LOCALIZATION OF SEISMIC EVENTS IN 3D MEDIA BY DIFFRACTION STACKING

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ABSTRACT

The localization of seismic events is of great importance not only in seismology but also in exploration geophysics for monitoring of for instance hydraulic fracturing. It can be successfully implemented by diffraction stacking, where the source location is obtained from the maximum of the so called image function. Since the maximum of the image function is distinct, even in the presence of noise very weak events can be detected. Previous research showed that the method works reliably for homogeneous 2D media. In this paper we demonstrate the extension to 3D and present numerical examples in both homogeneous and heterogeneous media. Strongly heterogeneous media are intensely affected by triplications. We show that the localization of events in such media is nevertheless possible if the most energetic arrivals are taken into account. Moreover, by using geometrical spreading as weighting factors for the input data, separation of propagation and source effects is achieved. Also, we have studied the source effects of radiation patterns. Finally, the method was tested on field data from Southern California. The acquisition footprint had to be considered. Both numerical and field data application confirm the potential of the method. The localization results deviate from the source position obtained by a standard picking method less then 1 km in all three directions. Both numerical and field data applications reveal the potential of the method. Conventional source location methods by event picking locate the event with a maximum spatial deviation of 1 km when compared to the location method presented here.

INTRODUCTION

The problem of seismic event localization is a key problem in seismology. Most classic localization methods require picking of P- and S-wave arrivals of the event at each receiver position. Data is often strongly affected by noise and thus, challenges such techniques. Gajewski and Tessmer (2005) introduced a localization method based on reverse modeling, which does not require any picking of events. The advantage of this method is that the focusing of energy in the back projection process allows to image very weak events, which could not be identified in the individual seismogram of the recording network. Gajewski et al. (2007) proposed a new technique using a stacking approach to backproject passive seismic observations. In this approach the subsurface is discretized and each subsurface location is considered to be a potential location of a seismic event. For the calculation of diffraction travel times for each subsurface point a velocity model is required. Travel time tables are computed using the NORSAR-3D ray tracer. These travel time trajectories for the first arrivals are used for stacking. As the event time is not known, the trajectory has to be moved through the whole time window of the data and stacked for each time. The stack results for each time are summed and then squared. The resulting value forms the value of an image function for this position. The source location corresponds to the position of the maximum of the image function.

A previous numerical study on this topic by Anikiev et al. (2006) demonstrated that the localization by diffraction stacking works very well in 2D. Here we will extend this method to 3D media. Finally, we present a field data example from Southern California.

METHOD

In the following section a brief description of the method is given.

We explain the technique for 2D media here. The extension to 3D is straight-forward. In passive seismics, different events are recorded during a certain time period. The number of receivers and their positions are given by the acquisition geometry of the experiment. We assume that seismic events are caused by point sources. In other words, the extent of the source region is relatively small in comparison to the prevailing wavelength. The position of a so called acoustic emission can be reconstructed from surface or borehole measurements by applying a diffraction stack, which is described in the next paragraph.

Firstly, the subsurface is discretized, where the spatial sampling should resemble the prevailing wavelength of the seismic events under consideration. Every subsurface point is a potential source and a so called image point. The recorded seismograms serve as input data. The choice of a time window is a very important point to be mentioned. If $t_2 \gg t_1$ and there are multiple events present in the time window, then the maxima corresponding to different events can overlap and this would lead to a less focused image function. In the worst case the detection of events could be hampered. The best way to solve this problem is to split the time window into several buffers and then perform the diffraction stacking for each of them separately. This strategy saves the computational time if several buffers are processed in parallel. The velocity model of the subsurface is assumed to be known. Then the travel time curve has to be computed for every image point by using, e.g., the ray tracing program NORSAR-3D. As soon as the travel times for each image point are available, the following procedure is performed:

1. stack (=sum) the amplitudes along the calculated diffraction travel time curve for an image point;
2. repeat for each sample in the considered time buffer
3. add squared results from every time step over the chosen time buffer.

The result represents the amplitude of a so called image function for this particular image point. This procedure is repeated for all image points and as a result we get a spatial representation of the image function for the chosen time buffer. The source location corresponds then to the position of the maximum of the image function (Anikiev et al. (2006)).

