E023 GENERALIZATIONS OF THE COMMON-REFLECTION-SURFACE STACK

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Summary. The Common-Reflection-Surface (CRS) stack was originally introduced as a data-driven method to simulate zero-offset sections from 2-D seismic reflection pre-stack data acquired along a straight line. This approach is based on a second-order traveltime approximation parameterized with three kinematic wavefield attributes. An explicit knowledge of the subsurface model is not required, but only the near-surface velocity. Meanwhile, the attractive features of the CRS approach have been transferred to more general imaging problems: the simulation of 2-D and 3-D finite-offset sections and 3-D ZO sections. Our aim is to give an overview of these generalizations. Furthermore, we discuss different concepts how to consider the topography in the CRS stacking method for data acquired on smooth as well as on rugged acquisition surfaces.

Introduction. The Common-Reflection-Surface (CRS) stack was introduced by Müller (1998) and Müller et al. (1998) as a data-driven zero-offset (ZO) simulation method for 2-D that does not require an explicit knowledge of the macro velocity model. The reflection events in the pre-stack data are locally described by a second-order traveltime approximation of the kinematic reflection response of a reflector segment in depth. The CRS stacking operator is parameterized by means of three kinematic wavefield attributes which represent the curvatures and the coincident propagation directions of two wavefronts emerging at the acquisition surface, namely the so-called *normal-incidence-point* (NIP) *wavefront* and the *normal wavefront* (Hubral, 1983). These wavefronts are associated with two hypothetical experiments: the NIP wavefront stems from a point source located on the reflector segment, the normal wavefront is caused by a simultaneous excitation of the entire reflector segment (exploding reflector experiment).

The kinematic wavefield attributes represent the reflector segment's properties, i. e., its location, orientation, and curvature, as well as the effects of its inhomogeneous overburden. With this parameterization of the CRS stacking operator, the operator fitting best the actual reflection event can be directly determined by means of a coherence analysis in the pre-stack data. The actual properties of the reflector segment and its overburden are not required, thus the process is entirely data driven, similar as, e. g., an NMO/DMO/stack approach. Due to its more general parameterization of the reflection events, the CRS operators better fit the actual events and provide a higher signal-to-noise ratio as well as an entire set of wavefield attributes that are suited for various applications, e. g., the estimation of the projected first Fresnel zone and the geometrical spreading factor (Vieth, 2001), inversion (Majer, 2000), or an attribute-based time migration (Mann et al., 2000).

Our aim is to give an overview how these attractive features of the CRS stack can be transferred to more general imaging problems, namely the simulation of finite-offset (FO) sections for 2-D and 3-D as well as ZO sections for 3-D. The development of the CRS stacking operators and the number of wavefield attributes are compiled in Figure 1 and will be discussed more detailed in the following.

The originally introduced CRS stack approach was not able to handle the topography of the acquisition surface. As this problem can, in general, not be ignored for land data, we will discuss two different concepts to handle the topography in the CRS stack approach. These concepts can be integrated into all of the discussed imaging problems.

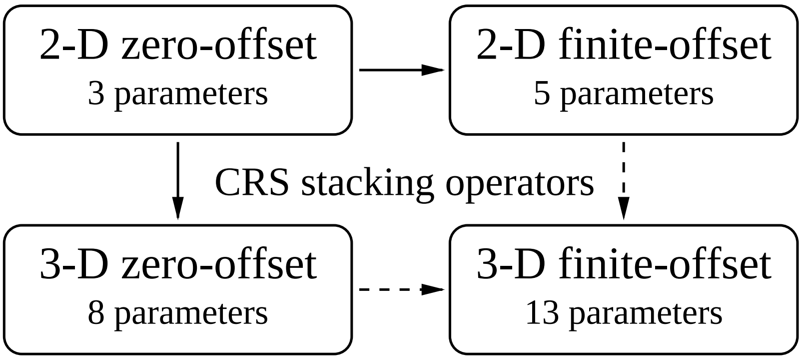

Figure 1: Development of the CRS stacking operators for different imaging problems. The number of search parameters, i. e., wavefield attributes increases with increasing complexity of the problem. The FO CRS stack for 3-D is subject of our current research.

