Event-consistent smoothing in generalized high-density velocity analysis

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Summary

High-density velocity analysis provides more detailed information about the seismic reflection data compared to the conventional approach with smooth stacking velocity models based on selected CMP locations and reflection events. However, the high-density stacking velocity is subject to fluctuations and outliers complicating its interpretation and further use. The Common-Reflection-Surface stack, a generalized multi-parameter multi-dimensional high-density stacking velocity analysis tool, provides an entire set of stacking parameters instead of stacking velocity, only. These stacking parameters easily allow an event-consistent smoothing based on a combination of median filtering and averaging that removes fluctuations and outliers without loss of information about the parameterized reflection events, even in case of conflicting dip situations. The smoothed stacking parameters not only improve the stack result but also provide a superior basis for subsequent applications like the determination of an interval velocity model.

Introduction

Conventional stacking velocity analysis is usually performed at selected, often coarsely spaced CMP locations, only. The stacking velocity determined for key events serves as basis for a smooth, interpolated stacking velocity model. This approach is not able to handle details in the stacking velocity section and, even worse, leads to the well-known pulse stretch phenomenon which introduces the need to mute the prestack data (e. g. Yilmaz, 2001). High-density velocity analysis overcomes these problems but, in turn, suffers from local fluctuations and outliers such that a physically reasonable smoothing of the stacking velocity is desirable. In particular, this implies that an appropriate smoothing algorithm has to preserve the local properties of the reflection events and must not mix any properties related to different reflection events. Furthermore, the smoothing algorithm should work in an automated manner without the need to explicitely identify reflection events.

The conventional parameterization in terms of stacking velocity is not well suited for event-consistent smoothing: firstly, the local shape of the simulated zero-offset (ZO) reflection events is unknown. Thus, no appropriate information is available to ensure event consistence. Secondly, stacking velocity is subject to systematic variations along the seismic wavelet in the time direction: on this small scale, stacking velocity *decreases* with *increasing* traveltime, whereas the large-scale behavior is just the opposite. Obviously, this further complicates any smoothing attempt.

An alternative, generalized velocity analysis as used in the Common-Reflection-Surface (CRS) stack technology (see, e. g. Jäger et al., 2001) allows to solve these problems in a simple and efficient way. As discussed by Mann and Höcht (2003), the parameterization in terms of so-called kinematic wavefield attributes has two advantages relevant in this context:

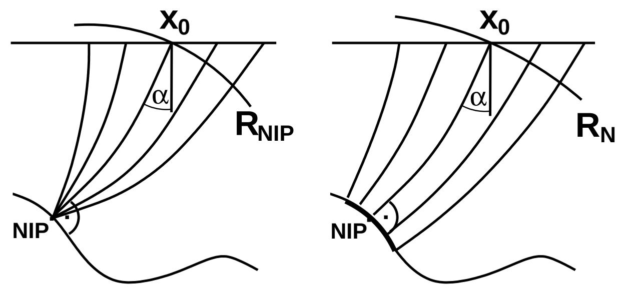

Fig. 1: Hypothetical experiments related to the CRS wavefield attributes.

- from a theoretical point of view, the wavefield attributes are virtually constant along the seismic wavelet and vary smoothly along the reflection events.
- the wavefield attributes characterize the local shape of the ZO events.

The attributes are related to the wavefronts due to two hypothetical experiments: an exploding reflection point experiment (normal-incidence-point (NIP) wave) and an exploding reflector experiment (normal wave). In the 2-D case, these wavefronts can be parameterized by means of three properties, the radii of curvature R_{NIP} and R_{N} of the NIP and normal wavefront, respectively, and the common emergence angle α of both wavefronts, see Figure 1. All properties are measured on the acquisition surface at the ZO location under consideration. Similar descriptions exist for the 3-D case (Höcht, 2002).

The CRS stack determines the optimum kinematic wavefield attributes separately for each ZO location by means of coherence analyses along various test stacking operators (for details see, e. g., Mann, 2002). The optimum attributes parameterize the spatial stacking operator yielding the highest coherence. The maximum coherence values provide additional information to identify reflection events and to evaluate the reliability of the wavefield attributes. The emergence angle α together with the coherence value allow to smooth the attribute sections along the reflection event without the need to explicitely identifying it.

