A Quick Review of 2D Topographic Traveltimes

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ABSTRACT

The Common-Reflection-Surface (CRS) was originally introduced as a data-driven method to simulate zero-offset sections from 2-D 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. In land data, topographic effects play an important role in seismic data processing and imaging. Thus, this feature has been recently considered by the CRS method. In this work we review the CRS traveltime approximations that consider the smooth and rugged topography. In addition, we also review the Multifocusing traveltime for a rugged topography. By means of a simple synthetic example, we finally provide first comparisons between the various traveltime expressions.

INTRODUCTION

The Common-Reflection-Surface (CRS) and the Multifocus (MF) methods are designed to produce clear stacked sections and useful time-domain attributes by means of coherence analysis methods directly applied to multicoverage reflection data. In this way, both methods, that have a similar purpose and approach as the well-established common-midpoint (CMP) method, represent powerful extensions of the latter. As opposed to the CMP method that is applied to CMP gathers and extracts a single parameter (the normal-moveout (NMO) velocity) on manually picked events, the CRS and MF methods (a) make full use of the available multicoverage data by applying the stacking procedure on supergathers that are free from the CMP restriction; (b) extract more parameters (three in the 2D situation) at each time sample of the stacked section to be constructed and (c) the procedure is applied to all time samples without the need of event selection. The CRS and MF methods fall into the category of the so-called macro-model independent or data-driven time-domain methods (see, e.g., Hubral (1999) for a general account and discussion).

A distinctive feature of the CRS and MF methods is the use of specific multiparameter traveltime moveouts. The parameters of these moveout expressions are directly inverted from the data by means of coherence analysis (semblance) procedures. With the help of the inverted parameters, the obtained moveouts are employed to stack the data. Note that this is exactly what the conventional velocity analysis method does under the restriction of the one-parameter NMO traveltimes applied to CMP gathers.

Originally, both the CRS and the MF have been derived under the following assumptions: (a) 2D propagation; (b) locally-constant and supposedly known near-surface velocity and (c) no topographic effects along the seismic line. The latter condition means that the data have been acquired on a horizontal seismic line or preprocessed for statics and residual statics to a horizontal datum before the application of the CRS or MF method.

Under these considerations, the CRS and MF moveouts are expressed as functions of three parameters, namely the emergence angle, β_0, of the zero-offset (ZO) ray with respect to the (planar) surface normal, and two wavefront curvatures, K_{NIP} and K_N, of the so-called NIP- and N-waves that relate to the ZO ray at its emergence point. We recall that the abbreviation NIP stands for normal-incident-point, namely the point where the ZO ray hits the reflector and that the NIP-wave is a fictitious wave that starts as a point source at NIP and progresses upwards to the measurement surface with half the medium velocity. In the same way, the abbreviation N-wave, stands for the normal wave, which is also a fictitious wave that starts as a wavefront with the shape of the reflector at NIP and progresses upwards with half of the medium velocity. For detailed description and discussion of the NIP- and N-waves, the reader is referred to Hubral (1983).

It is to be observed that the CRS and MF methods can also be normally applied in the case the above requirements are not met. In that case, the three-parameter CRS and MF represent simply stacking parameters that provide a best fit to the reflection events, but cannot be directly attached to the above-mentioned seismic propagation attributes (angles and curvatures). For example, the classical CRS and MF expressions consider the condition of a locally constant near-surface velocity. This means that that the near-surface velocity is considered constant *in the vicinity of each central point* but can vary as we change from each central point to another. To be consistent with the second-order formulation, the traveltime expression has to consider, not only the velocity, but also its gradient at each central point. As a consequence, wrong near-surface velocities will give rise to wrong emerging angles, even though correct ray parameters can be extracted. In the same way, topographic effects, if not correctly taken into account, will contaminate the CRS attributes affecting their interpretation.

For a planar or smoothly curved measurement surface, the 2D CRS (hyperbolic) traveltime that takes full consideration of the velocity gradient at the central point is presented in Chira et al. (2001). In the MF traveltime expressions, velocity gradients at the central points are not considered. To our knowledge, examples of the influence of the velocity gradients have not yet been provided in the literature.

