LOCALISATION OF SEISMIC EVENTS BY A MODIFIED DIFFRACTION STACK

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ABSTRACT

The localisation of seismic events is a key problem in seismology as well as in exploration seismics. We suggest a new localisation technique based on a modified diffraction stack. The method is target-oriented and can be applied to surface and/or downhole receivers. It is best suited for large networks. Application of the method leads to an image in which the source positions can be clearly identified, even in the case of a high noise level in the data. This is an advantage over conventional methods based on picking arrivals, which is not possible with noisy data. The method performs well in the presence of near-surface complexities as well in situations where the exact velocities are not available.

INTRODUCTION

Localisation of seismic events is an important task not only in seismology but also for a multitude of applications in exploration seismics, for example hydraulic fracturing and reservoir monitoring. Therefore, over the years, many different techniques have been suggested for seismic source localisation (for an overview, see, e.g., Pujol 2004).

However, most classic localisation methods require picking of the event at each station. In the presence of noise, it can be a problem to identify weak events in the individual seismogram. Also, in particular in exploration seismic, the larger number of stations on the recording network can make the picking procedure and the necessary quality control a tedious task.

Recently, Gajewski and Tessmer (2005) introduced a localisation technique based on reverse modelling. The measured data are back-projected and picking is, therefore, not required in the method. In addition, the focussing of the back-projected energy leads to an image even if the events cannot be identified in the input data.

The relatively high computational effort for the reverse modelling has motivated Anikiev et al. (2006) to develop a new localisation method that uses a modified diffraction stack for the back-projection. In contrast to reverse modelling, this method also permits to work in a target-oriented way, thus further enhancing the computational efficiency.

Synthetic studies revealed that the *image section* obtained from the stack for a given time window shows a distinct maximum at the position of the source. The localisation is reliable for data with a high noise level and in the presence of near-surface complexities. A modification even allows to apply the method if the velocity model isn't well-known.

In the next section, we will describe the method before illustrating it with the results of numerical experiments with high noise level, a complex overburden, and an unknown velocity model.

METHOD

For simplicity we will restrict this section to two dimension. The extension to 3-D is straight-forward. In the following, we will assume that the seismic events are caused by point sources, i.e. the extent of the source region is small compared to the wavelength, with small magnitudes.

The position of such an 'acoustic emission' in a homogeneous medium can be reconstructed from surface measurements by applying Kirchhoff theory. Here, the subsurface is discretized, and the seismic traces are weighted and stacked along the diffraction traveltime curve (surface in 3-D) for each subsurface point. The maximum amplitude is then located at the original source position.

In practice, application of this theory is not straightforward due to several reasons. The major drawback is that the simple diffraction stack described above requires knowledge of the excitation time. Furthermore, the classic Kirchhoff theory can be extended to heterogeneous media, but a velocity model is still required. Finally, whereas the theory assumes an infinite aperture of the experiment, in practice only a limited number of receivers is available. This last point will be addressed in a follow-up paper.

As shown by Anikiev et al. (2006), a modified diffraction stack leads to a localisation even if the source time isn't a priori know. The modification is intuitive as the diffraction stack is simply performed for all possible source times within a time window. For each subsurface point under consideration the individual stacks are then squared and summed, resulting in the *image section*.

The seismic traces contribute energy to the stack only if the subsurface point is close to the source point and if the assumed excitation time is close to the real source time. Therefore, the maximum of the image section occurs at the true source position although an additional stack was performed over the times. This has been proved by Anikiev et al. (2006) for the case of a homogeneous medium. The squaring of the individual diffraction stack results is necessary to allow for different signal phases.

This extension of the classical Kirchhoff theory even permits us to determine the excitation time of the source in a second step. More details can be found in Anikiev et al. (2006) and Gajewski et al. (2007).

To perform the localisation with an unknown velocity model we apply a similar strategy as for the unknown excitation time: the localisation is carried out for a range of velocities, and the results are summed. A stack for a given velocity model will make a significant contribution when the assumed model is reasonably close to the real velocity distribution. Therefore, the maximum of the image section will still occur at the real source position.

NUMERICAL EXAMPLES

In this section we demonstrate the performance of our method with several examples. First, we show results of a noise-free synthetic data set for a homogeneous medium as reference. Then we repeat the experiment with added noise. A third example illustrates the accuracy of the localisation in the presence of near-surface complexities. Finally, we apply the method to the case of an unknown velocity model.