Smoothing algorithm

With the kinematic wavefield attributes and the associated coherence values obtained as a by-product of the CRS stack, an event-consistent smoothing algorithm for the stacking parameters can be established in a simple and efficient manner. For a given ZO sample *P*, the smoothing is applied in the following steps:

- A parallelogram-shaped window of user-defined size centered around P is aligned with the local dip of the reflection event. The dip is related to the (known) emergence angle α.
- The coherence values (e. g., semblance coefficients) associated with all samples located within this window are used to reject samples with unreliable, possibly unphysical attributes by applying a coherence threshold.
- The emergence angle α, a very stable parameter, helps to avoid the mixing of different events, especially in case of conflicting dip situations: only ZO samples with similar emergence angles are accepted for the smoothing process, again controlled by a given threshold.
- The remaining ZO locations satisfying both criteria enter into a median filter to remove outliers: the associated attributes are sorted by magnitude and a user-defined fraction f of all values centered around the median is selected.
- The selected attribute values are averaged to remove fluctuations.
- The averaged attributes are assigned to the ZO sample P.

These steps are repeated for all ZO samples in the CRS stack results which yields entire sections of smoothed kinematic wavefield attributes that substitute the original, unsmoothed attribute sections in further processing. This might, e. g., include a further optimization of the wavefront attributes, the calculation of properties like the projected Fresnel zone or the geometrical spreading factor, a data-driven time migration (see, e. g, Mann, 2002), and—maybe the most important application—the determination of a velocity model (Duveneck, 2003, 2004).

Data examples

The smoothing algorithm was applied to various synthetic and real data sets. To demonstrate its effect on the attribute sections, a subset of a real data example is shown in Figure 2. For the sake of brevity, only the emergence angle α and the radius of curvature R_{NIP} of the NIP wavefront are displayed. In Figures 2(a) and (b), fluctuations of the unsmoothed attributes are present but can hardly be seen due to the limited resolution of the chosen representation. However, a significant roughness due to outliers is evident. The same attributes are shown in Figures 2(c) and (d) with a coherence-based mask applied: only attributes associated with a coherence value exceeding a certain threshold are displayed. This facilitates the identification of the areas with relevant attributes.

The smoothed attributes are shown in Figures 2(e) and (f). No more outliers can be observed and fluctuations are strongly reduced. The attributes of different events remain clearly separated, which is particularly obvious for the emergence angle section. In other words, the simple selection criteria listed above are suited to achieve the desired smoothness of the wavefield attributes along the reflection events. Of course, the smoothed attribute sections provide superior input to subsequent applications of the wavefield attributes like the determination of a velocity model for depth imaging (Duveneck, 2003, 2004) or the application of an entire CRS-stack-based imaging workflow (Mann et al., 2003).

The improvement of the stack results due to the smoothed attributes is depicted in Figure 3 for two subsets of a real data set acquired in a region with many faults. The stack results obtained with the smoothed attributes show far less speckles due to outliers. The continuity of the reflection events is strongly improved and several events can be clearly identified that appear highly disrupted in the original stack results. Similar improvements occur in the images obtained with the data-driven time migration based on CRS attributes (not displayed).

Conclusions

We introduced a simple but effective event-consistent smoothing algorithm for the kinematic wavefield attributes obtained by means of the CRS stack. The algorithm efficiently removes outliers and fluctuations from the attribute sections but preserves the kinematic properties of the reflection events. The stack result as well as subsequent applications of the attributes significantly benefit from this approach.