In this paper, the usual assumption of a locally-constant near-surface velocity will be also adopted, our attention being concentrated on the incorporation of topography into the traveltime expressions.

2D CRS AND MF TRAVELTIMES FOR A PLANAR MEASUREMENT SURFACE

We recall the “classical” 2D CRS and MF moveout expressions in the simple case of a planar measurement surface. More explicitly, we suppose that all source and receiver pairs are located on a horizontal seismic line. On the seismic line, we assume a fixed point, called central point, on which a simulated ZO trace is to be constructed by stacking along traces that belong to (generally non-symmetric) nearby source-receiver. As explained above, we also consider a constant velocity in the vicinity of the central point. We adopt midpoint and half-offset coordinates (x_m, h) for the location of a source-receiver in the vicinity of the central point $X_0 = (x_0, 0)$. We denote $m = x_m - x_0$, by T_0 the (two-way) reflection time along the ZO (central) ray and by v_0 the velocity at the central point. As explained above, we assume that the velocity remains constant for all source-receiver locations where the traveltime is to be computed. Finally, β_0, K_{NIP} and K_N denote the emergence angle and the curvatures of the NIP and N waves that refer to the ZO ray as observed at X_0. Under these considerations, the CRS traveltime reads (see, e.g., Jäger et al. (2001))

$$T^2_{CRS}(m,h) = \left[T_0 + \frac{2\sin\beta_0}{v_0}\; m\right]^2 + \frac{2\;T_0\;\cos^2\beta_0}{v_0}\;\left[K_N\;m^2 + K_{NIP}\;h^2\right]\;. \tag{1}$$

For the same situation of a planar measurement surface, the corresponding 2D MF traveltime is given by (see, e.g., Gelchinsky et al. (1999) with a different notation)

$$\begin{aligned} T_{MF}(m,h) = T_0 \quad &+ \quad \frac{1}{v_0\;K_S}\left[\sqrt{[K_S\;(m-h) + \sin\beta_0]^2 + \cos^2\beta_0} - 1\right] \\ &+ \quad \frac{1}{v_0\;K_G}\left[\sqrt{[K_G\;(m+h) + \sin\beta_0]^2 + \cos^2\beta_0} - 1\right]\;, \end{aligned} \tag{2}$$

where

$$K_S = \frac{K_N - \sigma\;K_{NIP}}{1-\sigma}\;, \quad K_G = \frac{K_N + \sigma\;K_{NIP}}{1+\sigma}\;, \tag{3}$$

and

$$\sigma = \frac{h}{m + (m^2 - h^2)\;K_{NIP}\;\sin\beta_0}\;. \tag{4}$$

CRS APPROXIMATION FOR SMOOTH TOPOGRAPHY

The CRS traveltime expression (1) admits a natural extension to the case of a smoothly curved measurement surface. More specifically, let us assume that, at the central point and with respect to a horizontal datum,