The synthetic seismograms for all examples were generated with a pseudo-spectral Fourier modelling code. The discretization of the subsurface grid was 2 m in either direction, and the source signal was a Ricker wavelet with a central frequency of 100 Hz, corresponding to a maximum frequency of 200 Hz.

Noisy data

For our first example, we have chosen a homogeneous medium with V=3000 m/s. The acquisition is sketched in Figure 1. Seismograms were computed for 198 receivers with a spacing of 10 m, corresponding to an aperture of 1970 m. The source was placed at a depth of 2000 m and at a lateral position of 1200 m, i.e. 215 m from the center of the aperture. Figure 2 shows the modelled seismograms.

The length of the time window for the localisation was 1 s with an increment of 0.5 ms.

The image function resulting from these data is displayed in Figure 3.The maximum of the image function is very close to the true source position also indicated in Figure 3. The focal region of the image function is oblique and elongated in depth. The obliqueness stems from the asymmetric aperture with respect to the source position. Since receiver coverage was only given at the surface, the resolution in depth is less high than the lateral resolution. If data were also registered at different depth levels (e.g. from a borehole), the depth resolution could be considerably enhanced.

In a second example, we have added white noise with a signal-to-noise ratio of 0.5 to the same data as in the previous example. In the resulting seismograms, shown in Figure 4, the event cannot be identified due to the high noise level.

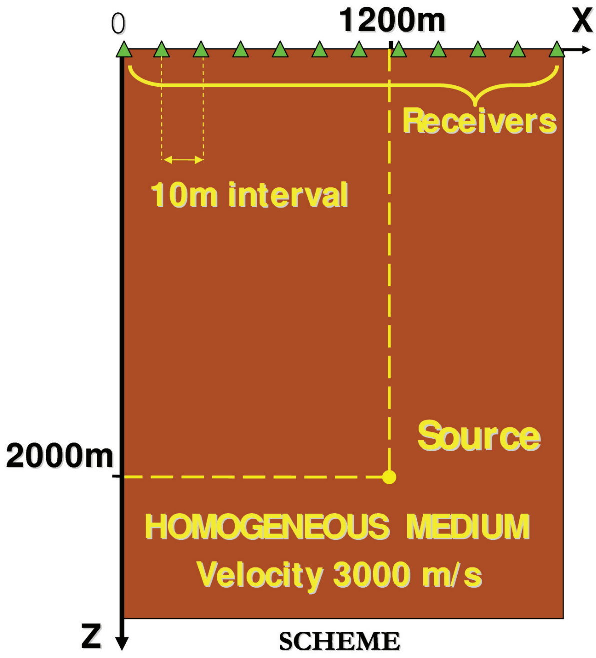

Figure 1: The model and acquisition scheme for the first two examples. The aperture of the synthetic experiment consists of 198 receivers with a 10 m spacing. The source is placed at (1200 m, 2000 m) in a homogeneous medium with V=3000 m/s.

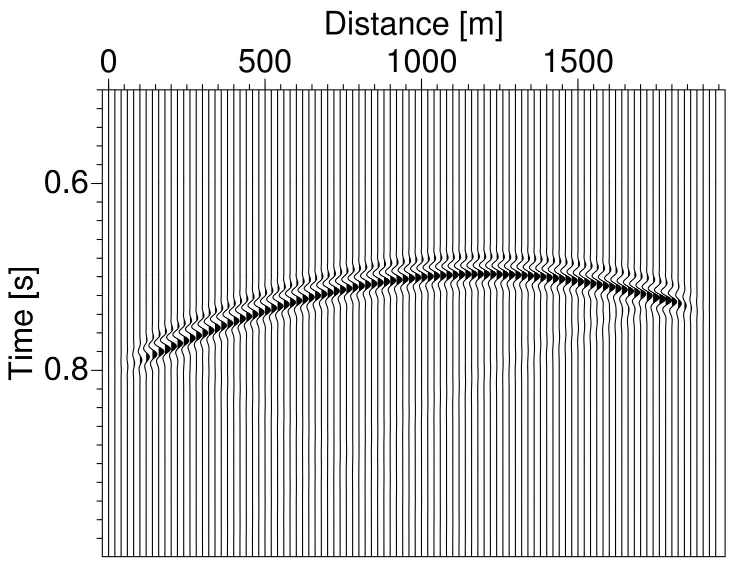

Figure 2: The synthetic seismograms generated for the model shown in Figure 1. A taper was applied toward the end of the aperture. Note that the time axis does not begin at zero.

