PRESTACK DATA ENHANCEMENT WITH FINITE-OFFSET CRS ATTRIBUTES

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ABSTRACT

Multiparameter stacking methods are nowadays established tools in seismic imaging. In this work, we consider the Common Reflection Surface (CRS) operator. Although its classic formulation was derived for the zero-offset situation, it shows reasonable accuracy for finite offsets as long as the media under consideration are moderately complex. Recent works indicate that the resolution and illumination for higher offsets and more complex structures can be improved when according finite-offset operators are applied. However, finite-offset processing requires more stacking parameters, which makes it computationally more expensive and less stable. We introduce a new method that allows to predict finite-offset attributes from zero-offset attributes, and thus allows to considerably reduce the computational effort. We demonstrate the method by performing prestack data enhancement on marine field data. The higher coherence and better resolution compared to the zero-offset operator that was so-far used for prestack data enhancement confirms the potential of our new method. Furthermore, we investigate the importance of second-order parameters. Although these lead to higher accuracy, we conclude that for some cases a reduced operator that includes only the first-order attributes can already provide reasonable results.

INTRODUCTION

Multiparameter methods serve as important tools in applied seismics. In addition to providing reliable time images of the subsurface in terms of stacked sections with improved signal-to-noise ratio, these methods have also gained recognition because the stacking parameters or so-called kinematic wavefront attributes contain additional information about the subsurface. Over the past years, several multiparameter operators have been introduced. The most prominent multiparameter formulations are the Common Reflection Surface (CRS, Müller, 1999), multifocusing (Gelchinsky et al., 1999; Landa et al., 2010), and the implicit CRS (i-CRS, Vanelle et al., 2010; Schwarz et al., 2014). In this work we focus on the CRS method.

One particularly successful application of multiparameter processing is the prestack data enhancement method introduced by Baykulov and Gajewski (2009). They suggest to carry out a partial stack with a reduced aperture to generate new prestack traces or enhance existing ones using the zero-offset CRS operator Müller (1999). Although their results are convincing, the restriction to zero-offset parameters poses limitations on the method as it is less suited for larger offsets, especially in the presence of complex geological structures.

A corresponding finite-offset CRS formulation exists (Zhang et al., 2001), but it requires five stacking parameters (compared to three for the zero-offset case), which calls for a computationally-demanding five-parameter optimisation.

Due to the decoupling of raypaths in the diffraction case, it is possible to decompose any finite-offset diffraction operator into to independent zero-offset diffraction operators (Bauer et al., 2016). This allows the generation of finite-offset diffraction stacks using the exact attributes without carrying out a computationally expensive search in the finite-offset domain.

In this work, we suggest a method to predict the five finite-offset attributes from zero-offset attributes as alternative to the global optimisation. Our method combines parameter extrapolation based on the hyperbolic CRS operator with a local refinement scheme following Schwarz et al. (2015).

In order to investigate not only the accuracy but also the efficiency of the prediction, we apply the finite-offset operator as well as a truncated, i.e., linear operator to a marine field data set. In comparison to images obtained with the method of Baykulov and Gajewski (2009), we find that our method leads to better results.

METHOD

The finite-offset (FO) Common Reflection Surface (e.g., Zhang et al., 2001) operator is a hyperbolic traveltime expression for an arbitrary midpoint (x) and half-offset (h) in the vicinity of an expansion point (x_0, h_0). It is obtained by squaring a Taylor expansion of the traveltime $T(x, h)$ and neglecting terms of higher order than two, which leads to

$$T^2(\Delta x, \Delta h) = (T_0 + p_0 \Delta x + q_0 \Delta h)^2 + T_0 \left(X_0 \Delta x^2 + H_0 \Delta h^2 + 2\, M_0 \Delta x\, \Delta h \right) \quad . \tag{1}$$

