Comparisons between FO-CRS and OCT stacking operators by quality measures

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Abstract

This paper compares two stacking operators based on traveltime approximations, namely the finite-offset common-reflection-surface (FO-CRS) and offset-continuation-trajectory (OCT) stacking operators. The effectiveness of both stacking operators is demonstrated using two controlled synthetic datasets, and the results show the advantages of physically coherent stacking in seismic data processing. However, the OCT operator proved more robust in the qualitative and quantitative analyses than the FO-CRS. Therefore, the OCT operator can be seen as a more promising alternative regarding prestack stacking quality for regularization or data enhancement.

Introduction

When working with seismic imaging algorithms, having a regular dataset geometry with a manageable number of traces is important to avoid spatial aliasing. Additionally, datasets with minimal noise levels are necessary to avoid aberrant images. Field data examples show that physically coherent stacking is more effective than other reconstruction methods in increasing the signal-to-noise ratio (SNR), particularly in datasets with low SNR and fold coverage. To address this issue, we analyze two stacking operators based on traveltime approximations: one based on the common reflection surface (CRS) and another based on the common reflection point (CRP). Both of these operators are designed to improve SNR and geometry regularization by exploiting the physical properties of the seismic-response data set. It's important to note that our analysis is limited to datasets acquired in a 2D seismic line.

The CRS stacking operator is a seismic processing technique that allows for a multidimensional stacking over offset-midpoint surfaces. It is an extension of the conventional normal moveout (NMO) stacking of seismic traces along the offsets introduced by Mayne (1962). While the original CRS traveltime is limited to constructing a zero-offset (ZO) section (Mann et al., 1999), which may be restrictive in some scenarios, the finite-offset CRS (FO-CRS) stacking operator was developed to address this limitation. This technique, as described in the literature by Zhang et al. (2001) and Hoecht et al. (2009), generalizes the CRS to the FO domain, thereby allowing for a more flexible and comprehensive characterization of seismic events compared to the ZO-CRS approach. Overall, the FO-CRS stacking operator represents a significant advancement in seismic data processing, providing a more general and coverage-rich approach to seismic data stacking than the original CRS method. It is worth noting that the FO-CRS traveltime is a second-order Taylor approximation of the traveltime of the wavefront propagation from sources to receivers, requiring the estimation of five parameters to fit its stacking surface over the dataset events. As such, it provides a more comprehensive data integration and processing technique.

The offset-continuation-trajectory (OCT) stacking operator (see, Coimbra et al., 2013, 2016; Faccipieri et al., 2018) is a powerful data-driven technique that uses wavefront propagation physics to transform a multiple-coverage of traces from a neighborhood of seismic responses into a source-receiver pair. Notably, this technique is designed explicitly for CRP gathers, where the source-receiver pairs share a common event point in depth. Also, one of the key advantages of the OCT stacking operator is its reduced parameter requirement compared to other methods, such as the FO-CRS method. Only two kinematic parameters, namely the event slope and average velocity, must be specified, leading to decreased degrees of freedom and a more efficient and streamlined processing workflow. This reduction in parameter quantity is attributed to the operator's adherence to wavefront propagation physics constrains, which ensures a physically consistent stacking. Overall, the OCT stacking operator represents a promising approach for seismic data processing, offering improved efficiency and accuracy in reconstructing neighboring events into traces that refer to a source-receiver pair, particularly for CRP gathers. The technique's reliance on wavefront propagation physics and reduced parameter requirement make it a valuable tool for seismic data analysis and interpretation.

Furthermore, it is worth noting that although stacking operators may differ in their surface-staking approaches, they all rely on parameter estimation to approximate seismic response events. These estimated parameters typically hold physical significance, and their accuracy can be validated using the Semblance function (Neidell and Taner, 1971). The Semblance function identifies the set of parameters that yield the highest value for a given point in the dataset, which are likely to be the most accurate. We utilize a coevolutionary algorithm called evolution by neighborhood similarity (ENS) to extract these optimal parameters (see, Ribeiro et al., 2023). This approach ensures that the estimated parameters are the most reliable and robust, obtaining the best-fit accuracy from the analyzed operators.

