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A field data example of Marchenko multiple elimination

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Summary

Multiple reflections are often considered as noise in seismic data. Dealing with them has attracted much attention from industry and academia. A variety of schemes have been developed for removal of free-surface multiple reflections and success has been achieved in numerical and field datasets. However, less attention has been directed toward internal multiple reflection removal. The Marchenko multiple elimination scheme is capable to eliminate internal multiple reflections without model information or adaptive subtraction. This scheme is derived from coupled Marchenko-type equations by projecting the focusing functions from the focusing level back to the acquisition surface. Primary reflections are filtered from acquired seismic data. We apply the Marchenko multiple elimination scheme to a deep water 2D field dataset from the Norwegian North Sea to test the performance. We show that the Marchenko multiple elimination scheme is an appropriate method for removing internal multiple reflections when high-quality pre-processing is performed.

Introduction

Standard migration schemes, such as reverse time migration, migrate measured seismic data to give the image of the interior structure of the model. They are based on the single-scattering assumption that all reflections in the measured seismic data are reflected once before they are recorded. It implies that multiple reflections need to be removed from the measured seismic data such that the processed dataset complies with the assumptions made in standard migration schemes. Therefore, the removal of multiple reflections plays a crucial role for the success of the standard migration schemes. Many approaches have been developed for dealing with multiple reflections contained in the acquired seismic data. Some of them focus on free-surface multiple reflections and some of them focus on internal multiple reflections.

The presence of free-surface multiple reflections has attracted much attention from industry and academia in the past decades. Most of the developed schemes focus on the removal of free-surface multiple reflections and, in contrast, some of them try to use free-surface multiple reflections as useful signal. The free-surface multiple reflection elimination (SRME) (Verschuur et al., 1992) and estimation of primaries by sparse inversion (EPSI) (van Groenestijn and Verschuur, 2009) are two successful schemes for removal of free-surface multiple reflections. Both have been validated by numerical and field datasets, and are widely accepted as robust tools in industry. The SRME scheme removes free-surface multiple reflections with a minimum-energy criterion. The EPSI scheme can be seen as an inversion process, where the two-stage processing of SRME, prediction and adaptive subtraction, are replaced by a full-waveform inversion step. As mentioned before, some researchers attempt to use free-surface multiple reflections as useful signal during the migration process (Brown and Guitton, 2005; Verschuur and Berkhout, 2011; Wang et al., 2017). The migration of free-surface multiple reflections gives extra illumination of the subsurface with crosstalk present as coherent noises.

Removal of internal multiple reflections is a relatively recent development in exploration geophysics. As pioneers, Araújo et al. (1994) derive an internal multiple attenuation scheme from Inverse Scattering Series (ISS). It is model-free but requires the adaptive subtraction in its implementation. The ISS scheme has been developed by Weglein et al. (1997). As shown by Jakubowicz (1998), the first-order internal multiple reflections can be predicted and attenuated by combing three primary reflections which need to be identified from the measured seismic data. Inspired by this idea, Ten Kroode (2002) and Löer et al. (2016) modified the ISS scheme with time truncations to attenuate internal multiple reflections in the data. It has been validated by field data examples (Luo et al., 2011). The internal multiple elimination (IME) (Berkhout and Verschuur, 1997) is a well-known scheme, where internal multiple reflections are predicted in a layer-stripping fashion extended from SRME. A macro velocity model and adaptive subtraction are required for the implementation. The success has been illustrated by numerical and field datasets (Verschuur and Berkhout, 2005). Berkhout (2014) tries to use internal multiple reflections in imaging via full wavefield migration (FWM) scheme. The success of the FWM scheme has been validated by a field data example in Davydenko and Verschuur (2018).

Marchenko imaging schemes have been proposed to image the subsurface of the media without artefacts arising from internal multiple reflections (Slob et al., 2014; Wapenaar et al., 2014). Singh et al. (2017) extend the Marchenko scheme to account also for free-surface multiple reflections. In that case, free-surface multiple reflections do not need to be removed before the Marchenko scheme can be applied. Ravasi (2017) adapts the Marchenko scheme to a marine dataset, where the measured dataset with multiple reflections and ghosts are used to retrieve the artefact-free image of the subsurface. Meles et al. (2015) combine the Marchenko scheme with convolutional interferometry to

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attenuate internal multiple reflections. A macro model and adaptive subtraction are required because of the approximate nature of the predicted events. Staring et al. (2018) propose an adaptive Marchenko double-focusing method for attenuating the first-order internal multiple reflections. Model information and adaptive subtraction are also required for the implementation. Van der Neut and Wapenaar (2016) derive an internal multiple elimination scheme by projecting the focusing functions back to the acquisition surface. It requires offset dependent time truncations for which a macro velocity model is needed. This idea has been modified by Zhang and Staring (2018), which we call the Marchenko multiple elimination scheme (MME). In theory, the MME scheme eliminates internal multiple reflections without requiring model information or adaptive subtraction. A small adaptation not only eliminates the internal multiple reflections but also compensates for transmission loss in the primary reflections (Zhang et al., 2019). Free-surface multiple reflections can be included in the removal scheme as well (Zhang and Slob, 2019a). Therefore, free-surface and internal multiple reflections are removed and compensation for transmission loss in primary reflections are achieved in one step without model information or adaptive subtraction.

