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Joint reconstruction and near-surface correction of land data with low-rank

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Summary

Seismic data acquired on land face multiple challenges due to the near-surface complexity. One of the challenges is the weathering layers' influence due to the low velocity and rapidly varying nature of these layers. To overcome that, dense source-receiver sampling can be used to characterize the near-surface. However, that increases the acquisition costs, which makes it less attractive for large-scale seismic acquisition. An alternative approach is to use compressive sensing to acquire the data. Although it enables economical data acquisition, compressive sensing requires data reconstruction, which is another challenge in the presence of complex weathering layers. To overcome that, we propose a joint reconstruction and near-surface correction algorithm using a model-independent low-rank-based approach. We apply the method to synthetic and real data, which shows superior results compared with the conventional approach of near-surface correction followed by data reconstruction.

Joint reconstruction and near-surface correction of land data

Introduction

Seismic data acquired on land face multiple challenges due to the complexity of the near-surface. One of the challenges is the weathering layers influence due to the low velocity and rapidly varying nature of these layers (Cox, 1999; Yilmaz, 2001). To overcome that, dense source-receiver sampling can be used to characterize the near-surface. However, this solution increases the acquisition costs, which makes it less attractive for large scale seismic acquisition. An alternative approach is to use compressive sensing to acquire the data (Herrmann et al., 2012). On the one hand, it can decrease the acquisition costs via randomized subsampling, which results in incoherent noise compared to the coherent aliasing that results from the conventional periodic subsampling. However, on the other hand, the combined near-surface and subsampling effects makes data reconstruction challenging.

The conventional approach to reconstruct such data is to use near-surface correction, followed by data interpolation (Trad, 2009). Although effective, both steps require access to a velocity model of the subsurface. Moreover, they typically require multiple- and noise-free data. These requirements are difficult to satisfy from data influenced by the weathering layers. Including additional subsampling makes subsurface model estimation, as well as multiple and noise elimination, more challenging.

To overcome the above requirements for near-surface correction, Alfaraj et al. (2021, 2023) propose to use a low-rank-based approach. The method requires no velocity model and can enhance both primaries and multiples, which makes it attractive to overcome rapid variations of the weathering layers. However, the method relies on obtaining a low-rank structure, which is also influenced by data subsampling. Therefore, data reconstruction becomes key for the performance of the low-rank-based near-surface correction.

There are plenty of methods for data reconstruction. One approach is to use rank-based methods as they are capable of processing large-scale and multi-dimensional seismic data with high computational efficiency (Aravkin et al., 2014). However, the performance of existing interpolation methods degrades in the presence of weathering layers as they decrease the coherency of the data. In this situation, the decrease in coherency is due to both, the weathering and subsampling effects. To overcome this hurdle, we propose a joint interpolation and near-surface correction algorithm suitable for randomly subsampled land data influenced by the weathering layers.

Methodology

Seismic data acquired with multiple sources and receivers exhibit a low-rank structure. In the presence of acquisition gaps due to randomized subsampling, Kumar et al. (2015) show that the low-rank structure gets destroyed. To reconstruct densely-sampled data, the authors promote the low-rank structure by solving the following optimization problem per frequency slice:

$$\underset{\mathbf{X}}{\text{minimize}} \quad \|\mathbf{X}\|_* \quad \text{subject to} \quad \|\mathbf{A}(\mathbf{X}) - \mathbf{b}\|_2 \leq \varepsilon, \quad (1)$$

where \mathbf{b} is a subsampled frequency slice organized as a vector, and \mathbf{X} is the densely-sampled frequency slice to estimate. $\|\cdot\|_*$, ε and \mathbf{A} are, respectively, the nuclear norm, noise-level, and sampling-transform operator. The sampling operator removes the unmeasured samples, while the transform operator transforms the frequency slice from the midpoint-offset domain to the source-receiver domain. Using the midpoint-offset transform is key to avoid the need for data windowing, which is typically required to be able to approximate seismic data with low-rank. In the presence of weathering layers, \mathbf{b} becomes incoherent not only due to subsampling, but also due to the weathering layers effects. That is why near-surface correction is crucial prior to data reconstruction.

