The CRS stack as a tool for pre-stack depth migration

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Abstract

The Common-Reflection-Surface (CRS) stack is a new seismic processing methodology for simulating zero-offset (ZO) and common-offset (CO) sections. It is based on a second-order hyperbolic paraxial approximation of reflection traveltimes in the vicinity of a central ray. For ZO section simulation the central ray is a normal ray, while for CO section simulation the central ray is a finite-offset ray. In addition to the ZO section, the CRS stack method also provides estimates of wavefield kinematic attributes useful for solving interval velocity inversion, geometrical spreading calculation, Fresnel zone estimate, and also diffraction events simulation. In this paper we propose a new methodology to do a pre-stack depth migration by using the CRS derived wavefield kinematic attributes, so-called CRS based pre-stack depth migration (CRS-PDM) method. The CRS-PDM method uses the CRS results (ZO section and kinematic attributes) to construct an optimized stack traveltime surface along which the amplitudes of the multi-coverage seismic data are to be summed and the result is put in a point of the migration target zone in depth. In the same sense as in Kirchhoff type pre-stack depth migration (K-PDM), the CRS-PDM method needs a migration velocity model. Unlike the K-PDM method, the CRS-PDM needs only to calculate zero-offset traveltimes. The final result is a zero-offset time-to-depth converted seismic image of reflectors from pre-stack seismic data.

Introduction

The improvement of the subsurface imaging has been the target of important scientific works in geophysics. During the 2001 year in the SEG/EAGE Workshop on Seismic True Amplitudes in Karlsruhe, Germany, and by the special issue of the Journal of Seismic Exploration edited by Tygel (2001), new aspects of the pre-stack seismic migration were presented to construct a reliable earth image. The Kirchhoff depth migration is one of the most used method to obtain an image of seismic reflectors from pre-stack data. It is based on the construction of diffraction traveltime surfaces using one a priori known migration velocity model. Recently, new strategies to improve the imaging process were proposed without using a macro-velocity model. One of them is the Common-Reflection-Surface (CRS) method (Mann et al., 1999; Jaeger et al., 2001; and Garabito et al., 2001) for simulating high-resolution zero-offset sections and providing kinematic wavefield attributes. These wavefield attributes are useful for several seismic applications, e.g. interval velocity inversion, geometrical spreading calculation, Fresnel zone estimate and simulation of diffration events.

In this work it is proposed a new strategy for pre-stack depth migration starting from multi-coverage seismic data and using CRS stacked results (CRS zero-offset section and the wavefield attribute sections). The CRS based pre-stack depth migration (CRS-PDM) is done by means of a stacking surface that approximates the finite-offset diffraction events, depends on the CRS stack attributes and does not depend on the macro-velocity model. The amplitudes of the multi-coverage seismic data are summed along the CRS-PDM traveltime surface by putting the result into a depth point of the migration target zone. The final result is a seismic image of reflectors from pre-stack seismic data.

Pre-stack depth Kirchhoff migration

By pre-stack depth Kirchhoff migration method, the amplitudes of seismic reflection events in the reflection traveltimes curve Γ are summed (stacked) along of a diffraction curve Γ_D. The stacked result is put into a point M in subsurface, Figure 1. The diffraction curve, also called stacking curve, is given by

$$\tau_D(\xi, M) = \tau(S, M) + \tau(M, G), \quad (1)$$

where τ (*S*, *M*) and τ (*M*, *G*) designate the traveltimes along the rays *SM* and *MG*, respectively.

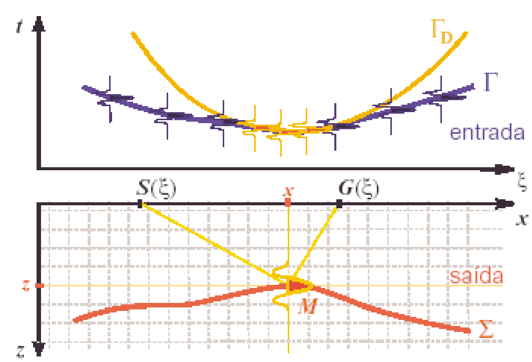

Figure 1 – seismic data stacking along the diffraction curve Γ_D (Huygens curve) constructed for the point M in subsurface.