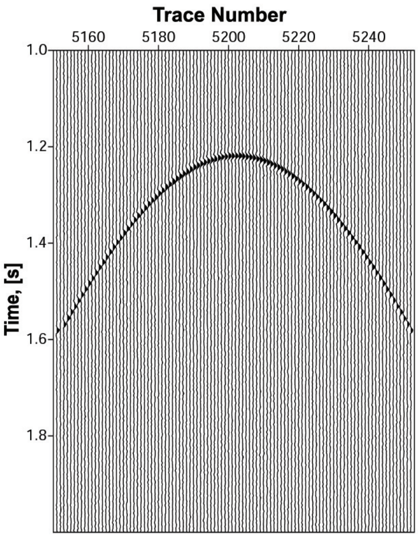
NUMERICAL EXAMPLES

In this section numerical examples in both homogeneous ad heterogeneous media and for both explosive and double couple source are presented.

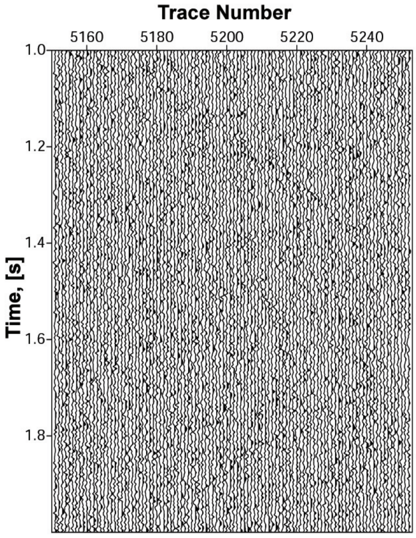
Explosive source in 3D homogeneous medium

In this section we apply the method to synthetic data. The seismograms were generated by the NORSAR-3D ray tracer. A 40 Hz Ricker wavelet was used as a source-time function of an explosive point source. The source is located at (2500; 2500; 3000), its position is symmetric to the center of the recording network. A homogeneous medium with a P-wave velocity of 2500 m/s is used. Gaussian noise with different signal to noise ratios was added to the data. For the synthetic seismogram with a S/N ratio of 10 the event is easily recognizable, as it can be seen in Figure 1(a). The diffraction stacking procedure was applied to the data and the resulting image function is shown in Figure 2(a). Then the S/N ratio was reduced to 0.5 and it becomes almost impossible to detect the event in the traces of the seismogram section, as shown in Figure 1(b). Localization methods requiring picking cannot be used for such input data. Despite such a high noise level, the distinct maximum of the image function still corresponds to the real source position, which is illustrated in Figure 2(b). Both image functions are normalized by their maximum values. However, the noise leads to scattered spots of increased amplitudes in the image.

Amplitudes of seismic events contain source effects as well as propagation effects, i.e. geometrical spreading. Geometrical spreading compensation permits to separate source effects from propagation effects. This can be achieved by applying a corresponding weighting function comprising geometrical spreading factors during the diffraction stacking procedure. The resulting amplitude of the image function normalized by the number of receivers is an indicator for the source strength and allows us to directly



(a) S/N=10, the event can be easily recognized



(b) S/N=0.5, the event is barely detectable

Figure 1: Seismograms for (a) S/N=10 and (b) S/N=0.5.

compare the strengths of sources. For non-regular receiver grids, e.g., Voronoj cells can be used to determine proper weights in the stack to account for the acquisition footprint (see also field data example below).

