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Marchenko scheme based internal multiple reflection elimination in acoustic wavefield

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ABSTRACT

Marchenko imaging is a methodology to image the subsurface with two important properties: (1)accurate amplitude and (2)free from free-surface and internal multiple artefacts. It requires an estimate of the first arrival of the focusing function which is commonly obtained from a macro velocity model. Inspired by this limitation, a projected Marchenko scheme has been introduced from which an internal multiple reflection elimination scheme has been derived. This internal multiple reflection elimination scheme requires an estimate of the two-way travel time surface of a selected horizon in the subsurface instead of a macro model. In order to make it totally model free we have rewritten the scheme by replacing the estimate of the two-way travel time surface by a fixed truncation for all traces. The output of the current scheme contains primary reflections without contamination from internal multiple reflections. We apply this scheme to a 2D numerical example to illustrate the procedure of this method and show how the internal multiple reflection eliminated data set can be retrieved and the migration image is improved.

1. Introduction

Strong artefacts due to internal multiple reflections can occur in migration of images produced from marine (Hadidi and Verschuur, 1997; Van Borselen, 2002) and land data (Kelamis et al., 2006). Several schemes have been developed to predict and subtract internal multiple reflections from measured data, such as internal multiple elimination (IME) (Berkhout and Verschuur, 2005) and inverse scattering series (ISS) (Weglein et al., 1997). For IME, the identification of the internal multiple reflection generators in the input data is required. The subtraction of the predicted internal multiple reflections is applied by a least-square matching filter with a minimum-energy criterion. For ISS, the internal multiple reflections can be predicted with approximated amplitude (Löer et al., 2016). Ten Kroode et al. (2002) derive a multiple reflection elimination scheme from ISS and source-receiver interferometry with specific truncation. However, global or local matching filter is usually required to subtract the predicted internal multiple reflections from measured data (de Melo et al., 2014).

Recently, Marchenko imaging has been introduced to deal with internal multiple reflections (Slob et al., 2014; Wapenaar et al., 2014a; da Costa Filho et al., 2015). For this scheme, up- and downgoing focusing functions with focal point at an arbitrary position in the subsurface can be retrieved by solving the coupled Marchenko equations and up- and downgoing Green's functions can be solved from Green's function representations by using the solved focusing functions as inputs. By deconvolving the retrieved upgoing Green's function with the downgoing Green's function, a virtual reflection response with virtual source and virtual receivers in the subsurface can be obtained. The virtual reflection response forms the basis for obtaining an artefact-free image when the zero-time-lag crosscorrelation between the retrieved up- and downgoing virtual responses is extracted at any image point (Wapenaar et al., 2014b; Broggini et al., 2014). Based on Marchenko redatuming and convolutional interferometry, an approximate primary reflection retrieval scheme has been proposed (Meles et al., 2016). Van der Neut and Wapenaar (2016) rewrite the coupled Marchenko equations by projecting them to the acquisition surface. Based on the revised Marchenko scheme an adaptive overburden elimination approach is introduced. All orders of internal multiple reflections above a specified horizon can be removed without having to remove internal multiple reflections from shallower horizons.

Based on the revised Marchenko equations, van der Neut and Wapenaar (2016) present a scheme to eliminate internal multiple reflections from the measured acoustic wave field and apply it to a 1D numerical example. In order to make it totally model free we have rewritten the scheme by replacing the estimate of the two-way travel time surface by a fixed truncation for all traces in this paper. The rewritten scheme entirely obviates the requirement of estimating the first arrival in the focusing wave field from one-sided Marchenko equations (Slob et al., 2014; Wapenaar et al., 2014b) to eliminate internal multiple reflections from the measured acoustic wave field. One-sided reflection data is required as input. Because of the elimination of internal multiple

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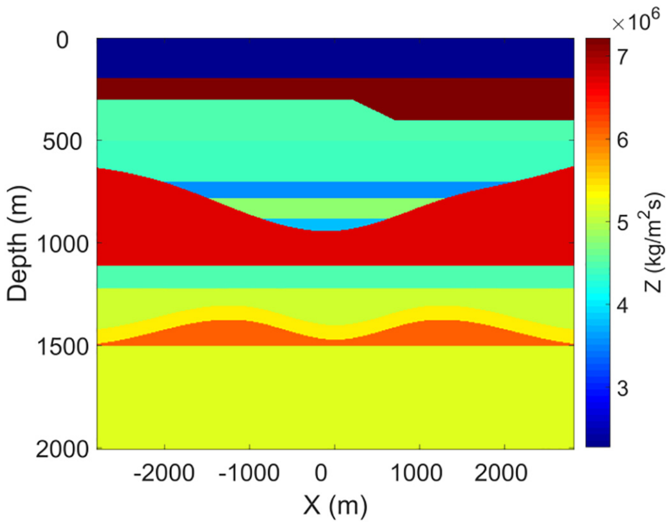

Fig. 1. Acoustic impendance of the model.

reflections, the retrieved data set contains only primary reflections. The obtained data set is more suitable for subsequent AVO or AVA analysis and as input for velocity model building. The updated model can subsequently be used to image the medium, it can also be used to image the medium without artefacts due to internal multiple reflections. We present a 2D numerical example to illustrate how a dataset free from internal multiple reflections can be retrieved using the current scheme leading to improved quality in the resulting migrated image.