In conclusion, the FO-CRS and OCT stacking operators are powerful techniques for seismic data processing, but they hold some key differences. Although the FO-CRS stacking operator extends the conventional stacking of seismic traces, i.e., providing a more flexible and comprehensive characterization of seismic events than the ZO-CRS approach, there is an increased potential for generating coherent noise when we apply the optimal values derived from Semblance analysis of its parameters. However, when we apply the optimal values derived from Semblance analysis to the FO-CRS parameters, there is an increased potential for generating coherent noise. This is because the operator has a higher degree of freedom in its traveltime parameters. On the other hand, the OCT stacking operator proved to be more robust and suitable for regularized geometry interpolation and enhancement of the seismic-response datasets.

Method

As mentioned before, this work examines FO-CRS and OCT stacking operators in two synthetic datasets. A Kirchhoff modeling scheme was considered for the first dataset, while a ray-tracing modeling was used for the second. Both datasets are designed to introduce varying degrees of noise and coherent noise. Besides, the first dataset, namely Dataset 1, has one hundred CDPs with a total fold of twenty-six traces per CMP gather. Figure 1 shows the ZO section (Top) and the CMP gather located at the middle of the dataset (Bottom). While the second dataset, namely Dataset 2, has three hundred CDPs with a total fold of one hundred and one traces per CMP gather. Figure 2 shows the ZO section (Top) and the CMP gather located at the middle of the dataset (Bottom). Besides, all datasets have time samples of 4 ms.

In order to compare these two stacking operators, we consider several aspects of seismic data analysis, including quantitative analysis, frequency modification observation, SNR improvement, incorrect position events, and non-physical event removal. Quantitative analysis involves the computation of the Semblance value using the quantity of Semblance by the response (QSR) formula, which considers only the Semblance value over truth events in the trace. Frequency modification is crucial to prevent the unintentional amplification of low- or high-frequency signals during stacking, which may arise from inaccurate positioning of traces or poor fitting of the stacking operator. SNR improvement is critical to obtain accurate seismic data detection and analysis by measuring the strength of the desired signal compared to the noise or interference present in the system. A higher SNR allows for high-resolution images with fewer artifacts. Incorrect positioning of events can occur for various reasons, including misinterpreting subsurface features' location or depth, which may result from inaccuracies in the seismic wave velocity models or errors in positioning the stacked data. Finally, non-physical event removal involves eliminating inaccurate or irrelevant events that may appear in the data, which could affect the subsequent data processing and interpretation accuracy and reliability.

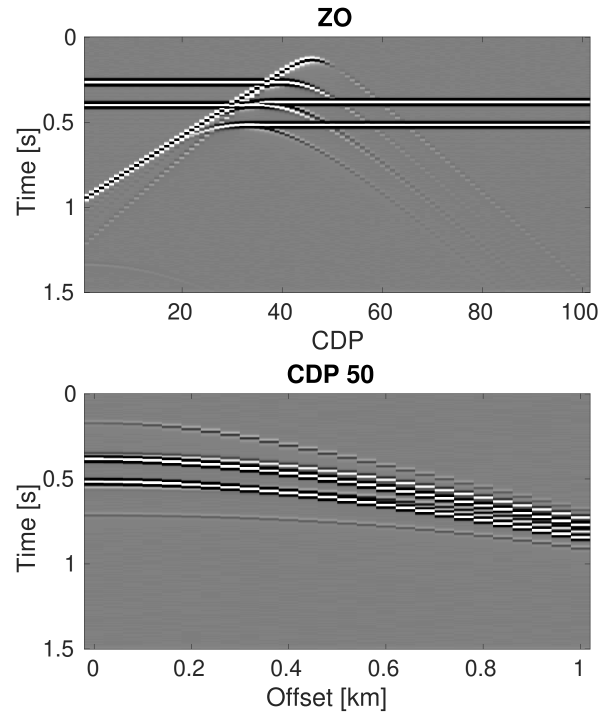

Figure 1: Dataset 1: Raw data ZO section (Top) and the central CMP gather (Bottom).

