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Multi-Focusing stacking using the Very Fast Simulated Annealing global optimization algorithm

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Summary

Multi-Focusing (MF) is a non-CMP based highly effective multi-coverage zero-offset stacking algorithm and has been utilized to generate very detailed and high-resolution images for comprehensive interpretation from geologically complex areas. However, currently, the implementation of Multi-Focusing comprise several isolated steps and also lacks an efficient optimization component. In a two-dimensional case, MF time correction depends on three kinematic attributes measured at the central point. Determining global optimal parameters of MF move-out correction is a very important and crucial step of the MF stacking, especially for complex structures and low-fold data. It is a nonlinear three-dimensional optimization problem and can be addressed by adopting a Very Fast Simulated Annealing (VFSA) optimization approach. We investigate the potential of using VFSA to optimize the estimation of MF parameters. The stacking velocity model derived from conventional velocity analysis is used to determine the lower and upper bound constraints of the VFSA search range for normal incidence point wave (R_{NIP}). We also used a global optimization strategy to speed up the accuracy and convergence of VFSA method. The results of applying MF on a synthetic data show that our proposed method improves the quality of time imaging and alignment of reflection events compared to the conventional CMP processing.

Introduction

Imaging the complex subsurface geological structures is one of the challenging tasks in the geophysical prospecting methods. Seismic data processing methods play an important role in constructing an accurate subsurface image from reflection seismic surveys. The application of seismic methods encounters difficulties due to the complex geologic structures, complicated surface conditions, low fold, noisy data, and numerous steeply dipping interfaces and heterogeneities (faults, fracture zones, etc.). Conventional seismic data analysis could not deal with these issues because it uses relatively a low fold single common midpoint gather (CMP) and simplified velocity models that limit the S/N improvement. Recently, some attempts have been made to improve stacking procedures by utilizing non-CMP based imaging methods to obtain the zero-offset stack sections. The Multi-Focusing (MF) approach proposed by Berkovitch et. al. (1994) is based on the homeomorphic imaging theory. This method provides an alternative to the depth processing sequence and is based upon a transformation of multi-coverage pre-stack data into a simulated zero-offset stack section. In particular, The MF transformation involves stacking large super-gathers of seismic traces, each of which can cover many common-midpoint (CMP) gathers. Stacking large super-gathers is made possible by the use of a generalized move-out correction. The primary advantage of MF is the enhancement of the signal-to-noise ratio of stacked sections through stacking a much larger number of traces than in conventional CMP stacking. This method does not require any knowledge of the subsurface model and can produce an accurate zero-offset section for seismic data with arbitrary source-receiver distribution according to a new local double-square-root move-out correction formula. Other advantages of MF method are stretch-free stacking, non-hyperbolic move-out correction, automatic estimation of MF parameters, and determination of dip-independent velocities. In addition, the MF can also be considered a method for wave-field analysis, which reliably estimates wavefront parameters of each individual seismic event at each observation point (Landa et al., 1999). These wavefront parameters may have broad applications in seismic data processing and imaging. The main challenge in the MF stacking method is the determination of the MF kinematic attributes from the pre-stack super-gather through an automatic search process based on coherency measure (semblance). This task is carried out by a computationally expensive iterative parameter-search algorithm for the entire zero-offset points (X_0) and travel-times (t_0). Furthermore, the semblance needs to be maximized using a nonlinear global optimization method in order to convergence to an accurate estimation. In this article, we solve the optimization problem of the MF stacking method by applying the well-known multidimensional global optimization algorithm called Very Fast Simulated Annealing (VFSA). This algorithm improves the convergence and estimation accuracy of the MF method via introducing boundary constraints in the global optimization of the three MF attributes.