Here, we apply the MME scheme to a 2D deep water field dataset from the Norwegian North Sea to test its performance in the removal of internal multiple reflections without model information or adaptive subtraction. The abstract is organized as follows. In the theory section, we give a brief overview of the theory underlying the MME scheme. In the field data example section, we apply the MME scheme to a 2D field dataset for internal multiple reflection elimination. In the discussion section, the advantages and disadvantages of the MME scheme are analysed in detail, and we end with conclusions.

Theory

Here, we give a brief overview of the MME scheme. The impulse reflection response is denoted $R(\mathbf{x}'_0, \mathbf{x}_0, t)$ with a receiver placed at $\mathbf{x}'_0$ and source placed at $\mathbf{x}_0$, and t denotes time. The sources and receivers are placed at the acquisition surface which is taken to be transparent such that the measured dataset $R(\mathbf{x}'_0, \mathbf{x}_0, t)$ is free from free-surface multiple reflections. The formula of the MME scheme can be given as (Zhang and Staring, 2018)

$$R_t(\mathbf{x}'_0, \mathbf{x}''_0, t) = R(\mathbf{x}'_0, \mathbf{x}''_0, t) + [\sum_{m=1}^{\infty} (\mathbf{R}\Theta_\tau^{t-\tau}\mathbf{R}^*\Theta_\tau^{t-\tau})^m R](\mathbf{x}'_0, \mathbf{x}''_0, t). \quad (1)$$

where $\Theta_\tau^{t-\tau}$ is a truncation operator to exclude values outside of the window $(\tau, t-\tau)$ and τ indicates a small positive value to account for the finite bandwidth of the input data, the truncation time $(\tau, t-\tau)$ is constant for all offsets. The impulse reflection response as a time-convolution and spatial integral operator is denoted as $\mathbf{R}$ and $\mathbf{R}^*$ indicates the same operator in time reverse. R_t denotes the retrieved multiple-free dataset. Details of the theory can be found in Zhang and Staring (2018). The integral form of the second term in the right hand side of equation 1 with $m=1$ can be given as

$$\begin{aligned} M_1(\mathbf{x}'_0, \mathbf{x}''_0, t) = \int_0^{+\infty} dt' \int_{\partial\mathbf{D}_0} d\mathbf{x}'''_0 \{ R(\mathbf{x}'_0, \mathbf{x}'''_0, t') H(t-t'-\tau) \times \\ \int_0^{+\infty} dt'' \int_{\partial\mathbf{D}_0} d\mathbf{x}_0 [R(\mathbf{x}'''_0, \mathbf{x}_0, t'') H(t'-t''-\tau) \\ R(\mathbf{x}_0, \mathbf{x}''_0, t-t'+t'')]\}. \end{aligned} \quad (2)$$

where H denotes the truncation operator and M_1 denotes the second term in the right hand side of equation 1 with $m=1$. As discussed in Zhang and Staring (2018), all orders of internal multiples are predicted by equation 2 with incorrect amplitudes and following terms $m=2,...,\infty$ work to correct the amplitudes of events predicted by M_1.

The first term in the right hand side of equation 1 is the original reflection data with internal multiple reflections and R_t in the left hand side of equation 1 is the achieved multiple-eliminated dataset, such that the second term in the right hand side of equation 1 gives all orders of internal multiple reflections with opposite polarity, which cancel internal multiple reflections contained in the original reflection response. Only the measured data is required for the implementation. Thus, the MME scheme presented in equation 1 is a true data-driven scheme for internal multiple reflection elimination.