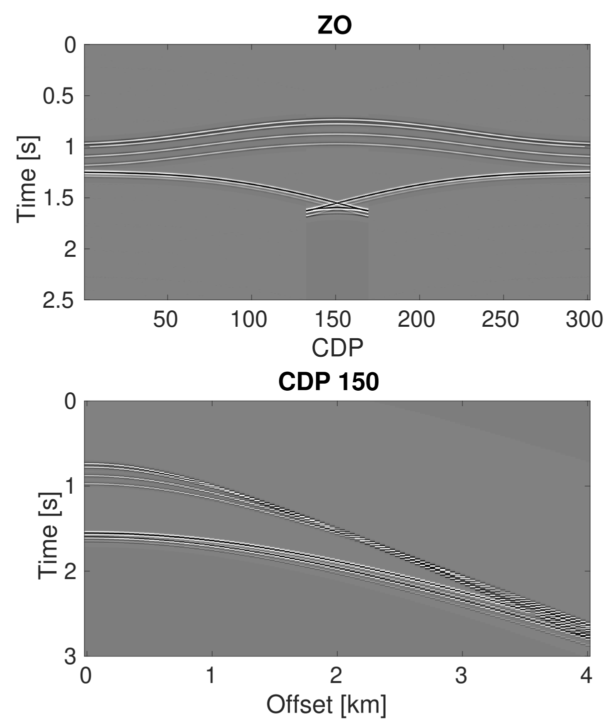

Figure 2: Dataset 2: Raw data ZO section (Top) and the central CMP gather (Bottom).

Qualitative analysis

As this section relies heavily on subjective and visual interpretation, we present the stacking panels for both datasets with both operators. Our results were obtained

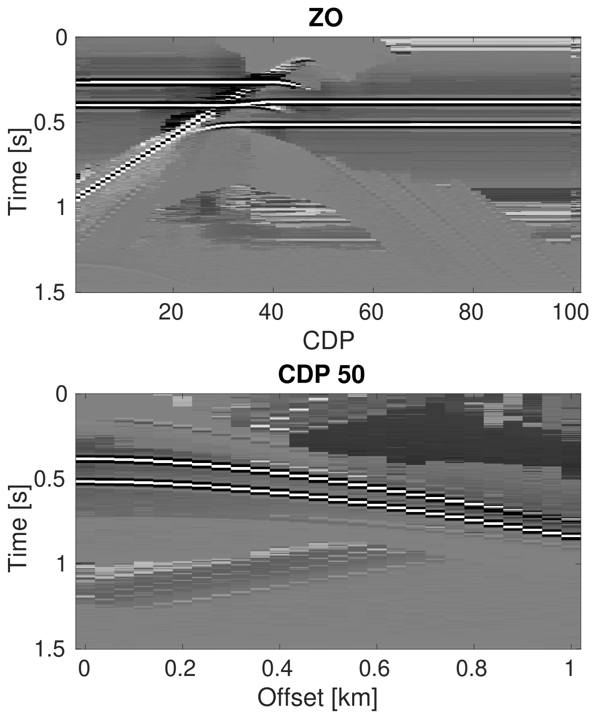

Figure 3: Dataset 1: FO-CRS stacked dataset at ZO (Top) and the central CMP gather (Bottom).

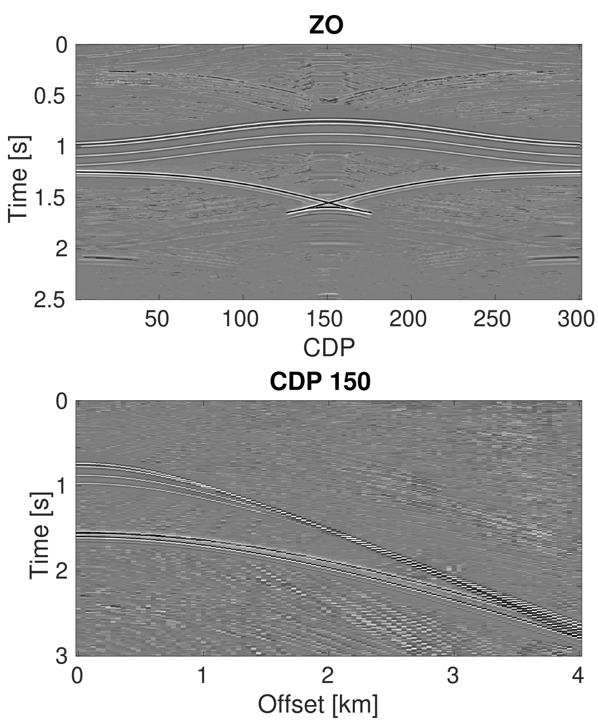

Figure 4: Dataset 2: FO-CRS stacked dataset at ZO (Top) and the central CMP gather (Bottom).