The Multi-Focusing (MF) method

For a given source-receiver pair, in a 2D case, the MF move-out correction depends on three parameters: the wavefront curvatures of the normal wave (R_N), the normal incidence point wave (R_{NIP}), and the emergence angle of the normal ray (β). For each super-gather and each zero-offset time, these parameters are obtained through a coherency analysis of the move-out-corrected super-gather (Berkovitch et al., 2008). Figure 1a shows a normal ray starting at point X_0 (which is referred to as the central point) with the angle β to the vertical line. The ray reflects at normal-incidence-point (NIP) and returns to X_0. A paraxial ray from the randomly located source S intersects the central ray at point F, arriving back to the surface at point R of the receiver. The point F in Figure 1a can be considered as a fictitious source of two fictitious waves with the wavefront rays Σ^+ (emitting from F upward to the surface) and Σ^- (emitting from the point F downward, reflected at the reflector and emerging again at the point X_0).

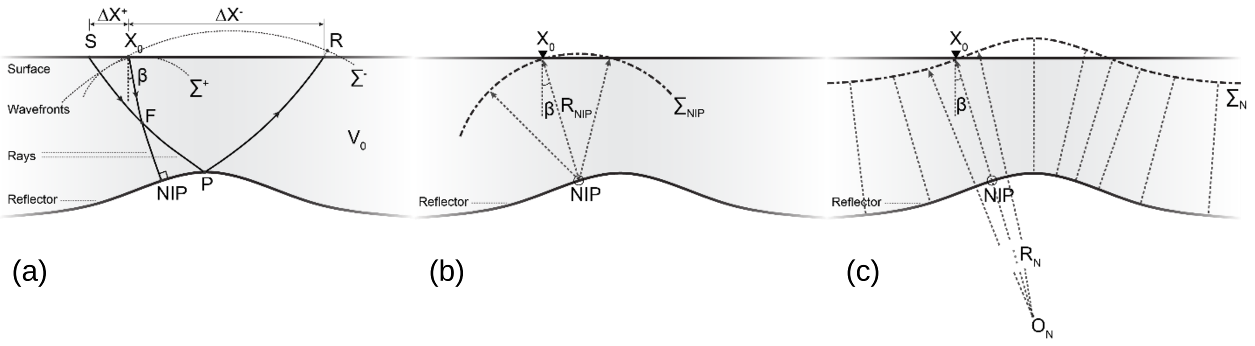

Figure 1. a) Ray scheme of the MF method for an arbitrary media, b) Wavefront Σ_{NIP} of the NIP wave and, c) Wavefront Σ_N of the normal wave produced by a curved reflector under a homogeneous overburden with near-surface velocity of V_0.

For multi-fold seismic reflection data, the MF stack method produces a zero-offset section by using a stacking operator. Figure 2 summarizes the MF stacking workflow. Interested readers can find the details of the MF stacking operators in Gelchinsky et al. (1999) and Berkovitch et al. (1998).

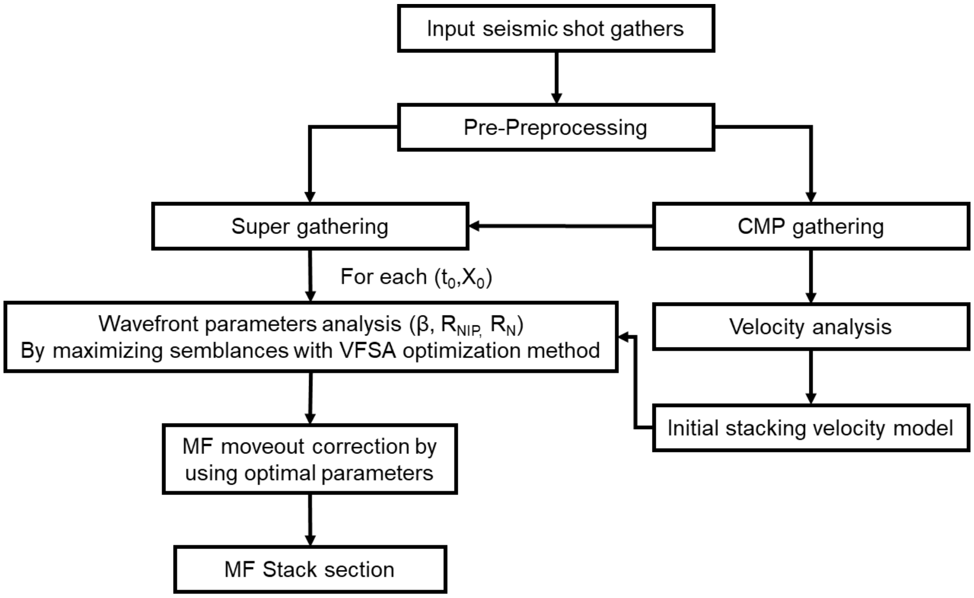

Figure 2. The flowchart for MF stacking technique.

