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Towards 3D near-surface correction without NMO – A rank-based approach

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Summary

To avoid multiple iterations of normal moveout (NMO) velocity estimation followed by short-wavelength statics estimation usually performed on land data, and to also improve the accuracy and computational efficiency of the latter, a low-rank-based residuals statics (LR-ReS) estimation and correction framework has been recently proposed. The method iteratively promotes the low-rank structure in the midpoint-offset-frequency domain of 2D data as statics-free data can be approximated by low-rank matrices, while data influenced by the weathering layers exhibits slow singular values decay. For 3D data, there exist different options to organize it into 2D matrices to be able to compute the singular value decomposition (SVD) required for low-rank approximation. It is also essential to find an organization that reveals the rank structure. We examine the different organization options. Based on finding a suitable sorting domain, we extend the LR-ReS estimation and correction to 3D data. We demonstrate the performance of the method on simulated data and will show field data results during the presentation.

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Introduction

The complex near-surface weathering layers can pose a challenge to imaging and inversion of land seismic data. Limitations in acquisition and model-building engines may prevent creating an accurate near-surface model that captures its heterogeneous and rapidly-varying nature. To overcome these limitations, statics correction has been used as an effective alternative solution (Cox, 1999; Yilmaz, 2001). However, statics estimation relies on simplification of the near-surface model due to the surface-consistency assumption (Sheriff, 2002). Therefore, surface-consistent short wavelength statics estimation and correction are usually followed by a non-surface-consistent step to be able to account for the majority of the statics. While this approach can be effective, it lowers the computational efficiency and it may create non-existing structures when using trim statics (Ursenbach and Bancroft, 2005).

Moreover, both surface- and non-surface-consistent techniques need access to normal moveout (NMO) corrected gathers. As a result, one need to perform multiple iterations of NMO velocity estimation followed by residual statics estimation as they influence each others, which can be efforts and time consuming.

To avoid the above limitations by estimation and correction of surface- and non-surface-consistent statics without NMO correction, Alfaraj et al. (2021, 2022) propose a low-rank-based residual statics (LR-ReS) estimation and correction framework. Since LR-ReS estimation and correction is not limited by the surface-consistency assumption and, it is capable of estimating more accurate statics. Moreover, NMO velocity errors do not affect the LR-ReS estimation, which can reduce the multiple iterations of NMO velocity and residual statics estimation. As a result, data windowing of NMO corrected and noise-free primaries or mute to avoid the NMO stretch effect becomes unnecessary. The LR-ReS estimation and correction was proposed and implemented on 2D data using the midpoint-offset transform. In this work, we extend the method to 3D data and propose suitable data domain sorting to render effective results.

LR-ReS estimation and correction

Alfaraj et al. (2021, 2022) demonstrate that frequency slices affected by the weathering layers exhibit slowly decaying singular values, while static-free frequency slices are of low-rank nature. Therefore, LR-ReS estimation and correction use low-rank approximation of frequency slices affected by the weathering layers to promote the low-rank structure and obtain ones with less near-surface imprint that may also contain erroneous amplitudes due to neglecting data of importance. To preserve the amplitude versus offset (AVO) response, the low-rank-approximated frequency slices are cross-correlated with the original ones, or with those from previous iterations, to estimate the LR-ReS, which are used for statics correction. The framework is applied iteratively over multiple rank-scales, i.e. different ranks that are necessary for low-rank approximation, and multiple frequency bands to extract multi-scale statics and to improve low-rank approximation of high frequencies, which is challenging otherwise.

