, recorded at two stations. In case of wave propagation from the event to both stations along a single great-circle, the average (frequency dependent) phase velocity between the stations can be estimated from the cross-correlation.

However, several studies[1,2,3] show evidence of propagation off the great-circle. Also, it is practically impossible to find earthquakes that are located exactly on the great-circle of interest. Hardly any research has been done to check whether the interpretation of the interstation method is adequate. The effect that a known perturbation at a certain location would have on the seismograms should therefore be quantified.

Using the adjoint method[4], sensitivity kernels can be determined. Here we calculate sensitivity kernels for a 1-D Earth model (PREM[5]) based on cross-correlations. Simulations are done using the spectral element programme package SES3D[6]. Since single-frequency measurements are difficult to obtain, the source time function is based on a band of frequencies. In the following, kernels that are based on a broad frequency band (25 – 35 s) will be referred to as group velocity measurements. By decreasing the frequency range, phase velocity (30 s) is approached.

APPROACH

The basic procedure of the adjoint method is that the 'forward' wavefield, excited by the actual source, interacts with an 'adjoint' wavefield, which is based on the misfit. The adjoint wavefield travels from the receiver to the source, and is excited by an adjoint source, located at the receiver.

The misfit χ which is minimized is defined by:

$$\chi = T_{syn} - T_{obs}$$

T : traveltime between station A and B, found from maximum of cross-correlation

Which results in the following expression for the vertical component of the adjoint source $f_z(x,t)$, where s_z refers to the vertical component seismogram:

$$f_z(\mathbf{x},t) = \frac{\dot{s}_z^B(t - T_{syn})\delta(\mathbf{x} - \mathbf{x}^A) - \dot{s}_z^A(t + T_{syn})\delta(\mathbf{x} - \mathbf{x}^B)}{\int_{-\infty}^{\infty} \ddot{s}_z^A(t + T_{syn}) s_z^B(t)\,dt}$$

The adjoint source is a force consisting of two terms, normalized by the term in the denominator:
- At location of station A: velocity seismogram at station B, shifted forward in time by T_{syn}.
- At location of station B: velocity seismogram at station A, shifted backward in time by T_{syn}.

Note that the adjoint wavefield does not depend on the observed data.

For a source time function with a large frequency band, the traveltime difference T_{syn} refers to the group velocity, whereas a small frequency band approaches a travel time difference that gives the phase velocity.

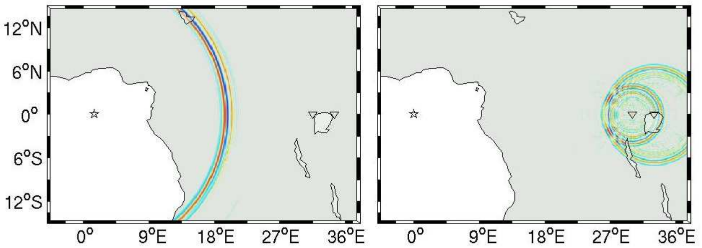

Figure 1: Forward (left) and adjoint (right) wavefields after 3000 time steps. Stars represent source, triangles represent receivers.

RESULTS

Group versus phase velocity

Figures 2 and 3 show the sensitivity kernels based on a single source and two receivers, for a wide frequency range (group velocity) and a narrow band (phase velocity).

Although in both cases the sensitivity between the receivers is relatively large, the kernel is not zero for a large region outside the interstation area. However, the sensitivity for the phase velocity measurement decreases from receiver to source, whereas the group velocity measurement has a more uniform kernel.

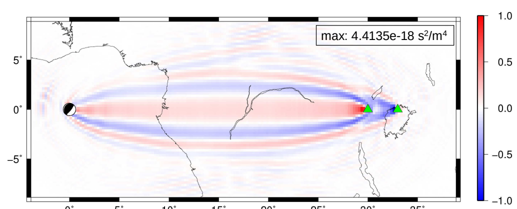

Figure 2: Shear velocity sensitivity kernels at 100 km depth for a single source, based on surface wave data. The kernel is obtained for group velocity with a period range of 25 – 35 s. The interstation distance is 3°.