Here, T_0 is the traveltime in the expansion point, and $\Delta x = x - x_0$ and $\Delta h = h - h_0$ are the distances to it. The parameters in (1) are the first- and second-order derivatives, namely, the slownesses,

$$p_0 = \left. \frac{\partial T}{\partial x} \right|_{x_0, h_0} , \quad \text{and} \quad q_0 = \left. \frac{\partial T}{\partial h} \right|_{x_0, h_0} , \tag{2}$$

and, accordingly,

$$X_0 = \left. \frac{\partial^2 T}{\partial x^2} \right|_{x_0, h_0} , \quad H_0 = \left. \frac{\partial^2 T}{\partial h^2} \right|_{x_0, h_0} , \quad \text{and} \quad M_0 = \left. \frac{\partial^2 T}{\partial x\, \partial h} \right|_{x_0, h_0} \quad . \tag{3}$$

In the zero-offset (ZO) case, the coefficients q_0 and M_0 vanish due to the symmetry with respect to interchanging the source and receiver positions. With $h_0 = 0$ and, therefore, $\Delta h = h$, Equation (1) reduces to

$$T^2(\Delta x, h) = (T_0 + p_0 \Delta x)^2 + T_0 \left(X_0 \Delta x^2 + H_0 h^2 \right) \quad . \tag{4}$$

This expression coincides with the zero-offset CRS operator introduced by Müller (1999),

$$T^2(\Delta x, h) = \left(T_0 + 2\, \frac{\sin \alpha}{V_0}\, \Delta x \right)^2 + 2\, T_0 \frac{\cos^2 \alpha}{V_0} \left(\frac{\Delta x^2}{R_N} + \frac{h^2}{R_{NIP}} \right) \quad , \tag{5}$$

where V_0 is the near surface velocity, and the wavefront attributes α, R_N, and R_{NIP} are the incidence/emergence angle at the coinciding source and receiver position, x_0, and the radii of curvature of two hypothetic wavefronts, the normal (N) and normal incidence point (NIP) wave (Hubral, 1983), respectively. Comparing the coefficients of (4) and (5) we find, as expected, that q_0 and M_0 are zero. Furthermore,

$$p_0 = \frac{2\, \sin \alpha}{V_0} \quad , \quad X_0 = 2\, \frac{\cos^2 \alpha}{V_0\, R_N} \quad , \quad \text{and} \quad H_0 = 2\, \frac{\cos^2 \alpha}{V_0\, R_{NIP}} \quad . \tag{6}$$

Equation (5) can be considered as an extension of the classic CMP operator (Mayne, 1962). Instead of a stacking line over offset, it describes a stacking surface over midpoints and offsets, which leads to a significantly improved signal-to-noise ratio in the resulting stack. Furthermore, the wavefront attributes are useful for many applications in seismic data processing (see, e.g., Baykulov et al., 2011), where the stacking parameters are determined by semblance analysis (Neidell and Taner, 1971).

One application of particular interest is the prestack data enhancement method introduced by Baykulov and Gajewski (2009). The authors suggest to carry out a stack with a small aperture using the zero-offset operator (5), but for a finite offset. The result of this so-called partial stack yields an improved prestack trace at the considered offset. However, it has been argued that the zero-offset operator and the corresponding attributes may not be the best choice for such a partial stack. We therefore suggest to use Equation (1) to determine parameters p, q, M, X, H at a midpoint and (half) offset (x, h) from those in the expansion point (x_0, h_0), i.e., p_0, q_0, M_0, X_0, H_0.

Provided that the distances Δx and Δh are small, the first- and second-order derivatives of Equation (1) serve as an approximation for the parameters in the new midpoint and offset. We find

$$
\begin{aligned}
p &= \frac{\partial T}{\partial x}\Big|_{x,h} &&= \frac{p_0}{T}\left(T_0 + p_0\Delta x + q_0\Delta h\right) + \frac{T_0}{T}\left(X_0\Delta x + M_0\Delta h\right) \quad , \\
q &= \frac{\partial T}{\partial h}\Big|_{x,h} &&= \frac{q_0}{T}\left(t_0 + p_0\Delta x + q_0\Delta h\right) + \frac{T_0}{T}\left(H_0\Delta h + M_0\Delta x\right) \quad , \\
X &= \frac{\partial^2 T}{\partial x^2}\Big|_{x,h} &&= \frac{T_0\, X_0 + p_0^2 - p^2}{T} \quad , \\
H &= \frac{\partial^2 T}{\partial h^2}\Big|_{x,h} &&= \frac{T_0\, H_0 + q_0^2 - q^2}{T} \quad , \\
M &= \frac{\partial^2 T}{\partial x\, \partial h}\Big|_{x,h} &&= \frac{T_0\, M_0 + p_0\, q_0 - p\, q}{T} \quad , \qquad (7)
\end{aligned}
$$

