LOCALIZATION OF ACOUSTIC EMISSIONS BY BACK-PROJECTION: INHERENT LOCALIZATION AND TIMING ERRORS

D. Gajewski, B. Kashtan, E. Tessmer, and C. Vanelle

email: *gajewski@dkrz.de*

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ABSTRACT

The passive seismic method gains more and more attention in the hydrocarbon industry since it can be used for reservoir characterization and monitoring. For deposits with poor 4-D signatures like carbonate reservoirs the imaging of acoustic emissions during production may be the only tool to detect 4-D effects. The localization of seismic events in space and time is of utmost importance for the passive method. Localization of seismic events by reverse seismic modeling or other back-projection techniques increasingly attracts attention since it does not require any event picking and works even for very poor signal to noise ratio. Synthetic reverse modeling studies in the past have shown that the method works surprisingly well even in complex media. In this paper we discuss the back-projection techniques for event localization which reveal that inherent localization and timing errors are present in these methods. The location errors are in the order of the prevailing period of the signal and depend on the acquisition aperture and the signal length. Numerical experiments confirm the qualitative considerations.

INTRODUCTION

The passive seismic method gains an increased interest in the hydrocarbon industry. It has the potential as a powerful tool for reservoir characterization and for reservoir monitoring or hydro-frac imaging. The passive method may also provide a tool for reservoirs with too weak 4-D seismic effects, like carbonate reservoirs (Dasgupta, 2005). Here the impedance changes with time are so small that classical 4-D seismics do not produce visible signatures. The imaging of acoustic emissions may provide the only working technique to observe 4-D effects here. The localization of seismic events in time and space is the most important step in interpreting passive seismic data. Recently back-projection methods or reverse modeling methods were introduced which do not require any picking in the seismograms of the network (Kao and Shan, 2004; Gajewski and Tessmer, 2005). Due to the involved stacking of energy these techniques work very well even for noisy data, where the event can not be recognized in the seismograms. A detailed numerical study was presented by Gajewski and Tessmer in the 2004 WIT report and in Gajewski and Tessmer (2005). Time reversal is a key ingredient of the reverse modeling approach and the technique therefore belongs to the class of methods which are currently discussed in the exploration community (e.g., during the SEG workshop on " Seismic interferometry, daylight imaging and time-reversal" in Houston, 2005).

For the location methods using time reversal or inverse modeling the recorded wavefield is back-projected into the structure assuming a velocity model. For point sources and the correct velocity model the observed seismograms should focus at the source position at the excitation or hypocentral time of the event under consideration. Let us for simplicity consider a 2-D case now, assuming a seismic source at a position (x_0, z_0). The radiated energy of this source is observed by a linear receiver array covering an aperture $2L$. It is intuitive that we can not reconstruct the correct amplitude of the emitted signal even for the correct velocity model since our observation aperture is limited. We are therefore not stacking all emitted energy of the source when we back-project the recorded wavefield. The reconstruction of the amplitude would require an acquisition surrounding the source position which is practically impossible for a reservoir. For isotropic media the point source radiation, however, displays a high symmetry and the observation of one quadrant may be sufficient to determine the emitted energy in simple types of media. Complex models with strong lateral velocity variations may require larger apertures. For the sake of simplicity, we will assume an isotropic source radiation of magnitude A in the following.

It may be less obvious that the localization of the point source event is also affected by the limited aperture and bandwidth of the data. This statement applies even if the correct velocity model is used for back-projection. The major cause of this feature is the length of the signal of a bandlimited event when we go from a distance-time (x, t) section to a distance-depth (x, z) section by back-projecting the observations. In this paper we qualitatively describe the influence of signal length and aperture on the location accuracy of seismic events. The graphical explanation of the problem is verified by numerical examples using reverse modeling. The numerical experiments also enable us to provide a first empirical quantification of the effects. In the outlook we briefly describe the strategy to develop a theory for a detailed quantification of the location error. The result of this theory will enable us to correct the location of the event under consideration to its real position.

GRAPHICAL EXPLANATION OF THE LOCATION ERROR

The location error is best visualized and explained if we consider a homogeneous medium and a back-projection method based on Kirchhoff migration. We assume a seismic point source at (x_0, z_0). The energy of this seismic source is radiated at hypocentral time t_0 and is recorded by a receiver network with aperture $2L$ either at the surface or in a borehole. In the following we will assume that the recording network is located at the surface and that the acquisition aperture is symmetrical with respect to the position of the source. We consider a model which is reasonably discretized, i.e., similar to the discretization in migration. For every subsurface point (x_i, z_i) of this model we compute the diffraction traveltimes to the receiver array. This basically means we consider each subsurface position as a potential source position.