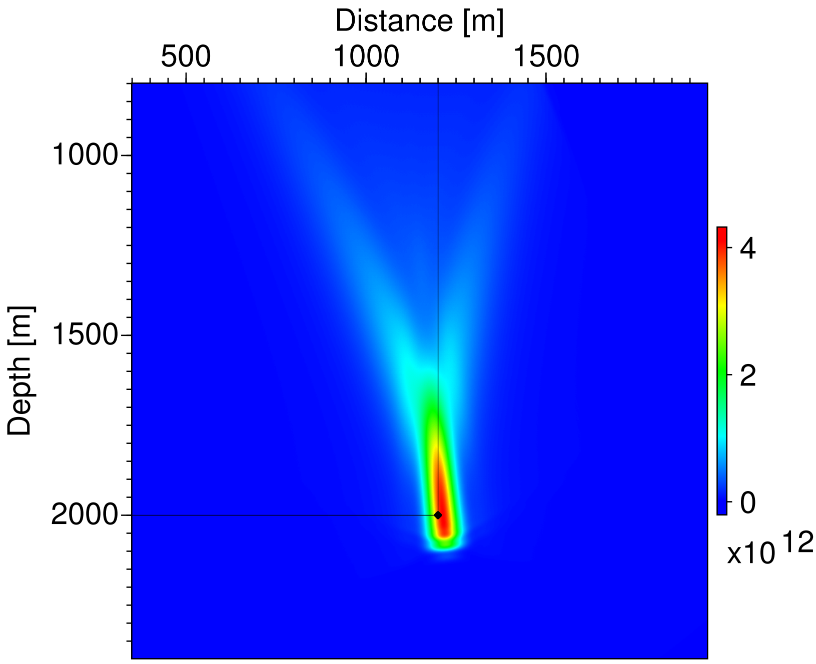

Figure 3: Image function obtained from applying the localisation to the data shown in Figure 2. The maximum amplitude in the focal region corresponds to the most likely source position. It is close to the real source position indicated by the circle. The shape of the focal region depends on the aperture of the experiments; please refer to the main text for details.

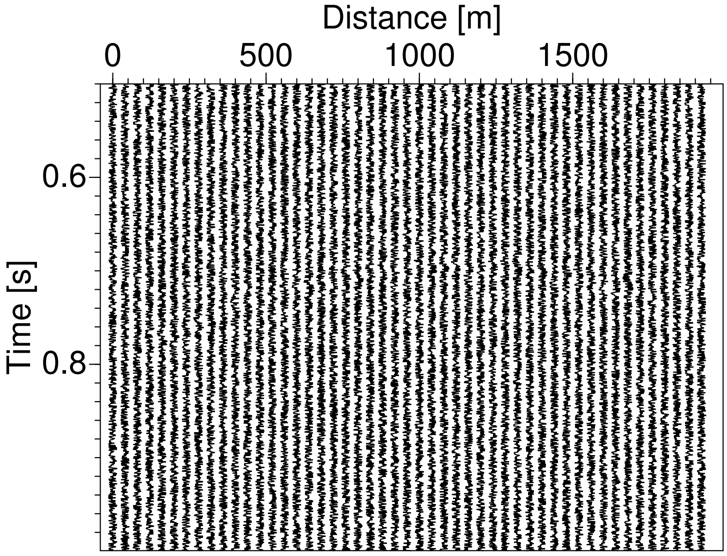

Figure 4: The same seismograms as shown in Figure 2, but with white noise added (S/N ratio of 0.5). The event cannot be identified on the individual traces. Classic localisation methods requiring picking cannot be applied in this case.

Figure 5 displays the image function obtained from the noisy data. Despite the high noise level in the input data the focal region still shows a distinct maximum and the accuracy of the localisation is the same as for the same data without noise. Due to the stacking process involved in the localisation procedure the signal-to-noise ratio of the image section increases with the number of receivers.

