CRS stack using global simultaneous multi-parameter optimization: a better velocity analysis for near-surface data.

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SUMMARY:

CRS stacking employs a spatial three-parameter stacking operator that extents in offset and midpoint direction. Since this operator covers several CMP gathers, a large number of traces contribute to every single stacking process, thus generating a large improvement in signal-to-noise ratio. However, the standard implementations use the spatial operator *only* for stacking and *not* for the global stacking parameter search. Instead, they rely on a sequence of three one-dimensional searches which decreases the computational effort compared to the full simultaneous three-parameter search by two orders of magnitude, but does not always deliver optimal results. Particularly for near-surface data, characterized by low signal-to-noise ratio and modest CMP fold, the efficiency gain is not crucial. Considering the huge computing power available today, we propose a new pragmatic search strategy using a spatial two-parameter diffraction operator for the global search, followed by a local optimization using the full CRS operator with the diffraction parameters as initial guess. For shallow shear-wave data, we show that while the computational cost of this hybrid approach reduces by an order of magnitude the results are still very close to those obtained by the full global three-parameter search and far superior to those obtained by three cascaded one-parameter searches.

Introduction

The Common Reflection Surface (CRS) stack method (see Mann et al. 1999, Hertweck 2007, and references given therein) can be seen as a generalization of the classical CMP stack. It extents CMP stacking into the off-CMP direction by adding the midpoint coordinate to the traveltime approximation. For 2D acquisition on a flat surface over an inhomogeneous but isotropic medium the hyperbolic CRS stacking operator in midpoint displacement and half-offset coordinates reads

$$t^2(\Delta x_m, h) = \left[t_0 + \frac{2\sin\alpha}{v_0}\Delta x_m\right]^2 + \frac{2t_0\cos^2\alpha}{v_0}\left[\frac{\Delta x_m^2}{R_N} + \frac{h^2}{R_{NIP}}\right], \; with\, \Delta x_m = x_m - x_0. \quad (1)$$

It approximates the reflection traveltime of rays, which propagate in the vicinity of a zero-offset ray, defined by its emergence location x_0 and two-way traveltime t_0. The near-surface velocity v_0 in the vicinity of x_0 is assumed to be known. It can be seen as a constant of proportionality necessary to express the three independent parameters that describe a hyperbolic surface by kinematic properties of the wavefield measured in x_0; namely α, the emergence angle of the central ray and R_{NIP} and R_N, the wavefront radii of two notional eigenwaves known as normal incident point (NIP) wave and normal (N) wave. These so-called CRS parameters represent the generalized counterpart to the NMO velocity. A basic difference to the conventional NMO correction + CMP stack approach is that, following the paradigm of data-driven imaging, an automated search for the optimum stacking parameter triple is performed for every sample of the output section instead of stacking with NMO velocities extra- and interpolated from a limited number of visually detectable reflection events. In other words, for every zero-offset sample $P_0 = (x_0, t_0)$, those three parameters are searched for, which parameterize the hyperbolic reflection traveltime surface (1) in such a way that it fits best to an actually measured reflection in the data. If P_0 does not lie on a reflection event, the attribute triple with the maximum coherence will achieve only a low coherence value and stacking will not result in a constructive summation of amplitudes. A positive side effect of the fact that every sample of the reflection event is treated independently is: the NMO velocity that corresponds to the CRS stacking parameters will in general decrease along the wavelet since the (apparent) traveltime t_0 increases but the depth of the reflecting interface remains the same. Doing so, the NMO-stretch effect can be avoided since it is mainly caused by NMO velocities kept constant along the event or that even increase due to velocity extra- or interpolation.

Cascaded search strategy

In the last years of the 20th century, when the CRS stacking method was developed and firstly implemented, it was impractical to apply for every sample of the zero-offset section a global simultaneous search for the parameterization of the best fitting hyperbolic three-parameter reflection operator (1). Therefore, Mann et al. (1999), proposed the *pragmatic search strategy* which employs a sequence of three global one-parameter line searches; the first applied in single CMP gathers and the second and third in a preliminary stack section, created as result of the first search. Assuming to be now close to the global coherency maximum the parameter search is concluded by a local three-parameter optimization. Since then, this strategy was applied in the vast majority of the published 2D case studies and quite similar also in 3D. Crucial for the success of this cascaded approach is the first line search, a kind of automatic CMP stack, which risks failing in case of low signal-to-noise ratio and insufficient CMP fold, especially for small traveltimes where the range of usable offsets is very limited. Stacking along operator (1) with erroneous parameters creates apparent holes in the zero-offset image of the reflection events. As a way to compensate the breakdown of the pragmatic search in certain CMPs, Mann and Duveneck (2004) proposed the so-called event-consistent smoothing of stacking parameters[1], iteratively applied and each time followed by a new local optimization. This method was then used with good success, in Heilmann et al. (2004) and several other studies on deep

