# Application of Marchenko-based isolation to a land seismic dataset

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## Summary

The Marchenko method is capable of estimating Green's functions between the surface of the Earth and arbitrary locations in the subsurface. These Green's functions are used to redatum wavefields to a deeper level in the subsurface. The Marchenko method enables the isolation of the response of a specific layer or package of layers, free from the influence of the overburden and underburden.
In this study, we apply the Marchenko-based isolation technique to land S-wave seismic data acquired in the Groningen province, the Netherlands. We apply the technique for combined elimination of the overburden and underburden. Our results indicate that this approach enhances the resolution of reflection data. These enhanced reflections can be utilised for imaging and monitoring applications.

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## Introduction

The Marchenko method – a data-driven method – provides a tool for extracting information about the subsurface properties of the Earth. The Marchenko method redatums wavefields to arbitrary locations in the subsurface and can further be utilised to retrieve Green's functions in the subsurface from seismic reflection data at the surface. A virtual source or receiver can be created at any point in the medium of interest. This method employs reflection data from the sources and the receivers at the surface and an estimation of the first arrival, which can be modelled in a macro-velocity model (Slob et al., 2014; Wapenaar et al., 2014).

In recent years, there has been significant progress in developing the Marchenko method and extending its applicability, for example, for utilising it for isolating the response of a specific subsurface layer without interference from overburden or underburden. This application results in a reflection response with sources and receivers at the surface and with fewer internal multiples. This allows for more accurate characterisation of the properties of the target layer, and can be particularly useful in target-oriented imaging and monitoring. Wapenaar and van IJsseldijk (2021) introduced the Marchenko-based isolation to identify the reservoir response from a seismic reflection survey by applying a two-step approach for removing the overburden and underburden interferences.Van IJsseldijk et al. (2023a) showed that using this application effectively isolates the target response, which can then be used to extract more precisely the local time-lapse changes in a reservoir. The Marchenko application for isolating a target response has been successfully applied to marine time-lapse datasets of the Troll Field for monitoring reservoir changes (van IJsseldijk et al., 2023b).

As with any other method, the Marchenko method has some limitations. For its application, evanescent waves are ignored, the medium of interest is assumed to be lossless, and it is sensitive to inaccuracies in the reflection response. These attributes can pose challenges, particularly when for field datasets. Nevertheless, the method has been successfully applied to several marine field datasets for imaging and monitoring (Staring et al., 2018; Zhang and Slob, 2020; van IJsseldijk et al., 2023b). These advances have opened up a new opportunity for applying it to land seismic data. However, applying the method to land seismic data is more problematic because a reflection dataset free of surface waves and surface-related multiples is required, but also because the recorded data is inherently elastic.

Here, we apply the Marchenko-based isolation method for isolating the target response by removing the overburden and the underburden using an SH-wave seismic dataset that we acquired specifically for this purpose in Groningen, the Netherlands. In the following section, we first introduce some references for the methodology. Next, we show the seismic acquisition parameters and the steps for preparing the input data for the Marchenko method. Finally, we discuss the results and how this study enables future applications of the method, particularly for land-based applications.

## Method

The Marchenko method retrieves Green's functions between the acquisition surface and a focal depth in the subsurface, using focusing functions. A complete derivation of the Marchenko method can be found in Wapenaar et al. (2021). Van der Neut and Wapenaar (2016) proposed extrapolating the virtual sources and receivers to the surface where the extrapolation operator is integrated into the Marchenko method. This ensures that the travel times of events in the redatumed response do not change compared to the original reflection data, which facilitates the comparison of results before and after applying the Marchenko method. Using two extrapolated Green's functions, isolated reflection responses are retrieved by a multi-dimensional deconvolution (Wapenaar et al., 2011). Van IJsseldijk et al. (2023a, 2023b) fully derived the Marchenko-based isolation for removing the overburden and underburden.

## Seismic data acquisition

In the summer of 2022, we acquired reflection seismic data along a line close to the town of Scheemda in the Groningen province of the Netherlands. We employed an electric seismic vibrator (Noorlandt et al., 2015) as a source, with a spacing of 2 m, and 601 three-component geophones as receivers, with a spacing of 1 m. We made use of the Lightning electrical vibrator from Seismic Mechatronics (https://seismic-mechatronics.com/) in S-wave mode and oriented in the crossline direction. To apply the Marchenko method, we then used the data recorded by the crossline horizontal component of the geophones. Because of the orientation of the sources and the receivers, and assuming no scattering from the crossline direction, the horizontally polarised S-waves (SH-waves) we record are generally decoupled from the compressional and vertically polarised S-waves. This makes the dataset more convenient for applying the Marchenko method.

## Results

The raw seismic reflection data cannot directly be used with the Marchenko method because of amplitude errors/mismatches due to the other waves in the data, for example, surface waves. For data pre-processing, first, we apply source signature deconvolution as using high-resolution reflections as input is crucial for the Marchenko method. In seismic land surveys using sources and receivers at the surface, the surface waves are dominant and mask reflections. To eliminate surface waves, we employ careful muting in the time domain and apply bandpass filtering based on the power spectrum of the common-source gathers. The subsequent steps involved in preparing the reflection data for applying the Marchenko method incorporate amplitude corrections. First, we compensate the amplitudes for absorption and geometrical spreading. Secondly, we correct the amplitudes for recording a 2D line in a 3D world. The final, time-independent gain factor we apply, is determined by minimising cost functions proposed by Brackenhof (2016). This factor aims to address an overall amplitude mismatch in the reflection dataset. It also appeared useful to kill the 20 traces around the source location. Figure 1 shows an example of a common-source gather before and after pre-processing steps.