Under the assumption of a macro-velocity model considered a priori, the two dimensional pre-stack depth Kirchhoff migration operator (Hanitzsch, 1997, Martins et al, 1997 and Cruz et al., 2001) can be formulated as the integral

$$V(M,t) = \frac{1}{\sqrt{2\pi}} \int_A d\xi \, w(\xi, M) \partial_{t-}^{1/2} U(\xi, t) \Big|_{t=\Gamma_D(\xi, M)} \quad (2)$$

In the equation (2), $w(\xi, M)$ represents the weight function and the symbol $\partial_{-t}^{1/2}$ is the anti-causal time half-derivative operator and corresponds, in the frequency domain, to the filter $\sqrt{-i\omega}$. The function $U(\xi, t)$ represents the seismic data by considering only primary reflections. As we can see, the stack operator (2) depends on a velocity model to construct the stacking curve Γ_D, along which the seismic amplitudes must be summed. Moreover, in the pre-stack Kirchhoff migration, the stacking curves Γ_D need be constructed for each one of finite-offset sections that define the multi-coverage seismic data.

CRS method attributes

The CRS stack is a method to simulate a zero-offset seismic section with high signal-to-noise ratio, from multicoverage data, and to provide three important kinematic wavefield attributes, which are related to two hypothetical experiments described below.

By following the description of Mann et al. (1999) for a model with two homogeneous layers (Figure 2), the first experiment consists of placing a point source at a normal inicidence point R in depth, providing the eigenwave so called upgoing normal-incidence-point (NIP) wave. The second experiment consists of an exploding reflector (i.e, an initial simultaneous excitation along the reflector), providing the eigenwave so called normal wave (N wave). The wavefront attributes are the emergence angle β_0 at the surface of a normal ray to the reflector at R, and the radii of curvatures R_{NIP} and R_N.

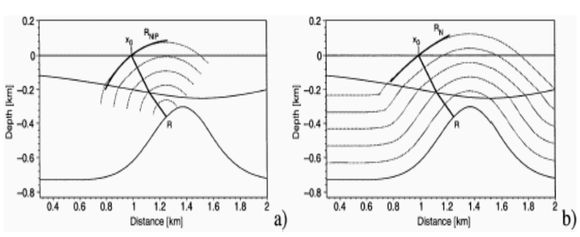

Figure 2 – hypothetical waves. (a) NIP (normal- incidence-point) wave for a point source at R. (b) N (normal) wave for the exploding reflector at R.

CRS traveltime approximation

Based on paraxial ray theory, following Schleicher et al. (1993), the CRS stack operator is obtained through an hyperbolic second-order Taylor expansion of the reflection traveltime as given by (Chira, 2001)

$$t^2(x_m, h) = \left(t_0 + \frac{2\sin\beta_0}{v_0}(x_m - x_0)\right)^2 + \frac{2t_0\cos^2\beta_0}{v_0} \times \left(\frac{(x_m - x_0)^2}{R_N} + \frac{h^2}{R_{NIP}}\right) \quad (3)$$

The expression above describes the reflection traveltime t along a ray reflecting in the vicinity of the reflection point R for a source at position x_S and a receiver at position x_R, in the vicinity of the emergence point x_0 of normal ray in the seismic line. The half-offset between the source and receiver is specified by $h = (x_R - x_S) / 2$ and the midpoint coordinate is given by $x_m = (x_R + x_S) / 2$. Let $P_0 = (x_0, t_0)$ be a reference point of the zero-offset section to be simulated, to which the operator (3) is to be applied, where t_0 denotes the two-way traveltime along of normal ray connecting x_0 to point R. The β_0 is the angle between normal reflection ray and the normal at the surface. Given the point P_0 in the zero-offset section, the required model parameter for the CRS stacking operator (3) is the near-surface velocity v_0.

