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Up- and downgoing borehole wavefield retrieval using single component borehole and reflection data

Yi Liu [a,*], Børge Arntsen [b], Joost van der Neut [c], Kees Wapenaar [c]

[a] Department of Electronic Systems, Norwegian University of Science and Technology, 7491 Trondheim, Norway
[b] Department of Geoscience and Petroleum, Norwegian University of Science and Technology, 7491 Trondheim, Norway
[c] Department of Geoscience and Engineering, Delft University of Technology, 2628CN Delft, the Netherlands

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ABSTRACT

A standard procedure in processing vertical seismic profile (VSP) data is the separation of up- and downgoing wavefields. We show that these wavefields in boreholes can be retrieved using only single-component data, given that a full set of surface reflection data is also available. No medium parameters are required. The method is an application of the Marchenko method and uses a focusing wavefield. It is a wavefield that satisfies certain focusing conditions in a reference medium. We show that the method is applicable to boreholes with any orientation, and no receiver array is required. By this work, we present two contributions. One is that we investigate the effect of using only the traveltime from borehole data to form the focusing wavefield. The second is that we validates standard separation methods (PZ summation and *f*-*k* filtering) by retrieving the one-way wavefields from a completely different approach. We use the numerically modelled data from a realistic field velocity model in the North Sea. Three borehole geometries (horizontal, deviated and vertical) are tested. We discuss the practical aspects for field application in the end.

1. Introduction

Seismic data acquired in boreholes have long been used in aiding the geological interpretation of the subsurface. For vertical wells, these data are called vertical seismic profiles (VSP). VSP data are useful for identification and confirmation of the events seen on surface seismic data, seismic-stratigraphic analysis, seismic velocity analysis and calibration, imaging and time-lapse reservoir monitoring, and predicting ahead of the drill bit (Hardage, 1985; Poletto et al., 2004). Overviews of conventional VSP processing techniques and successful field examples can be found in Kennett et al. (1980) and Balch et al. (1982).

Due to its acquisition geometry, an important VSP processing step is the separation of the up- and downgoing fields. Conventional VSP up-down separation methods are based on the separation of different apparent velocities (or dips) of the up- and downgoing fields. Generally speaking, upgoing events have positive dips and downgoing events have negative dips. Velocity filters are commonly used to separate them in the frequency-wavenumber (*f*-*k*) domain (Embree et al., 1963; Treitel et al., 1967). Besides the separation in the *f*-*k* domain, separation in the τ-p domain after applying Radon transform is suggested by Moon et al. (1986). In this approach, the up-down components are mapped to different τ-p quadrants according to their dips so that they can be separated. This technique is useful when the separation is difficult in the *f*-*k* domain.

With the availability of multi-component data, more sophisticated wave-equation based decomposition methods are developed. Dankbaar (1985) proposes a decomposition scheme which uses weighted summations of vertical and horizontal geophone measurements in the *f*-*k* domain. Wapenaar et al. (1990) present a scheme to decompose land surface data into up-downgoing P- and S-waves. Other separation methods that are based on eigenvalue decomposition of the equation of motion with certain boundary conditions in horizontally-layered media. Ursin (1983) show that the up- and downgoing fields can be computed as an angle-dependent combination of two or more measured data components. Barr and Sanders (1989) show the use of a scalar combination of the hydrophone (pressure) and vertical geophone (particle velocity) measurements to suppress water-column reverberations. This approach is commonly referred to as PZ summation. It is simple to implement but valid for normal incidence only. An angle-dependent decomposition for multi-component sea-floor data is proposed by Amundsen (1993) and Amundsen and Reitan (1995), which requires the seabed velocity and density. Schalkwijk et al. (2003) propose a 5-step adaptive decomposition scheme that obtains the necessary information from data, and it is further extended by Muijs et al. (2004) to be applied in an efficient automated manner.

In this paper, we show another approach that is also wave-equation based, but retrieves the up- and downgoing fields in boreholes using

* Corresponding author.
E-mail address: yi.liu@ntnu.no (Y. Liu).