[1] Today's ESA astronaut Alexander Gerst developed a first version of this approach as a student assistant.

seismic imaging. From this experience and the experience gathered later applying the CRS stack to near-surface data we can state that for hydrocarbon exploration (deep targets and large CMP fold) the shortcomings of the pragmatic search are usually insignificant compared to the efficiency benefit; for near-surface data the same logic works but in the opposite direction: if the CMP fold is low (e.g. 12 traces), simultaneous search becomes easily affordable and highly beneficial for a stable stacking parameter optimization, particularly for very heterogeneous and noisy data.

Simultaneous search strategies

To estimate the effort related to a global three-parameter simultaneous search in the prestack data relative to a sequence of three line searches in specific gathers one has to account for two things. First the total number of coherency calculations necessary to create a stacked sample. Second the number of traces that enter into every single coherence calculation. For a simultaneous three-parameter search, a 3D coherence matrix has to be calculated where each individual value corresponds to a certain parameter combination, while for the pragmatic search we have to calculate three 1D coherence vectors, successively. For the simultaneous search, all prestack traces within a spatial search aperture enter a single coherence calculation, while for the line searches the search aperture is either limited to an offset range in a CMP gather or to a midpoint range in the preliminary stacked section. To give the reader a rough quantitative understanding of the numerical effort, we assume a grid search with 10 parameter values per dimension. If we neglect the actually applied refinement steps we end up with 1000 coherence calculations for the simultaneous search. Compared to this, three subsequent line searches require only 30 coherence calculations. In addition, a single coherence calculation for a spatial operator in the prestack data covers in average 5 CMP gathers, whereas each of the three line searches involves only a number of traces comparable to 1 CMP gathers. From this simple calculation one can estimate that the pragmatic search is about 166 times faster than the simultaneous search. In both cases the resulting attributes are afterwards locally optimized.
A global 1x3 parameter search was proposed and applied to synthetic data by Garabito et al. 2007 using a simulated annealing strategy to reduce the computational effort related to the multi-parameter search. Later this approach was also applied to real data (Garabito et al. 2012 and Minato et al. 2012). A systematic comparison between the pragmatic search strategy of Mann et al. (1999) and a global 1x3 parameter search on a very fine grid was conducted by Barros et al. (2013) for a simple synthetic dataset with a single dipping reflector. Heilmann et al. (2014) applied a global 1x3 parameter grid search with local optimization to very shallow SH-wave data from an urban environment with strong lateral velocity changes and low S/N ratio. The use of local slopes instead of coherence as alternative parameter estimation strategy was first proposed by Santos et al. (2009) and applied to a global 3x1 parameter search scheme before Hellman (2014) applied multi-dimensional local slopes for a global 1x3 parameter search in a real data study. All of these cases showed clearly that a simultaneous estimation of the CRS parameters results in better image quality and more reliable stacking parameters, particularly for noisy data and low CMP folds. For the presented case study we are using a global three-parameter grid-search with iterative refinement followed by a local Simplex optimization as reference. To make this rigorous approach easily applicable we employ a parallelized code running on a Linux cluster under the SmartGeo cloud infrastructure (Heilmann et al. 2014). Later the results of this approach will be compared to the results of the original pragmatic 3x1 parameter search of Mann (1999) and to the results of a new pragmatic search strategy that we introduce in the following section.

Hybrid global diffraction / local reflection search

If we put in equation (1) $R_N = R_{NIP}$, we obtain the CRS diffraction operator. The computationally cheapest algorithm that uses a spatial operator for the global parameter search is the Common Diffraction Surface (CDS) stack of Soleimani et al. (2009). It employs this two-parameter diffraction operator, but searches on a grid for R_{NIP} only and stacks over all grid values of α, resolving in this way the conflicting dip problem. Passing one more step towards the global 1x3 parameter optimization, Garabito et al. (2001) proposed a global 2+1 parameter search method which starts with

a two-parameter search using the CRS diffraction operator followed by a one-parameter search using the full CRS reflection operator, keeping the two previously determined parameters constant.
As a kind of compromise between the global simultaneous three-parameter search and the pragmatic search strategy of Mann (1999) we propose a global simultaneous diffraction search as used by Garabito et al. (2001), followed by a local three-parameter optimization that starts with $R_N = R_{NIP}$ as initial guess. This means that, with the same assumptions that we made in the previous section, we have 100 coherence calculations for the simultaneous two-parameter search and end up with a computational effort that is about 16.6 times bigger than the one of the pragmatic search. However, we obtain for this prize all the benefits related to the use of a spatial operator for velocity analysis.