3-D zero-offset simulation. For the 2-D ZO case, the reflector segment's properties and the associated wavefield attributes are related to each other by the two hypothetical experiments mentioned above. These experiments can be readily extended to the 3-D case: the reflector segment is now a surface in 3-D space (which lead to the term CRS stack as all considered rays are reflected at the same surface). Again, a point source is placed on the reflector segment to obtain the NIP wavefront. An exploding reflector experiment yields the normal wavefront. In 3-D, both wavefronts are surfaces. Consequently, their curvatures and propagation directions along the normal ZO ray can no longer be represented by scalars. Instead, the curvatures are expressed by means of symmetric 2×2 matrices. Each of them has three independent elements that depend on the two principal curvatures and the orientation of the principal axes with respect to the global coordinate system. We express the propagation direction either by means of two angles, emergence angle and azimuth, or by a vector $\mathbf{w_z}$ with two components, the projection of the normalized propagation direction to the acquisition surface.
With these eight wavefield attributes we can parameterize the CRS stacking operator for 3-D, a four-dimensional hyper-surface in the five-dimensional pre-stack data hyper-volume set up by the shot/receiver midpoint vector $\mathbf{m}$ relative to the emergence location of the normal ray, the half-offset vector $\mathbf{h}$, and the traveltime t:

$$t^2 = \left(t_0 + \frac{2}{v}\,\mathbf{w_z}\cdot\mathbf{m}\right)^2 + \frac{2\,t_0}{v}\,\mathbf{m^T}\,\hat{\mathbf{A}}\,\mathbf{m} + \frac{2\,t_0}{v}\,\mathbf{h^T}\,\hat{\mathbf{B}}\,\mathbf{h}\;, \tag{1}$$

where v denotes the near-surface velocity, and t_0 is the ZO traveltime to be simulated at the emergence location of the normal ray. $\hat{\mathbf{A}}$ and $\hat{\mathbf{B}}$ represent the curvatures of the NIP and the normal wavefront, respectively, expressed in global coordinates. This hyperbolic second-order approximation has the same structure as the CRS operator in the 2-D ZO case. Thus, similar strategies as in 2-D (see, e. g, Jäger et al., 2001) can be used for an efficient determination of the wavefield attributes: in specific subsets of the pre-stack data, e. g., CMP or ZO volumes, the number of attributes reduces which allows to split the search for the eight attributes into optimization problems with less dimensions.
An alternative way is to apply the 2-D CRS stack separately for different azimuth directions: in this case, the detected curvatures are the curvatures of the actual spatial wavefronts in the direction given by the azimuth of the seismic line. The 2-D propagation direction refers to the plane defined by the seismic line and the actual propagation direction. This has two consequences: firstly, the 2-D CRS stack *does not* imply a 2-D model, but yields a correct result even for 3-D models, namely one ZO section as a subset of an entire 3-D ZO volume. Secondly, the eight wavefield attributes of the 3-D problem can be determined from the 2-D attributes if they are available for at least three different azimuth directions.
Note that a set of 2-D pre-stack data volumes acquired along parallel lines is not a 3-D pre-stack volume in a strict sense: such a data hyper-volume contains no offset-dependent information in cross-line direction.

Finite-offset simulation. For the ZO simulation, we considered only unconverted rays with coincident up-going and down-going ray branches. This allowed us to use two hypothetical experiments with up-going wavefronts such that the actual reflection had not to be considered explicitely. However, in case of finite offset (FO) and/or converted waves, the two ray branches no longer coincide and the NIP and normal wave experiments are not applicable. For the FO case, Zhang et al. (2001) recently proposed two other experiments to establish a relationship between the reflector segment's properties and kinematic wavefield attributes in the time domain: the first experiment is the actually performed physical experiment with a point source at the shot location. This experiment provides three kinematic wavefield attributes, namely the propagation directions of the wavefront along the central FO ray at the shot and receiver location, respectively, and the curvature of the emerging wavefront at the receiver. The second experiment is a hypothetical CMP experiment and provides two additional wavefield attributes: the curvatures of the wavefront at the shot and the receiver, respectively.

For 2-D FO case, the reflection events are parameterized with a total of five kinematic wavefield attributes. Similar to the ZO case, the search for these attributes can be performed in different subsets of the pre-stack data. This reduces the number of attributes that have to be simultaneously optimized. The two experiments proposed for the 2-D FO case can, of course, also be transferred to 3-D: the propagation directions of the wavefronts along the ray are then represented by vectors with two components instead of scalars and the wavefront curvatures are 2×2 matrices, each with three independent parameters. Thus, we obtain a total of 13 wavefield attributes for this most general situation that is able to handle converted and unconverted central rays for any offset in 3-D. The development of an efficient strategy to determine all these parameters is a topic of our current research.