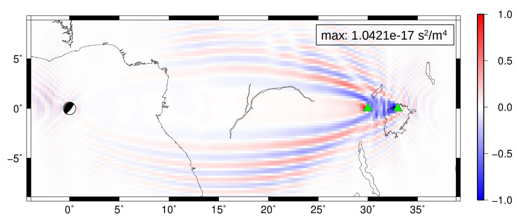

Figure 3: Shear velocity sensitivity kernels at 100 km depth for a single source, based on surface wave data. The kernel is obtained for phase velocity with a period of 30 s. The interstation distance is 3°.

Source effects

The radiation pattern of a source has a large effect on the Rayleigh wave excitation and therefore also on the sensitivity kernel (see figures 4 and 5). However, reduced sensitivity close to the source for phase velocity kernels, compared to group velocity, is still visible.

The sensitivity kernels are independent of magnitude; focal depth was found to have a negligible effect.

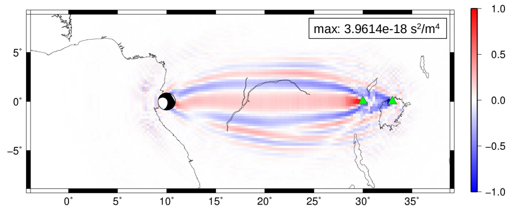

Figure 4: Shear velocity sensitivity kernels at 100 km depth for a single (different) source, based on surface wave data. The kernel is obtained for group velocity with a period range of 25 – 35 s. The interstation distance is 3°.

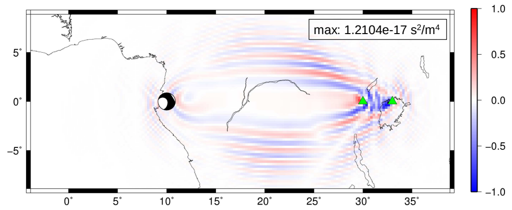

Figure 5: Shear velocity sensitivity kernels at 100 km depth for a single (different) source, based on surface wave data. The kernel is obtained for phase velocity with a period of 30 s. The interstation distance is 3°.

Number of sources:

Since the sensitivity kernels are independent of the observed data, they can be combined by adding the values of each separate kernel per grid cell. Adding kernels of three different sources (figure 6) shows that combining multiple sources increases the relative interstation sensitivity significantly, whereas the values close to the sources are reduced.

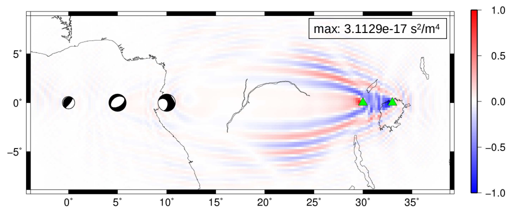

Figure 6: Sum of shear velocity sensitivity kernels at 100 km depth for three different sources, based on surface wave data. The kernels are obtained for phase velocity with a period of 30 s. The interstation distance is 3°.

Sources from two directions

Since often events from two different directions are used, it is useful to include this in the sensitivity kernel. Figure 7 shows that when sources from both sides of the station pair are included, the interstation sensitivity is increased. However, additional sensitivity is introduced at the other side of the station pair.

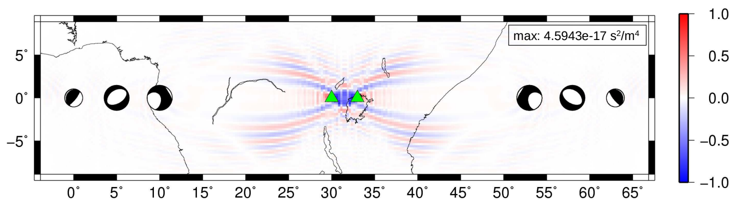

Figure 7: Sum of shear velocity sensitivity kernels at 100 km depth for six different sources, based on surface wave data. The kernels are obtained for phase velocity with a period of 30 s. The interstation distance is 3°.

SUMMARY & CONCLUSIONS

In the figures shown above the sensitivity between the stations is relatively large. However, the streaks that are located outside the interstation area and slightly north and south of the great-circle will remain dominant features, even if phase velocity measurements of many sources are combined. Perturbations in these areas have a large effect on the traveltime difference between the stations. Assuming that the traveltime difference is caused by the interstation area only might result in wrong interpretations of the measurement. Therefore, the kernels should be included in inversion, rather than just assuming that the interstation method is adequate.

FUTURE RESEARCH

- Investigate other frequencies
- Investigate the effect of interstation distance
- Distribute sources randomly (off great-circle)
- Perform similar tests for more complex Earth models

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