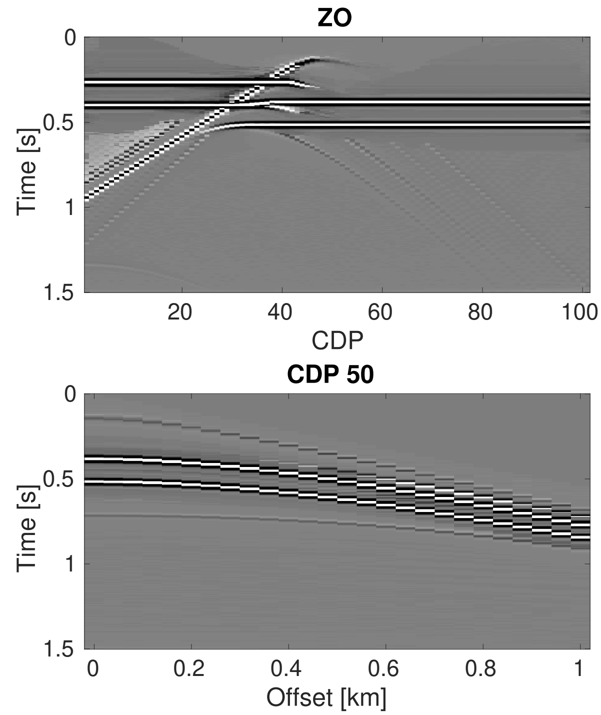

Figure 5: Dataset 1: OCT stacked dataset at the ZO (Top) and the central CMP gather (Bottom).

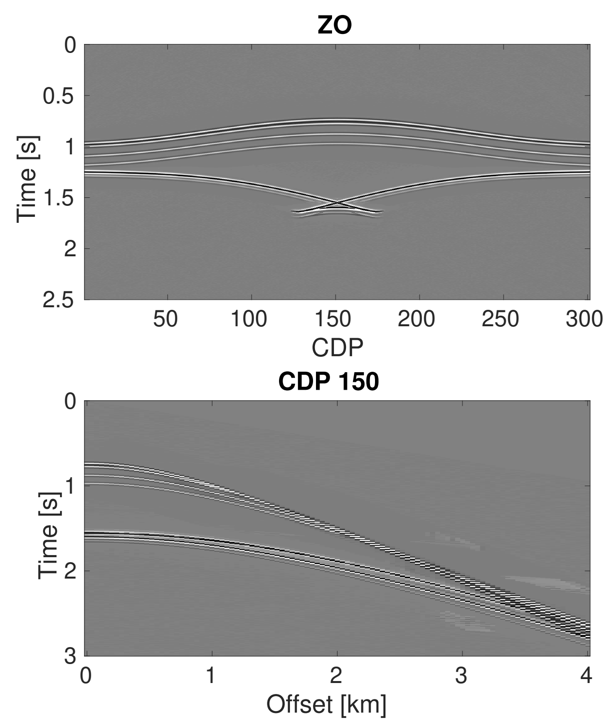

Figure 6: Dataset 2: OCT stacked dataset at the ZO (Top) and the central CMP gather (Bottom).

without using any initial traveltime parameter to guide the processes, ensuring a fair comparison of strategies. For the Semblance estimation and stacking, we use midpoint apertures radius of 75 m and offset apertures radius of 1000 m in all data. Also, the time-window length has 24 ms for Semblance estimation. Finally, for ENS algorithm, we use $N_P = N_G = 20$, $N_{\text{skip}} = 0$, and the other parameters as defined in Ribeiro et al. (2023).