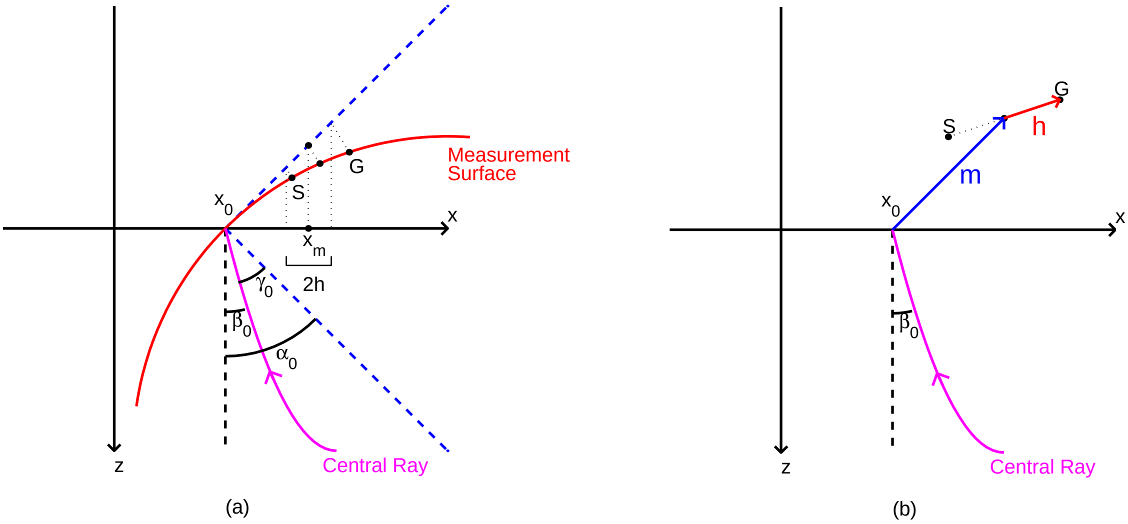

Figure 1: Cartesian system of coordinates for: (a) Smooth topography; (b) Rugged topography.

the seismic line has curvature, K_0 and dip α_0. See Figure 1(a). Moreover, let γ_0 denote the emergence angle of the ZO central ray with respect to the normal to the curved seismic line at the central point. As shown in Chira (2003) (with a different notation), the CRS traveltime for a source-receiver pair located by (m, h) is given by

$$T^2_{CRS}(m,h) = \left[T_0 + \frac{2\sin\gamma_0}{v_0\cos\alpha_0}\, m\right]^2 + \frac{2\,T_0\ \cos\gamma_0}{v_0\cos^2\alpha_0}\left[K_N\ \cos\gamma_0 - K_0\right]\, m^2 + \frac{2\,T_0\ \cos\gamma_0}{v_0\cos^2\alpha_0}\left[K_{NIP}\ \cos\gamma_0 - K_0\right] h^2 \,. \tag{5}$$

We ready verify that, in the case of a horizontal seismic line, we have $K_0 = \alpha_0 = 0$ and $\gamma_0 = \beta_0$, so that equation (5) reduces to its previous counterpart equation (1), as expected.

As reported in Chira (2003), the traveltime moveout (5) were tested for a synthetic model of smooth topography with good results. The formulation breaks down, however, as the topography becomes more pronounced.

CRS AND MF APPROXIMATIONS FOR RUGGED TOPOGRAPHY

We now consider the extension of the CRS traveltime to the case of arbitrary (rugged) topography. Following Zhang et al. (2002), we find useful to consider *vector* midpoint, $\mathbf{m}$, and half-offset, $\mathbf{h}$, coordinates with respect to the Cartesian system of horizontal datum and downward vertical. See Figure 1(b). More specifically, we set $\mathbf{m} = (m_x, m_z)$ and $\mathbf{h} = (h_x, h_z)$ which locate the corresponding source and receiver pair as $S = \mathbf{m} - \mathbf{h}$ and $G = \mathbf{m} + \mathbf{h}$, respectively. As shown in Zhang et al. (2002), we have

$$T^2_{CRS}(\mathbf{m},\mathbf{h}) = \left[T_0 - \frac{2}{v_0}(m_x\ \sin\beta_0 + m_z\ \cos\beta_0)\right]^2 + \frac{2\,T_0\,K_N}{v_0}\,(m_x\ \cos\beta_0 - m_z\ \sin\beta_0)^2 + \frac{2\,T_0\,K_{NIP}}{v_0}\,(h_x\ \cos\beta_0 - h_z\ \sin\beta_0)^2 \tag{6}$$