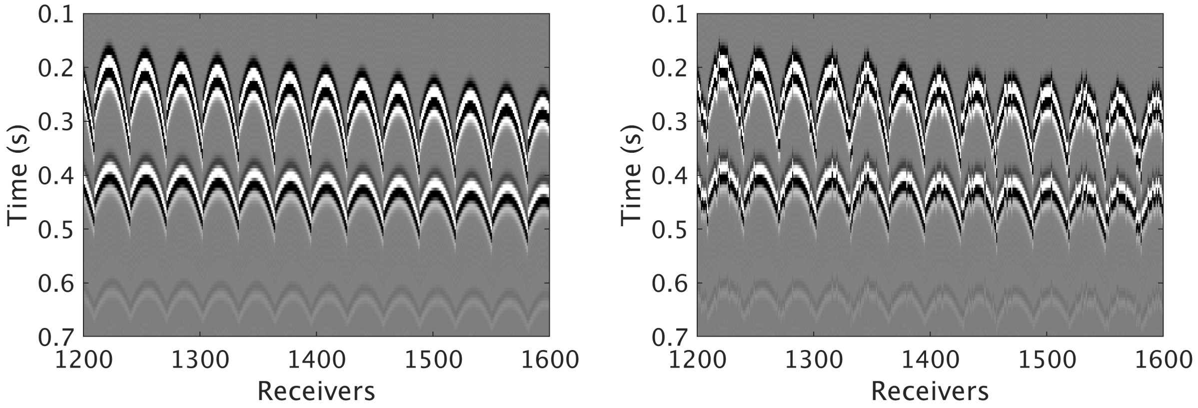
An essential step of the 2D LR-ReS estimation and correction is transformation of the data from the source-receiver domain to the midpoint-offset domain to satisfy the aforementioned singular values decay requirements and consequently, enables accurate low-rank approximation. Therefore, to extend the method to 3D data, we need to find suitable organization to obtain 2D matrices so that we can compute the singular value decomposition (SVD). Another important requirement is that these matrices need to satisfy the singular values decay requirements. In the next section, we examine different options to arrange 3D data into 2D matrices.

3D data organization

While LR-ReS estimation and correction can be applied to separate 3D lines, we prefer to use the 3D nature of the data, which can also increase its redundancy to increase the accuracy of low-rank approximation. This means that we need to organize the 3D data volume into 2D matrices, i.e. perform matricization, so that we can calculate the SVD that is needed for low-rank approximation. We examine two of the possible organizations: (*i*) organizing the data by x and y source coordinates (x_{src}, y_{src}), where we place the source coordinates and receiver coordinates along two different dimensions of a matrix and (*ii*) organizing the data by placing source and receiver coordinates along one direction (x_{src}, x_{rec}) on one dimension of a matrix, while placing the sources and receivers of the other direction (y_{src}, y_{rec}) on the other dimension.

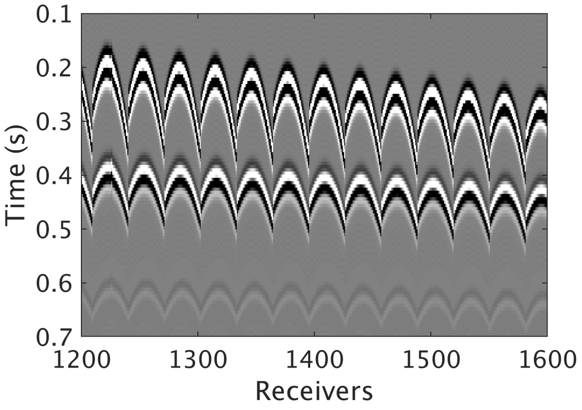
Synthetic data

To observe the effect of the different organizations, we use 3D synthetic data acquired with sparse 9×4 shot lines and carpet 61×31 receiver lines spaced at 150×300 m and 25×50 m, respectively (Figure 1a). To mimic rapid variations in surface elevation and near-surface weathering layers, we time shift the data with ±12 ms (Figure 1b). Using these two data sets, we analyze the rank structure in the frequency domain.