Topography. So far, we assumed that pre-stack data are acquired along a straight line (2-D) or on a plane surface (3-D). These assumptions hold for marine data but, in general, not for land data. Depending on the complexity of the topography, this problem can be addressed with two different approaches:

In case of a smooth topography, the CRS operator itself is not affected by the topography. Wherever the hyperbolic approximation is sufficiently accurate for data acquired on a plane surface, it is also applicable for a smooth acquisition surface. In this context "smooth" means that the curvature of the acquisition surface does not significantly vary inside the aperture used for the CRS stack. In other words, the topography has not to be considered for the simulation of the ZO or FO section itself. However, the kinematic wavefield attributes no longer describe the propagation directions and curvatures of hypothetical wavefronts but also depend on the local curvature and slope of the acquisition surface. For a further use of the attributes, they have to be corrected for this influence by means of simple relations, see Bergler et al. (2001). Each simulated ZO or FO trace refers to the original datum given by the pre-stack data.

For a rugged topography, the above approach is not applicable as the actual events in the pre-stack data might be of very complex shape. In this situation, additional terms have to be introduced to the CRS stacking operator that consider the known shot and receiver elevations. As the wavefield attributes include the incidence and emergence angles of the central ray, the ray segments between the actual acquisition surface and a chosen datum plane can be easily calculated. This situation for the 2-D FO case is depicted in Figure 2. The number of wavefield attributes remains the same. This approach readily provides the correct wavefield attributes referring to the chosen datum without a need for a subsequent correction.

Conclusions. The CRS stack method, originally introduced for the simulation of 2-D ZO sections and a straight acquisition line, has been generalized for the simulation of 3-D ZO sections as well as 2-D and 3-D FO sections. For the 3-D ZO and 2-D FO case, the generalized CRS stack has already been successfully applied to synthetic data. The global optimization problems, i. e., the determination of the optimum wavefield attributes, can be performed more efficiently in specific subsets of the pre-stack data.

For each of the discussed four imaging problems, the topography of the acquisition surface can be considered in two different ways, either by simple corrections of the wavefield attributes in case of smooth topography, or by directly using the actual source and receiver elevations in case of a rugged topography. The latter approach includes a redatuming without the in common practice made assumption of vertical rays near the

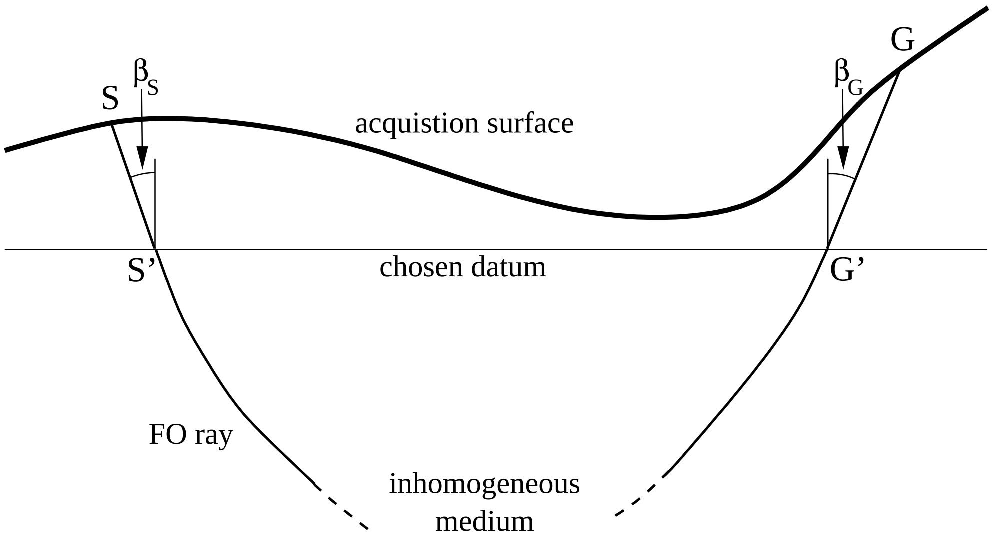

Figure 2: FO ray for a rugged topography. The CRS stacking operator for rugged topography considers the ray from S to G as if it was acquired on the datum plane at S' and G'. The near surface velocities between S' and S and between R' and R, respectively, are assumed to be known and constant. The angles β_S and β_G are two of the five wavefield attributes in the 2-D FO case.

surface. Additional wavefield attributes are not required to handle the topography.

With the discussed generalizations of the CRS stack method any arbitrary section can be simulated from 2-D and 3-D pre-stack data in an entirely data-driven way. This allows the application of the CRS stack method for a multitude of situations and purposes.

Acknowledgments

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