In Figure 3, we presented Dataset 1 stacked by the FO-CRS operator. Unfortunately, we can observe that the presence of conflicting dips has made the process of diffraction stacking quite challenging. Furthermore, this method has generated a considerable amount of coherent noise, which did not exist in the data before. On the other hand, Figure 5 displays the output of the OCT operator, which has experienced fewer issues with conflicts. The data presented using this method (in a visual comparison) is of higher quality concerning the FO-CRS operator.

Continuing our analysis, we observe in Figure 4 that despite the FO-CRS operator well preserving the reflections of the original dataset, a great deal of low-frequency noise was generated. This is due to the freedom introduced by the first-order traveltime parameter in the offset direction; such a parameter requires tighter control, as it influences the operator very abruptly. On the other hand, the OCT operator has no such problems, as the traveltime approximation is built on strict rules related to wavefront propagation. Therefore, it presents the behavior more oriented to adjust to the reflection event, not being able to deviate too much from them. Such rigidity makes its stacking response cleaner, as seen in Figure 6.

Frequency modification

Poor fitting of the stacking operator may inadvertently amplify low-frequency signals during the stacking process in seismic data. This can occur when the traveltime operator is not correctly aligned with the seismic response event, resulting in out-of-phase stacking within trace coverage. As a result, poorly positioned traces may disproportionately contribute to the stacked signal, unintentionally boosting the low-frequency components. Accurate positioning by stacking operators is essential to avoid introducing artifacts that could impact subsequent data processing and interpretation accuracy and reliability.

Figure 7 shows the average of the frequency spectrum of the data. We observed that concerning the source data for the case of Dataset 1, the operator FO-CRS showed a high modification in the low frequency. For Dataset 2, we observed that the FO-CRS operator amplified both the low and high. On the other hand, the OCT operator showed a low modification in frequency content.

SNR improvement

In order to start our quantitative analysis, we begin with the SNR analysis. SNR is a fundamental concept in signal processing and data analysis that provides a quantitative measure of the quality of a signal. It compares the strength of the desired signal to the strength of any noise or interference in the system. A higher SNR indicates that the signal is stronger than the noise, allowing for accurate detection and analysis. In comparison, a lower SNR indicates that the noise is stronger than the signal, which can lead to errors and inaccuracies in the analysis. Moreover, a high SNR is significant in seismic datasets because it allows for the construction of high-resolution images with greater accuracy and fewer artifacts. However, a low SNR can result in poor image quality and other image-aberration problems. Similarly, in data analysis, a high SNR is essential for accurate measurement and interpretation of data. A low SNR can result in errors and uncertainties in the analysis, making it difficult to draw meaningful conclusions from the data. Mathematically, in this work, the SNR can be expressed as

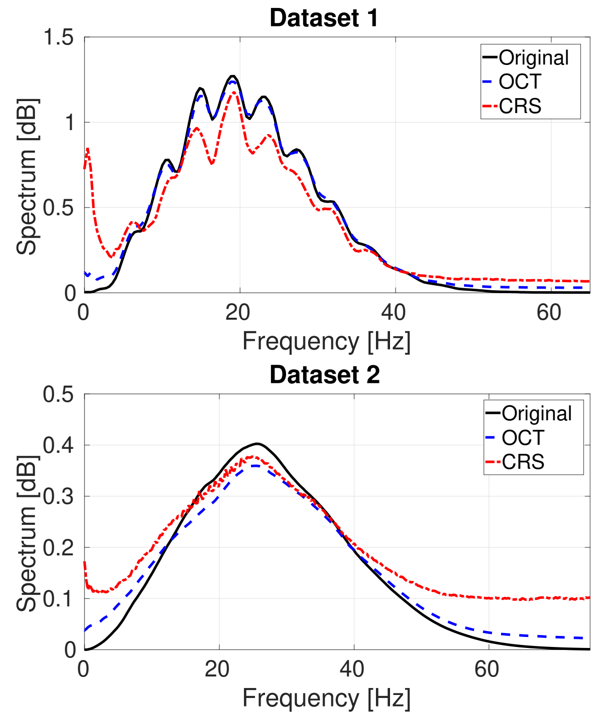

Figure 7: Frequency domain for the original data (black line), OCT (blue dashed) and FO-CRS (red dashed-dot). Results for Dataset 1 (Top) and Dataset 2 (Bottom).