Acknowledgments

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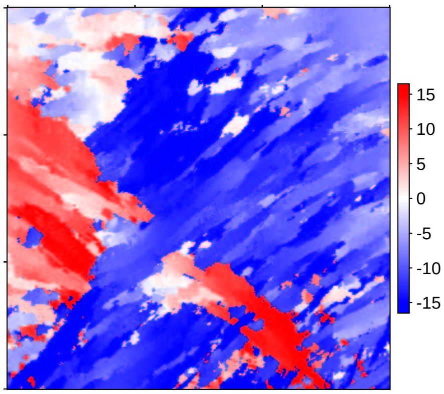
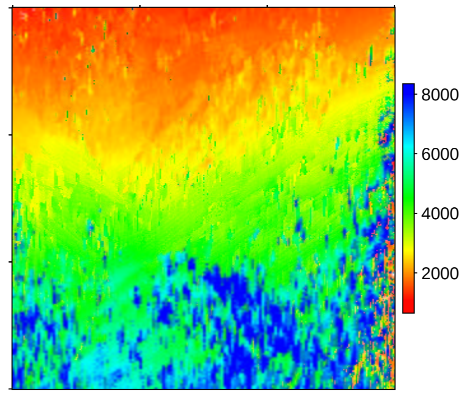
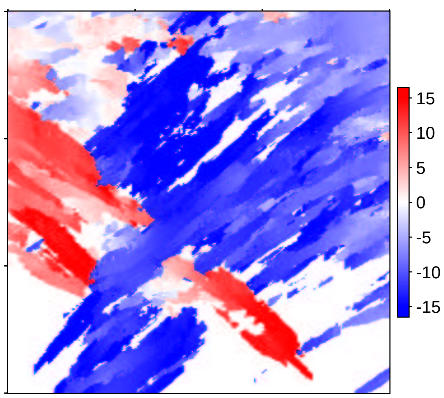


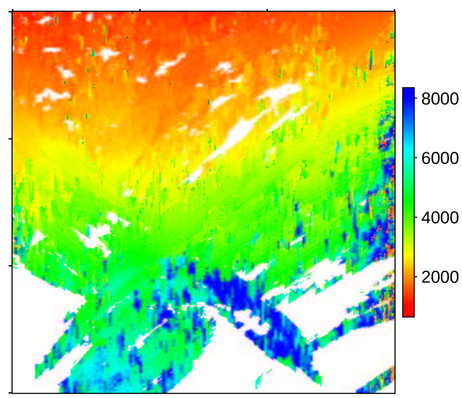
(a) Original emergence angle [°]



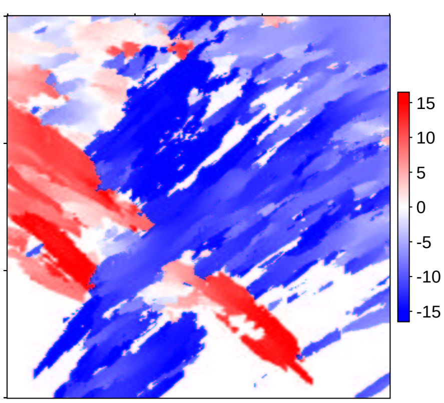
(b) Original NIP wavefront radius [m]



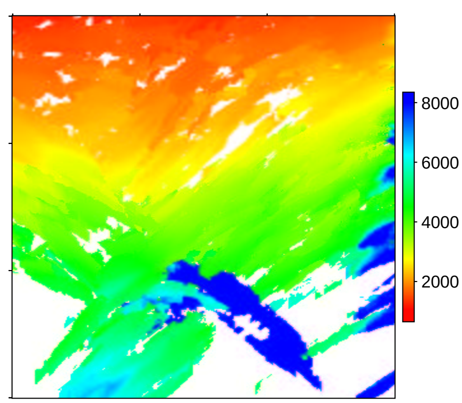
(c) Masked emergence angle [°]



(d) Masked NIP wavefront radius [m]

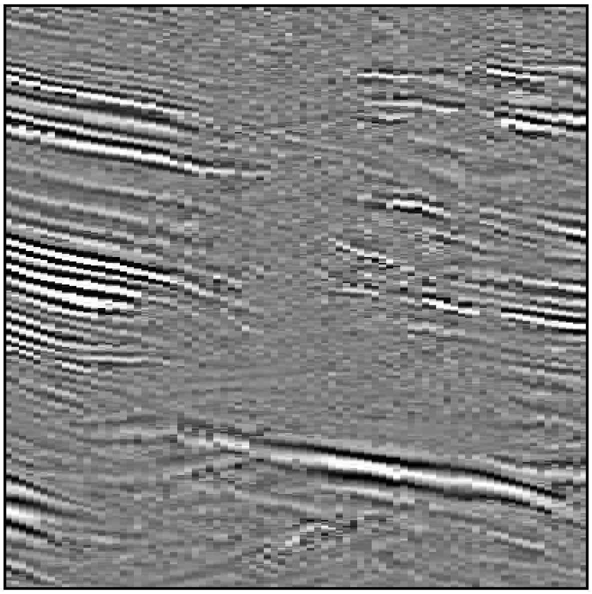


(e) Smoothed emergence angle [°]