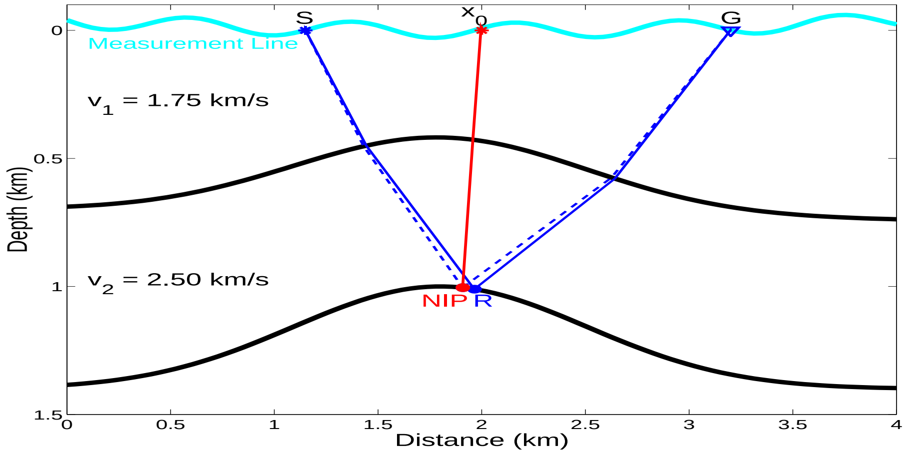

Figure 2: 2D acoustic model for the numerical experiments. The ZO ray is ploted in red, the reflection ray in blue and the diffraction ray in dashed blue. Also indicated are the normal-incident-point (NIP) and the reflection point (R).

The corresponding MF traveltime for rugged topography has been described in Gurevich et al. (2002). In our notation, the MF is given by

$$T_{MF}(\mathbf{m},\mathbf{h}) = t_0 + \frac{1}{v_0\, K_S}\left[\sqrt{[K_S\,(m_x - h_x) + \sin\beta_0]^2 + [K_S\,(m_z - h_z) + \cos\beta_0]^2} - 1\right] + \frac{1}{v_0\, K_G}\left[\sqrt{[K_G\,(m_x + h_x) + \sin\beta_0]^2 + [K_G\,(m_z + h_z) + \cos\beta_0]^2} - 1\right] , \quad (7)$$

where

$$K_S = \frac{K_N - \sigma\, K_{NIP}}{1-\sigma} , \quad K_G = \frac{K_N + \sigma\, K_{NIP}}{1+\sigma} , \quad (8)$$

$$\sigma = \frac{h_x - h_z\ \tan\beta_0}{m_x - m_z\ \tan\beta_0 + Q\ K_{NIP}\ \sin\beta_0} , \quad (9)$$

and

$$Q = (m_x^2 - h_x^2 - m_z^2 + h_z^2) + (m_x\, m_z - h_x\, h_z)\cos 2\beta_0 . \quad (10)$$

NUMERICAL EXPERIMENTS

In order to check the accuracy of the traveltime formulas discussed in this work, we consider the simple 2D model depicted in Figure 2. It consists of two homogeneous acoustic layers, with velocities 1.75 km/s and 2.5 km/s, respectively, separated by a curved interface. The measurement line has a rugged (nonsmooth) topography. We have used the ray tracing package SEIS88 (Červený and Psěnsik, 1988) to model the reflection traveltimes for the reflecting interface. We have simulated a multiple coverage around the central point with $x_0 = 2$ km.

Figures 3–5 show the modelled reflection traveltimes for three different configurations, Common-Source (CS), Common-Offset (CO) and Common-Midpoint (CMP), and the respective approximation formulas, CRS smooth [CRS-S], equation (5), CRS rugged [CRS-R], equation (6), and Multifocus, equation (7). Also depicted are the relative errors for the three approximations.

As readily observed, the CRS-S formula gives poor approximations, whereas CRS-R and Multifocus present good results with relative errors of the same order.

We have also compared the exact reflection traveltimes with the corresponding diffraction traveltimes approximations, i.e., taking $K_{NIP} = K_N$ in CRS and Multifocus formulas. The objective of this experiment is to check the possibility of its use as a two-parameter search in the application of the CRS method. We note that such a strategy has been already implemented by Garabito et al. (2003) in the case of Marmousi data with good results. Figures 6 and 7 depict the results obtained in the present experiment.