In contrast to the migration of reflection data we usually do not know the excitation time of the event. Therefore, we have to investigate the total recorded time range t_b to t_e which contains the event with a time step Δt. This means that we are moving the diffraction curves for every considered subsurface position from time t_b to time t_e with increment Δt through the seismic section and stack the amplitudes for every time step. This is repeated for each subsurface position and time t. In this way we construct a set of $N = (t_e - t_b)/\Delta t$ images where each image represents the stacked result for all possible subsurface positions and one particular time in the time window from t_b to t_e. The process transforms the seismograms from the (x, t) domain to the (x, z) domain for every time between t_b to t_e. This is similar to depth migration of reflection data but here we obtain only one image since we know the excitation time of the event.

The resulting amplitudes in each image are searched for the maximum. For the correct velocity model we expect from our physical intuition an optimal focussing of the amplitudes of the back-projected event. We expect the maximum amplitude at the location (x_0, z_0) for the imaged section of time $t = t_0$. If the seismograms are impulsive (i.e., delta peaks with zero signal length), we would in fact observe the maximum amplitude for the image at time $t = t_0$ and for the diffraction curve computed for position (x_0, z_0) (see Fig. 1). The total strength of the imaged source amplitude depends on the size of the aperture of the acquisition since larger apertures stack more energy.

If we consider band limited signals, i.e., the length of the recorded event is non zero, the maximum stacked energy is found at a position which deviates from the actual source position and zero time even if the correct velocities are used for back-projection.

This is best explained by Fig. 2 which shows the seismic section for the exact hypocentral time $t = t_0$ and the traveltime curves corresponding to three different depth locations. The solid traveltime curve represents the traveltimes obtained for the exact source location (x_0, z_0), the dotted traveltime curve corresponds to a deeper position $z > z_0$ and results in a smaller moveout and an apex shifted to later times compared to the curve for the exact location (x_0, z_0). The dashed curve corresponds to a position shallower than the actual source position, i.e., $z < z_0$ and results in a higher moveout and the apex appears at earlier times

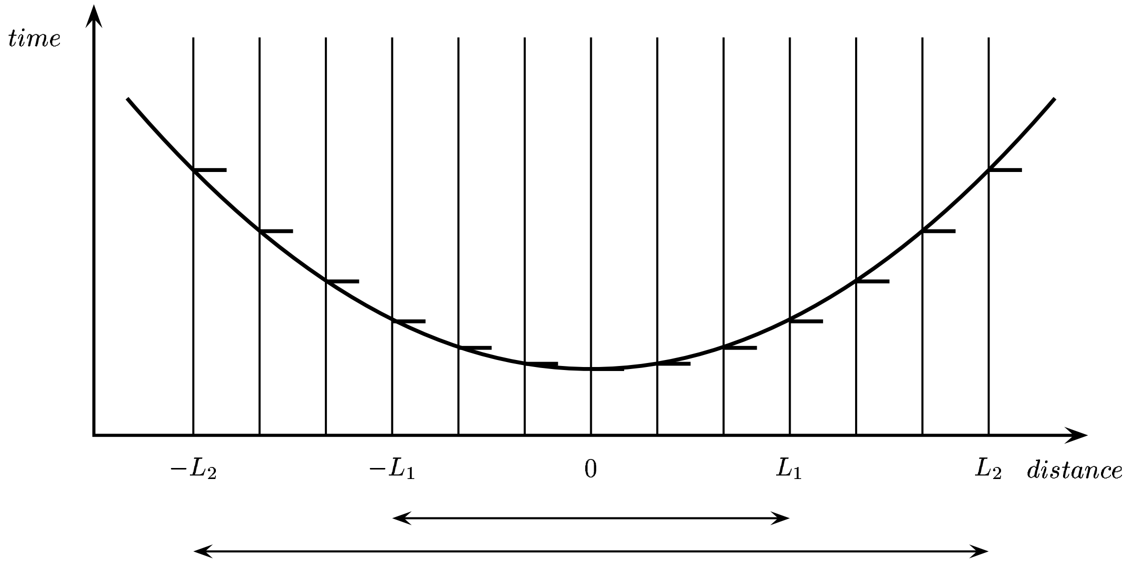

Figure 1: Impulse synthetic seismograms of an event with the diffraction traveltime curve for the exact hypocentral time and correct source position. Stacking along this curve provides maximum amplitude. The strength of the amplitude, however, depends on the size of the aperture L_1 or L_2.

compared to the curve for the exact location (x_0, z_0).