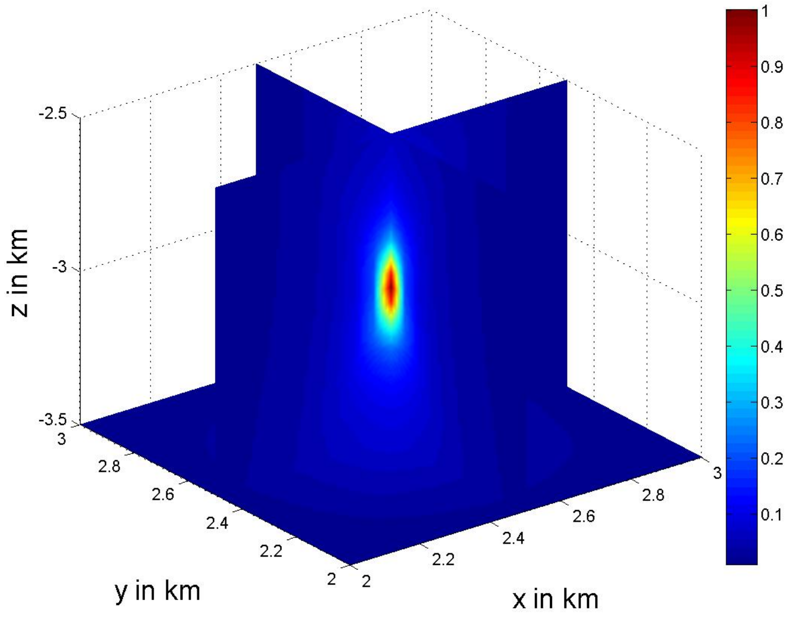
Explosive source in 3D heterogeneous medium

From reflection seismic imaging with Kirchoff migration techniques we know, that for complex media not only the first arrivals should be considered but the most energetic arrivals. The most energetic arrival usually is not the first arrival. In this section we investigate the influence of complex media on the localization of seismic events.

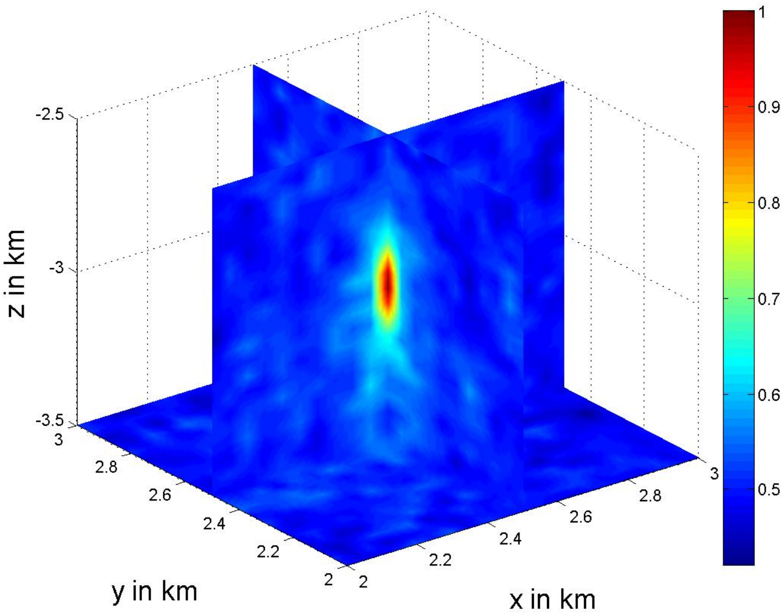
Seismic events in heterogeneous media are strongly affected by triplications and therefore the strongest events may not refer to the first arrivals. We consider a low velocity lens in a homogeneous background velocity model. The P-wave velocity in the center of lens is 1500 m/s and the background velocity equals 2500 m/s. The velocity model is shown in Figure 3(a). Such a lens works as a collecting lens, which leads to the triplication in seismograms (see Figure 3(b)). Image functions using first arrivals only and the most energetic arrival were computed. The maximum of the image function for the first arrivals does not correspond to the real source position and is shifted along the vertical axis (see Figure 4(a)). The resolution of the image function by using first arrivals only is greater than $\lambda/2$. The maximum of the image function using the most energetic arrivals corresponds to the real source position as seen in Figure 4(b). Similar to Kirchhoff reflection imaging it is important to take the most energetic arrivals into account in passive seismic imaging using the diffraction stack.