$$\#\text{SNR}(X) = \frac{1}{Ntr}\sum_{j=1}^{Ntr}\left(\frac{\sum_{i=1}^{Nt}\left(s_j[t_i]\right)^2}{\sum_{i=1}^{Nt}\left(s_j[t_i]-d_j[t_i]\right)^2}\right), \quad (1)$$

where s_j and d_j are the original-signal and stacked traces at the $j-$th position. Also, Nt are the total number of time-samples, and t_i is the time-sample value at the $i-$th position. Finally, Ntr is the total trace number in each common-offset (CO) panel for the offset value X.

In Figure 8, which values are constructed by equation (1), given as an input dataset with a low SNR, we observe from these two datasets that the two operators increased the SNR. However, the OCT had a much more efficient improvement than the FO-CRS. In Dataset 1, the two operators were efficient in short offsets and lost quality for longer offsets, while in Dataset 2, also with a low SNR input dataset, the behavior was the opposite. In addition, OCT was much superior in this dataset concerning FO-CRS. It is important to remember that both operators had the exact estimation and stacking apertures.

QSR analysis

In this section, we analyze the Semblance value on the event response in the dataset. Therefore, to measure this value, we use a quantity of Semblance by the response (QSR) given by the following expression

$$\#\text{QSR}(X) = \frac{1}{Ntr}\sum_{j=1}^{Ntr}\left(\frac{\sum_{i=1}^{Nt}\left(C_j[t_i]\times D_j[t_i]\right)}{\sum_{i=1}^{Nt}D_j[t_i]}\right), \quad (2)$$

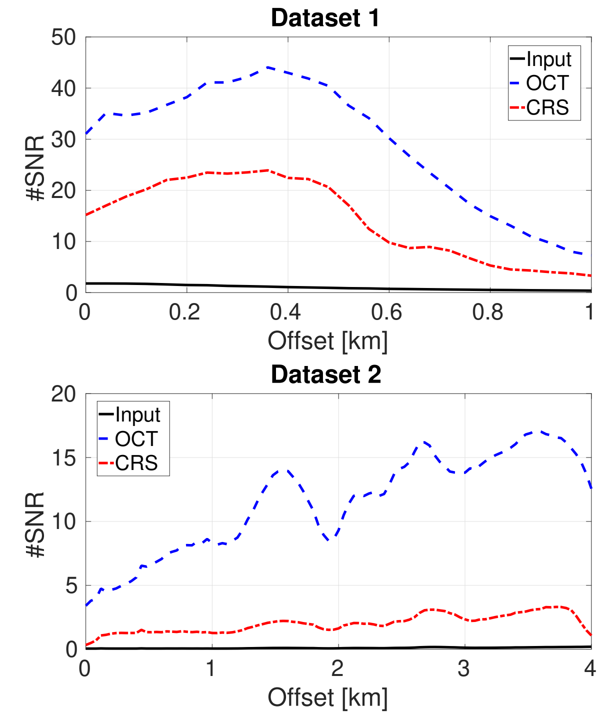

Figure 8: SNR value per offset on noise input data (black line), the OCT (blue dashed) and FO-CRS (red dashed-dot). Results for Dataset 1 (Top) and Dataset 2. (Bottom)

where C_j is the Semblance value trace at the $j-$th position, D_j is the absolute value trace of the analytical trace of d_j.

