Interpolating Sparse Seismic Data via Horizon-Guided Inverse Distance Weighting

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Summary

In frontier areas, 3D seismic surveys are sometimes unavailable due to their high operational costs, necessitating the use of 2D seismic surveys. However, 2D seismic surveys are generally not ideal for accurate interpretation because of their limited spatial coverage, leading to a growing need to interpolate 2D seismic surveys to generate 3D data volumes. Interpolating 2D seismic data to 3D is challenging due to large spatial gaps between seismic lines, which can span up to several kilometres. This study presents a method that combines inverse distance weighting (IDW) with pre-defined horizons to guide the interpolation process and ensure geological consistency. By leveraging horizon information, the proposed method effectively fills large gaps in 2D seismic data and generates a 3D seismic data volume, preserving structural continuity across the seismic volume. The method was successfully applied to a real dataset from the UK Continental Shelf (UKCS), demonstrating its effectiveness in interpolating sparse seismic data from 2D seismic surveys.

Interpolating Sparse Seismic Data via Horizon-Guided Inverse Distance Weighting

Introduction

In some scenarios, 3D seismic surveys are unavailable due to high operational costs, requiring reliance on 2D seismic surveys. However, 2D seismic surveys are generally not ideal for accurate interpretation because of their limited spatial coverage. This limitation creates a growing need to interpolate 2D seismic surveys into 3D data volume to improve the interpretation quality. Additionally, in some cases – particularly during the last century, 2D seismic surveys were the only option due to technology constraints, resulting in a significant amount of legacy 2D data. When modern 3D surveys are conducted in an area with existing vintage 2D survey data, effectively integrating this legacy data with the new surveys can provide valuable insights. Moreover, in recent years, most seismic surveys for offshore wind farms have been conducted in 2D, and there has been an ongoing discussion about utilizing 2D seismic lines to build the 3D data volume for accurately designing wind farm foundations. All these scenarios highlight a strong demand for methods capable of converting 2D seismic lines into 3D data volumes. However, 2D seismic lines are typically far apart, with gaps that can reach several kilometres, posing significant challenges to traditional seismic interpolation methods.

Since the 1980s, there have been several efforts to convert 2D seismic lines into the 3D data volumes (Lin and Halloway, 1988; Bondeson et al., 2013). A widely used approach involves combining a geological model with an interpolation kernel to ensure that the interpolation method conforms to the geological model. While geostatistical approaches such as kriging could potentially be used for interpolating dense 3D data, the kernel is highly computationally intensive. Another strategy involves utilizing deep learning techniques, such as generative modelling, to reconstruct the data (Wang et al., 2024). Based on the geological-model-guided approach, we investigated and introduced a method that combines an efficient inverse distance weighting (IDW) kernel with horizon information to construct the 3D seismic data volume. Our method leverages pre-defined horizons to guide the interpolation and maintain geological consistency across sparse datasets.

We will first describe the methodology, including the IDW algorithm and how horizon information is used to guide IDW interpolation. We will then demonstrate the effectiveness of this methodology by presenting a case study of its application.

Method

The inverse distance weighting (IDW) interpolation, proposed by Shepard (1968), is based on the principle that the influence of a known data point decreases with increasing distance from the target location. Following this principle, the estimated value at an unknown location is calculated as a weighted sum of the known values, where the weights are inversely proportional to the distances. The interpolation formula is given by:

$$\hat{Z}(x) = \frac{\sum_{i=1}^{n} \frac{Z_i}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \quad (1)$$

In this equation, $\hat{Z}(x)$ represents the interpolated values at location x, Z_i is the known value at the i-th sample point, and d_i is the distance between the target location x and the i-th sample point. The power parameter p controls how quickly the influence of the point decreases with distance. A higher value of p gives greater weight to nearby points and reduces the influence of more distant points. The weighted sum of values is then normalized by the sum of weights.

For lower values of p (e.g., $p = 0.5$), the weights are distributed more evenly across all sample points, meaning that even distant points contribute significantly to the interpolated result. As p increases, the influence becomes more localized, with closer points receiving significantly higher weights, while the contribution from distant points diminishes. The parameter n denotes the total number of sample points used in the interpolation. These are selected using a nearest-neighbour search algorithm and the choice of *n.* Therefore, it also allows a degree of control over the influence of points as a function of distance.

In our horizon-guided extension, we constrain IDW interpolation using pre-defined horizons to ensure stratigraphic consistency across time slices. For a given unknown point, interpolation is performed only with respect to the known points lying on the same horizon. This ensures that the interpolated values conform to the geological layering by following how the horizons are propagated throughout the entire area. This approach enables the interpolation of data across large gaps and results in a seismic volume that preserves structural continuity and accurately represents subsurface features.

We tested the horizon-guided IDW interpolation on UKCS (United Kingdom Continental Shelf) data and achieved promising results. In the example section, we will now illustrate how we interpolated and processed the data.