Very Fast Simulated Annealing for MF stacking

The practical implementation of the MF method requires determination of appropriate three imaging parameters (β, R_{NIP}, and R_N) for each (X_0, t_0). We propose an automatic procedure, which consists of finding a set of parameters by maximizing a coherency measure. The procedure is repeated for each central point and for each time sample producing an MF time section. A summation along the trajectories corresponding to an optimal combination of wavefront parameters enables the calculation of an MF stack (MFS) without stretching the signals. We used the VFSA algorithm (Ingber, 1989; Sen and Stoffa, 1995) to optimize the MF attributes. This algorithm follows a similar minimization procedure as the standard SA algorithm, but differs in how it perturbs the parameters and how the temperature is reduced. The new solution is chosen from a temperature-dependent distribution that allows a wide range of solutions at higher temperatures and narrows the range with decreasing temperature.

For optimization of the MF attributes, we used a coherency (semblance) measure of the seismic signals as follows:

$$Semblance(\beta, R_{NIP}, R_N; X_0, t_0) = \frac{\sum_{j=k(i)-w/2}^{k(i)+w/2}\left(\sum_{i=1}^{M} f_{i,j(i)}\right)^2}{M\sum_{j=k(i)-w/2}^{k(i)+w/2}\sum_{i=1}^{M} f_{i,j(i)}^2}, \quad (1)$$

where, $f_{i,j(i)}$ is the amplitude of the j_th time sample at the i_th trace among M traces that are used for the MF stack, and $k(i)$ is the travel-time of the MF stack operator for the i_th trace. The summation of j is performed to provide a window around the MF parameters. The length of the window (w) should approximate the wavelength of the seismic signal. The Coherency values range from 0 to 1, where 1 indicates the highest coherence. Figure 3 summarize the application of VFSA method for optimizing the MF stacking method.

