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# Multi-datum based estimation of near-surface full-waveform redatuming operators

Jan-Willem Vrolijk, Peter Haffinger, Eric Verschuur *

*Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ, Delft, The Netherlands*

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ABSTRACT

A complex near surface can impact the quality of land data, despite the fact that the geology below the near surface complexities can be laterally smooth. Redatuming with operators based on a high-frequency parameterization in terms of traveltimes and simple geometric spreading factors will fall short if there are large lateral and vertical variations in propagation velocity and buried anomalies in the near surface layer. Recently, a method was introduced that can estimate the involved redatuming operators in a full-waveform sense. Application to synthetic data shows an uplift to the redatuming quality, but residual imprint is still observed. In this paper an extension is introduced that estimates redatuming operators based on two datum reflections simultaneously.

In this way the full-waveform estimation process becomes more robust and shows another level of improvement for synthetic data. This conclusion is further amplified by the results obtained on field data from an area with a severe near-surface problem.



## 1. Introduction

In many seismic land data acquisitions, the complex near surface imposes a strong imprint in the subsurface image, because the waves propagate twice through this often strongly heterogeneous region. Adequately compensating for these complex propagation effects is one of the challenges in land data processing (Keho and Kelamis, 2009). Conventionally, these effects are treated using so-called static corrections (Cox, 1999), but this method assumes vertical ray paths in the near surface region. These static corrections can be extended to bring in more propagation-like effects, such as described in Bagaini and Alkhalifah (2006). However, when the near-surface region becomes more complicated, e.g. due to buried anomalies and strong lateral heterogeneities, a wave equation-based solution needs to be adopted, meaning that the near-surface propagation effects are removed from the data by a redatuming process. Berryhill (1984) and Shtivelman and Canning (1988) already proposed such a solution, using redatuming operators that were based on a velocity-depth model.

However, deriving a velocity-depth model from the data that accurately describes the propagation through the near surface region is a non-trivial task (Vesnaver et al., 2006). Therefore, a data-driven approach for focusing seismic data to a certain reflection boundary was introduced by Berkhout (1997a, 1997b) and further exemplified by Thorbecke (1997). It was shown that this technology can indeed be used to remove the imprint of complex near-surface propagation effects from seismic data (see e.g. Al-Ali and Verschuur, 2006; El-Marhfoul et al., 2009; Hindriks and Verschuur, 2001; Kelamis et al., 2002). To reduce user-interaction, Verschuur and Marhfoul (2005) have described a semi-automatic method to find the one-way traveltimes between surface and datum reflector. Nevertheless, the current implementation of the method is based on the estimation of the redatuming operators in terms of *traveltimes* and does not allow a correct amplitude preservation during redatuming. This is true for most redatuming approaches currently available (Schuster and Zhou, 2006). Note that simplified redatuming operators also lead to structural errors in the redatuming result. This means that after redatuming the data will still suffer from residual imprint due to lateral amplitude and phase changes that are not accounted for in the simplified redatuming operators. Hindriks et al. (2002) have described an attempt to also update the amplitudes of the redatuming operators, but still based their algorithm on the high-frequency approximation, assuming redatuming operators to be parameterized with traveltimes and amplitudes.

Using more exact full-waveform redatuming operators instead of the currently used simple traveltime-based operators is expected to lead to a better solution of the near-surface problem. In case of downhole receivers being present, the virtual source method can be used to redatum the sources using measured propagation operators (Bakulin, 2006). However, even then it is difficult to get well-defined omni-directional virtual sources (van deer Neut and Bakulin, 2009). In Haffinger and Verschuur (2010), an updating procedure was introduced to determine such full-waveform, near-surface redatuming operators. On synthetic data this method was shown to reduce the residual transmission imprint on the seismic data after redatuming. However, the imprint was not fully removed. One reason is that full-waveform updating process based on a single datum reflection

* Corresponding author. Tel.: +31 15 2782403; fax: +31 15 2783499.
*E-mail address:* D.J.Verschuur@tudelft.nl (E. Verschuur).

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event does not guarantee a good result for the reflections from below the datum level, because noise due to the event selection process will leak into the estimated redatuming operators. In this paper the method of full-waveform redatuming operator updating is extended to use two reference reflection events: the responses from the actual datum reflector and from a strong reflector below this datum. In this way, the full-waveform updating process becomes more robust, because the event selection noise for both events will be different and thus there is less chance of such noise leaking into the estimated operators. This will be demonstrated for 2D synthetic data and for a 2D line of field data from an area with a complex near-surface problem. Note that in principle, more reflectors from below the datum could be included, however, each additional reflected event will make the updating method more extensive in terms of user-interaction, and thus less applicable.

## 2. Redatuming theory

For the redatuming theory we will use the matrix notation from Berkhout (1982), in which a matrix contains a multi-record wavefield for one frequency component. One column contains the wavefield for one source and a row represents a monochromatic common-receiver gather. The data measured by a geometry with sources and receivers located at the surface, $\delta\mathbf{P}(z_0, z_0)$, containing the response of one reflector at a single depth level $z_d$, can be mathematically described by:

$$\delta\mathbf{P}(z_0,z_0) = \mathbf{W}^T(z_o,z_d)\mathbf{R}(z_d)\mathbf{W}(z_d,z_0)\mathbf{S}(z_0). \tag{1}$$