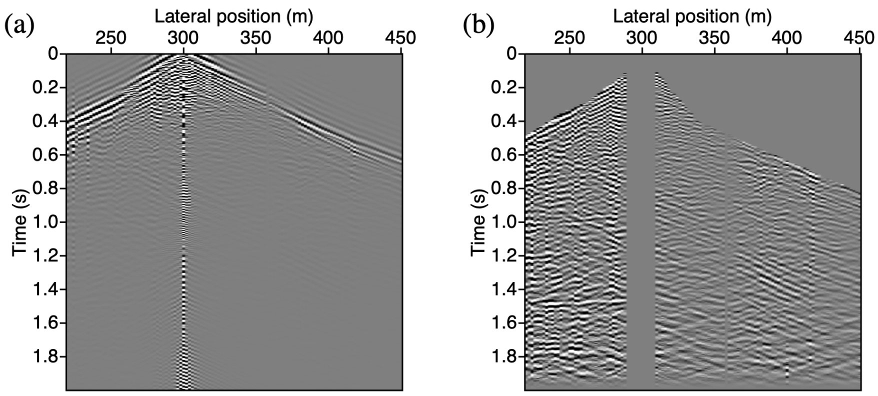


***Figure 1*** *An example of a common-source gather: (a) raw dataset, (b) after pre-processing steps.*

After completing the pre-processing steps, we employ the processed reflection data to extract the Green's function and isolate responses using the Marchenko-based isolation technique. To account for both overburden and underburden effects, a two-step procedure is employed. In the first step, we eliminate the overburden effect by choosing a focal depth of 30 m. Subsequently, using the results obtained from the first step, we eliminate the underburden effect by choosing a focal depth of 270 m. This two-step approach leaves the isolated response of the target region between 30 and 270 m depth.

To facilitate a more accurate comparison of results, a Normal Moveout (NMO) stack is performed on all common-midpoint (CMP) gathers for both the regular and isolated responses. First, the data is sorted into CMP gathers, followed by an NMO correction using a constant velocity of 350 m/s, and finally, the stacking process is performed. We then apply an automatic gain control (AGC) to enhance the visual comparison. The results of these stacks for both the regular and Marchenko-based isolated responses are shown in Figure 2.

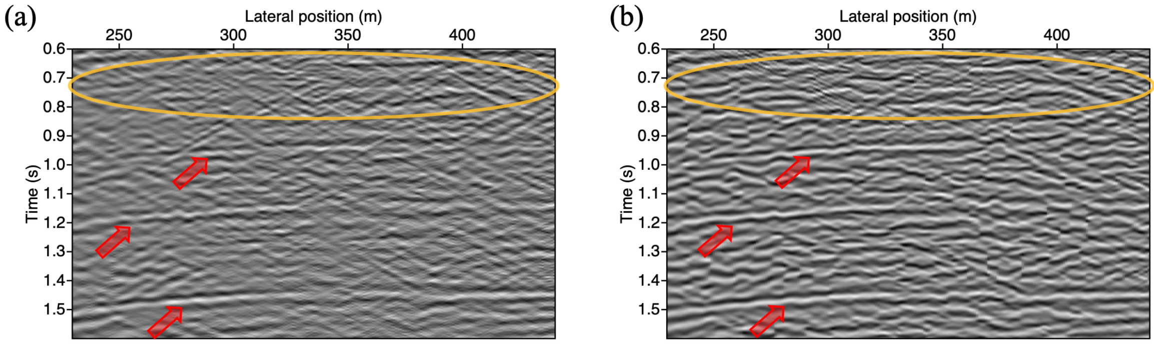


***Figure 2*** *The stacked sections from (a) the full reflection response and (b) the reflection response after the Marchenko-based isolation. Red arrows indicate enhanced reflections. The improved part for the shallower part is marked by the orange ellipse.*

The stacked section obtained from the Marchenko-based isolated response in Figure 2b is significantly cleaner than the stacked section of the full reflection responses in Figure 2a. Moreover, the isolated stacked section exhibits more continuity, helping to interpret the data better. Some events are marked with red arrows to indicate potential improvements in the stacked section of the Marchenko-based isolation method. The geology of this site, known from Cone Penetration Test (CPT) profiles, comprises alternating clay and sand layers that contribute to generating internal multiples at the shallow part. The presence of more continuous events in the shallower section, as indicated by the orange ellipse, suggests a potential elimination of internal multiples originating from the overburden.

## Conclusion

We showed the result of applying the Marchenko-based isolation method to SH-wave land seismic data that we acquired in Groningen province, the Netherlands. Land data are intrinsically elastic, known for dominant surface waves and low signal-to-noise ratio, and hence pose a challenge for the Marchenko method, which requires high-quality reflection data. We retrieved the extrapolated Green's function and the isolated target responses for the combined elimination of the overburden and the underburden. The resulting stacked section is cleaned up, providing a better image of the target zone compared to the stacked full reflection response. These results open the door for future applications of the Marchenko method on land seismic datasets, particularly in time-lapse monitoring, where isolating the responses from the target layers is crucial.

Although the results indicate an improvement in the resolution of the reflection data, there are some ideas for potential improvement for future studies. Firstly, investigating the overall scaling factor for amplitude mismatch is crucial, particularly when using land seismic data and SH-waves. Secondly, eliminating surface-related multiples before applying the Marchenko method could further enhance the resolution of the reflection data. Finally, we suggest applying velocity analysis followed by migration and comparing the migration results.

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