2. Theory

We indicate time as t and the position as $\mathbf{x} = (x,y,z)$, where z denotes depth and (x,y) denotes the horizontal coordinates. The acoustically transparent acquisition boundary $\partial\mathbf{D}_0$ is defined as $z_0 = 0$. For convenience, the coordinates at $\partial\mathbf{D}_0$ are denoted as $\mathbf{x}_0 = (\mathbf{x}_\mathrm{H}, z_0)$, with $\mathbf{x}_\mathrm{H} = (x,y)$. Similarly, the position at an arbitrary depth level $\partial\mathbf{D}_i$ is denoted as $\mathbf{x}_i = (\mathbf{x}_\mathrm{H}, z_i)$, where z_i denotes the depth of $\partial\mathbf{D}_i$. We express the acoustic impulse reflection response as $R(\mathbf{x}_0{}', \mathbf{x}_0, t)$, where $\mathbf{x}_0$ denotes the source position and $\mathbf{x}_0{}'$ denotes the receiver position, both located at the acquisition surface $\partial\mathbf{D}_0$. In practice, it means that free-surface related multiple reflections should first be removed from the measured reflection response, in which step the source locations are redatumed to the receiver depth level and the source wavelet should be recovered and accurately deconvolved from the data. The focusing wave field $f_1(\mathbf{x}_0, \mathbf{x}_i, t)$ is the solution of the homogeneous wave equation in a truncated medium and focuses at the focal point $\mathbf{x}_i$. We define the truncated domain as $\partial\mathbf{D}_0 < z < \partial\mathbf{D}_i$ with $z_0 < z < z_i$. Inside the truncated domain, the properties of the medium are equal to the properties of the physical medium. Outside the truncated domain, the truncated medium is reflection-free. The Green's function $G(\mathbf{x}_i, \mathbf{x}_0, t)$ is defined for an impulse source that is excited at $\mathbf{x}_0$ and a receiver is positioned at the focal point $\mathbf{x}_i$. The Green's function is defined in the same physical medium as the measured data. The focusing and Green's functions can be partitioned into up- and downgoing constituents and for this we use power-flux normalized quantities (Wapenaar et al., 2014a).

We start with the 3D versions of one-way reciprocity theorems for flux-normalized wave fields and use them for the depth levels z_0 and z_i. When the medium above the acquisition level z_0 is reflection-free, we have the Green's function representations (Wapenaar et al., 2014a),

$$G^-(\mathbf{x}_i, \mathbf{x}_0', t) = \int_{\partial\mathbf{D}_0} d\mathbf{x}_0 \int_0^{+\infty} R(\mathbf{x}_0', \mathbf{x}_0, t') f_1^+(\mathbf{x}_0, \mathbf{x}_i, t-t') dt' - f_1^-(\mathbf{x}_0', \mathbf{x}_i, t), \tag{1}$$

$$G^+(\mathbf{x}_i, \mathbf{x}_0', -t) = -\int_{\partial\mathbf{D}_0} d\mathbf{x}_0 \int_{-\infty}^{0} R(\mathbf{x}_0', \mathbf{x}_0, -t') f_1^-(\mathbf{x}_0, \mathbf{x}_i, t-t') dt' + f_1^+(\mathbf{x}_0', \mathbf{x}_i, t). \tag{2}$$

Superscripts + and − stand for downgoing and upgoing fields, respectively. The downgoing component of the focusing function $f_1^+(\mathbf{x}_0, \mathbf{x}_i, t)$ is the inverse of the transmission response in the truncated medium. We can write both the focusing function and the transmission response as the sum of a direct part and a coda

$$f_1^+(\mathbf{x}_0, \mathbf{x}_i, t) = f_{1d}^+(\mathbf{x}_0, \mathbf{x}_i, t) + f_{1m}^+(\mathbf{x}_0, \mathbf{x}_i, t), \tag{3}$$

$$T(\mathbf{x}_i, \mathbf{x}_0, t) = T_d(\mathbf{x}_i, \mathbf{x}_0, t) + T_m(\mathbf{x}_i, \mathbf{x}_0, t), \tag{4}$$