with traveltime T given by Equation (1). We can now compute traveltimes in the vicinity of (x, h) by using Equation (1) with (x, h) as the new expansion point and the parameters from Equation (7).

In the special case of extrapolation from zero offset, where $q_0 = 0$ and $M_0 = 0$, to a finite offset at the same midpoint position, Equations (7) reduce to

$$
\begin{aligned}
p &= \frac{p_0\, T_0}{T} \quad , \\
q &= \frac{T_0\, H_0 \Delta h}{T} \quad , \\
X &= \frac{T_0\, X_0 + p_0^2 - p^2}{T} \quad , \\
H &= \frac{T_0\, H_0 - q^2}{T} \quad , \\
M &= -\frac{p\, q}{T} \quad . \qquad (8)
\end{aligned}
$$

This case is of particular interest for the prestack data enhancement (Baykulov and Gajewski, 2009).

An alternative to the extrapolation using Equations (7) and (8) is the CRS-based slope determination by Schwarz (2015), see also Lavaud and Baina (2004), in which only the slopes, i.e., the angles or slownesses, are extrapolated but not the higher order coefficients. The expressions for the extrapolation are the same as in (7) and (8), however, instead of Equation (1) for the traveltimes, a truncated operator of the following form is used:

$$T(\Delta x, \Delta h) = T_0 + p_0\, \Delta x + q_0\, \Delta h \quad . \qquad (9)$$

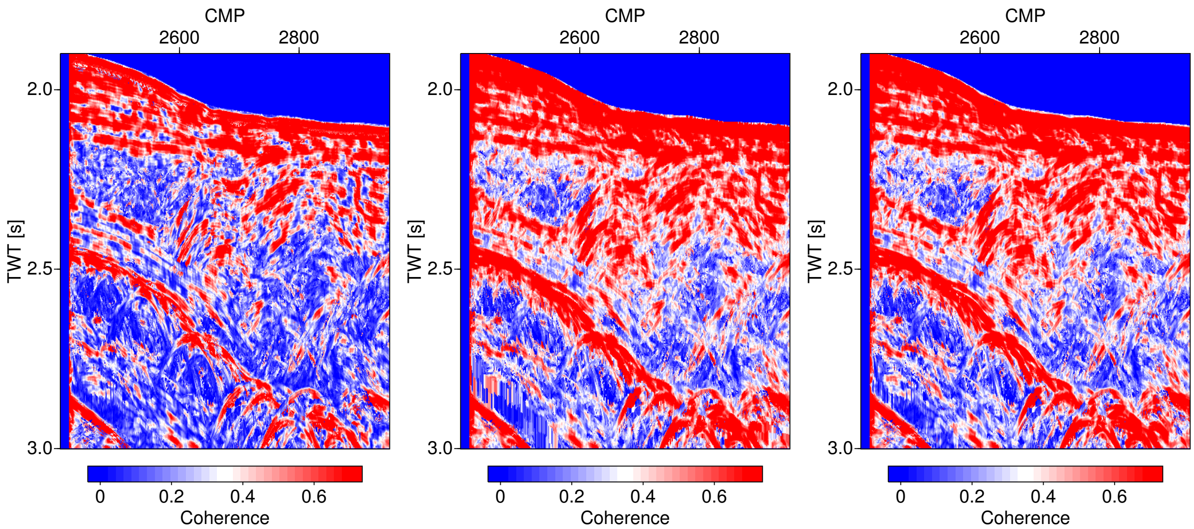
For the smaller apertures used in the partial stacks (Baykulov and Gajewski, 2009), the truncated operator still provides a good fit to the data.