Field Example

In this section, we show results from applying the MME scheme to a 2D field dataset acquired by SAGA A.S. (now part of Equinor) in 1994. We use this dataset to validate the successful removal of internal multiple reflections without any model information or adaptive subtraction. The field dataset was acquired in the Norwegian part of the North Sea. In the 2D field dataset, there are 399 shot gathers and 399 traces per shot gather. The sampling of sources and receivers is 25m. Because of the deep-water bottom (1.5km), the free-surface multiple reflections are well separated from primary and internal multiple reflections in the first 4s of the data. The internal multiple reflections (from 2.5s to 3.5s) are visibly present before free-surface multiple reflections, thus we keep the free-surface multiple reflections in the 2D field dataset without needing to remove them. As illustrated in

Davydenko and Verschuur (2018), the following pre-processes were applied to the 2D field dataset:

- Muting the direct wave
- De-noising
- Near offset traces interpolation via the parabolic Radon transform (Kabir and Verschuur, 1995)
- 3D effects compensation
- Source wavelet deconvolution

The pre-processed dataset can be used with a single overall amplitude factor as input for the MME scheme.

Figure 1 shows the macro velocity model of the target basin estimated from the acquired dataset. This model is not used to eliminate the internal multiple reflections but serves to give an idea about the geological setting. Red stars indicate source positions of three shot gathers which are used as examples for illustrating the performance of the MME scheme. The shot gathers after pre-processing are shown in Figures 2a, 2c and 2e, where internal multiple reflections between 2.5s and 3.5s, indicated by red arrows, are present. We use the measured 2D field dataset as input to solve equation 1 for removal of internal multiple reflections contained in the 2D measured field dataset with $m = 6$. The corresponding retrieved multiple-eliminated datasets are given in Figures 2b, 2d and 2f. Compared with the input shot gathers shown in Figures 2a, 2c and 2e, most internal multiple reflections are successfully removed or attenuated after the processing. Furthermore, events indicated by green arrows in Figures 2b and 2d, are not present in original shot gathers shown in Figures 2a and 2c. This does not necessarily mean that new events are introduced by the MME scheme. These events indicated by green arrows are primary reflections that were cancelled by overlapping internal multiple reflections in the input shot gathers. After the internal multiple reflection elimination, these primary reflections are successfully recovered. This is why these events are absent in original shot gathers but present in the multiple-eliminated shot gathers. This is made possible because we do not use adaptive subtraction. Application of the MME scheme to the 2D field dataset validates its success for removal of internal multiple reflections.

Discussion

The application of the MME scheme to the measured 2D field dataset shows that it has excellent performance, most internal multiple reflections are successfully predicted and removed after the processing as shown in Figure 2. Furthermore, the primary reflections cancelled by internal multiple reflections are recovered by the MME scheme. Not having to use adaptive subtraction on field dataset is a unique advantage of the MME scheme. From the previous study in Verschuur and Berkhout (2005), where the IME scheme was applied to the same 2D field dataset, most internal multiple reflections were successfully attenuated by the IME scheme. However, the primary reflections indicated by green arrows in Figure 2 cannot be recovered because of adaptive subtraction. Similarly, the adaptive subtraction used in the ISS-based scheme can successfully reduce the amplitude of most internal multiple reflections but cannot restore the primary reflections which are cancelled by overlapping internal multiple reflections. That is why we claim that the MME scheme is a robust internal multiple reflection elimination scheme.

It should not be ignored that the success of the MME scheme in the 2D field dataset is made possible by the high-quality pre-processing. As any data-driven scheme, the MME scheme is sensitive to amplitudes of the input dataset. Without high-quality pre-processing, the amplitudes of internal multiple reflections predicted by the second term in the right hand side of equation 1 would differ from actual events in the input shot gathers. In that case, internal multiple reflections contained in input shot gather cannot be removed or attenuated effectively. The measured laboratory dataset used in Zhang and Slob (2019b) can be taken as an example. The MME scheme was applied to remove internal multiple reflections contained in the measured laboratory dataset, although some internal multiple reflections were successfully removed or attenuated, some internal multiple reflections were present with opposite polarity or even stronger after the processing because of the low-quality of the input dataset. We can conclude that high-quality pre-process plays a central role for the success of the MME scheme.

Conclusions

We have applied the MME scheme to a measured 2D field dataset to test the performance. No model information or adaptive subtraction is used in the implementation. The example shows that most internal multiple reflections are successfully removed or attenuated, and the primary reflections that were not visible due to overlap with internal multiple reflections in the input shot gathers are recovered by the MME scheme. The high-quality wave-equation consistent pre-processing helps to successfully use the MME scheme in this field example. Given the successful application to the 2D field dataset, we think that the MME scheme is an appropriate method for internal multiple reflection elimination. We expect that this scheme can be used on many field datasets.