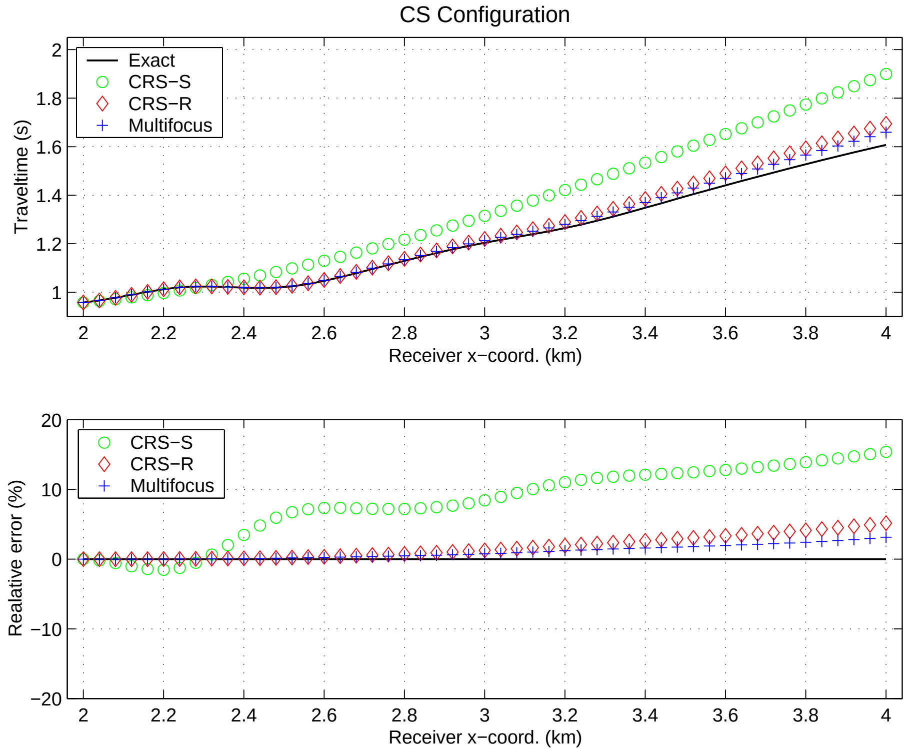

Figure 3: Reflection traveltime approximations for a CS configuration with $x_S = 2.0$ km.

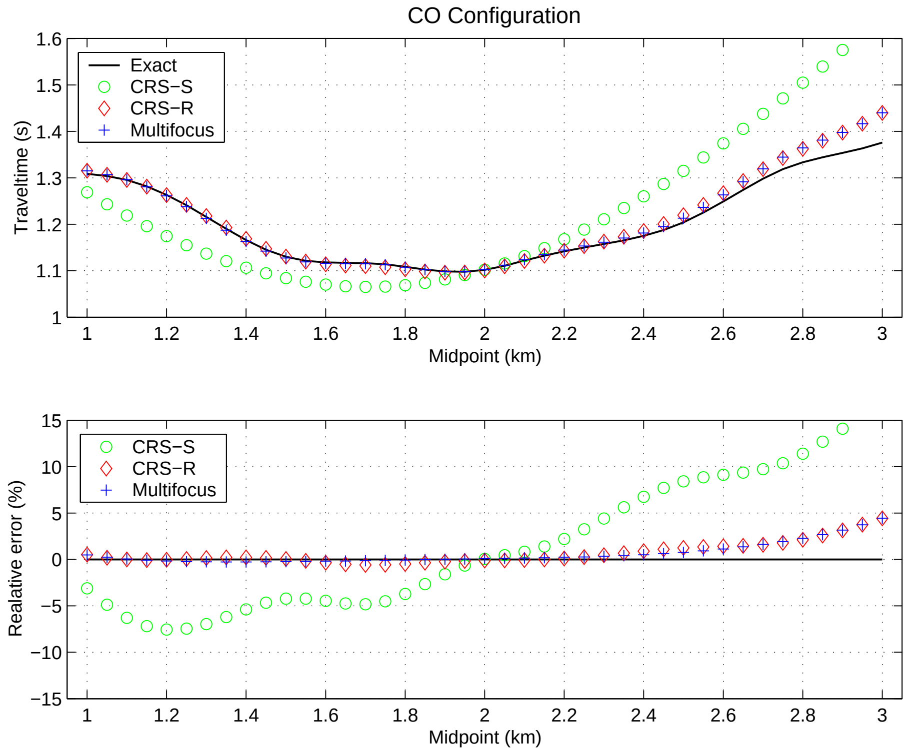

Figure 4: Reflection traveltime approximations for a CO configuration with $h = 0.5$ km.