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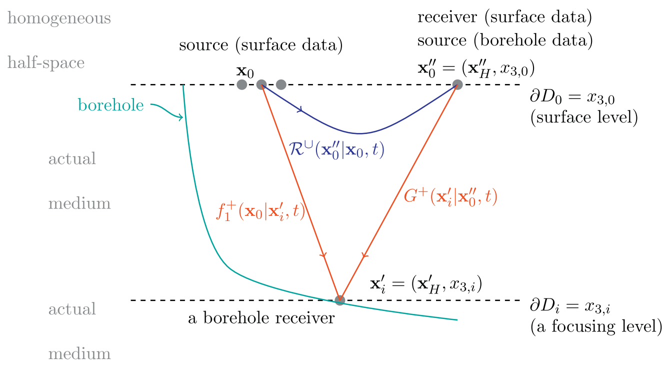

Fig. 1. Notation convention and data acquisition overview. Each spatial position is denoted by ($\mathbf{x}_H$, $x_{3,\,i}$), with $\mathbf{x}_H = (x_1, x_2)$, and i represents a certain depth level. The upper dashed line denotes a transparent surface level ∂D_0, above which the medium is homogeneous, and the lower dashed line denotes a focusing level ∂D_i (below which the medium is reflection-free for the focusing function, see Fig. 2). The solid blue line represents the known surface reflection response $R^{\cup}(\mathbf{x}''_0|\mathbf{x}_0,t)$ after source deconvolution and surface multiple removal. The solid red lines represent the unknown quantities, where $f_1^+(\mathbf{x}_0|\mathbf{x}_i',t)$ is the downgoing component of the focusing function with the focus position $\mathbf{x}'_i$ and $G^+(\mathbf{x}'_i|\mathbf{x}''_0, t)$ is the retrieved downgoing wavefield from a surface source at $\mathbf{x}''_0$. Note that G^+ additionally contains the interaction with the medium below the focusing level. For f_1^+, the medium below the focusing level is homogenous and not the actual medium. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

only the acoustic pressure data recorded at the surface and in the borehole. The method is valid for a general lossless inhomogeneous medium with moderately curved interfaces. It accounts for all internal multiples and is not limited to normal incidence. No medium parameters are required, and it can be used for a single borehole receiver (an array of receivers is not needed). The method uses the so-called focusing wavefields from the Marchenko method (Rose, 2002; Broggini et al., 2012; Wapenaar et al., 2013; Behura et al., 2014), which are computed from surface reflection data and borehole data. From these focusing functions, one is able to retrieve at a borehole receiver, the up- and downgoing wavefields. We show that the method works for any general borehole orientation, and its results agree with those by other methods. This approach is tested with synthetic data, modelled for a density and velocity model realistic for North Sea. Three borehole geometries are included, namely, horizontal, deviated, and vertical. The retrieved up- and downgoing fields are compared with those by conventional methods in each case. In the horizontal configuration, we also investigate the effect from a less-than-ideal initial focusing wavefield, where only the smoothed traveltime from borehole data is used. We then discuss these results and their applicability to field data.

2. Method

The Marchenko method (Wapenaar et al., 2014) is able to retrieve up- and downgoing subsurface wavefields from surface sources. It

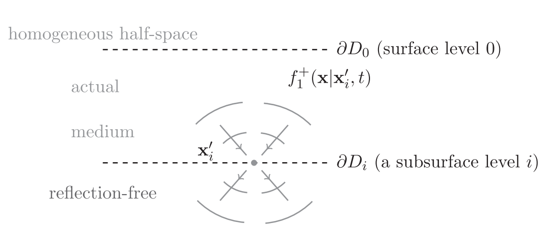

Fig. 2. An illustration of the downgoing focusing wavefield $f_1^+(\mathbf{x}|\mathbf{x}_i',t)$. After being injected at the surface level ∂D_0 at $t = -t_d(\mathbf{x}_0|\mathbf{x}'_i)$, it propagates downward and focuses at $\mathbf{x}'_i$ at $t = 0$. $t_d(\mathbf{x}|\mathbf{x}'_i)$ is the direct travel time from $\mathbf{x}_0$ to $\mathbf{x}'_i$. Then the wavefield continues propagating downward from the level i. Notice that the medium below that level is defined as reflection-free, which is different from that in Fig. 1, where the retrieved G^+ additionally contains the interaction with the medium below the focusing level.