Complex overburden

In the next example we have investigated the influence of a scattering layer on the localisation. Figure 6 displays the model structure and acquisition. The experiment uses 143 receivers with a spacing of 10 m, leading to an aperture of 1420 m. The source is located at (360 m, 400 m) in a homogeneous medium with a complex layer comprising the topmost 150 m, represented by a Gaussian random medium. The homogeneous medium velocity is V=2000 m/s, and this is also the background velocity in the scattering layer.

The length of the time window for the localisation was 0.5 s and the time step was 0.5 ms. We have carried out the localisation with data modelled for different correlation lengths and standard deviations. The traveltime curves applied during the stacking process were computed for the homogeneous background medium.

Figure 7 shows seismograms generated for a correlation length of 50 m, a third of the layer thickness, and a standard deviation of 5 %. This means that velocity deviations up to $\pm$20 % or $\pm$400 m/s can occur. Nevertheless, the maximum of the image function (Figure 8) is close to the real source position.

We have repeated the experiment for a correlation length of 10 m. Figure 9 shows the seismograms and Figure 10 the image function. The localisation accuracy obtained for the correlation length of 10 m is slightly higher than for 50 m. For comparison, Figure 11 displays the image function for data modelled without surface heterogeneities. The difference in localisation accuracy is insignificant.

Furthermore, in Figure 12 we show seismograms generated for a correlation length of 50 m and a standard deviation of 12 %. In this case, the velocity variations can be up to almost $\pm$50 %, i.e.$\pm$1000 m/s. The shape of the event in Figure 12 is no longer hyperbolic. In this case, the traveltime for a homogeneous

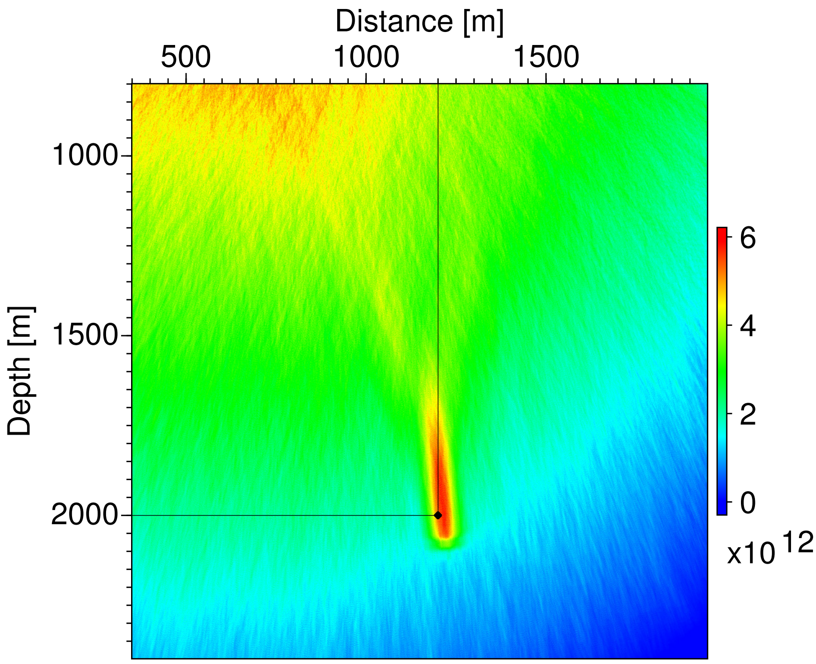

Figure 5: Image function obtained from applying the localisation to the noisy data shown in Figure 4. The maximum is still distinct and close to the real source position.

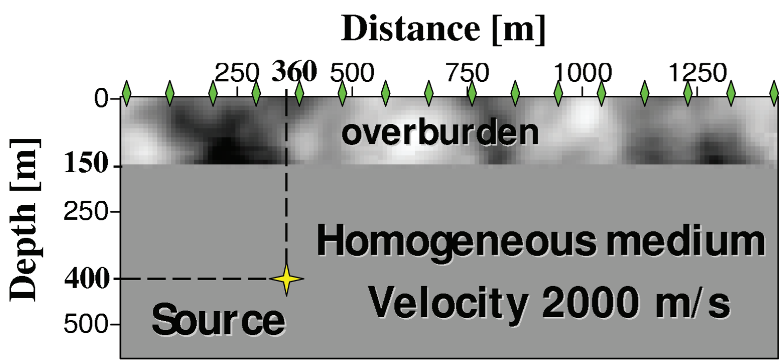

Figure 6: The model and acquisition for the experiment with near-surface complexities. The aperture consists of 141 receivers with a 10 m spacing. The source is placed at (360 m, 400 m) in a homogeneous medium with V=2000 m/s. A scattering layer of 150 m thickness was simulated with a Gaussian random medium.