However, the near-surface weathering layers also contribute to the low-rank structure destruction as they decrease the coherency of the data (Alfaraj et al., 2023). The authors show that by promoting the low-rank structure in an iterative and multi-scale approach, they can estimate the statics and statics-corrected

data without the need of a subsurface velocity model. Even though data reconstruction becomes feasible after low-rank-based near-surface correction, such approach fails to provide satisfactory statics-corrected densely-sample data when the subsampling or weathering effects are large. To overcome that, we solve for both subsampling and weathering effects in a joint approach.

The low-rank-based near-surface correction operates on frequency bands, starting from low to high frequency. After initial statics correction of the low frequency band, the coherency of the data gets improved. Therefore, we can reconstruct this data, and also use it for near-surface correction of the next frequency band. As a result, both near-surface correction and interpolation improve each others performance.

Since the low-rank-based near-surface correction is performed in the midpoint-offset domain, we modify the subsampled data in the source-receiver domain \mathbf{b} in equation 1 to also become in the same domain on the desired grid of densely sampled data \mathbf{b}_{mh} . Therefore, we no longer need the transform operator component of \mathbf{A} , which improves the computationally efficiency as we avoid the repetitive transforms between the midpoint-offset and source-receiver domains. We also modify the measurement operator that removes the unmeasured samples in the source-receiver domain to become in the midpoint-offset domain \mathbf{M}_{mh} . Therefore, equation 1 becomes:

$$\underset{\mathbf{X}}{\text{minimize}} \quad \|\mathbf{X}\|_* \quad \text{subject to} \quad \|\mathbf{M}_{mh}(\mathbf{X}) - \hat{\mathbf{b}}_{mh}\|_2 \leq \varepsilon, \quad (2)$$

where the superscript $\hat{\cdot}$ indicates statics-corrected data. To further enhance the computational efficiency of equation 2, we use the following initial solution \mathbf{X}_0 :

$$\mathbf{X}_0 = \sum_{j=1}^k s^{(j)} \mathbf{u}^{(j)} \mathbf{v}^{(j)H}, \quad (3)$$

where, s , \mathbf{u} and \mathbf{v} are respectively, the singular values, the left and right singular vectors. By setting k to be much smaller than the dimensions of the matrix \mathbf{X} , we obtain low-rank approximated frequency slice. However, computing the singular value decomposition, or an economical flavour of it, increases the computational costs. Since we are performing a joint interpolation and near-surface correction, which also relies on low-rank approximation, the initial solution for interpolation becomes cost-free.

Results

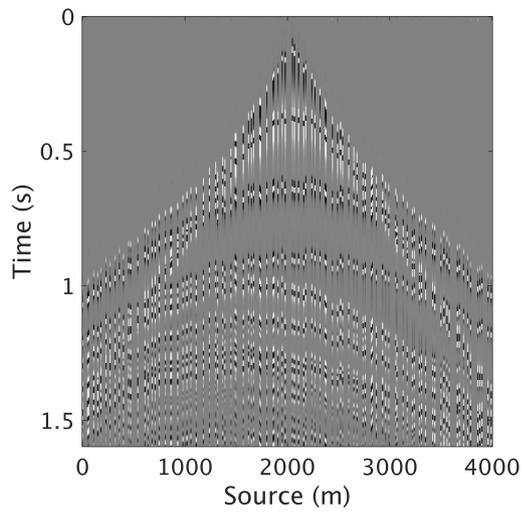
We show the potential of the proposed method on synthetic and field data:

Synthetic data

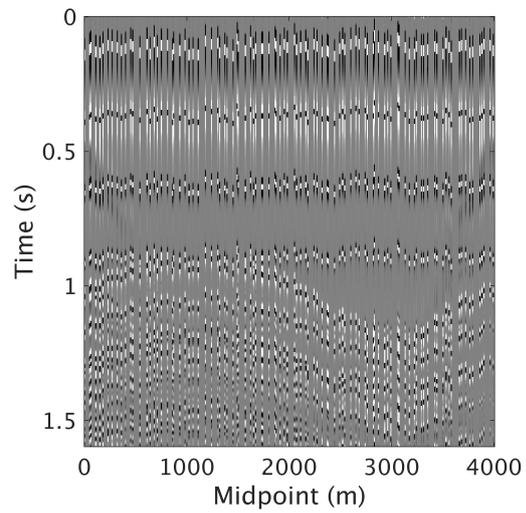
After modelling synthetic data, we add apply statics to mimic the weathering layers effect and randomly subsample the data by removing 75% of the shots (Figures 1a and 1b). We then reconstruct the data using the conventional stepwise approach of near-surface correction followed by data interpolation with rank minimization (equation 2) to obtain the results in Figures 1c and 1e. We notice that the reconstruction is not satisfactory, which is attributed to the mixing effects of subsampling and statics. As a result, the stepwise approach faces difficulties. To overcome that, we apply our proposed joint near-surface correction and interpolation to provide the results displayed in Figures 1d and 1f.

Field data

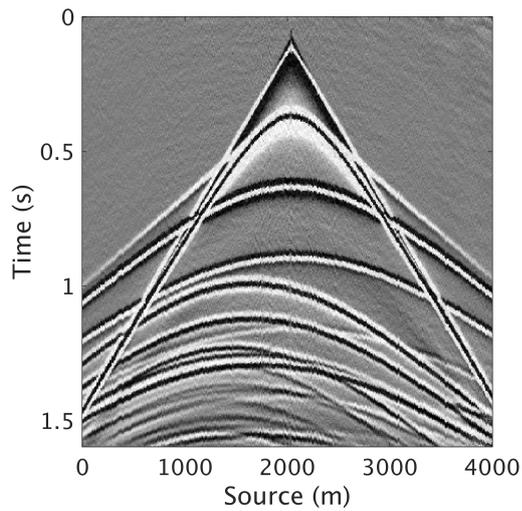
The field data we use for testing is acquired with 30 m source-receiver sampling (Al-Ali and Verschuur, 2006). It is influenced by rapidly varying weathering layers composed of loose sand, fast carbonates and karsts (Figure 2a). We subsampled the data by removing 50% of the shots at random (Figure 2b). Figure 2c show the stack after stepwise reconstruction, while Figure 2d is the stack after applying our proposed method, which provides higher resolution image, improved continuity and less noise.