Ultra-shallow SH-wave data example

The data used for the presented comparison of search strategies was collected in a high-resolution SH-wave reflection survey aiming at delineating the overburden-bedrock surface as well as reflectors within the overburden (see also Deidda et al. 2012). It was recorded with a 24-channel seismograph using 100 Hz natural-frequency special horizontal detectors. The source for 61 shots was a 70-kg steel plate with ground grippers, struck at only one side (along a direction perpendicular to the seismic line) by an 8 kg sledgehammer. An off-end spread with a shot interval of 0.5 m and a group interval of 0.5 m was used, with offsets ranging from 1 to 12.5 m, resulting in a CMP fold of 12 traces.

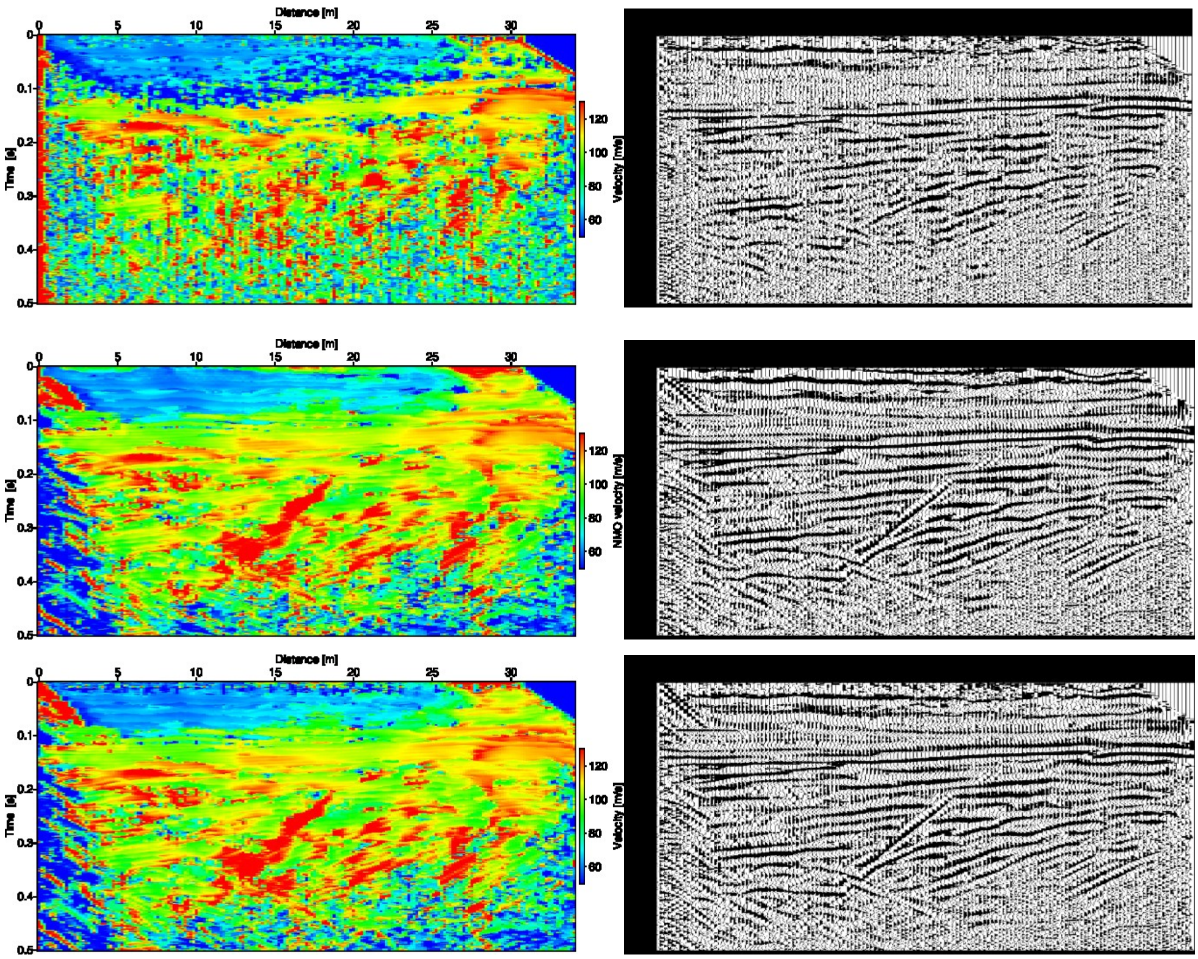

Figure 1 *NMO velocity sections (left) and CRS stack sections (right) using 3x1 parameter search (top), simultaneous 3 parameter search (middle), and simultaneous 2+1 parameter search (bottom). Runtime on 16 cores: <1 minutes (top), 22 minutes (middle), 2 minutes (bottom), including a fixed amount of time required by the scheduler to submit the parallel jobs to the cluster.*