The CRS stacking operator, also called CRS stacking surface, is an approach to the kinematic reflection response of the curved interface in the heterogeneous medium (Figure 2). The reflection amplitudes of multi-coverage seismic data are then summed (stacked) along the stacking surface, which is defined by means of the three parameters (β_0, R_{NIP}, R_N). The desired stacking surface is the surface that better fits to the multicoverage seismic data. Therefore, the definition of the best stacking surface by means of the expression (3) requires the determination of the optimal parameter triplet (β_0, R_{NIP}, R_N) for each point $P_0 = (x_0, t_0)$.

The three parameters (β_0, R_{NIP}, R_N) of CRS stacking operator (3) can be determined from multicoverage seismic data for a given point P_0, by multi-parameter search process that uses as objective function a certain coherence measure. The zero-offset section and kinematic wavefield attributes sections are then obtained by stacking of multicoverage seismic data, using the optimized stack parameters.

In oder to use the CRS stack formalism to do a pre-stack depth migration, we have to particularize the CRS stack operator for simulating finite-offset diffraction events. This is reached by considering in the expression (3) the condition $R_{NIP} = R_N$, which means the reflector element collapses to a diffracion point, providing the new stack operator

$$t^2(x_m, h) = \left(t_0 + \frac{2\sin\beta_0}{v_0}(x_m - x_0)\right)^2 + \frac{2t_0\cos^2\beta_0}{v_0} \times \left(\frac{(x_m - x_0)^2 + h^2}{R_{NIP}}\right) \quad (4)$$

The operator (4) depends on two wavefield attributes, namely the emergence angle and the radius of curvature fo the NIP wave, (β_0, R_{NIP}). It is a good approximation of the finite-offset diffraction traveltimes starting from a normal-incidence-point (NIP). The stacking surface defined by this operator, called Common-Diffraction-Surface (CDS), is used to stack the amplitudes of the pre-stack seismic data. The summed result is then put into a depth point of a mesh in target region. For each point $P_0 = (x_0 , t_0)$ of the zero-offset section, it is to be stacked a multi-coverage seismic data set and afterwards converted to a point in the depth, so-called image point. The location of the image point is velocity model driven. For that it is necessary and suficient to determine the depth point corresponding to the zero-offset traveltime t_0 from the point source at x_0 in the seismic line.

Traveltimes by wavefront construction

The traveltimes are calculated either using raytracing algorithms or through of the numerical solution of eikonal equation. In this work, the traveltimes are determined by using an algorithm developed by Portugal (2001), which uses the method of wavefronts construction, originally introduced by Vinje et al., 1993. This method is based on the construction and propagation of rays and wavefronts. For better understanding this method, it considers that if a wavefront is well defined in time step τ, then the new wavefront in step $\tau + d\tau$ can be constructed, since we have the medium velocity. For that, we must consider each point on the wavefront in instant τ as an initial point of propagation of a ray that initiates its propagation perpendicularly to the considered wavefront.

The propagation of rays is done by a numerical integration method of Runge-Kutta of fourth order applied to the ray equation system. The set of all end points of propagated rays within $d\tau$ units of time defines the new wavefront. Finally, after the construction of a irregular mesh, defined by rays and wavefronts, Figura 4, now remains to transfer the information contained in this mesh for a new regular mesh, called target mesh, previously defined. This new mesh is defined conveniently such that it coincides with migration target zone, which is represented by a rectangle (red line), Figure 5(b).

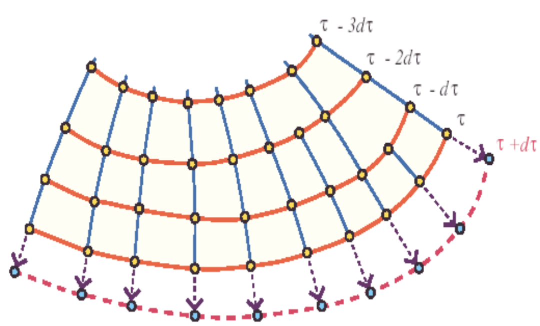

Figure 4 – Rays and wavefronts construction. A new wavefront in instant $\tau + d\tau$ is constructed from wavefront before and the velocity of media (Portugal, 2002).