Double couple source in a 3D homogeneous medium

Microseismic events are rarely events of explosive type. Usually they are considered as dislocation sources. Such sources display a specific radiation pattern including nodal planes whereas the radiation of explosive sources is isotropic (see, e.g., Aki and Richards (2002)). The double-couple seismic source represents a good model for earthquakes that are caused by a shear or slip on a fault. We consider a strike-slip source here. The source is located at (5000; 5000; 3000) m. Both P- and S-wave travel times need to be computed for such data. A homogeneous medium with constant P-wave velocity of 2500 m/s and a

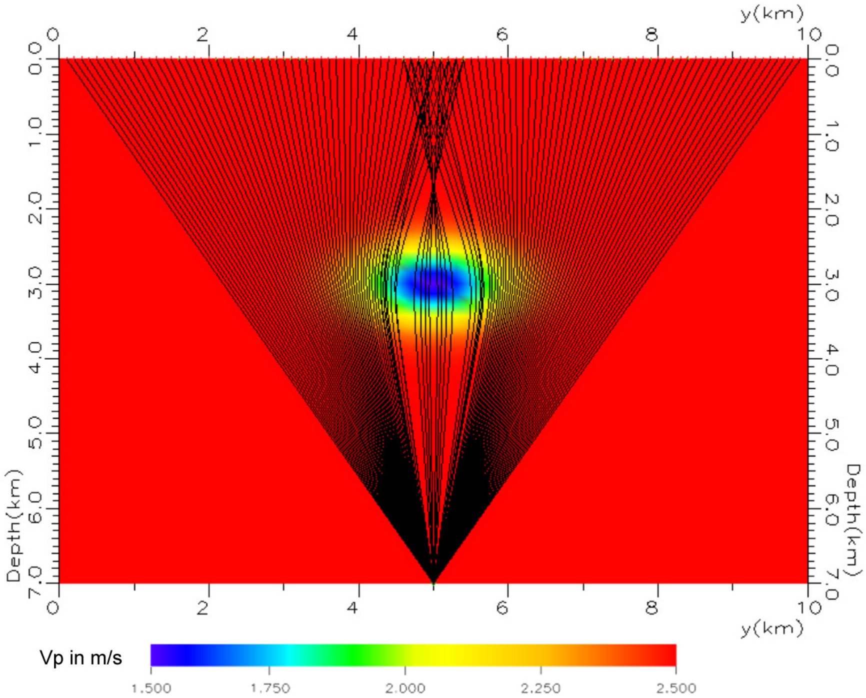


(a) Image function for the explosive source data with S/N=10

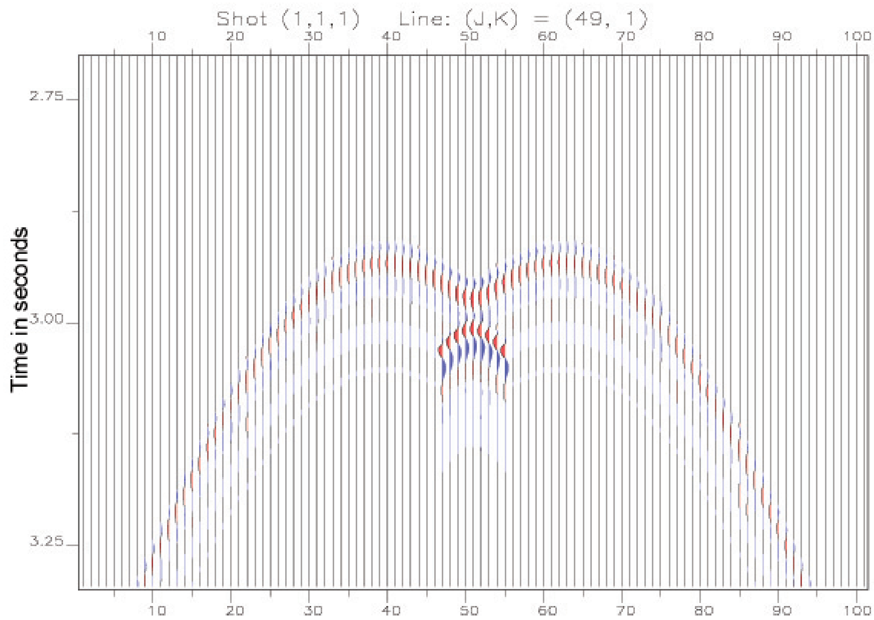


(b) Image function for the explosive source data with S/N=0.5

Figure 2: Normalized image functions for (a) S/N=10 and (b) S/N=0.5. The maxima of both image functions correspond to the real source position.