The comparison displayed in Figure 1 shows the superior behaviour of the global simultaneous search strategies, both with respect to stack and NMO velocities that were calculated from α and R_{NIP}. In addition, diffractions such as those at the left boarder (house wall) and in the centre of the stack section (shallow object at the right end of the line) are much clearer imaged.

Conclusions

When CRS stacking was introduced as a data-driven imaging method, the biggest problem to solve was how to estimate three stacking parameters per stack sample within a reasonable time. A straight forward solution such as a global simultaneous three-parameter grid search was totally impractical. However, following Moore's law, computing power increased by 128 times during the last 14 years and thus methods have now become affordable that directly optimize the coherence between a spatial multi-parameter stacking operator and the prestack data---particularly for the relatively small datasets used in near-surface imaging. The presented data example shows clearly the large improvement in resolution and reflection continuity that can be obtained, together with a far better velocity field, for this kind of noisy low-fold near-surface data. Using the global 1x3 parameter optimization as reference, we proved that the presented hybrid global diffraction / local reflection search algorithm can deliver nearly identical results with only 10% of the computational cost.

References

Barros, T., Ferrari, R., Krummenauer, R., Lopes, R. and Tygel, M. [2013] The Impact of the Parameter Estimation Strategy in the CRS Method. *13th International Congress of the Brazilian Geophysical Society*, Expanded Abstracts, 1534-1539.

Deidda, G.P., Battaglia, E. and Heilmann, Z. [2012] Common-reflection-surface imaging of shallow and ultrashallow reflectors. *Geophysics*, 77, B177—B185.

Garabito, G., Cruz, J., Hubral, P. and Costa, J. [2001] Common reflection surface stack: a new parameter search strategy by global optimization. *70th Annual International Meeting SEG*, Expanded Abstracts, 2009–2012.

Garabito, G., Cruz, J. and Hubral, P. [2007] 2-D CRS Stack: one-step versus multi-step strategies. *10th International Congress of the Brazilian Geophysical Society*, Expanded abstracts, 1497-1500.

Garabito G., Stoffa P.L., Ferreira C.A.S. and Cruz J.C.R. [2012] Part II – CRS-beam PSDM: Kirchhoff-beam prestack depth migration using the 2D CRS stacking operator. *Journal of Applied Geophysics*, 85, 102-110.

Hertweck T., Schleicher J. and Mann J. [2007] Data stacking beyond CMP. *The Leading Edge*, 26, 818-827.

Heilmann, Z., Mann, J., Duveneck, E. and Hertweck, T. [2004] CRS-stack-based seismic reflection imaging – a real data example. *66th EAGE Conference and Exhibition*, Extended Abstracts, P211.

Heilmann, Z., Müller, H.-P., Satta, G., and Deidda, G.P. [2014] Real-time or Full-precision CRS Imaging Using a Cloud Computing Portal - Multi-offset GPR and Shear-wave Reflection Data. *20th European Meeting of Environmental and Engineering Geophysics*, Extended Abstracts.

Hellman, K. [2014] Simultaneous estimation of CRS parameters with multi-dimensional local slopes. *84th Annual International Meeting SEG*, Expanded Abstracts, 4686-4690.

Mann J., Jäger R., Müller T., Höcht G. and Hubral P. [1999] Common-reflection-surface stack – a real data example. *Journal of Applied Geophysics*, 42, 301-318.

Mann, J and Duveneck, E. [2004] Event-consistent smoothing in generalized high-density velocity analysis. *73rd Annual International Meeting SEG,* Expanded Abstracts, 2176-2179.

Minato, S., Tsuji, T., Matsuoka, T., Nishizaka, N. and Ikeda, M. [2012] Global optimization by simulated annealing for common reflection surface stacking and its application to low-fold marine data in southwest Japan. *Exploration Geophysics,* 43, 59–69.

Santos L. T., Schleicher J., Costa J. C., and Novais A. [2009] Fast estimation of CRS parameters using local slopes. *78th Annual International Meeting SEG*, 3735-3739.

Soleimani, M., Piruz, I., Mann, J. and Hubral, P. [2009] Common reflection surface stack; accounting for conflicting dip situations by considering all possible dips. *Journal of seismic exploration*, 18, 271-288.