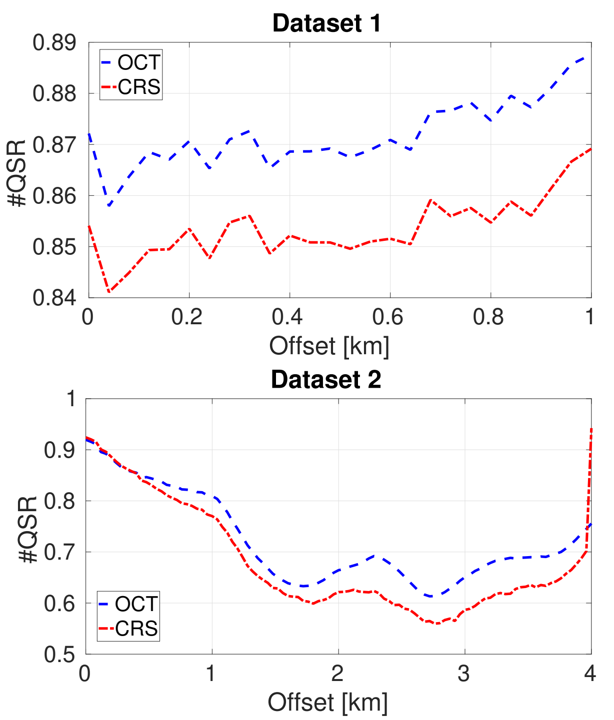

Figure 9: QSR value per offset (blue dashed) OCT (red dashed-dot) FO-CRS; Results for (Top) Dataset 1 (Bottom) Dataset 2.

In summary, Semblance is a coherence measure commonly used in geophysics to assess the quality of seismic wave reflection. It measures the similarity between the waveforms of seismic reflections on different traces in a seismic dataset. In other words, Semblance measures the degree of similarity between wavefront responses recorded at various points along the seismic profile. Based on that, equation (2) is designed to isolate the Semblance quantity present in seismic responses and enable a comparison of the similarity in outcomes achieved by operators using their best-fit traveltime. This analysis approach effectively eliminates the influence of spurious events that may be present in the seismic response values, ensuring a highly accurate assessment. Finally, Figure 9 shows the QSR values form the stacked datasets given by Figures 3, 4, 5 and 6. Besides, we observed that the operators were very consistent with a slight advantage for the OCT operator.

Incorrect position of events

In seismic imaging, incorrect positioning of events refers to anomalies in the seismic dataset processing that result in misinterpretation of the form, location or depth of subsurface features. These misplaced events can occur for various reasons, such as low-precision seismic wave velocity models, steeply dipping geological features, and errors in positioning the stacked data. In order to evaluate such information, we used a coherency coefficient (CC) value, as described follow

$$\#\mathrm{CC}(X) = \frac{1}{Ntr}\sum_{j=1}^{Ntr}\left(\frac{\left(\sum_{i=1}^{Nt} s_j[t_i]\times d_j[t_i]\right)^2}{\sum_{i=1}^{Nt}\left(s_j[t_i]\right)^2\times\sum_{i=1}^{Nt}\left(d_j[t_i]\right)^2}\right). \quad (3)$$

These CC values measure the coherence between two CO datasets, CC takes values between zero and one, with zero indicating no linear relationship between these two COs and one indicating a perfect linear relationship.

Finally, Figure 10 shows the CC values for the two operators in both datasets where the first 0.5 km of offsets were removed. Both techniques were used to extrapolate these missing offsets (mainly in the ZO). The FO-CRS showed little correlation, and it becomes coherent again as it advances in the offsets. However, such a problem does not occur in the OCT operator in any of the extrapolated offsets.

Non-physical event removal

In Figure 11, we show a modified version of Dataset 2, now contaminated by a coherent noise, so our analysis may focus on verifying which operators removed more of such noise. Figure 12 shows the SNR of the three datasets concerning the modified Dataset 2. We observe that the OCT operator increased the SNR values while the FO-CRS maintained or decreased these values. This result is because the FO-CRS traveltime is a Taylor-type adjustment with more degrees of freedom, while the OCT must obey the physics of wavefront propagation.