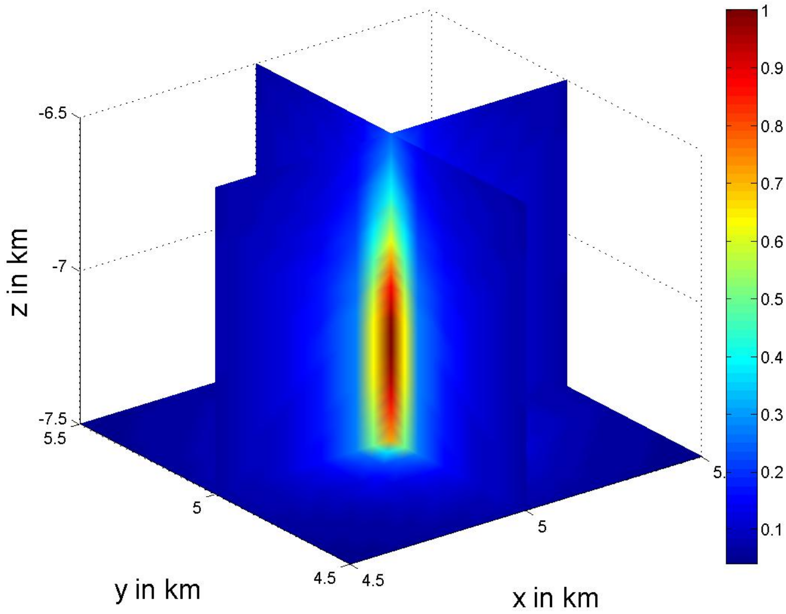


(a) Velocity model and ray paths for a heterogeneous medium with a low velocity lens.

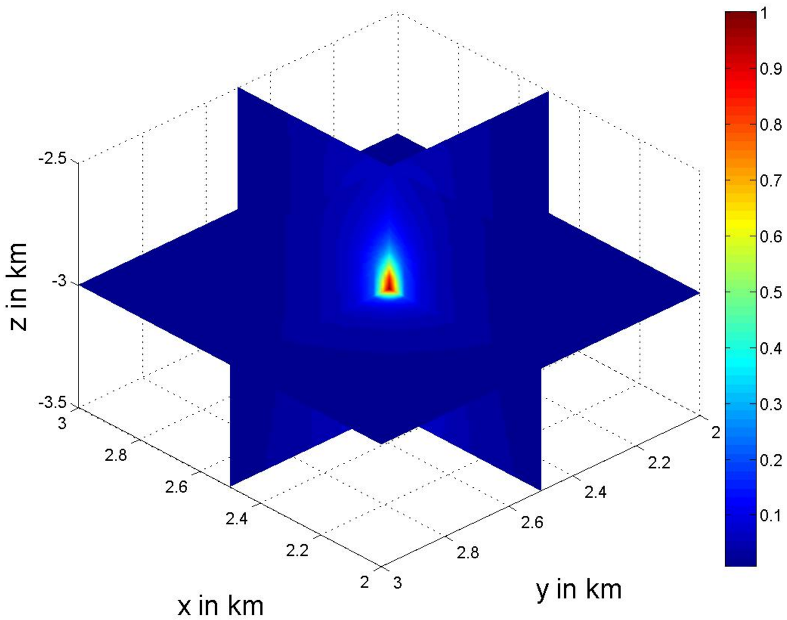


(b) Seismogram resulting from the model shown in Figure 3a

Figure 3: (a) Velocity model and (b) the corresponding seismogramm for a numerical example in a heterogeneous medium with a low velocity lens.



(a) Image function for the first arrivals only



(b) Image function for the most energetic arrivals only

Figure 4: Normalized image functions for (a) the first arrivals and (b) the most energetic arrivals. The maximum of the image function for the first arrivals does not correspond to the real source position, but it is shifted downwards the vertical axis. The maximum of the image function for the most energetic arrivals coincides with the real source position.