Although the extrapolation using Equations (7) and (8) already leads to reasonable accuracy (Vanelle et al., 2014), the coefficients can be improved by a subsequent local refinement step. Following Schwarz et al. (2015), this step is carried out by a local optimisation that uses the extrapolated parameters as starting values. The resulting local semblance is denoted as partial coherence in accordance with the partial stacks.

The combination of parameter extrapolation and subsequent local optimisation is referred to as prediction. In the following section, we investigate the prediction for a field data example.

APPLICATION

We have applied our method to a marine field data set located in the Levantine Basin in the Eastern Mediterranean. The region is known to be strongly influenced by complex salt tectonics. Details can be found in



(a) (b) (c)

Figure 1: Marine field data: Coherence sections obtained (a) without prediction, (b) with slope prediction, and (c) with full prediction.

the work by (Netzeband, 2006). We show results for

a.) *full prediction:* first- and second-order wavefront attributes are predicted according to Equation (7) or (8). The traveltime surface is given by the hyperbolic finite-offset expression (1).

b.) *slope prediction:* only the first-order attributes are predicted. The traveltime surface is given by the truncated operator (9).

If for a given sample, the partial coherence using the extrapolated values is higher than 0.8, we assume that the parameters are sufficiently accurate. In that case, local refinement is not carried out. If the partial coherence is below 0.1, we do not further consider the sample.

For comparison, we also show results obtained with Baykulov and Gajewski's (2009) technique, without prediction. All methods were applied under the same conditions, e.g., apertures, and using the same zero-offset attributes obtained with a global optimisation (Walda, 2016). Conflicting dips were not considered in this study.

Figure 1 shows the coherence sections for the part of the data we investigated. We recognise that the coherence resulting from both prediction methods in Figure 1(b) and (c) is higher compared to (a), where the zero-offset operator, i.e., no prediction, was applied. As both prediction methods show almost identical coherence, we show difference plots in Figure 2, where (a) depicts the difference between slope prediction and no prediction and (b) the difference between full and slope prediction.

Figure 3 displays newly-generated prestack data for the three methods at a half offset of 1 km. As we can expect from the higher coherence, the prediction methods lead to better resolution, e.g., between CMP 2400 and 2600 for 2.3 to 2.6 seconds, which we show as a close-up in Figure 4, and between CMP 2850 and 2950 and 2.1 to 2.4 seconds, shown in Figure 5. Both prediction methods perform with overall similar quality although the slope prediction leads to slightly noisier results than the full prediction.

CONCLUSIONS

We have introduced a method to predict second-order wavefront attributes for prestack data enhancement by partial stacking. The prediction consists of two steps. In the first step, zero-offset CRS parameters are extrapolated to finite offsets. The second step consists of a local optimisation of the extrapolated parameters with a reduced aperture. This approach makes the determination of the finite-offset parameters more efficient than a full search.