We first consider the traveltimes for the correct source position, i.e., the solid curve in Fig. 2. Stacking along this curve provides a zero amplitude since physical signals are minimum phase signals. Just from this fact it is immediately obvious that the maximum amplitude in the back-projected (x, z) section for the correct hypocentral time t_0 can not coincide with the correct source position. At the correct source position (x_0, z_0) we obtain zero amplitude. This result is independent of the size of the aperture.

The dashed curve in Fig. 2 is computed for a shallower location and is therefore shifted to earlier times. Due to its larger moveout the traveltime curve cuts through the seismograms for larger offsets. Stacking along this curve leads to a non-zero amplitude in the image at a position shallower than the actual source position.

Finally, the dotted curve in Fig. 2 is obtained for a deeper location and is therefore shifted to later times compared to the curve for the actual source location. However, owing to its smaller moveout it also cuts through the seismograms and a stack along this curve has a non zero amplitude and depends on the size of the aperture. This explains that the source image is in fact not a point but a bright region where the spatial extension of this area depends on the signal length and the aperture of the acquisition.

Form these considerations we can conclude that the source location obtained by searching the maximum amplitude in back-projected images of the recorded wavefields will occur shifted in time and space. The shift in space will be towards the receivers of the acquisition since we obtain non zero amplitudes already for positions above the actual source location. The time of the image with maximum amplitude will therefore be smaller than the real hypocentral time. The maximum magnitude of the location error will be in the order of the prevailing wavelength of the signal since it is determined by the signal length. The maximum timing error will be in the order of the signal length. Both errors depend on the acquisition aperture. The numerical experiments discussed below confirm the qualitative considerations of this section.

The described phenomenon is a result of the limited bandwidth and the moveout of the seismic events and therefore related to the well-known pulse stretch phenomenon in depth migration as reported by Tygel et al. (1994). As described above we shift the diffraction curves through the seismic section from time t_b to time t_e with increment Δt and stack for each time step. This corresponds to non-stretch-NMO and the source localization by back-projection is therefore related to the work by Perroud and Tygel (2004). Moreover, there is also a link to the influence of velocity errors on the imaged amplitude in pre-stack depth migration. The relations between these phenomena are not yet put into a unified theory.

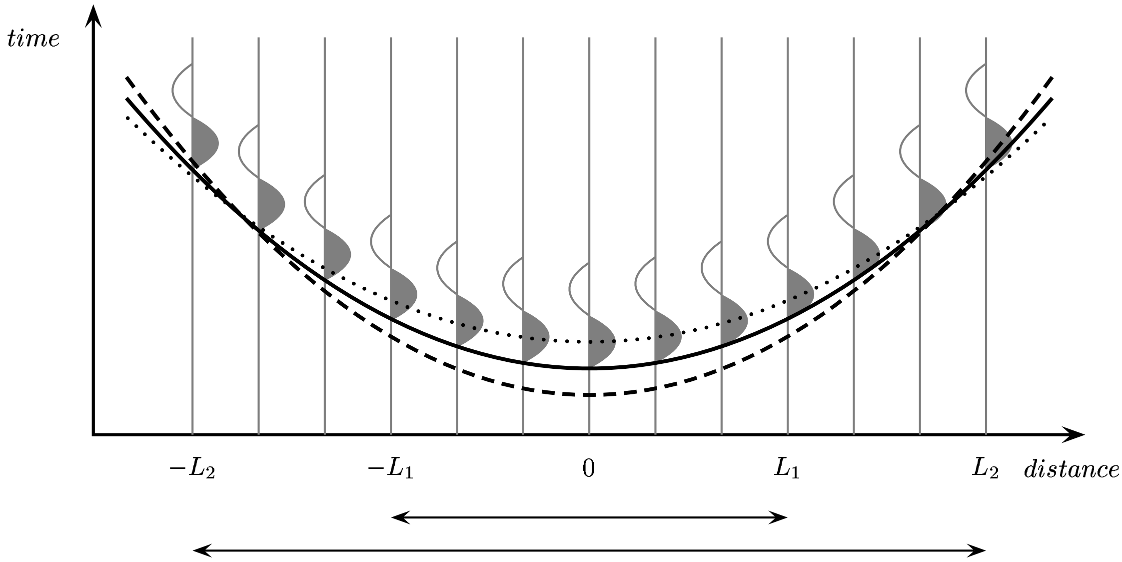

Figure 2: Seismic section for the exact hypocentral-time $t = t_0$ with three traveltime curves representing sources at the exact location (x_0, z_0) (solid) and for positions above (dashed) with higher move out and below (dotted) with smaller move out. Details are given in the text.