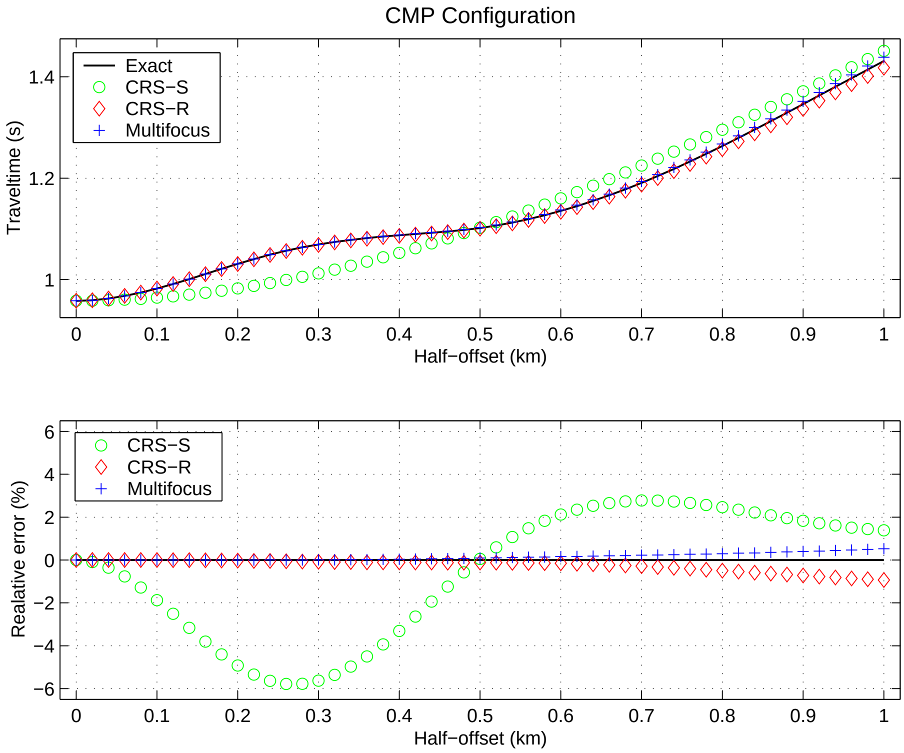

Figure 5: Reflection traveltime approximations for a CMP configuration centered at $x_m = 2.0$ km.

Observe that the CMP configuration is not shown since the traveltime expressions are the same as in the previous case.

As expected, the relative errors were now increased. Once again, the CRS-S formula has the worst behaviour whereas CRS-R and Multifocus formulas behave similarly. We verify that, for small aperture the relative errors remain very reasunable, so that the CRS-R and Multifocus formulas for diffraction traveltimes are able to well approximate the exact (modelled) reflection traveltimes. As a conclusion, a two-parameter search in the CRS method using $K_{NIP} = K_N$ in the formulas, have the potential of producing good initial approximations for the CRS attributes.

CONCLUSIONS

We quickly revisited the Common-Reflection-Surface (CRS) and Multifocus traveltime moveouts in the case of a topographic measurement surface. By means of a simple synthetic example, we provided first comparisons on their accuracy and validity. Our results show that the approximation formulas for rugged topography yield good results, not only to approximate the exact (modelled) reflection traveltimes, but also as a two-parameter formula in the search for initial approximations for the CRS attributes.