Conclusions

The FO-CRS and OCT stacking operators are compared based on traveltime approximations. The comparison is made using two controlled synthetic datasets, demonstrating the effectiveness of both stacking operators. The qualitative and quantitative analyses

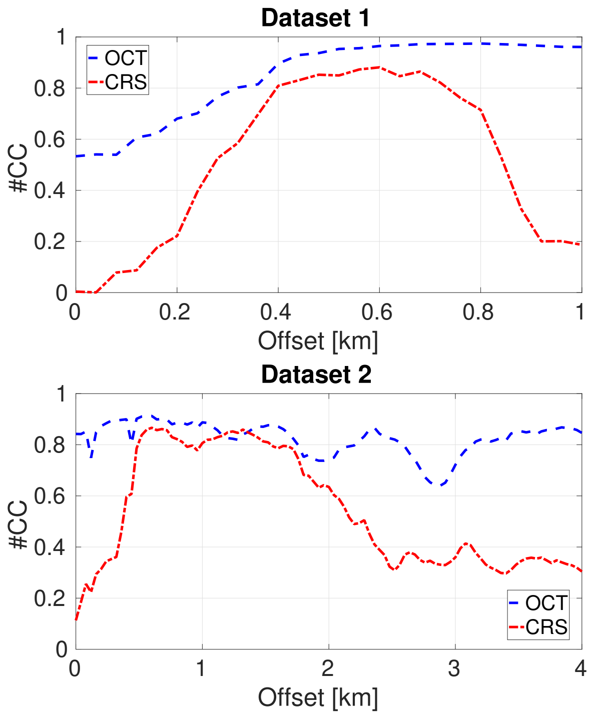

Figure 10: CC value per offset (blue dashed) OCT (red dashed-dot) FO-CRS; Results for (Top) Dataset 1 (Bottom) Dataset 2. The input datasets do not contain the initial offsets up to 0.5 km.

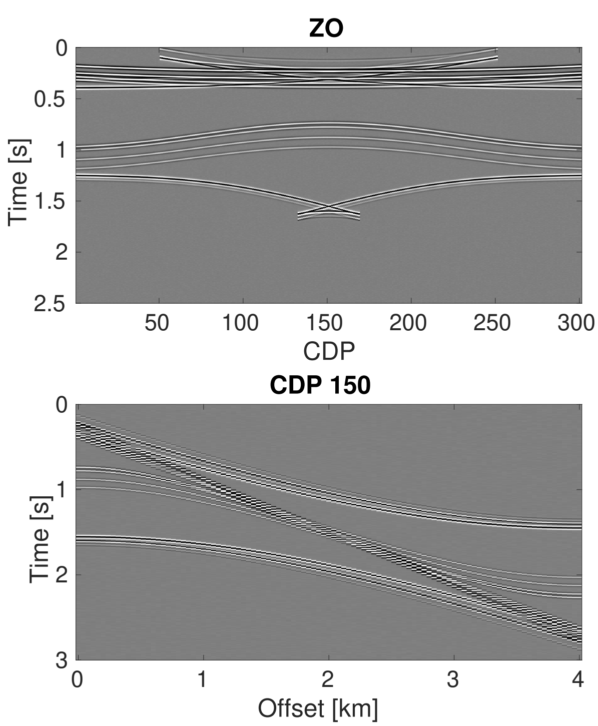

Figure 11: Coherent noise added in Dataset 2: Sections ZO (Top) and central CMP gather (Bottom).

show that the OCT operator is more robust than the FO-CRS operator. Therefore, OCT has physically coherent

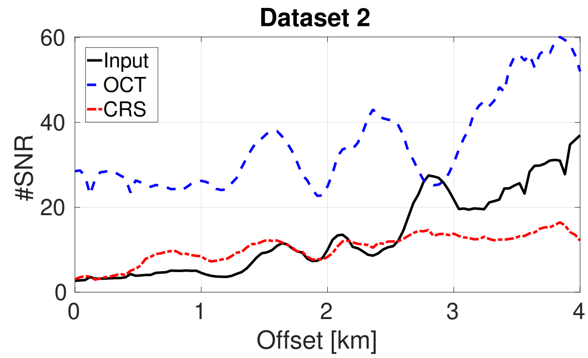

Figure 12: SNR value per offset noise input data (black line), OCT (blue dashed) and FO-CRS (red dashed-dot).

stacking advantages in the seismic data processing. We can conclude that the OCT operator is a more promising alternative for partial stacking in the FO domain, ensuring better quality for regularization or data enhancement procedures. This study highlights the importance of choosing the appropriate stacking operator for seismic data processing, and the OCT operator can be a valuable addition to the existing seismic data processing techniques.

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