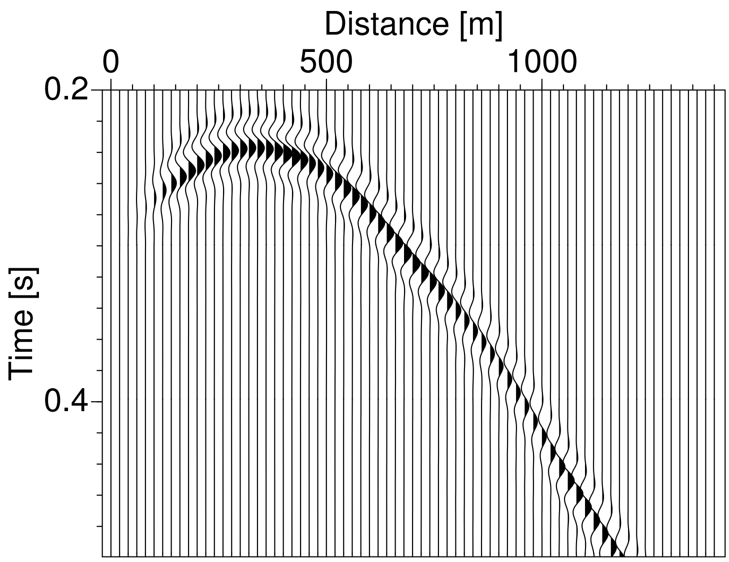

Figure 7: Seismograms for the overburden model shown in Figure 6. The correlation length of 50 m and a standard deviation of 5 % cause the shape of the event to deviate from a hyperbola.

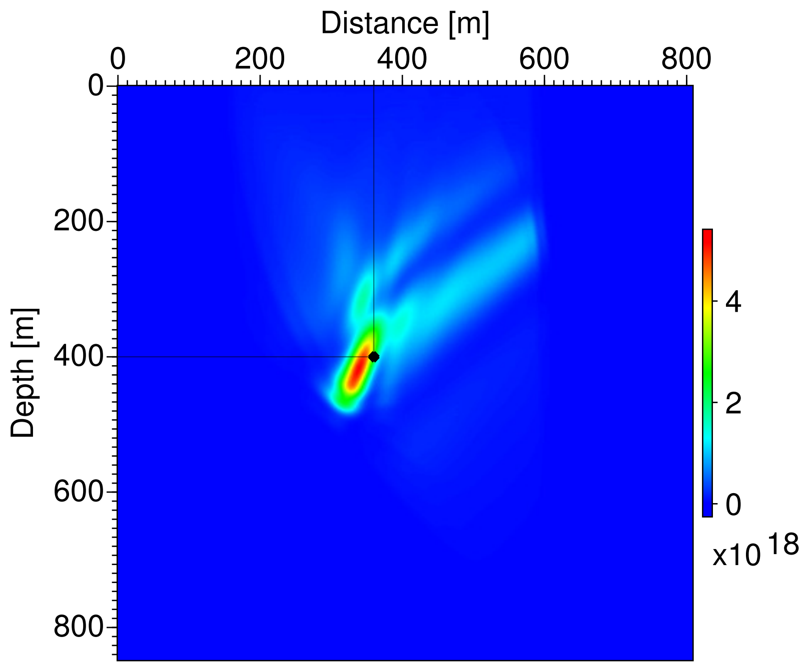

Figure 8: Image function obtained from localisation assuming constant velocity where the data was generated with a correlation length of 50 m and a standard deviation of 5 %. The maximum is still reasonably close to the real source position.

