SENSITIVITY KERNELS FOR INTERSTATION CROSS-CORRELATIONS

ISES — The Netherlands Research Centre for Integrated Solid Earth Science — Searching deeper

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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, even for a simple Earth model such as PREM[1], it is likely that small velocity perturbations, that are located slightly off the great-circle, can influence the arrival times at both stations. The effect that a known perturbation at a certain location would have on the seismograms should therefore be quantified.

Using the adjoint method[2], sensitivity kernels can be determined. For the cross-correlations of the interstation method, one would expect large values between both stations, whereas the sensitivities between the source and the closest station are expected to cancel because of the similarity of the ray paths. However, hardly any research has been done to check whether this is true. The first step of this research is to create sensitivity kernels for a simple Earth model (PREM), based on interstation cross-correlations. Simulations are done using the spectral element programme package SES3D[3].

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 receivers (found from maximum of cross-correlation)

Which results in the following expression for the vertical component of the adjoint source $f_z(\mathbf{x},t)$, 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 2 terms:

→ 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, which is an advantage for this study.

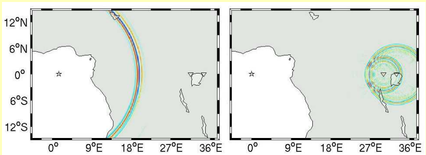

Figure 1: Forward (left) and adjoint (right) wavefields after 3000 time steps. Stars represent source, triangles represent receivers.

RESULTS

NUMBER OF SOURCES - Sensitivity kernels that are based on a single source and two receivers (as in the left part of figure 2), give relatively large values between the source and the closest receiver. Although the sensitivity between the stations is larger than in surrounding areas, the effects between the source and the nearest receiver do not cancel.

Adding kernels based on ten different sources (right part of figure 2) show that combining multiple sources increases the relative interstation sensitivity significantly, because the values in surrounding areas partly cancel out.

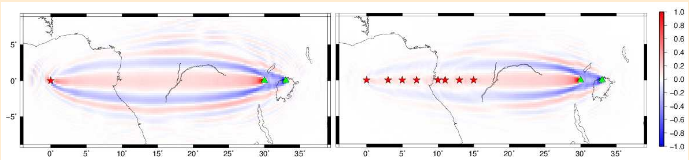

Figure 2: Horizontal sections at 100 *km* depth through sensitivity kernels for shear wave velocity, based on one source (left) and ten sources (right). Surface wave data were used, with a period range of 35 – 45 *s*. Stars represent sources, triangles represent receivers. The interstation distance is 3°.

SOURCES FROM TWO DIRECTIONS - Figure 3 shows that when sources from both sides of the station pair are included, the interstation sensitivity is relatively increased. However, additional sensitivity is introduced at, in this case the right side of the station pair.

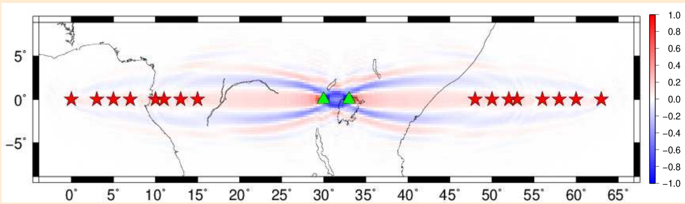

Figure 3: Horizontal section at 100 *km* depth through sensitivity kernel for shear wave velocity, based on twenty sources, symmetrically distributed along the great-circle. Surface wave data were used, with a period range of 35 – 45 *s*. Stars represent source, triangles represent receivers. The interstation distance is 3°.

INTERSTATION DISTANCE - Similar tests were performed for station pairs with larger interstation distances. Figure 4 shows the resulting sensitivity kernels based on six sources; three on both sides of the station pair. The relative interstation sensitivity depends on interstation distance. Other tests have shown that this is also dependent on the frequency band considered.

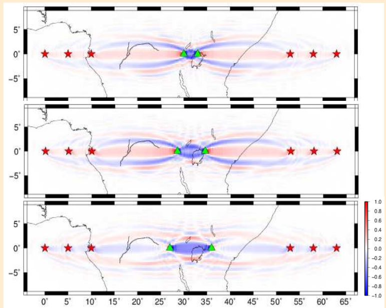

Figure 4: Horizontal sections at 100 *km* depth through sensitivity kernels for shear wave velocity, with different interstation distances (3°, 6°, and 9°). Surface wave data were used, with a period range of 35 – 45 *s*. Stars represent source, triangles represent receivers.

SOURCE MECHANISM - The source mechanism has a large effect on the seismogram. As a consequence, the traveltime difference between both stations, which is obtained from the cross-correlation between the seismograms at both receivers, is influenced by the source. Since the sensitivity kernels are based on this traveltime difference, they are indirectly affected by the source as well (see figure 5).

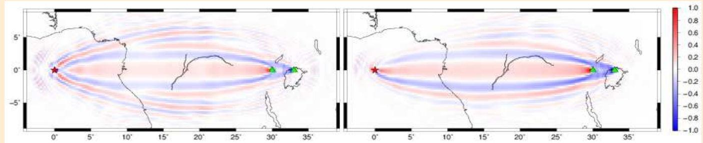

Figure 5: Horizontal sections at 100 *km* depth through sensitivity kernels for shear wave velocity, using a symmetric (left) and an asymmetric (right) moment tensor. Surface wave data were used, with a period range of 35 – 45 *s*. Stars represent sources, triangles represent receivers. The interstation distance is 3°.

EPICENTRAL DISTANCE - Tests for larger epicentral distances (about 60° instead of 30°) give very similar results to those shown above. Increasing the model is therefore not useful in this stage of the research.

CONCLUSIONS

Figures 2 - 5 show that the assumptions made in the interstation method (i.e. the great-circle path only affects the arrival times) are too simple, even for a 1D Earth model.

The sensitivity kernels are dependent on

- The number of sources.
- The location of sources (on one, or both sides of the station pair).
- The interstation distance.
- The frequency range considered.
- The source mechanism.

NEXT STEPS IN FURTHER RESEARCH

- Create sensitivity kernels for one frequency (i.e. use phase velocity instead of group velocity).
- Investigate relation between interstation distance and frequency.
- Distribute sources randomly (off great-circle).
- Investigate the effects of source mechanism, magnitude and depth.
- Investigate smaller periods → sensitive to smaller scale.
- Perform similar tests for more complex Earth models.

REFERENCES

[1]Dziewonski, A. and Anderson, D. (1981). Preliminary Reference Earth Model. *Physics of the Earth and Planetary Interiors*, 25: 297 – 356.

[2]Fichtner, A. Bunge, H.-P. and Igel, H. (2006). The adjoint method in seismology I. Theory. *Physics of the Earth and Planetary Interiors*, 157: 86 – 104.

[3]Fichtner, A. (2009). SES3D version 2.1: Programme Description and Mathematical Background. 51 p.