Using spectral attributes to detect seismic tremor sources – a synthetic study

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Summary

A method is presented to detect subsurface seismic tremor sources by analyzing surface data. Spectral attributes of the recorded seismic wave-field at low frequencies are used to map the surface projection of the sources. We illustrate the concept on a synthetic data-set generated with a homogenous forward model and show how spectral attributes can be used for detecting locations of seismic tremor sources. In a second part we apply the method to an example of hydrocarbon reservoir related tremors. The results show that increased complexity of the subsurface seismic properties and/or the presence of several tremor sources can strongly complicate the interpretation. In addition, the presence of dominant surface noise may mask the signals emitted by the subsurface tremor sources and make it impossible to detect them at the surface without additional processing. F-K filtering is successfully applied to noise-contaminated data and retrieves masked anomalies. Care has to be taken for using a proper data-set and proper processing parameters in order to avoid artifacts introduced by the F-K filter. Although we discuss an application for possible hydrocarbon reservoir related tremors, we believe that the methods can also be applied to any other type of seismic tremor signal.

Introduction

We define seismic tremor as non-transient seismic signals without clear arrival times and generally low S/N-ratios. Analysis of such signals has become of more interest during the last decades. For example, microtremors are used to derive site specific information on earthquake hazard and to estimate seismic properties of the subsurface (Bard, 1999, and references therein). Non-volcanic tremors have drawn the attention of seismologists in recent years. Although the mechanism underlying the generation of non-volcanic tremor is as yet unresolved, the signals seem to provide useful insights on processes in deep subduction zones (Shelly et al., 2007).
Another field of research related to seismic tremors is low-frequency seismic spectroscopy applied to hydrocarbon reservoir detection. Several published case studies report a correlation between modifications in the low-frequency (< 10 Hz) ambient seismic wave field at the surface and the presence of hydrocarbons in the subsurface (e.g., Dangel et al., 2003; van Mastrigt and Al-Dulaijan, 2008; Saenger et al. 2009). Similar to non-volcanic tremors, there is no generally accepted theory on the physical mechanism responsible for the observed signals. Also, one has to be aware of potential pitfalls and misinterpretations (Hanssen and Bussat, 2008; Ali et al., 2009).

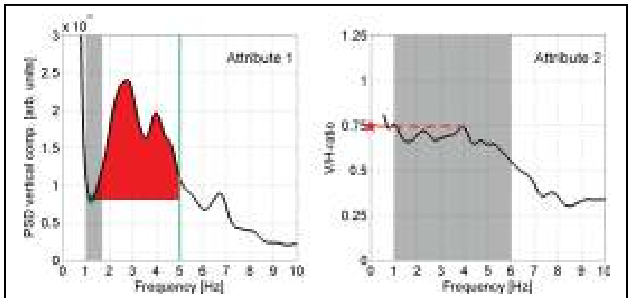

Figure 1. *Definition of the two spectral attributes used in this study.*

In this paper we present a method to detect tremor sources by analyzing surface seismic data in the frequency domain. In particular, we map spectral attributes of the recorded wave-field at low frequencies. Figure 1 illustrates the two attributes used in this study: Attribute 1 (red area) quantifies an integral value of the power spectral density (PSD) of the vertical component. Attribute 2 (red star) is the maximum amplitude of a dominant peak in the vertical-to-horizontal spectral ratio (V/H-ratio). A more detailed description of the attributes is given by Lambert et al. (2009). We describe a purely synthetic study on tremor source detection. First we introduce the numerical model and explain the main concepts on a simple homogenous case. Second, we investigate a more realistic model. This model describes the conditions at an oil and gas field in Voitsdorf, Austria, and is based on the assumption that hydrocarbon reservoirs can act as (secondary) sources of seismic energy at low frequencies. Although we discuss an application for possible hydrocarbon related seismic tremors, we believe that the methods introduced in this paper can also be applied to any other type of seismic tremor signal.