A great advantage of this method is that new rays can be created, when necessary, in such way that traveltimes and amplitudes can be determinated in regions of low ray density (due to caustics). Another advantage of this method is to determine the traveltimes and amplitudes corresponding to more energetic arrival, making possible a better image of subsurface in complex geological models, Geoltrain et al., 1991

CRS based pre-stack depth migration algorithm

In this section we present a new strategy for doing a pre-stack depth migration of a multi-coverage seismic data, based on CRS stack results, by using the CDS stack operator (4).

The requirements to do a pre-stack depth migration with the CDS operator are:

- **Input data:** multi-coverage seismic data.
- **Information a priori:** migration velocity model, CRS zero-offset section, CRS derived kinematic wavefield attributes β_0 and R_{NIP}.

Below we present a short description of the steps involved in the CRS-PDM algorithm:

1) By using the migration velocity model we propagate wavefronts following Portugal (2002), from each x_0 in the seismic line to the depth through points M of a regular mesh in the target zone. The one-way traveltimes are calculated and used to construct a zero-offset traveltime map with t^*_0.

2) Seleting a t^*_0 of the zero-offset traveltime map, at each point (x_0, t^*_0) we now determine a point $P_0 = (x_0 , t_0 = t^*_0)$ in the CRS stacked zero-offset section, and pick up the values of β_0 and R_{NIP} from CRS derived attribute sections.

3) Finally, obtained the kinematic attributes β_0, R_{NIP} and the two-way traveltime t_0 (extracted from CRS results), we construct the CDS stack operator (4), along which the amplitudes are summed, beeing the result of stack put in a corresponding image depth point. The whole sequence of steps presented before can be visualized in the flowchart of Figure 3.

An important feature of this new pre-stack migration method is that even if the migration velocity is not accurate the obtained reflector image can have a high resolution, because the CDS stack operator does not depend on the macro-velocity model. Otherwise, the correct location of the image depth point is macro-velocity model dependent, i.e. without to know an accurate migration velocity it is not possible to construct the true reflector image.

Thus we have that for applying the CRS-PDM operator it is necessary to have suficient control of the velocity model. This means that some velocity inversion problem must be solved before doing the pre-stack depth migration. The CRS derived kinematic attributes must be used to obtain an initial interval velocity model, which should be refined through a residual velocity analysis during migration process.

For illustrating the CRS-PDM process we consider the geophysical model of Figure 5(b) consisting of a homogeneous and isotropic layer above a half-space. At each point x_0 in the seismic line, we locate a point source and propagate a wavefront for computing the one-way traveltimes for all the points in a regular mesh defined in the depth (rectangle represented by red line). The Figure 5(b) shows the propagation of rays and wavefront into the media for a point source located at the position (1000 , 0) m. The values of traveltimes are stored in each point of the migration target mesh to construct the zero-offset traveltime map.

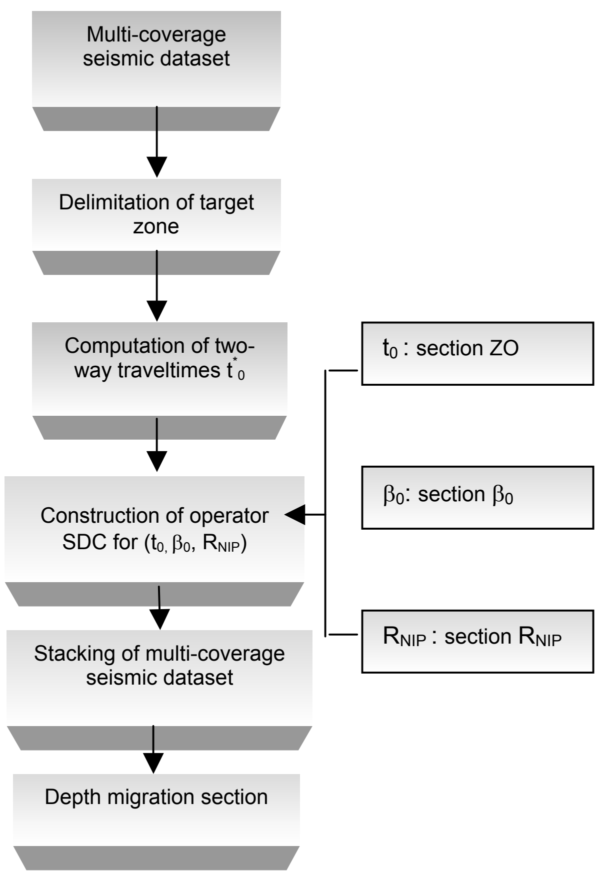

Figure 3 – Flowchart showing all steps of pre-stack depth migration algorithm.