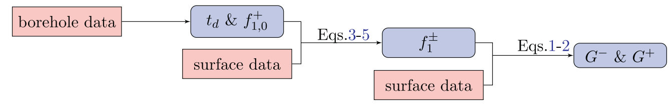

Fig. 3. The general workflow for retrieving the up- and downgoing fields. The red boxes denote the input data, and the round-cornered purple boxes denote the computed results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

requires surface reflection responses and the direct wavefield from the subsurface location to the surface source positions, which can be obtained from a smooth background velocity model. However, velocity

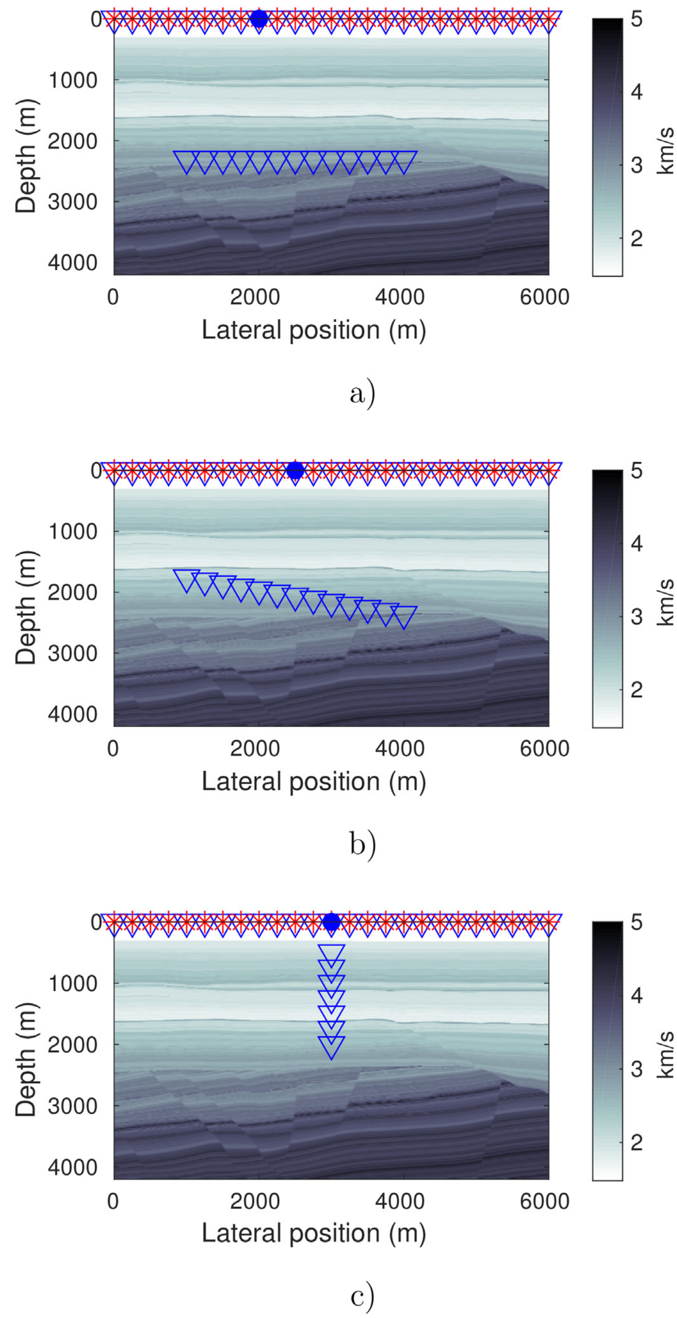

Fig. 4. The P-wave velocity model and the acquisition geometries for the a) horizontal borehole, b) deviated borehole and c) vertical borehole. The stars denote the sources in both the surface and borehole data, and the triangles denote the receivers. The blue circles denote the reference source positions, where the retrieved one-way wavefields are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)