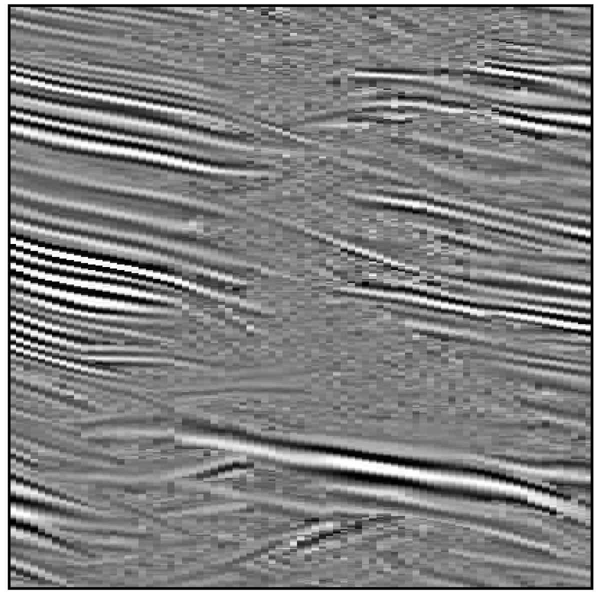


(f) Smoothed NIP wavefront radius [m]

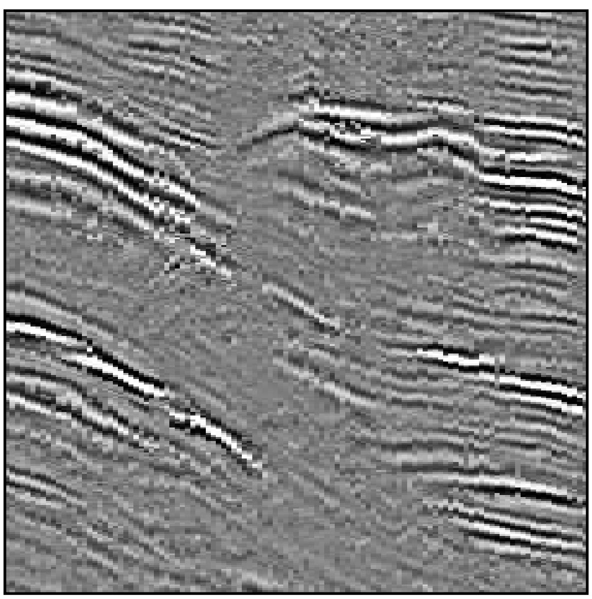
Fig. 2: Kinematic wavefield attributes α and R_{NIP} for a real data example. For display purposes, a coherence-based mask was applied to Figures (c)-(f) to suppress noisy areas with meaningless attributes.



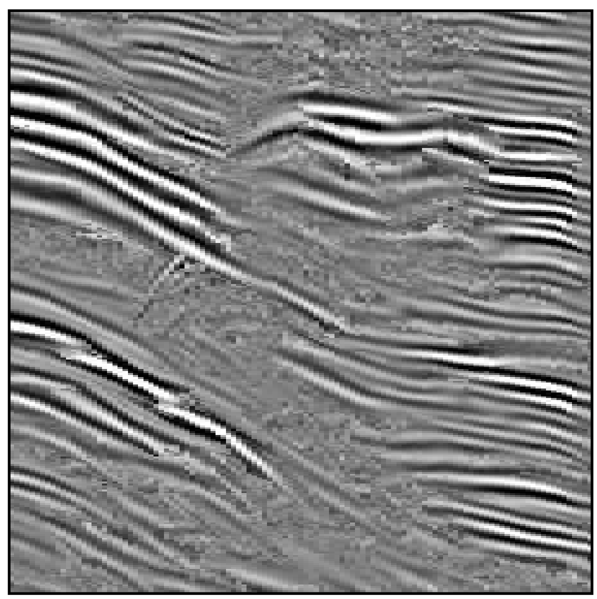
(a) Original stack



(b) Stack with smoothed attributes



(c) Original stack



(d) Stack with smoothed attributes

Fig. 3: Details of a CRS-stacked section obtained before/after smoothing of the attributes. Note the significant improvement of reflector continuity.