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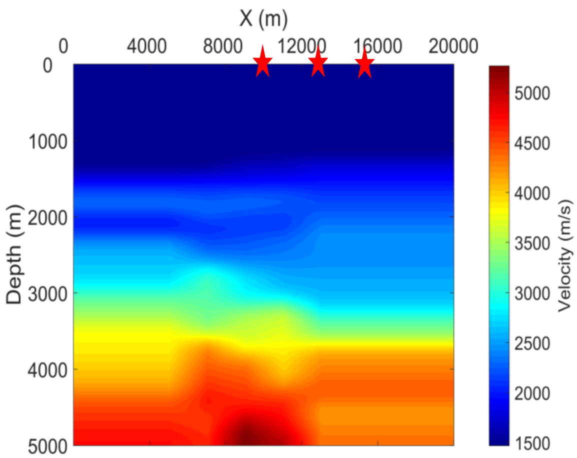
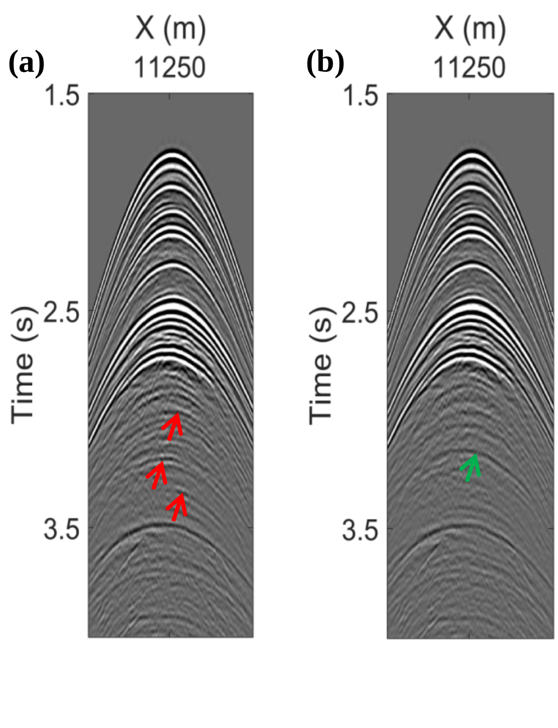


Figure 1: The macro velocity model estimated from the 2D field dataset. Red stars indicate source positions of shot gathers shown in Figure 2.



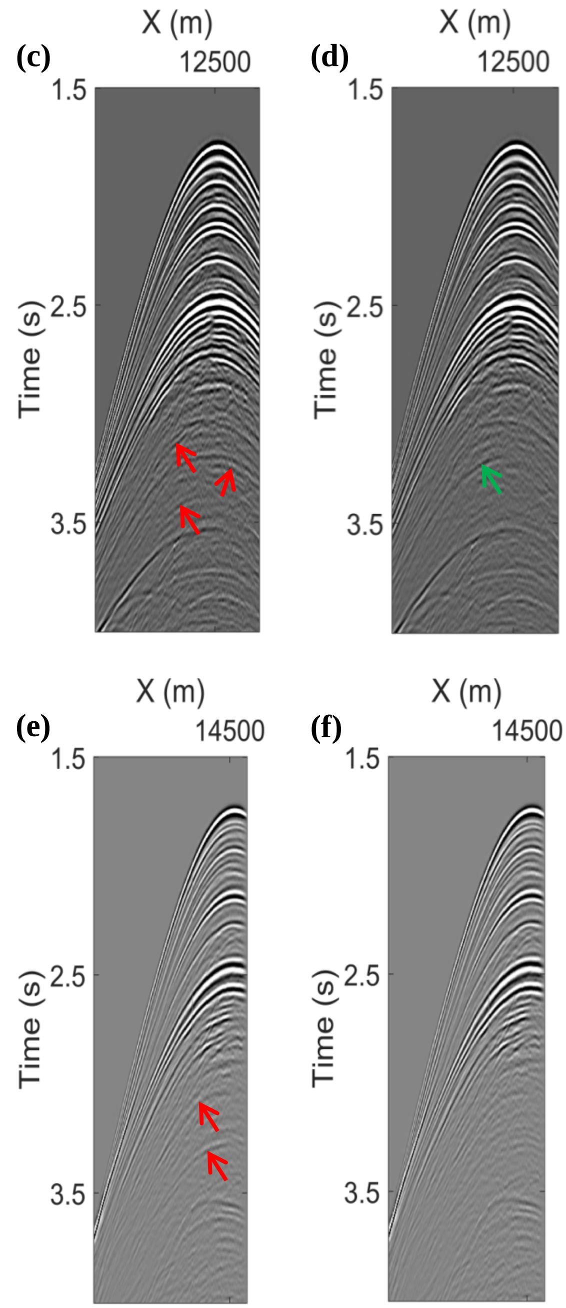


Figure 2: The (a), (c) and (e) are original shot records; (b), (d) and (f) are the corresponding multiple-eliminated shot records. Red arrows indicate internal multiple reflections, green arrows indicate primary reflections recovered after the processing.

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