Examples

In 1997 BHP acquired a 2D seismic survey in the English Channel, about forty kilometres south of Lulworth, comprising two dozen lines around ten to fifteen kilometres long. This has been released to the National Data Repository and was selected as a small yet representative example. The lines are reasonably spaced, and the geology is interesting, but simple enough not to cause unusual problems. There are clear reflections from the Jurassic Selbourne, Oolite and Lias formations as well as the Mercia Mudstones and Sherwood Sandstone, all in the first second of data. The horizons were carefully picked and selected later to ensure the accuracy in the following interpolation.

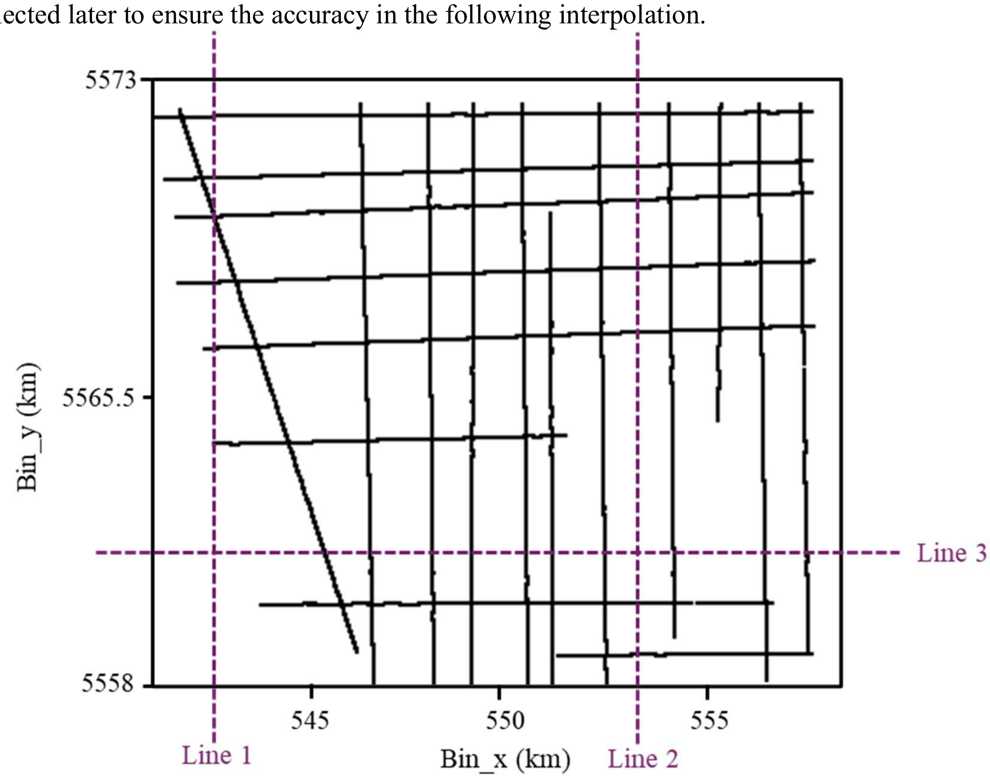

***Figure 1**. The survey area, with black lines representing the 2D seismic lines. The purple dashed lines (Lines 1–3) indicate the selected lines used for interpolation display in Figure 2.*

Regarding the input data, most 2D seismic lines do not exactly align with the grid of our 3D target seismic volume. Therefore, we assign the 2D seismic line onto the nearest grid in the 3D target seismic volume. The criterion for assigning a point to the grid is based on Euclidean distance. After assignment, we have a sparse 3D data volume.

The available horizons are only defined along the 2D seismic lines. To apply horizon-guided IDW interpolation, our method requires horizons across the entire 3D seismic data volume. Thus, we first interpolate the horizons from the 2D seismic lines to the entire 3D data volume based on the basic IDW interpolation of equation 1.

Once the horizons are interpolated, we use them to perform horizon-guided IDW interpolation. We selected three gathers from Lines 1, 2, 3, as shown in Figure 1, and presented the interpolation results before and after applying the method in Figure 2. The selected gathers along the Lines 1, 2 and 3 are shown in Figure 2a, 2b and 2c, respectively. The gathers are extremely sparse, with a maximum gap of up to 7 km, making it impractical to solve this problem using traditional seismic interpolation methods.

Our method interpolates the data, and the results are shown in Figure 2d, 2e and 2f. The five picked horizons are displayed in different colours in Figure 2. The interpolated traces clearly demonstrate how the interpolation follows the horizons, indicating that the method effectively enforces the conformance to the horizons during the interpolation process.