P/S - wave velocity ratio of $\sqrt{3}$ was considered. The resulting image function is shown in Figure 5(a). There are 4 maxima in this image function and none of them corresponds to the real source position; on the contrary, at the source location there is the minimum of the function. The image function reminds us of the radiation pattern of a double couple source, which may be interpreted as an indicator for such a source type. Unfortunately, it does not lead to the correct location of the source. To solve the problem, absolute values of the data were used and the resulting image function is shown in Figure 5(b). A distinct maximum is present which corresponds to the real source position. Another way to avoid the effect occurred in Figure 5(a) is to use envelopes formed from the analytic signal of the data. The corresponding image function can be seen in Figure 5(c); its maximum also corresponds to the real source position, but it is not as focused as the previous one. This effect is expectable since using envelopes of input data reduces the frequency content, which leads to a less focused iamge function.

The localization results in case of a double couple source, where both P- and S-waves were considered, show that we would not obtain the correct source location if we do not either use the envelopes of the signal or the absolute values of the amplitude. However, by applying the envelopes to the input data, we end up with the data of lower frequency.

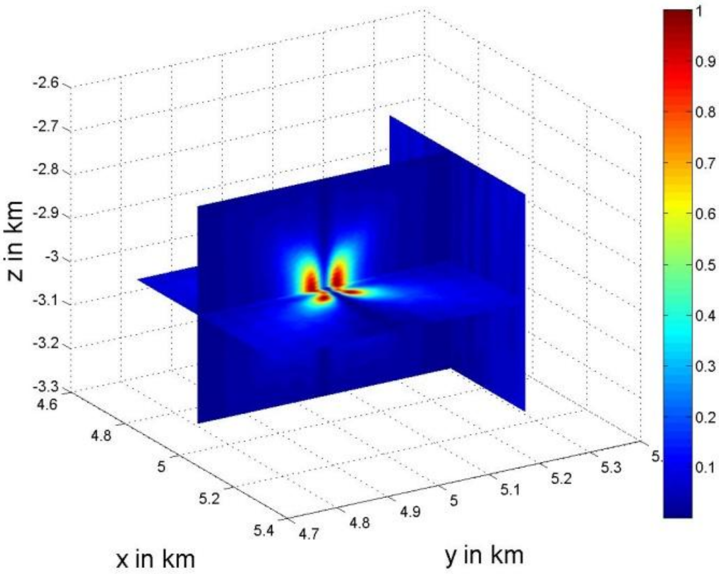
FIELD DATA EXAMPLE

To test the method on field data, vertical component seismograms were downloaded from the Southern California Earthquake Data Center database. The chosen event had a magnitude of 4.05. We chose this particular event since it had been investigated previously by Baker et al. (2005). It gave us the opportunity to compare our results with the localization of other authors and methods.

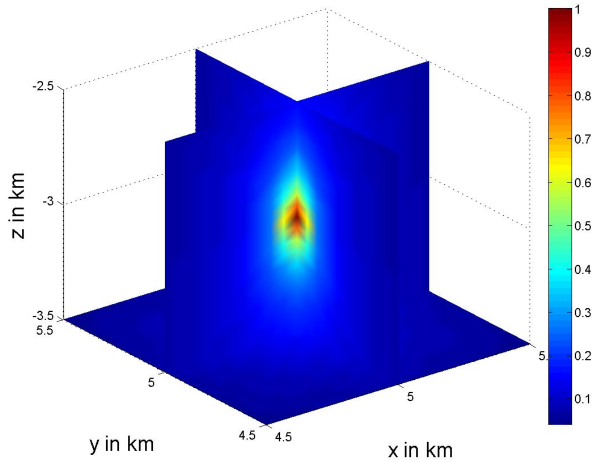
For the localization of this event we considered the same velocity model as in previous studies,namely a constant P-wave velocity of 6000 m/s with a P/S - wave velocity ratio of $\sqrt{3}$ was used. The maximum frequency of the data is 40 Hz. The acquisition geometry of the experiment is highly irregular, which leads to overweighting or underweighting of certain traces. In order to compensate the acquisition footprint, weighting factors were calculated by constructing Voronoj cells (Voronoj (1908)). The diffraction stack was then performed for the envelopes and the obtained image function is shown in Figure 6. Both P- and S-wave travel times were used. The focus of the image function is scattered in all three directions. This could be the result of using a homogeneous velocity model. Moreover, the focus is inclined, which can be explained by an unsymmetrical location of the source related to the acquisition. The presence of local maxima of smaller amplitude may indicate that multiple events occurred in the time window. The maximum of the image function has a deviation of less than 1 km compared to the results obtained by a method, that requires picking of P- and S-waves arrivals.