where f_{1d}^+ and T_d indicate the direct part, whereas f_{1m}^+ and T_m indicate the following coda. Wapenaar et al. (2014b) show that

$$\int_{\partial\mathbf{D}_i} d\mathbf{x}_i \int_0^{+\infty} T_d(\mathbf{x}_i, \mathbf{x}_0'', t') f_{1d}^+(\mathbf{x}_0, \mathbf{x}_i, t-t') dt' = \delta(\mathbf{x}_\mathrm{H}'' - \mathbf{x}_\mathrm{H}) \delta(t), \tag{5}$$

where $\delta(\mathbf{x}_\mathrm{H})$ is a spatially band-limited 2D delta function in space and $\delta(t)$ is a delta function in time. Eq.(5) means that T_d is the inverse of f_{1d}^+. Following van der Neut and Wapenaar (2016), we apply multidimensional convolution with T_d as shown in Eq.(5) to Eqs.(1)and (2) to find

$$U^-(\mathbf{x}_0'', \mathbf{x}_0', t) + v^-(\mathbf{x}_0', \mathbf{x}_0'', t) = \int_{\partial\mathbf{D}_0} d\mathbf{x}_0 \int_0^{+\infty} R(\mathbf{x}_0', \mathbf{x}_0, t') \times \left(\delta(t-t')\delta(\mathbf{x}_\mathrm{H}'' - \mathbf{x}_\mathrm{H}) + v_m^+(\mathbf{x}_0, \mathbf{x}_0'', t-t')\right) dt', \tag{6}$$

$$\delta(t)\delta(\mathbf{x}_\mathrm{H}'' - \mathbf{x}_\mathrm{H}') + v_m^+(\mathbf{x}_0', \mathbf{x}_0'', t) - U^+(\mathbf{x}_0'', \mathbf{x}_0', -t) = \int_{\partial\mathbf{D}_0} d\mathbf{x}_0 \int_{-\infty}^{0} R(\mathbf{x}_0', \mathbf{x}_0, -t') v^-(\mathbf{x}_0, \mathbf{x}_0'', t-t') dt', \tag{7}$$

With v^- defined as

$$v^-(\mathbf{x}_0', \mathbf{x}_0'', t) = \int_{\partial\mathbf{D}_i} d\mathbf{x}_i \int_0^{+\infty} T_d(\mathbf{x}_i, \mathbf{x}_0'', t') f_1^-(\mathbf{x}_0', \mathbf{x}_i, t-t') dt', \tag{8}$$

where v_m^+ is convolved version of f_{1m}^+, U^- and U^+ are convolved versions of G^- and G^+, similar as is shown in Eq.(8) for f_1^-. Based on the fact that the convolved Green's and focusing functions in Eqs.(6)and (7) are separated in time except for the first event in the convolved downgoing focusing function and last event in the convolved time-reversed downgoing Green's function in Eq.(7) (both of them are delta functions after the convolution) that coincide with each other. We rewrite Eqs.(6)and (7) as

$$v^-(\mathbf{x}_0', \mathbf{x}_0'', t) = \int_{\partial\mathbf{D}_0} d\mathbf{x}_0 \int_0^{+\infty} R(\mathbf{x}_0', \mathbf{x}_0, t') \times \left(\delta(t-t')\delta(\mathbf{x}_\mathrm{H}'' - \mathbf{x}_\mathrm{H}) + v_m^+(\mathbf{x}_0, \mathbf{x}_0'', t-t')\right) dt', \quad \text{for} \varepsilon < t < t_2 - \varepsilon \tag{9}$$

$$v_m^+(\mathbf{x}_0', \mathbf{x}_0'', t) = \int_{\partial\mathbf{D}_0} d\mathbf{x}_0 \int_{-\infty}^{0} R(\mathbf{x}_0', \mathbf{x}_0, -t') v^-(\mathbf{x}_0, \mathbf{x}_0'', t-t') dt', \quad \text{for} \varepsilon < t < t_2 - \varepsilon \tag{10}$$

where t_2 denotes the two-way travel time from a surface point $\mathbf{x}_0{}'$ to the focusing level z_i and back to the surface point $\mathbf{x}_0''$, and ε is a positive value to account for the finite bandwidth. Then we give Eqs.(9)and (10) in the operator form as

$$v^-(\mathbf{x}_0', \mathbf{x}_0'', t) = \left(\Theta_\varepsilon^{t_2-\varepsilon}\mathbf{R}\delta + \Theta_\varepsilon^{t_2-\varepsilon}\mathbf{R}v_m^+\right)(\mathbf{x}_0', \mathbf{x}_0'', t), \tag{11}$$