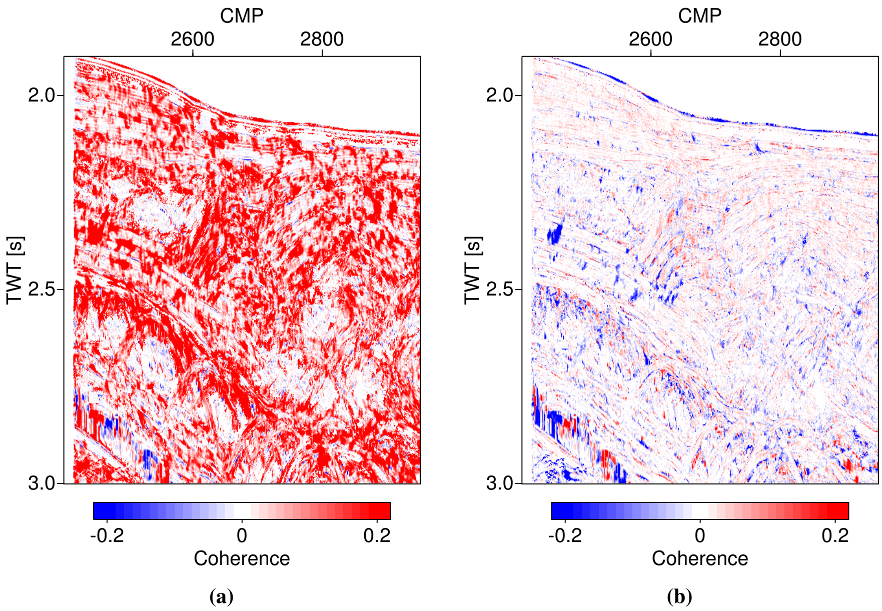


Figure 2: Marine field data: Difference in coherence between (a) slope prediction vs no prediction, (b) full prediction vs. slope prediction.

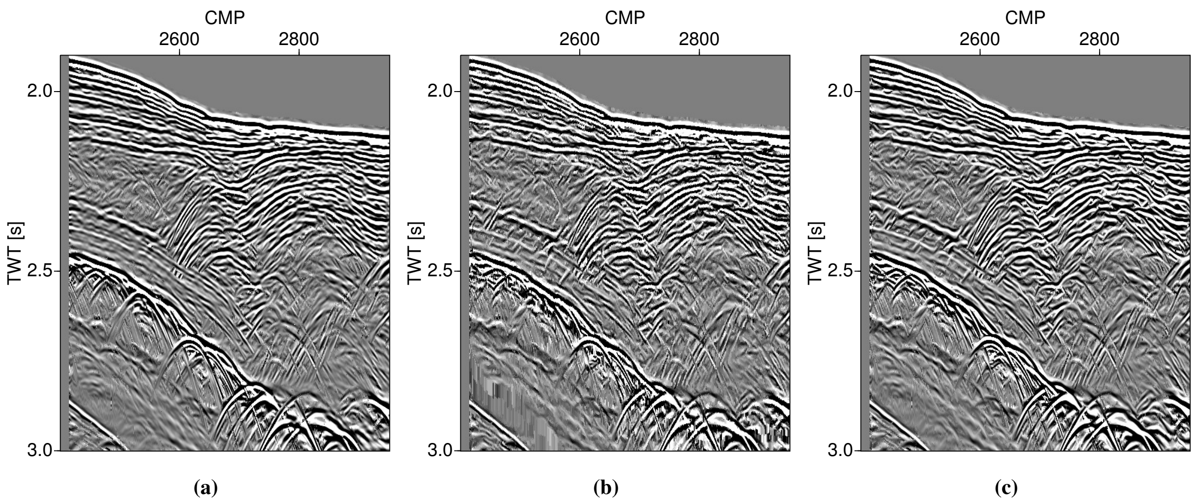


Figure 3: Marine field data: finite-offset sections for $h = 1$ km obtained (a) without prediction, (b) with slope prediction, and (c) with full prediction.