While in the conventional Kirchhoff migration, the stack operator is constructed based on diffraction traveltimes calculated for each point of a mesh in depth, the CDS stack operator is constructed based on the two-way traveltimes calculated for all points M in depth. Because this last feature the CDS operator provides that each seismic trace is inspected once.

Let us assume by hypothesis that point M belongs to the unknown reflector. If we have that after the point source assumes all the positions of coordinates x_0 in the seismic line, beeing calculated all the values of two-way traveltimes t^*_0 for this point, only one two-way traveltimes t^*_0 would be equivalent to the trajectory of the normal ray connecting the point x_0 to the arbitrary point M in depth (Figure 5(b)). In this case the CDS surface fits well to the multi-coverage seismic dataset, Figure 5(a). It is performed the stacking of multi-coverage dataset, putting the stacked value into the point M. The points M on the reflector will be identified by contrasting the values of the stacked amplitudes. The values of the amplitudes in these points will be significantly higher than in the others points of the mesh, due to CDS stack surface constructed at these points better fit the multi-coverage seismic data.

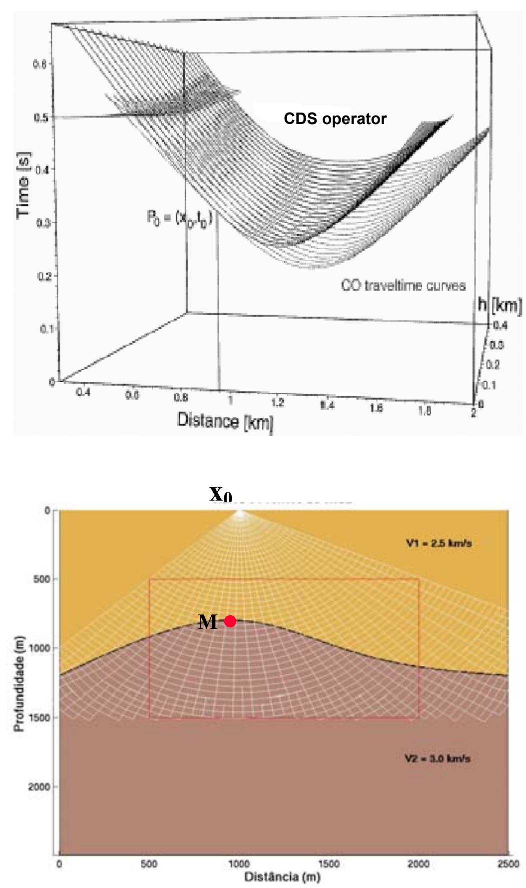

Figure 5 – (a) Stack operator CDS correspondent to point M in subsurface. (b) Synthetic model consisting of two homogeneous layers. Point source at position (1000, 0) m and the rays and wavefront propagate on the media (Portugal, 2002). The times values are stored in the migration target zone represented by red line.

Conclusions

A new pre-stack depth migration method has been proposed in this work. It is based on result of the CRS stack process, namely the zero-offset section and the kinematic wavefield attributes. These informations are used to construct a new stack operator called CDS, which are used to fit the multi-coverage seismic dataset, stacking the amplitudes and putting the result into the image depth point. While the conventional migration operator depends on the velocity model, the CDS stack operator depends only of near-surface velocity and the seismic attributes provided by CRS stack. This means that even if the migration velocity is not accurate the obtained reflector image can have a high resolution. Otherwise, without to know an accurate migration velocity it is not possible to construct the true reflector image.

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