We want to add a final remark here: Our intuition is usually driven by a high frequency approach, i.e., we think in terms of rays, traveltimes, i.e., high frequency signals with zero lengths. It was shown above, this intuition sometimes is misleading.

NUMERICAL TESTS

In this section we want to quantify the above described effects of location and timing errors in event localization utilizing a back-projection approach of the recorded wave field. For the back-projection we use the reverse modeling approach as described by Gajewski and Tessmer (2005). For the reverse modeling we apply a numerical technique based on the Fourier-method. This generally allows using coarse grids, i.e., the shortest wavelength can be represented by only two grid points which satisfies the Nyquist sampling condition.

Since the maximum location errors are in the order of the prevailing wavelength of the signal we use a fine numerical grid which is oversampled with respect to the stability conditions for the modeling. We consider an acoustic homogeneous 2-D model with spatial discretization of 2.5 m. Since the acoustic velocity is 2000 m/s and the cut-off frequency of the source wavelet is 100 Hz the shortest wavelength is 20 m. This would require a sampling interval of at least 10 m. Therefore, we are dealing with a four times oversampled spatial discretization. The dominant wave length is sampled by eight grid points. The total extent of the numerical model is 1430 m x 780 m. The source is located at x=715m and z=375m.

The first experiment was based on an acquisition with two receiver lines which were placed symmetrically above and below the source position (Fig. 3). Time reversed seismograms of two receiver lines at $z_1 = 0m$, called line 1, and $z_2 = 750m$, called line 2, were used as boundary conditions in the numerical algorithm. Using this acquisition geometry the reverse modeling led to the correct source position and excitation time. Such an acquisition is, however, very unlikely to be met in the real world.

In a second experiment we only used receiver line 1 of the above described experiment as input to the reverse modeling algorithm. In this case the source location is found one grid point, i.e. 2.5 m, too high. Therefore the error is of the order of an eighth of the shortest wave length. The excitation time was found correctly.

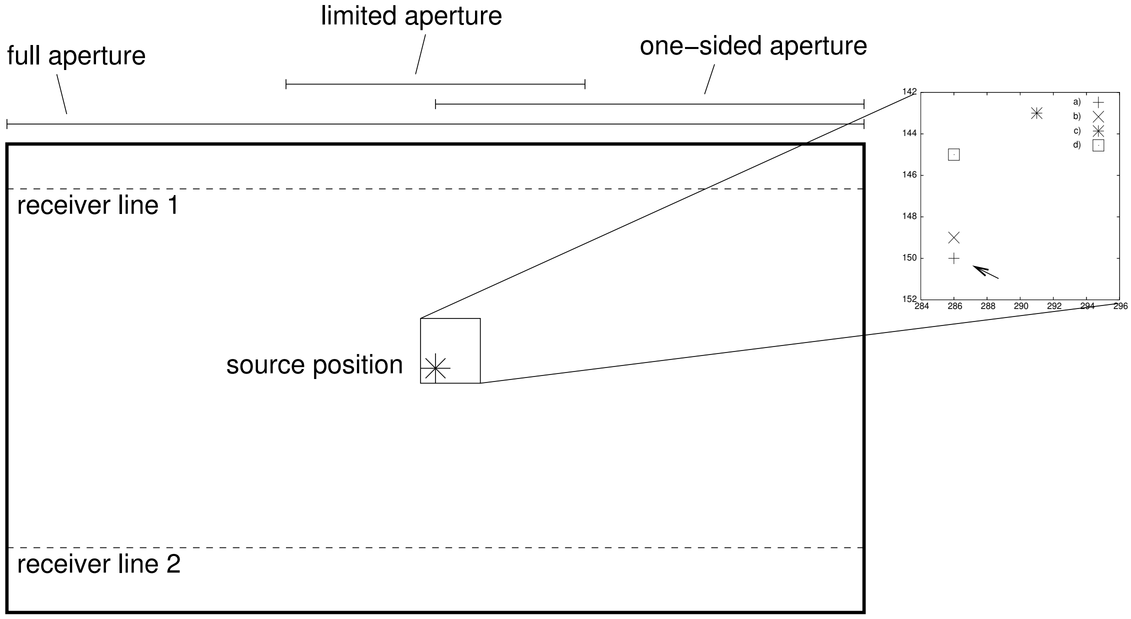

Figure 3: Localizations depending on different receiver line apertures. In insert: a) full aperture lines 1 and 2, b) full aperture line 1, c) one-sided aperture line 1, d) symmetric shortened aperture line 1. The arrow shown in the enhanced source region points to the exact source position indicated by a plus sign.