Numerical Model

Figure 2b shows the model domain consisting of a homogenous 2D medium with the following properties: P-wave velocity (v_p) is 3098 m/s, density (ρ) and Poisson ratio (ν) are 2000 kg/m^3 and 0.25, respectively. There is a free surface on top and non-reflecting boundaries at the three other sides of the domain. The 2D elastodynamic wave-equation is solved with a finite difference (FD) algorithm after Saenger et al. (2000). There is an area of seismic tremor sources into the subsurface (pink rectangle) and a receiver array along the surface to record the computed wave-field. The receiver spacing is 40 m. The seismic tremor is generated by a large number of horizontal line sources with a length of 500 m acting randomly distributed in time and space within the source area. Each line source consists of a number of aligned, simultaneously acting vertical body-forces with a Ricker wavelet as source function (central frequency is 3 Hz). Fig. 2a shows the vertical component seismograms of the wave-field recorded at the receiver array. The data is transformed into the frequency domain and the two spectral attributes in Fig. 1 are computed for each receiver position. As shown in Fig. 2c, the major anomaly in both attribute profiles nicely correlate with the location of the source area projected onto the surface. Thus, for this simple case, the location of the tremor source can be well detected by analyzing the surface records only.

Application

In this section we model an example of hydrocarbon reservoir related tremors. As mentioned in the introduction, there is no generally accepted theory on the source mechanism responsible for such signals. However, Saenger et al. (2009) discuss several theoretically possible explanations. All of them allow describing hydrocarbon reservoirs as sources of low-frequency tremor signals. These sources may be either primary or secondary (i.e. diffracted waves) in nature. Therefore, we build our model on the hypothesis that reservoirs emit seismic tremor signals at low-frequencies. The model domain is a medium with seismic properties given by the true P-wave velocity distribution of an oil and gas field in the area of Voitsdorf, Austria (Fig. 3b). Density and Poisson ratio are assumed to be constant with ρ=2000 kg/m^3 and ν=0.25, respectively. Tremor sources are set to the two known reservoir positions in that area (pink rectangles). Fig. 3a shows the seismograms of the vertical component recorded at the receiver array and Fig. 3c displays the two spectral attributes plotted along the array. The attribute anomalies are not very pronounced and do not perfectly correlate with the two locations of the source areas. The profiles look noisy due to reflections and refractions within the complex velocity model and due to cross-talk between the two spatially separated source areas. However, a source localization based on both attribute profiles would still be successful.

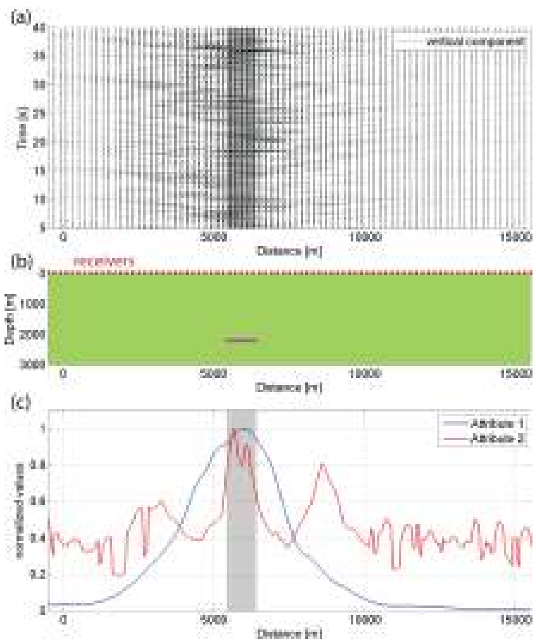

Figure 2. *Homogenous model. (a) Seismograms of the vertical component of the modeled wave-field, recorded by a surface receiver array. (b) Model domain of a homogenous medium with a subsurface tremor source area. (c) Profiles for both spectral attributes along the receiver array. The values are normalized to a maximum of 1. The major anomalies correlate with the location of the source area.*