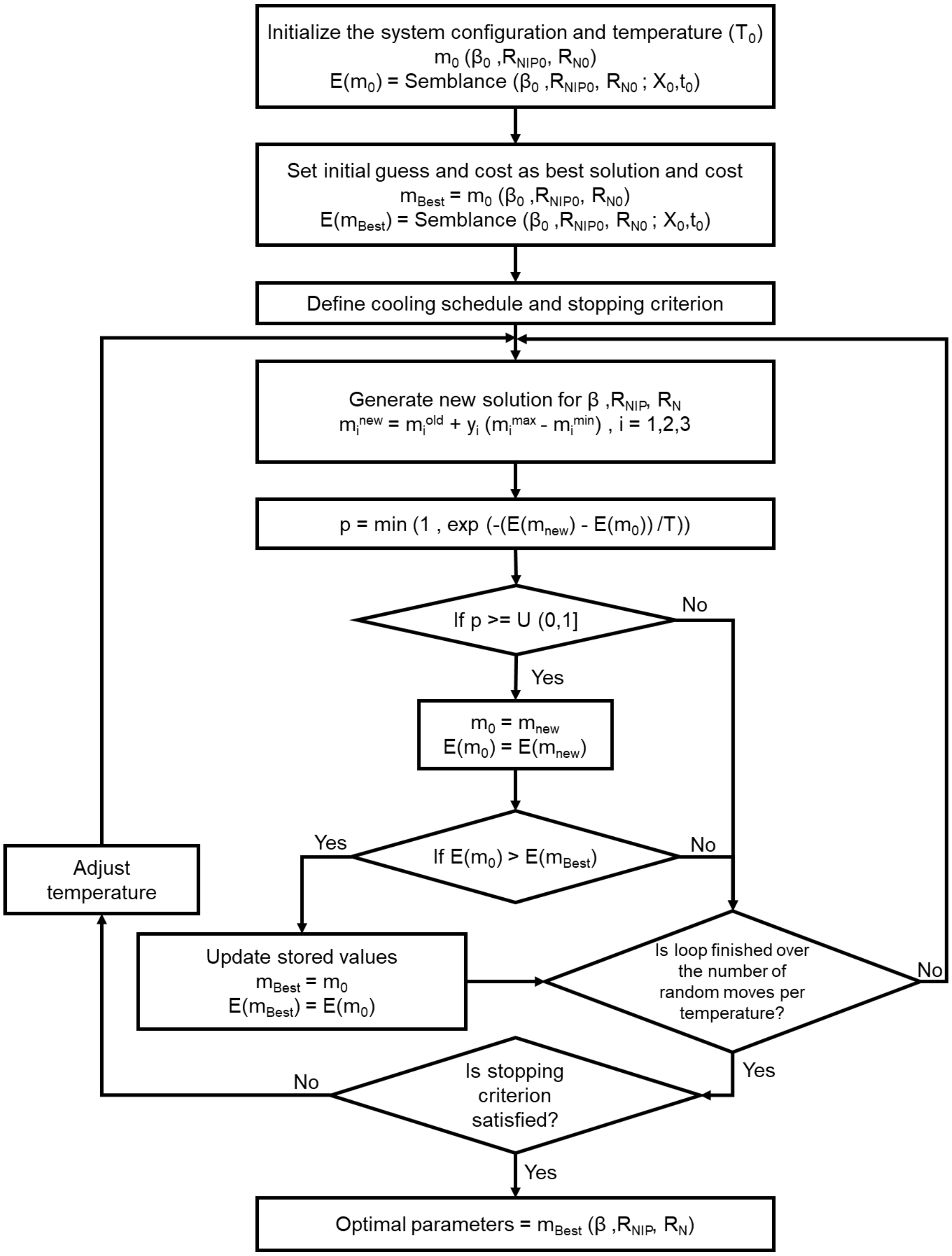

Figure 3. Flowchart of Very Fast Simulated Annealing (VFSA) algorithm for determining the MF optimal parameters.

Results

We examined the performance of the MF stacking optimized with the VFSA algorithm by applying it to a numerically modeled synthetic seismic reflection data. Figure 4 illustrates the designed anticline model and the generated wavefront for a source at the mid of model.

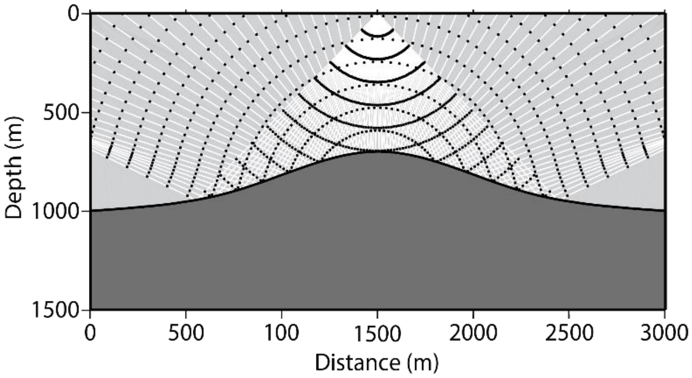

Figure 4. Synthetic model (V_1=1500 m/s, V_2=3000 m/s).

Figures 5a and 5b show a typical super-gather before and after applying the MF move-out correction, respectively. In this example, the original super-gather (left) comprises traces from nine CMP gathers (121 traces each). Figure 5b shows the same super-gather after applying the MF move-out correction. The reflection event is almost perfect alignement across all 1077 traces after the MF move-out correction. Stacking these traces increases the stack power by a factor of nine. The enhancement power of MF stacking increases with the number of traces included in the super-gathers. Figure 6 shows the final stacked section that was generated by optimal MF parameters estimated by the VFSA method. The original synthetic anticline was imaged successfully indicating that the MF stacking was done properly. Further tests of the proposed algorithm on more complex synthetic and real data examples are underway.