(a) Statics-free data

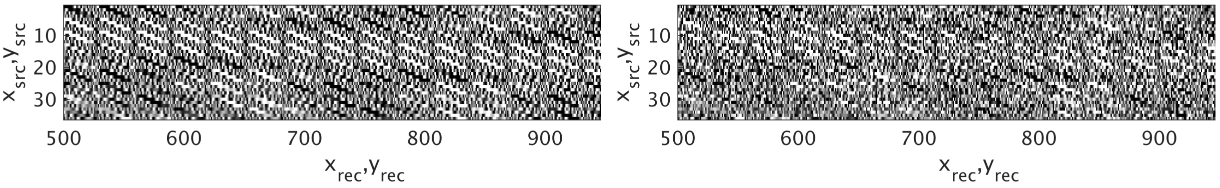
(b) Data with statics



(c) 3D LR-ReS corrected data

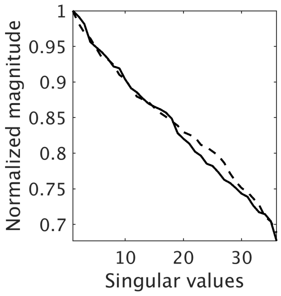
Figure 1: Subset of 3D shot gathers: (a) statics-free, (b) statics-contaminated and (c) after 3D LR-ReS estimation and correction.

Data matricization (*i*) (Figure 2) and the resultant singular values decay curves show that there is no desirable rank-structure that we can make use of. On the other hand, the singular values decay curves after matricization (*ii*) (Figure 3) reveal the rank structure since statics-free data is shown to be of low-rank nature, while data with statics exhibits slower singular values decay. Therefore, we replace the midpoint-offset transform of 2D data with matricization (*ii*) of 3D data. Algorithm 1 provides a summary of 3D LR-ReS estimation and correction, where the superscript $\tilde{}$ and subscripts $_{\text{lr}}$ and $_{\text{x}_{\text{s,r}}}$ indicate data in the frequency domain, low-rank approximated data and data after organization (*ii*), respectively. In the next section, we show results of the proposed method.