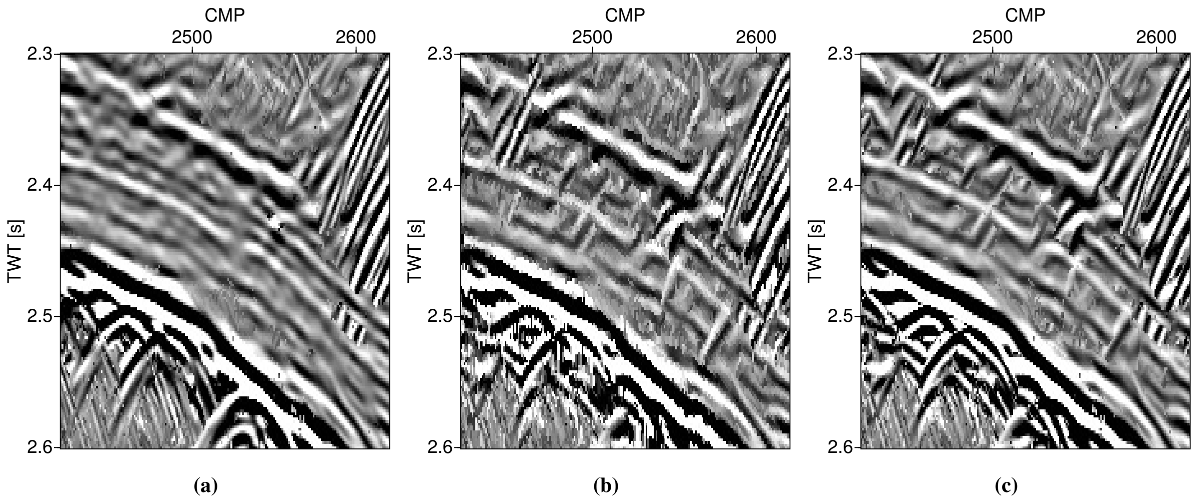


Figure 4: Marine field data: close-up 1 of finite-offset sections for $h = 1$ km obtained (a) without prediction, (b) with slope prediction, and (c) with full prediction.

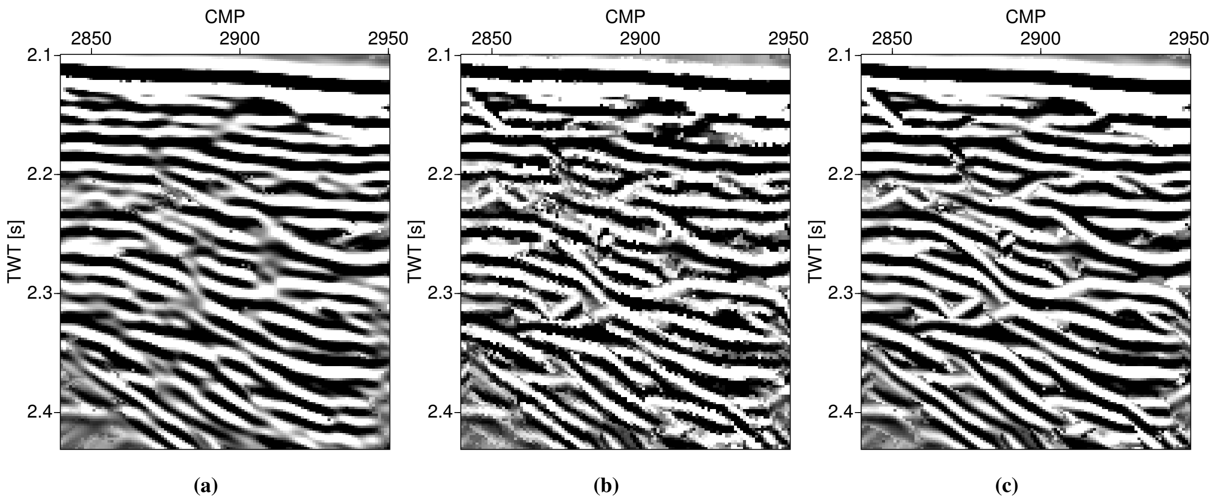


Figure 5: Marine field data: close-up 2 of finite-offset sections for h =1 km obtained (a) without prediction, (b) with slope prediction, and (c) with full prediction.

The method allows to predict parameters in midpoint and offset, also starting from finite-offset attributes. The latter case was, however, not investigated in this work.

Unlike the partial stacking introduced by Baykulov and Gajewski (2009), our method uses a finite-offset operator with locally-refined attributes. Our examples show that the local character as well as the better operator fit lead to better-resolved prestack traces.

We also investigated the performance of a reduced, i.e., linear, operator with predicted first-order attributes following Schwarz et al. (2015). This approach led to slightly noisier results in the data under consideration, but upheld the same improvement in reflector continuity and resolution. We conclude that the reduced operator is also a suitable choice for field data.

In order to enhance the accuracy of the prediction to higher offsets, a cascaded prediction could be applied, where parameters are extrapolated from one midpoint and offset to another midpoint and offset, followed by subsequent local optimisation.

Our results suggest that finite-offset CRS processing can be significantly enhanced if starting values for the optimisation are gained by prediction from zero-offset. In contrast to the work presented here, these could be used for a global optimisation and significantly enhance the efficiency of that otherwise very costly procedure.

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