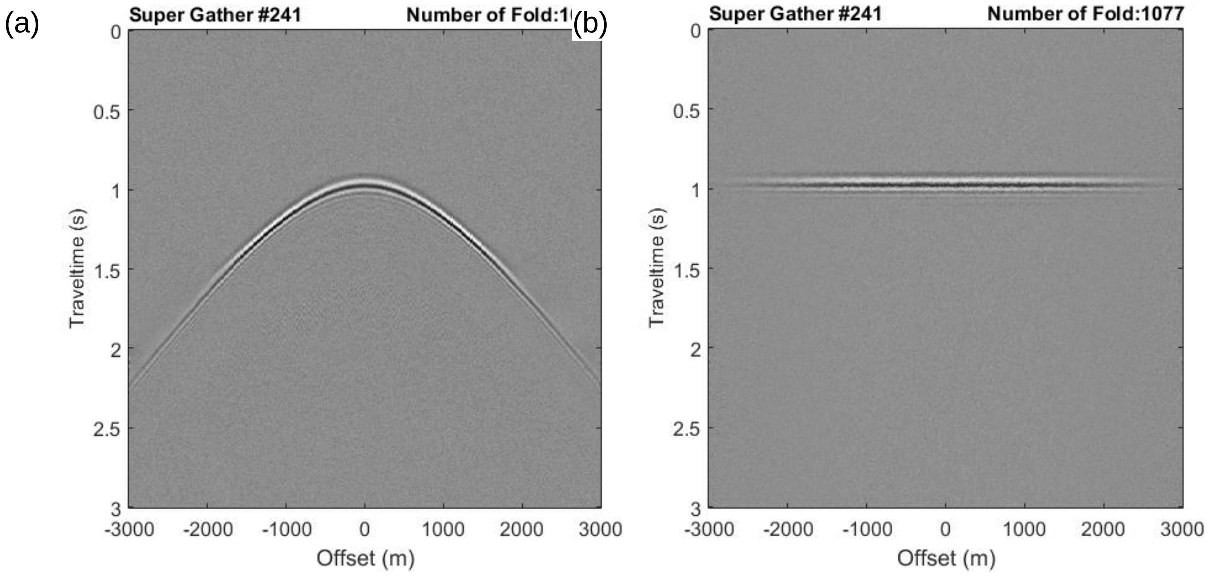

Figure 5. A super-gather before a) and after b) the MF move-out correction.

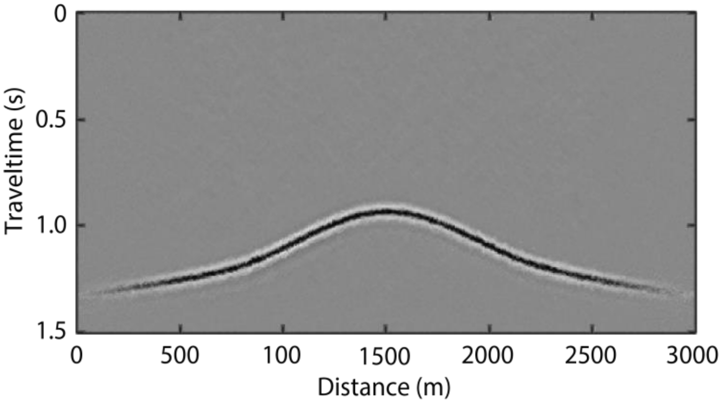

Figure 6. The MF stacked section generated from synthetic data simulated over.

Conclusions

The Multi-Focusing (MF) method is an alternative zero-offset stacking method to achieve a higher signal-to-noise ratio (SNR) than the conventional normal move-out (NMO)/dip move-out (DMO) stack methods. In this study, we applied a constrained metaheuristic global optimization algorithm (VFSA) to solve the non-linear 2D MF stack optimization problem. The MF stack method with this approach provided a clearer seismic profile with a higher SNR than a conventional NMO stack method. The results show that the VFSA algorithm is a suitable option for determining the MF attributes accurately within a reasonable number of calculations and it generates a high signal-to-noise ratio zero-offset stacked section. Also, the use of the stacking velocity as a priori information as a constraint for better R_{NIP} estimations, provides noticeable improvements in the estimation of the wavefront parameters of each individual seismic event and enhances the quality of the stacked section.

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