In a third experiment receiver line 1 was truncated to half of its original length but is chosen symmetrical with respect to the lateral position of the source. For this acquisition the estimated source positions appears five grid points too high. The excitation time is wrong by -5 ms, i.e., 5ms earlier than the exact hypocentral time.

In a last experiment the aperture was only half (right side) of the receiver line 1, i.e., unsymmetrical with respect to the source position. The localization was erroneous by five grid points in the horizontal direction (to the right) and seven grid points (upwards) in the vertical direction, respectively. Due to this positional error also the excitation time was found wrong by -9 ms, i.e., too early. In the insert of Fig, 3 the true (arrow) and the estimated source positions are shown.

The numerical experiments confirm the qualitative considerations of the section above. We observe a systematic location error which is below the prevailing wavelength of the considered signal. The events are localized to close to the receiver array than the real source location. Since this reduces the distance to the geophones the observed hypocentral times appear smaller than the real excitation time of the source.

QUANTIFICATION OF ERRORS

To quantify the location error theoretically we investigate the stack integral and express the seismic signal by its zero order ray theory representation. The integration boundary represents the size of the aperture. The stack integral is performed for any possible subsurface position (x_i, z_i) and any time t_k in the considered time window, producing the image $Im(x_i, z_i)_k$. In this set of images we search for the maximum amplitude $Max(Im(x_i, z_i)_k) = Im(\hat{x}, \hat{z})$. Due to the limited aperture and the finite signal length we have a deviation from the real source position (x_0, z_0). The goal is to estimate these deviations as a function of frequency of the signal and the size of the aperture. For this we expand the image function $Im(x, z)$ up to second order with respect to the spatial coordinates x, z and time. We recognize a similarity to the derivation of the pulse stretch in depth migration here (Tygel et al., 1994).

The details of this procedure will be presented in the next WIT report. For the determination of the deviations the first and second spatial derivatives of traveltimes from the subsurface position to the receivers are required. They are averaged (integrated) over the aperture of the recording network in the final results. The traveltime derivatives are a key element of the traveltime based strategy for true amplitude migration

(Gajewski et al., 2002) and can be determined from coarsely-gridded traveltime tables (Vanelle, 2002; Vanelle and Gajewski, 2002). These tables are in any case needed, since they are a prerequisite to perform the stacks to obtain the images for each time step in the localization procedure. The results enable us to update the imaged source location to its real position.

CONCLUSIONS AND OUTLOOK

The accuracy of seismic event localization by reverse modeling depends on the aperture and the signal length. In realistic acquisition geometries where a surface (horizontal) or vertical receiver line is available, there will always be a spatial shift of the estimated source location towards the receivers. This means that the source position appears too high when we consider a surface receiver network. Numerical experiments with a laterally asymmetric acquisition geometry show that the estimated source position appears laterally shifted towards the center of the receiver line. Since the imaged position is moved toward the recording receivers the hypocentral-time appears earlier than the real excitation time. The predictions made from simple graphical considerations concerning the stacked amplitudes were confirmed by numerical reverse modeling examples. For 3-D media and observations in 2-D geophone networks we expect similar effects, i.e., a shift of the actual position toward the recording array and a shift toward the center of the aquisition if the network is not located symmetrically to the position of the event. Du e to the greater proximity of the imaged location to the recording array the hypocentral-time is too small.

Most recent theoretical investigations allow us to quantify the errors introduced by the localization methods based on back projection of the observed seismograms. The implementation of these findings will enable us to build a localization tool which only needs coarsely-gridded travel time tables, very similar to our past work on true amplitude imaging. The obtained source location on the coarse grid can then be updated for its correct position where the bandwidth of the signal and the size of the aperture are properly taken into account. This tool will be computationally very efficient and may move us closer to the goal of a real time implementation of the localization methods by back projection.

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