Here the columns of $\mathbf{S}(z_0)$ contain the downgoing source wavefields for each of the shot experiments, $\mathbf{W}$ and $\mathbf{W}^T$ describe wave propagation down and up, respectively, between the surface and the reflector, $f\mathbf{R}$ is a matrix containing the reflectivity operators of a single depth level, (see also de Bruin et al., 1990) and $T$ stands for the transposed. Next, we define a hypothetical experiment $\mathbf{X}(z_d, z_d)$, in which virtual unit sources and virtual unit receivers are placed at depth level $z_d$. Then, the total data measured at the surface $\mathbf{P}(z_0, z_0)$ becomes:

$$\mathbf{P}(z_0,z_0) = \delta\mathbf{P}(z_0,z_0) + \mathbf{W}^T(z_0,z_d)\mathbf{X}(z_d,z_d)\mathbf{W}(z_d,z_0)\mathbf{S}(z_0), \tag{2}$$

where we neglect reflections from levels above $z_d$. Furthermore, we will assume that $\mathbf{S}(z_0)$ is a scaled unit matrix: $\mathbf{S}(z_0)=\mathbf{I}S(\omega)$, where $S(\omega)$ represents the source signature:

$$\begin{aligned}\mathbf{P}(z_0,z_0) = {}& \mathbf{W}^T(z_o,z_d)\mathbf{R}(z_d)\mathbf{W}(z_d,z_0)S(\boldsymbol{\omega}) \\ & + \mathbf{W}^T(z_0,z_d)\mathbf{X}(z_d,z_d)\mathbf{W}(z_d,z_0)S(\boldsymbol{\omega}).\end{aligned} \tag{3}$$

Assuming identical wavelets for each shot will limit the accuracy of the estimated full-waveform operators, because in practice the wavelet can differ for each shot. The same is true for receiver coupling effects (not explicitly mentioned in the above formulation). Thus, we assume some sort of source/receiver balancing has been applied as a pre-processing step. In the seismic measurement described by Eqs. (1) to (3), many sources and receivers are used. Therefore, the propagating operators $\mathbf{W}$ contain all corresponding Green's functions between the virtual sources/receivers and the true sources/receivers. Each column of $\mathbf{W}(z_d, z_0)$ describes the field of a source at level $z_0$ to receivers at level $z_d$ and each column of $\mathbf{W}(z_d, z_0)^T$ contains the response of a source at level $z_d$ and a receiver at the surface. Redatuming to a depth level $z_d$, which will be denoted as the datum level in the remainder of this paper, can be applied as follows:

$$\begin{aligned}\mathbf{P}(z_d,z_d) &= \left[\mathbf{W}^T(z_0,z_d)\right]^{-1}\mathbf{P}(z_0,z_0)[\mathbf{W}(z_d,z_0)]^{-1} \\ &= \mathbf{R}(z_d)S(\omega) + \mathbf{P}(z_d,z_d),\end{aligned} \tag{4}$$

where data $\mathbf{P}(z_d,z_d)$ is defined as:

$$\mathbf{P}(z_d,z_d) = \mathbf{X}(z_d,z_d)S(\omega), \tag{5}$$

containing the responses from the reflectors below the datum.

For perfectly redatumed data $\mathbf{P}(z_d,z_d)$ the datum reflectivity operator will give a well focused event in the origin, while all events from deeper reflections are located at positive times. This so-called focus point response $\mathbf{Q}(z_d) = \mathbf{R}(z_d)S(\omega)$ will be used to obtain a full-waveform solution to the redatuming problem.

The inverse propagation operators are called focusing operators in the remainder of this paper, indicated by symbol $\mathbf{F}$. With this definition Eq. (4) can be written as:

$$\mathbf{P}(z_d,z_d) = \mathbf{F}^T(z_d,z_0)\mathbf{P}(z_0,z_0)\mathbf{F}(z_0,z_d), \tag{6}$$

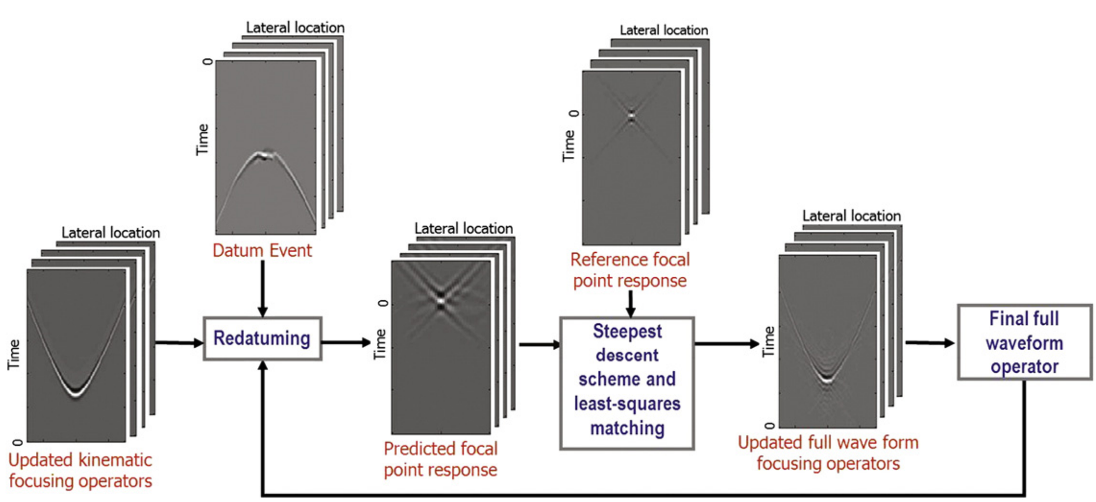


**Fig. 1.** At first, the actual focal point response is obtained by redatuming the datum event with the updated kinematic focusing operator. After that, the updated full-waveform focusing operators are calculated with the optimization method and a least-squares matching between the predicted focal point responses and reference focal point responses is applied. Again the updated actual focal point responses are obtained by redatuming the datum event with the new dynamic focusing operators and the process is repeated until it converges.