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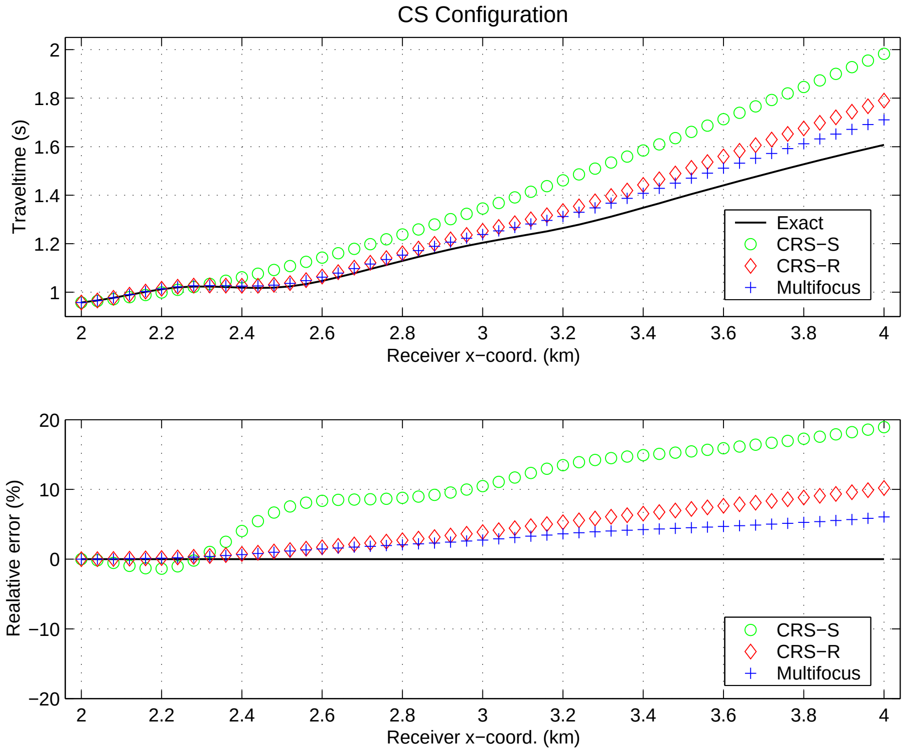

Figure 6: Diffraction traveltime approximations for a CS configuration with $x_S = 2.0$ km.

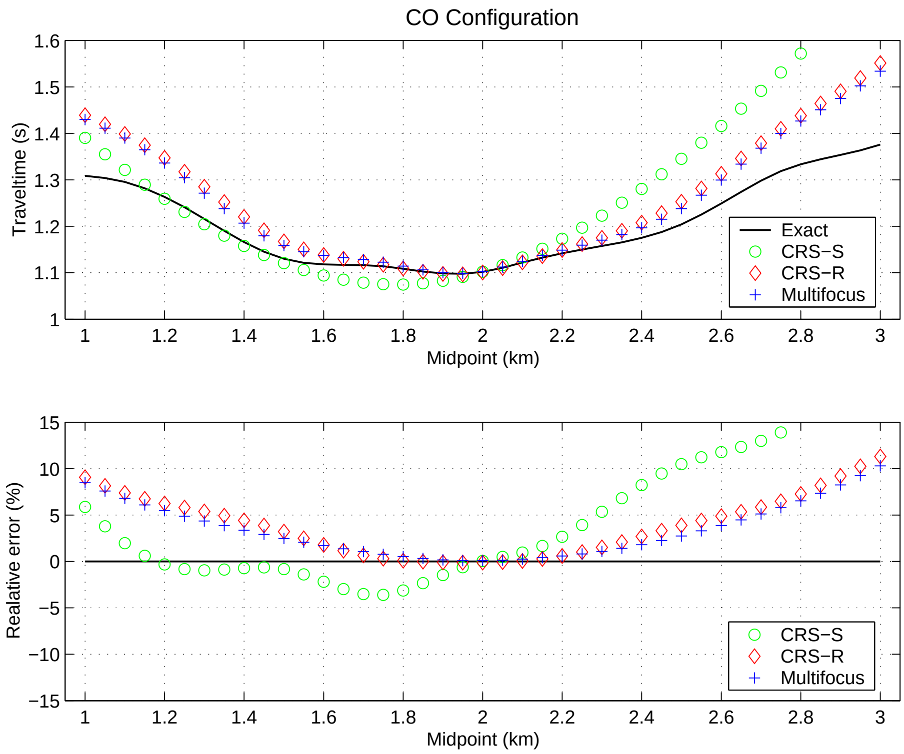

Figure 7: Diffraction traveltime approximations for a CO configuration with $h = 0.5$ km.

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