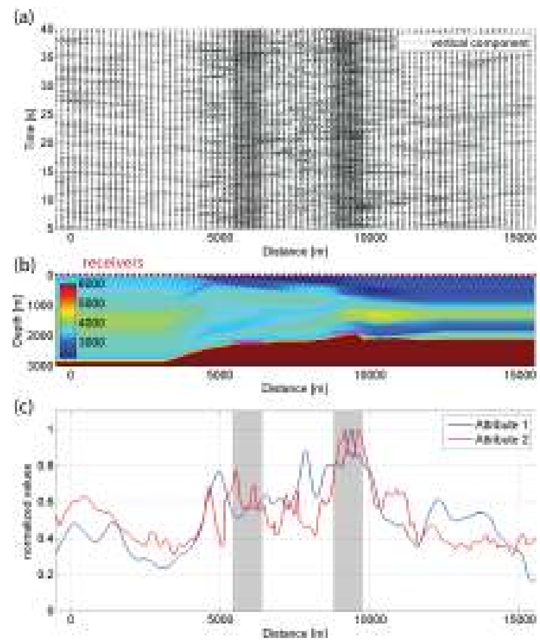

Figure 3. *Voitsdorf model. (a) Seismograms of the vertical component of the modeled wave-field, recorded by a surface receiver array. (b) Model domain. P-wave velocity distribution (in m/s) at the Voitsdorf oil and gas field. Two spatially separated tremor sources (pink rectangles) are set to the known reservoir positions. (c) Profiles for both spectral attributes along the receiver array. The values are normalized to a maximum of 1. The*

Artificial seismic surface noise (traffic, industrial machinery, structural resonances of buildings, etc.) can be a major issue for studying tremor signals (e.g., Hanssen and Bussat, 2008). Surface noise is often very dominant and can mask other signals. We therefore introduce surface noise in our model to make it more realistic. The surface noise is generated by randomly distributed single forces with random orientations in a surface layer of 50 m thickness. Number and strength of the forces is chosen in such a way that the mean S/N-ratio at the surface is 0.1. The thin blue line in Fig. 4a shows the corresponding profile for Attribute 1. The result is dominated by surface noise and its shape is mainly controlled by the near-surface seismic properties of the model. Note that the profile correlates with the inverse square of the S-wave velocity at the surface (green line). This is an expected result since the PSD of a seismic signal is inversely proportional to the square of the seismic velocity of the medium. The thin red line in Fig. 4b shows the profile for Attribute 2. It is very noisy and no obvious anomalies can be observed. In contrast to Attribute 1 there is no correlation with the near-surface S-wave velocity distribution. That is because the effect occurs on both, the vertical and horizontal component of the wave-field, and therefore cancels out when computing the V/H-ratio. The model with surface noise clearly demonstrates that it is not possible (without more data processing) to detect the tremor sources by analyzing spectral attributes of the surface data in the case of a S/N-ratio of 0.1.

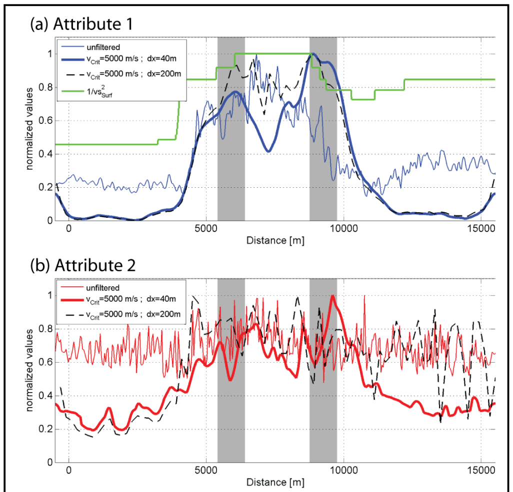

***Figure 4**. Effect of surface noise and F-K filtering. (a) Attribute 1, (b) Attribute 2. Thin solid lines show attribute profiles computed from data contaminated with surface noise (S/N-ratio=0.1). Bold solid lines show the attribute profiles after proper F-K filtering. Dashed black lines show the result of F-K filtering using poor filter parameters (spatial aliasing). The green line in panel (a) indicates the inverse square of the S-wave velocity at the surface (explanation see text).*