CONCLUSIONS

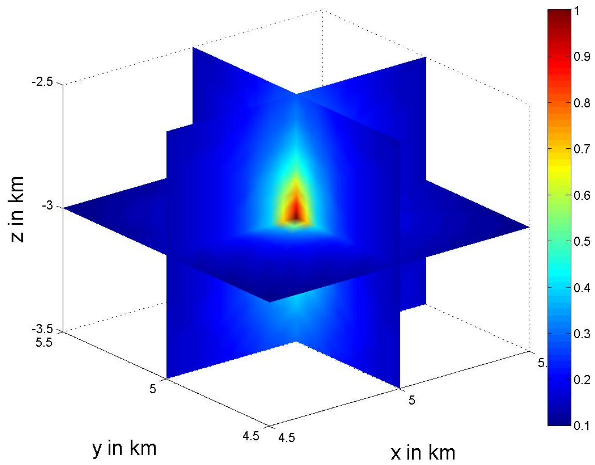
Numerical studies in both 3D homogeneous and heterogeneous media illustrate the potential of the diffraction stack for the localization of seismic events. It was shown that even weak events in data sets with a low S/N ratio can be detected. Compensation of geometrical spreading losses during the diffraction stack allow to separate source and receiver effects. Image functions generated this way allow a direct comparison of the source strengths. It was demonstrated that in case of strongly heterogeneous media, where the strongest events may not correspond to the first arrivals, but to the later ones, triplications should be taken into account to get a better image. The numerical experiments reveal that the consideration of the most energetic arrival leads to a correct and well focused location of the source whereas first arrivals did neither provide a well focused image function nor did the maximum occur at the source location. The numerical tests for the case of a double couple source show that we would not obtain the correct source location if we don't either use the envelopes or absolute values of the signal. Both techniques need further consideration in case of poor signal-to-noise ratio. The field data example demonstrates that the results obtained by diffraction stacking has a deviation of less than 1 km to the localization results obtained by a method, that requires picking of P- and S-wave arrivals. Since field layouts of recording arrays or networks are never regular, the acquisition footprint needs to be compensated in the diffraction stack. We used Vornoj cells in this study to account proper weights in the integration. The velocity model for the field data was considered to be homogeneous to make our study comparable to previous work based on this model. It is, however, very unlikely that the upper crust in Southern California is homogeneous. A velocity model closer to the



(a) Diffraction stack was applied to the data as they were.

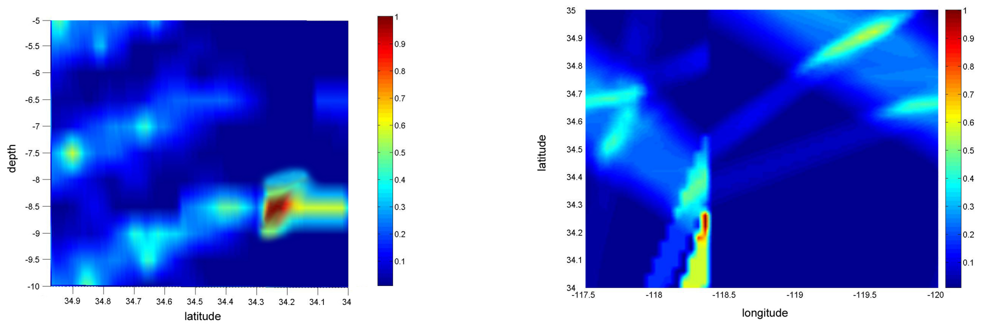


(b) Diffraction stack was applied to the absolute values of the data.



(c) Diffraction stack was applied to the envelopes of the data.

Figure 5: Normalized image functions for (a) the data as the were, (b) the absolute values of the data and (c) the envelopes of the data.



(a) Vertical slice through the maximum of the image function.

(b) Horizontal slice through the maximum of the image function.

Figure 6: (a) Vertical slice and (b) horizontal slice through the maximum of the image function.

geological reality of Southern California will certainly influence the localization result. this could influence the location itself and the focusing of the image function.

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