**Summary**

In recent years, the Common-Reflection-Surface stack has been evolved as an alternative to conventional stacking methods. A new hyperbolic travelt ime approximation for finite-offset to take arbitrary top-surface topography into account is presented. Based on this formula we derive a Common-Reflection-Surface stacking operator that is in principle able to handle data from vertical seismic profiles. Moreover, the application to ocean bottom seismic data is discussed. This is demonstrated with a synthetic example of a common-offset section with a high signal-to-noise ratio and kinematic wavefield attribute sections which can be used for further analyses.

**Arbitrary topography**

The most general second-order paraxial travelt ime approximation (e. g., Zhang, 2003) applicable in the framework of the CRS stack accounts for

- arbitrary data acquisition and processing,
- arbitrary top-surface topography as source and receiver elevations are explicitly considered,
- velocity gradients in the vicinity of the sources and receivers.

The travelt ime formula for the 2D CO CRS stack for arbitrary topography can directly be derived from the general moveout formula given in Zhang (2003). Assuming 2D data acquisition, 2.5D subsurface models, and negligible near-surface velocity gradients, the searched-for hyperbolic travelt ime formula reads

\[
i^2(\Delta S; \Delta z) = \left( \frac{\sin \beta S}{v G} \sin \beta G \cos \beta S - \cos \beta G \cos \beta S \right)^2 + n DB^{-1} (\Delta S - \Delta z \tan \beta S)^2
+ n GB^{-1} (\Delta S - \Delta z \tan \beta G)^2 - 2n B^{-1} (\Delta S - \Delta z \tan \beta S) (\Delta S - \Delta z \tan \beta G).
\]

**Vertical seismic profiling**

A typical 2D VSP acquisition geometry is characterized by receivers placed in a borehole while the sources are located along a straight line on the top-surface, see also Figure 4. We assume a vertical borehole and that all sources are disposed at the same level, i.e., on a measurement surface on land without topography or in the same water depth in marine environments.

Thus, the vertical displacements between the sources \( \Delta z \) and the horizontal displacements between the receivers \( \Delta x \) vanish, i.e., \( \Delta x = \Delta z \approx 0 \). With these assumptions, Equation (1) simplifies to

\[
i^2(\Delta S; \Delta z) = \left( \frac{\sin \beta S}{v G} \sin \beta G \cos \beta S - \cos \beta G \cos \beta S \right)^2 + n DB^{-1} (\Delta S - \Delta z \tan \beta S)^2
+ n GB^{-1} (\Delta S - \Delta z \tan \beta G)^2 - 2n B^{-1} \Delta S \tan \beta S \tan \beta G.
\]

Furthermore, CRS stacking operators for so-called reverse VSP and cross-well acquisition geometries can easily be derived by means of Equation (1), see Boelsen (2005). In the former case, the sources are placed downhole while the receivers are deployed at the surface. Thus, \( \Delta x = \Delta z \approx 0 \), assuming a vertical borehole and a horizontal measurement surface. Cross-well acquisition means that both, sources and receivers, are placed downhole in neighboring boreholes. In this case, \( \Delta x = \Delta z = 0 \), assuming vertical boreholes. First aspects of an efficient implementation strategy of the VSP stacking operator (3) are discussed in Boelsen (2005).
In this data example, we apply the 2D CO CRS stack to a complex synthetic OBS data set. The stacking operator is given by Equation (2). Figure 5 shows the blocky P-wave velocity model used to generate the multi-coverge prestack data set. The uppermost layer represents the water layer, the sources are located in a water depth of six meters and the receivers are deployed on the uppermost interface which represents a horizon-
tal ocean bottom at a depth of 1 km. For this model, primary PP-reflections were simulated for half-offsets from \( h = 0 \) km to \( h = 2 \) km in increments of \( \Delta h = 0.025 \) km and midpoint inter-
vals of \( \Delta m = 0.025 \) km in the range \( 1.5 \) km \( \leq m \leq 11.5 \) km. As seismic signal, a zero-phase Ricker wavelet of 30 Hz peak fre-
cquency was used. The sampling interval was 4 ms. Finally, ran-
dom noise was added to the data set such that all CO prestack sections look with respect to their S/N ratio similar to the one for half-offset \( h = 0.3 \) km (upper part of Figure 6).

It is the aim of this example to demonstrate the applicability of the CO CRS stack to OBS acquisition geometries. For this pur-
pose, only PP-reflections were modeled. A strategy to handle also converted-wave multi-component data in the framework of the CO CRS stack is presented in Boelsen and Mann (2005).

**Figure 5**: P-wave velocity model [m/s]. The receivers are lo-
cated on the uppermost interface which represents a horizontal

2D CO CRS stack results

In the following, we present the final results of the CO CRS stacking procedure. The lower part of Figure 6 shows the CO section for half-offset \( h = 0.3 \) km simulated with the CO CRS stack. Compared with the respective CO section from the prestack data (upper part of Figure 6) the S/N ratio is dramatically increased and all reflectors are clearly visible. This indi-
cates that the 2D CO CRS stacking operator given by Equation
(2) fits well the actual reflection events in the prestack data volume in the vicinity of the respective CO samples. The very high S/N ratio is due to the spatial CRS stacking operator yield-
ing much more traces contributing to the stacking result of each sample of the section to be simulated.

**Figure 6**: Upper CO section \( h = 0.3 \) km taken from the multi-coverge prestack data generated with the model de-
picted in Figure 5. Lower part: the same CO section simulated with the CO CRS stack.

Kinematic wavefield attributes

The five wavefield attributes \( \beta_0, \beta_1, \chi_0, \chi_1 \) and \( \chi_2 \) can be computed for each sample of the simulated CO section as the near-
surface velocities at the receivers and sources are known. Fig-
ure 7 shows the incidence and emergence angles as well as the coherence section. Figure 8 depicts the determined wave-
front curvatures. For almost all samples along the reflection events, the coherence values are sufficiently high. Thus, the respective wavefield attributes are expected to be reliable.

**Figure 7**: \( \beta_0 \)-section [\( \beta_0 \)] (top), \( \beta_1 \)-section [\( \beta_1 \)] (middle), and coherence section (bottom) determined by the CO CRS stack.

**Figure 8**: \( \chi_0 \)-section (top), \( \chi_1 \)-section (middle), and \( \chi_2 \)-section (bottom) [1/km] determined by the CO CRS stack.

Conclusions & Outlook

We presented a new hyperbolic paraxial traveltim approxima-
tion applicable in the framework of the 2D CO CRS stack to handle arbitrary top-surface topography.

Based on this formula, we derived CRS stacking operators for OBS and VSP acquisition geometries. In case of a virtually horizontal seafloor, the OBS stacking operator turned out to coincide with the original one developed to stack data acquired along one straight line on a horizontal measurement surface. Stacking operators for reverse VSP and cross-well seismic displays can also be derived.

It is also possible to take varying seabed elevations (for OBS data) as well as non-vertical boresholes and/or varying surface elevations (for VSP data) into account.

The OBS stacking operator was successfully tested on a com-
plex synthetic data set. We achieved a high-quality stacked section with a high S/N ratio and five kinematic wavefield at-
tribute sections which are useful for further calculations.

The results are of particular interest in combination with multi-
component data which can also be handled in the framework of the 2D CO CRS stack in order to obtain stacked sections as well as wavefield attribute sections for PP- and PS-reflections.

Further research will focus on the implementation and test of the VSP stacking operator, also in combination with multi-
component data processing. Applications of the CO CRS stack to real data (e.g., OBS data) are also required.

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