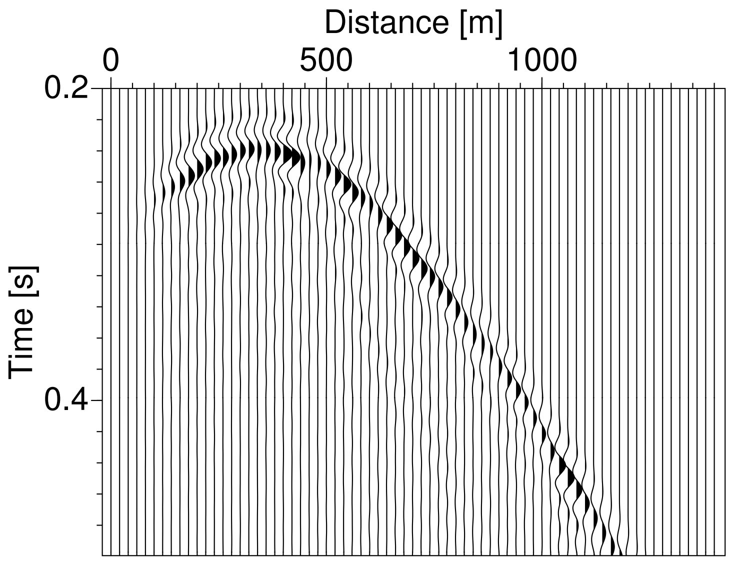

Figure 9: Seismograms for the overburden model shown in Figure 6. The correlation length of 10 m and a standard deviation of 5 % cause the shape of the event to deviate slightly from a hyperbola. The deviation is smaller than for a correlation length of 50 m, see Figure 7.

medium deviates too far from the real diffraction stacking curve. As expected, the localisation does not yield satisfactory results: In Figure 13, the focal area is separated into two regions, each of which has an individual maximum. Neither the positions nor the amplitudes of the maxima permit to identify the real source position.

Unknown velocity model

In our last example, we have again applied the method to data modelled for the overburden model (Figure 6) with a correlation length of 10 m and a standard deviation of 5 % (Figure 9). However, this time we have assumed that the medium velocity was unknown. As described above and initially suggested by Anikiev et al. (2006), we have repeated the stacking procedure over a range of velocities, from 1800 m/s to 2200 m/s with an increment of 40 m/s. The true medium velocity in the homogeneous part and background velocity in the scattering layer was 2000 m/s. Figure 14 shows the image section obtained from the localisation for unknown velocities. Although the focal region is slightly less well-defined in comparison to Figure 9, the image function for the same data computed for the known velocity, the maximum is still close to the real source position.

This is an important result as it shows that the localisation method is even reliable in the case that a detailed velocity model is not available.

OUTLOOK AND CONCLUSIONS

We have suggested an applied a new method for the localisation of seismic events. It is based on a modified diffraction stack and leads to a resulting *image section* where the maximum coincides with the source position. The method can be applied in a target-oriented way and requires no picking of arrival times in the individual seismograms.

In contrast to conventional localisation methods our technique produces reliable results even in situations where the noise level does not permit to identify the event in the seismic data. Another example was

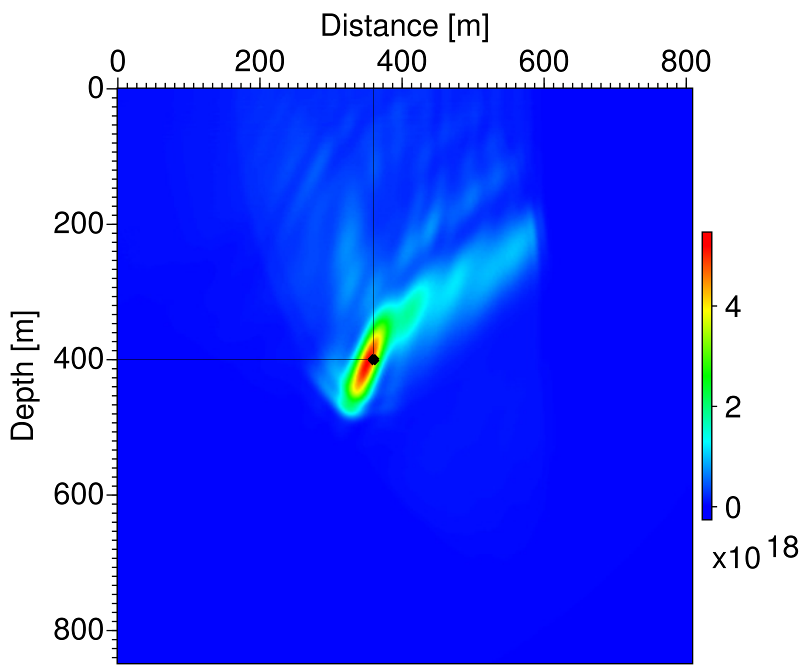

Figure 10: Result of localisation assuming constant velocity where the data was generated with a correlation length of 10 m and a standard deviation of 5 %. The localisation accuracy is higher than for a correlation length of 50 m (see Figure 8). The difference to localisation with data modelled without overburden (Figure 11) is negligible.