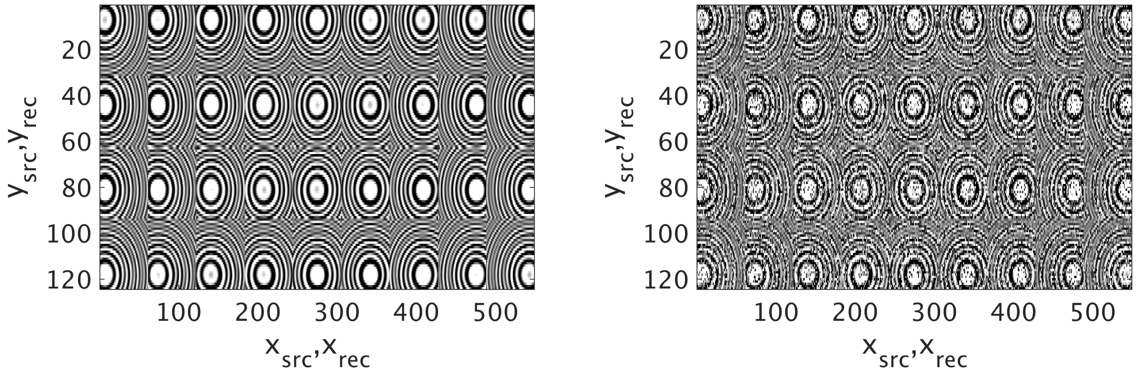
(a) Statics-free data

(b) Data with statics



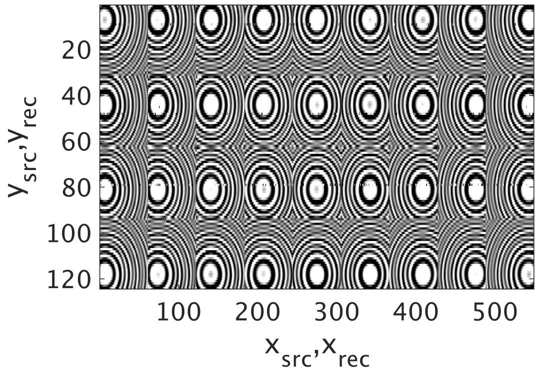
(c) Singular values curves

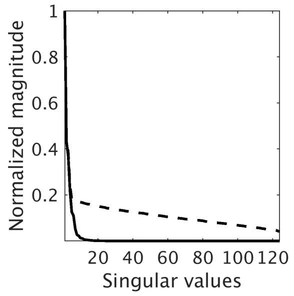
Figure 2: Data organization (*i*) by x and y source coordinates (x_{src}, y_{src}). Zoomed plots of 30 Hz frequency slices of (a) statics-free data and (b) data with statics. (c) The singular values of (a) and (b) plotted with solid and dashed lines, respectively.



(a) Statics-free data

(b) Data with statics





(d) Singular values curves

(c) LR-ReS corrected data

Figure 3: Data organization (*ii*) by x coordinates of sources and receivers (x_{src}, x_{rec}). 30 Hz frequency slices of (a) statics-free data, (b) data with statics and (c) data after 3D LR-ReS estimation and correction. (d) The singular values of (a) and (b) plotted with solid and dashed lines, respectively.

Algorithm 1: Summary of 3D LR-ReS estimation and correction

```
Input: 3D Data in the source-receiver domain, frequency bands and ranks for each frequency
Output: Data after near-surface correction and the estimated statics
$\mathbf{D}_{\mathrm{x_{s,r}}}$ ← Matricize input data with organization (ii)
$\widetilde{\mathbf{D}}_{\mathrm{x_{s,r}}}$ ← Fourier transformation from the time to the frequency domain
for loop over rank-scales do
    for loop over frequency slices do
        Compute SVD per frequency slice
        $\widetilde{\mathbf{D}}_{\mathrm{lr}}$ ← Low-rank approximation of each frequency slice
        if the desired frequency band for statics-estimation is reached then
            $\mathbf{D}_{\mathrm{lr}}$ ← Inverse Fourier transformation of $\widetilde{\mathbf{D}}_{\mathrm{lr}}$
            Select maximum lag after crosscorrelation of $\mathbf{D}_{\mathrm{x_{s,r}}}$ and $\mathbf{D}_{\mathrm{lr}}$ to estimate the statics
            $\mathbf{D}_{\mathrm{x_{s,r}}}$ ← statics correction of $\mathbf{D}_{\mathrm{x_{s,r}}}$
            $\widetilde{\mathbf{D}}_{\mathrm{x_{s,r}}}$ ← Fourier transformation of $\mathbf{D}_{\mathrm{x_{s,r}}}$
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Results

The application of Algorithm 1 to the synthetic data (Figures 1b and 3b) provides the results displayed in Figures 1c and 3c. When compared to the statics-free data (Figures 1a and 3a), we notice that the majority of the statics has been accounted for – without the need of NMO velocity estimation and correction. Therefore, the proposed method can be applied at an early stage of the processing workflow to improve the performance of subsequent processes. Note that the applied statics contain surface- and non-surface-consistent shifts, which we can estimate with one process rather than multiple ones. Additionally, the proposed method is computationally efficient. For the shown example, it takes 64 s to estimate and apply the 3D LR-ReS with three rank-scale iterations at three frequency bands.

Conclusions

We show that matricization of the 3D data with the coordinates of sources and receivers along one direction reveals the rank structure. Based on that, we extend the preciously proposed 2D LR-ReS estimation and correction to 3D data. While conventional data-driven near-surface correction is usually dependent on a velocity model, 3D LR-ReS estimation and correction can estimate surface- and non-surface-consistent statics with one process without the need to velocity estimation. As a result, we avoid the multiple iterations of velocity and statics estimation, as well as the need for an additional non-surface-consistent correction commonly needed for conventional methods. Therefore, the LR-ReS estimation and correction can improve the overall efficiency of data processing.

Acknowledgements

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