Frequency-wavenumber (F-K) filters are routinely applied to conventional reflection seismic data to suppress surface noise (Yilmaz, 1987). We apply it to our synthetic noise-contaminated tremor signals. An F-K filter transforms array data from the time-distance (t-x) domain via a 2D Fourier transform into the F-K domain. Here, signals can be discriminated upon their apparent velocity, v_{app}, across the array. v_{app} of a signal is affected by the properties of the medium as well as its wave-type, but mainly it is controlled by the angle of incidence of the waves with respect to the array. For instance, vertically incident signals from below the array have infinite apparent velocity. On the other hand, signals propagating parallel to the array have a minimum v_{app}, corresponding to the seismic velocity of the medium. We apply to the data an F-K filter that removes all the signals for which v_{app} < 5000 m/s and therefore suppresses the noise propagating along the surface. The result for the corresponding attribute profiles is shown in Fig. 4 (bold blue line for Attribute 1 and bold red line for Attribute 2). Both profiles show now pronounced anomalies that correlate with the locations of the tremor sources. The filtering process was therefore successful to retrieve the anomalies related to the tremor sources in the subsurface. After filtering, the tremor sources can clearly be detected. A critical issue with F-K filtering is spatial aliasing. This phenomenon occurs in case of spatial undersampling (receiver spacing too big) and introduces spurious signals (artifacts) into the data. The synthetic data discussed above with a receiver spacing of 40 m is not affected by spatial aliasing. The dashed black lines in Figure 4 are the result of sampling the wave field at 200m intervals. This sampling aliases the slow arrivals to such and extent that the process does not improve the result.

3D model

The synthetic results presented above are derived from 2D models. However, it is important for a deeper understanding to consider all 3 dimensions. There are three main reasons for using a 3D model: (1) Only a 3D model can account for the full 3D Green's functions in a heterogenous elastic medium. (2) A 3D model can be used to study out-of-plane effects on the attributes used to detect the tremor sources. (3) Designing a proper F-K filter for the 3D world. Only with a grid-array of receivers at the surface it is possible to suppress arbitrary incident surface waves (and not only surface waves propagating parallel to a line-array).

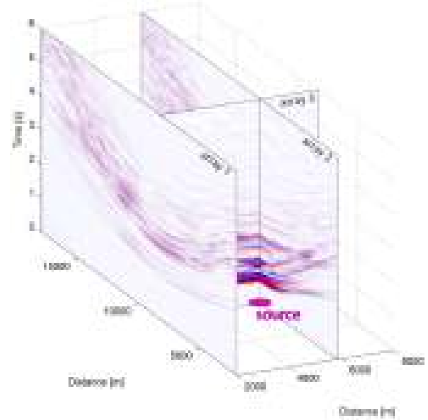

Figure 5. *Large-scale 3D simulation using the Voitsdorf velocity model. Shown is the vertical component of the wave-field recorded versus time at the surface for 3 different line arrays. The penny-shaped seismic source is indicated as a pink ellipse.*

Fig. 5 displays time-domain data from a large-scale 3D simulation (2000x1000x500 gridpoints, 4000 timesteps) using the Voitsdorf velocity model. Shown is the vertical component of the wave-field recorded versus time at the surface for 3 different line arrays. A seismic source (pink ellipse) is placed at one of the known reservoir positions. A vertical body-force with a Ricker wavelet is used as a source function (central frequency is 3 Hz). The spatial resolution is 10 m and the numerical timestep is 1.5 ms. This result shows how different the wavefield looks for a line array with a certain offset from the source location compared to arrays directly crossing on top of the source. Further analysis is part of ongoing research.

Conclusions and Outlook

Spectral attributes computed from surface passive seismic data allow detecting the location of seismic tremor sources in the subsurface (but no direct information on the depth is provided). Increased complexity of the subsurface seismic properties and/or the presence of spatially separated tremor sources can strongly complicate the interpretation of the results. In addition, the presence of dominant surface noise may mask the signals emitted by the subsurface tremor sources and make it impossible to detect them at the surface without any additional processing. F-K filtering is successfully applied to the noise-contaminated data to retrieve masked anomalies. F-K filtering only works properly if the receiver spacing of the surface array is sufficiently small to avoid spatial aliasing. Future plans include checking the synthetic results of this study against real data acquired at the survey area in Voitsdorf. The results of such a comparison could provide arguments to evaluate the hypothesis that hydrocarbon reservoirs can act as sources of seismic tremor signals. However, for a comprehensive study, a full 3D model and corresponding field data (grid array with dense enough receiver spacing to allow effective F-K filtering) would be essential.

Acknowledgements

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