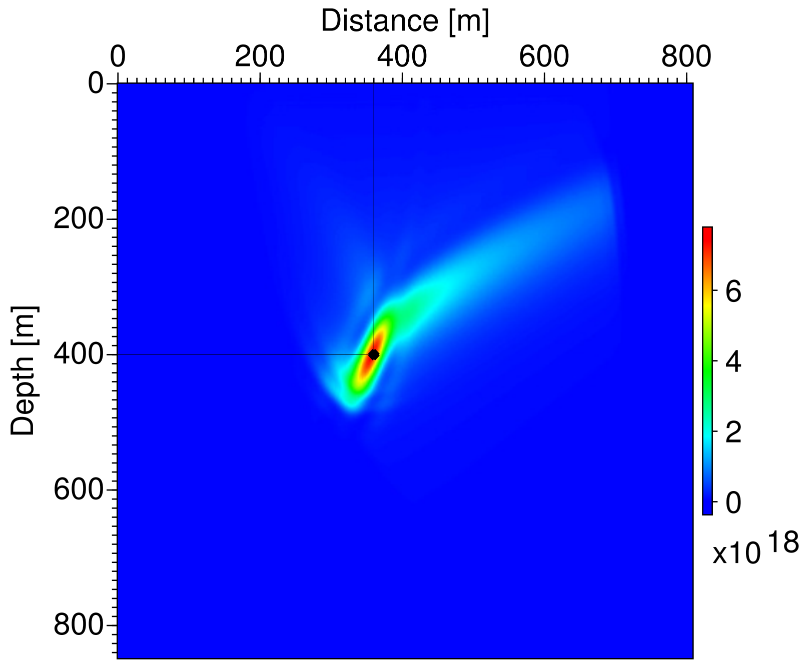

Figure 11: Image function for the homogeneous case, i.e. without the scattering layer.

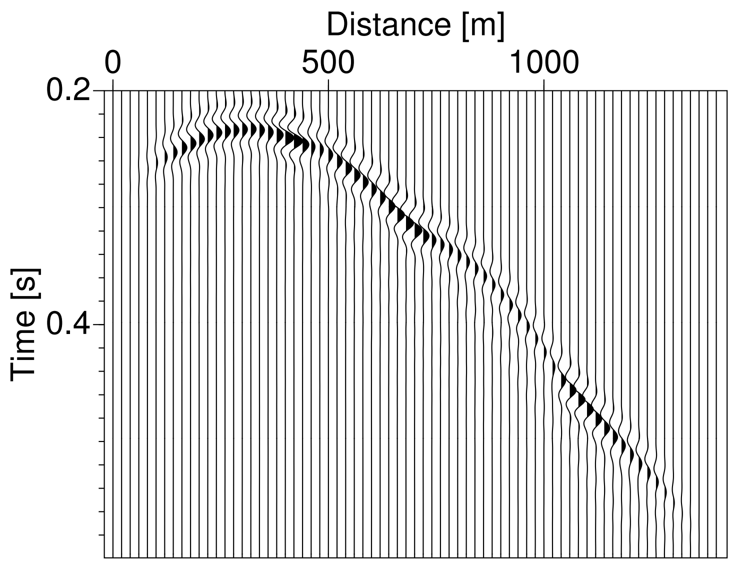

Figure 12: Seismograms for the overburden model shown in Figure 6. A standard deviation of 12 % leads to a much higher deviation from the hyperbolic shape of the event than a standard deviation of 5 % (Figure 7).