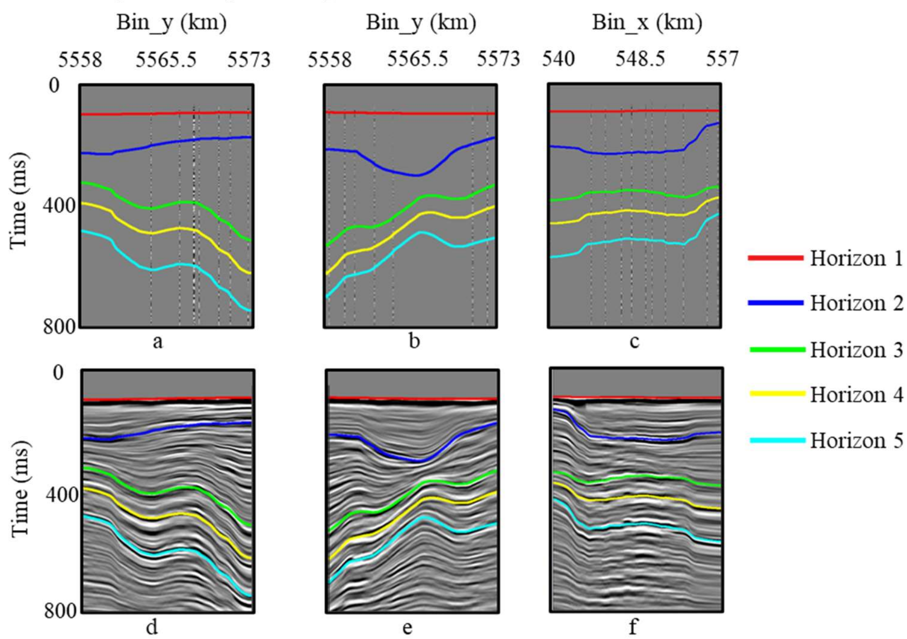

Figure 2*. (a-c) Sparse data selected at the location indicated by the dashed purple lines in Figure 1, corresponding to Lines 1, 2 and 3, respectively. (d-f) Corresponding interpolated results for (a-c). The coloured lines represent five horizons which have been used during the interpolation.*

Figure 3a-c shows the sparse data volume at different time slices - 242ms, 352ms and 406ms - where the selected time slices intersect different horizon zones, providing a better understanding of how our method interpolates the data and ensures that the interpolation conforms to the geological horizons. In Figure 3a-c, the gap between the seismic traces is significant, with some gaps reaching up to 7km and the minimum gap being 0.5km. The sparsity of the data again highlights the challenge of using traditional interpolation methods as they are unlikely to produce geologically consistent results across such large gaps with such limited available data.

Figure 3d-f presents the corresponding interpolation results obtained using the horizon-guided IDW interpolation method. The interpolated data shows continuous seismic events with improved lateral coherence, indicating that the method effectively fills in the large gaps between the 2D lines by following the geological layering. The results demonstrate that the interpolation conforms to the propagated horizons, ensuring structural continuity across the seismic volume.

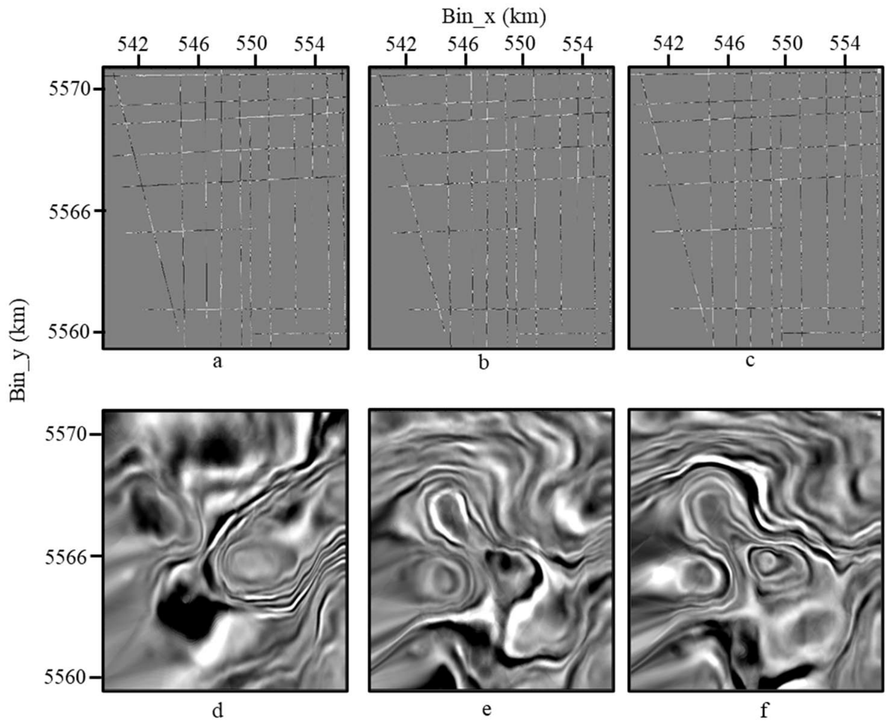

Figure 3 *Sparse data from the survey area at time slices 242ms, 352ms and 406ms shown in a-c and the corresponding interpolated results in d-f*

Conclusions

We have developed a horizon-guided inverse distance weighting (IDW) interpolation method for interpolating sparse seismic data. The method effectively fills large gaps in 2D seismic lines and produces geologically consistent 3D data volumes. By ensuring that the interpolated traces conform to pre-defined processed horizons, our approach preserves structural continuity. The successful application of this enhanced methodology to a field data example from the UKCS demonstrates its effectiveness.

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