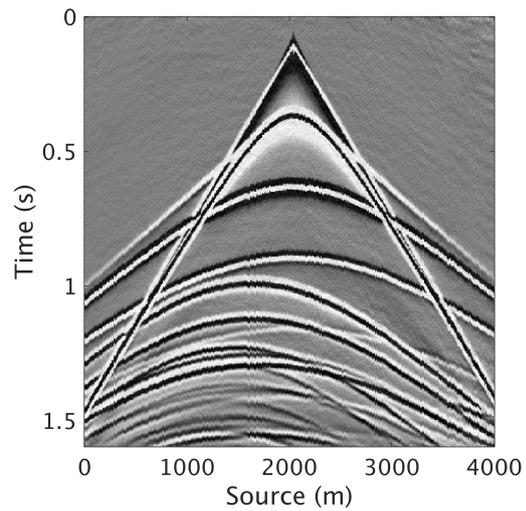
(a) Subsampled common receiver gather



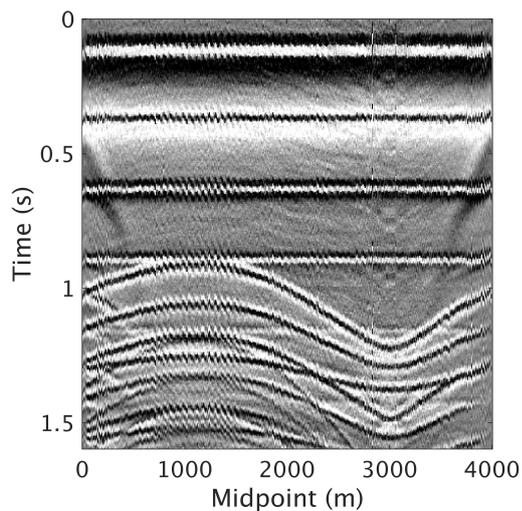
(b) Subsampled common offset gather



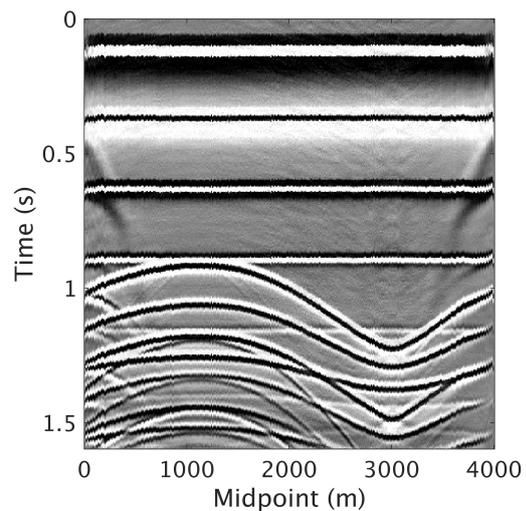
(c) Conventional reconstruction



(d) Proposed method



(e) Conventional reconstruction



(f) Proposed method

Figure 1: Common receiver (a, c, d) and (b, e, f) common offset gathers after (a, b) 75% randomized subsampling (c, e) conventional stepwise reconstruction and (d, f) applying our proposed method.

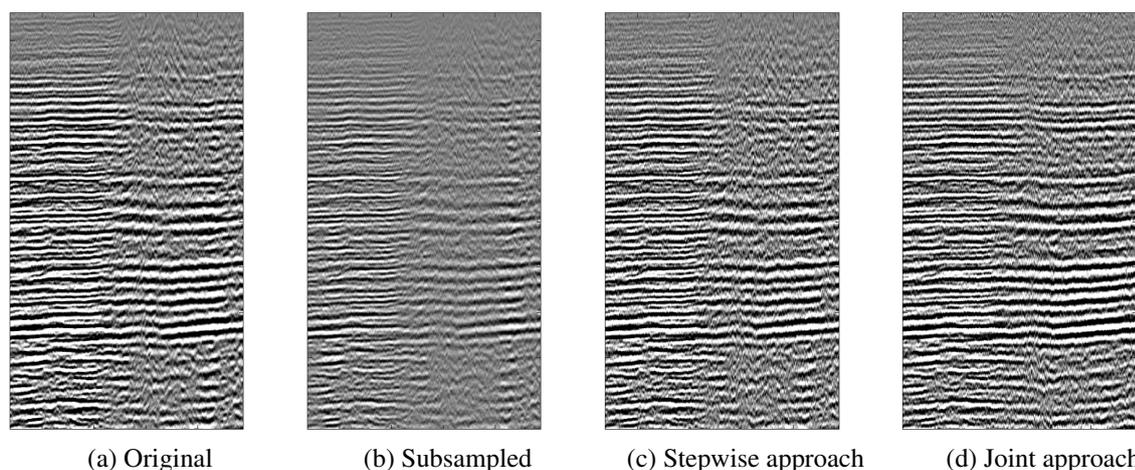


Figure 2: Stack sections of field data that extend to 10 km along space and 2 s along time: (a) original, and after (b) randomized subsampling, (c) conventional stepwise reconstruction and (d) result of proposed method.

Conclusions

To reconstruct subsampled data influenced by the near-surface weathering layers, we propose a joint reconstruction and near-surface correction method. The method is based on the assumption that seismic data is of low-rank, while subsampling and statics destroy the low-rank structure. We develop an algorithm that resolves both effects in a joint approach by promoting the low-rank structure, which provides improved results compared to stepwise statics correction followed by near-surface correction of synthetic and field data. An additional advantage of the proposed method is increasing the computational efficiency by using a cost-free accurate initial solution to the interpolation optimization problem and by minimizing transforms between the source-receiver and midpoint-offset domains.

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