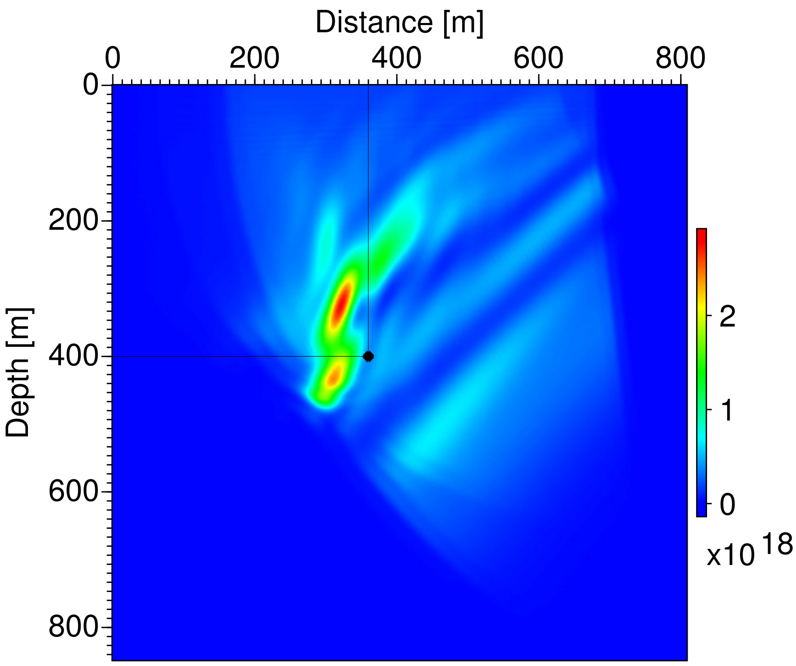

Figure 13: Result of constant velocity localisation for data modelled with a standard deviation of 12 %. The focal area of the image function displays two peaks that cannot be associated with the real source position.

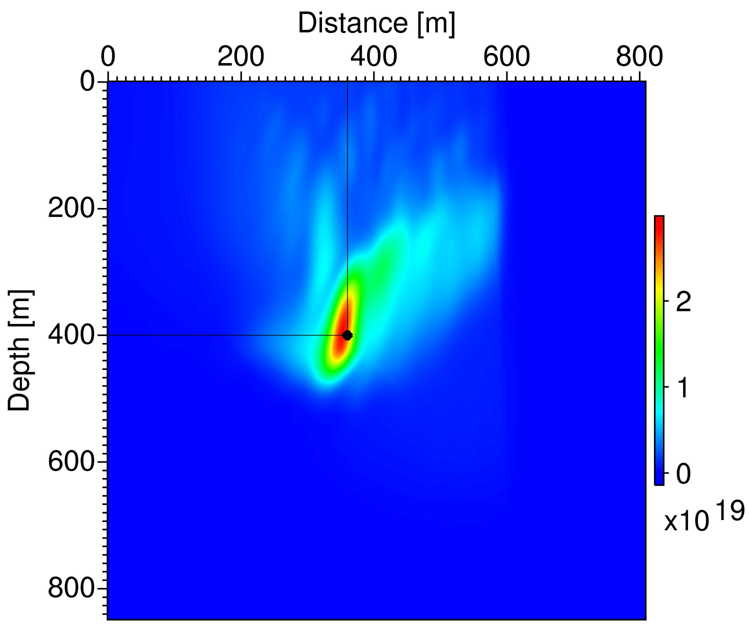

Figure 14: Image function obtained over a range of velocities. The data were generated for the overburden model (Figure 6) with a correlation length of 10 m and a standard deviation of 5 %. The data are shown in Figure 9. The velocity range considered in this example was from 1800 to 2200 m/s. The medium velocity was 2000 m/s.

shown to illustrate that our localisation also performs well in the presence of near-surface complexities.

With a final example, we have shown that our method can even be applied if the velocity model is not well-known. To obtain a reliable localisation we only require RMS velocities which are usually available.

For simplicity, we have shown only 2-D examples in this work. Also, the diffraction traveltimes were computed analytically. The extension to 3-D media is, however, straightforward. Application to complex models with vertically and laterally varying velocities can be carried out in the same fashion. In that case, the diffraction times need to be generated numerically, e.g. by ray tracing or finite-difference methods. Such techniques are widely available for 2-D as well as for 3-D media (for an overview see, e.g., Leidenfrost et al. 1999).

In the examples, only data from a surface array was considered. As the results show, surface data leads to a good lateral but a lower vertical resolution. If borehole data were available in addition to the surface registrations, the vertical accuracy of the method could be considerably enhanced.

Due to the computational efficiency and the possibility to implement it in a target-oriented way, our goal is the application of the method to real-time monitoring of passive seismic experiments. Tests on the localisation with real data are currently carried out.

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