Multiple attenuation using Common-Reflection-Surface (CRS) attributes

Fernando Gamboa, LGC, State University of Campinas, Brazil
Eduardo Filpo, UN-EXP/ST/TG, Petrobras, Brazil
Martin Tygel, LGC, State University of Campinas, Brazil

Abstract

Applied to multicoverage data, the Common-Reflection-Surface (CRS) method obtains, besides a clear stacked section, also a number of traveltime attributes defined at each point of that section. The CRS traveltime parameters provide useful information for a variety of seismic processing purposes. Here we investigate the role of CRS attributes in the important task of multiple identification and attenuation. We consider the 2D situation in which the CRS method produces three parameters associated with the resulting simulated (stacked) zero-offset (ZO) section. We propose and discuss simple algorithms designed to identify and, as a next stage, attenuate or eliminate multiples. First experiments show that the these algorithms have the potential of favorably replace well-established multiple suppression methods.

Introduction

The normal-moveout (NMO) method is a routine procedure designed to produce a simulated zero-offset section by means of a stacking procedure performed on common-midpoint gathers that relate to user-selected reflection events. As an important part of procedure, an NMO-velocity map on the simulated (stacked) ZO section is also obtained. For a general description and also practical considerations on the NMO method, the reader is referred to Yilmaz (2000) (see also more references therein).

The NMO method is based in the following requirements: (a) the stacking operation is performed on CMP gathers only; (b) the stacking is performed on a few user-selected reflection events and a few CMPs only and (c) for each selected event, a corresponding NMO-velocity is estimated by means of a (one-parameter) coherence analysis carried out the CMP gather that refer to this event. The full NMO-velocity map results from suitable interpolation (in time and CMP location) of the few, previously obtained NMO-velocities.

NMO-traveltime: We consider the 2D situation, in which the given seismic dataset stem from sources and receivers located on a single seismic line, that is, in addition, also assumed to be horizontal. Upon the consideration of a given CMP location, x_0, and a ZO traveltime, t_0, the coherence analysis and stacking operation are carried out using the NMO-traveltime

$$t^2(h) = t_0^2 + \frac{4h^2}{v_{NMO}^2} \,. \qquad (1)$$

As a function of half offset, h, the NMO-traveltime, $t(h)$, represents (second-order hyperbolic approximation of) the traveltime along the reflection ray that connects the source-receiver pair, $(x_0 - h, x_0 + h)$, in the CMP gather of x_0.

In recent years, the above-described requirements of the NMO method, namely its restriction to CMP data, user-selected events and extraction of a single attribute (the NMO-velocity) from the data, began to be questioned by the geophysical community. As a response to these limitations, more general approaches to the problems of stacking and extraction of traveltime parameters from multicoverage data have been proposed. In the seismic literature, the new approaches are referred to as macro-model-independent or time-driven imaging methods. The Common-Reflection-Surface (CRS) Method, as used in this work, is one of them. For a general description of macro-model-independent methods, the reader is referred to Hubral (1999) (see, more references therein).

The common feature of the new approaches is the use of general traveltime moveouts that are able to stack traveltimes of source-receiver pairs that belong to much larger gathers, namely that do not conform to the original CMP condition. Traveltime moveouts that are able to meet the new requirements are known for a long time. The CRS Method uses a natural extension of the NMO traveltime (1), the general hyperbolic traveltime. It is valid for arbitrary locations of source and receivers in the vicinity of a given ZO point, in most cases a CMP location. In the case of a horizontal seismic line, if the ZO point is located at x_0 along the seismic line and if v_0 is the medium velocity at that point, the hyperbolic traveltime can be written as

$$
\begin{aligned}
t^2(h) \quad &= \quad \left[t_0 + \frac{2\sin\beta}{v_0}\,(x_m - x_0)\right]^2 \\
&+ \quad \frac{2t_0\cos^2\beta}{v_0}\left[\frac{(x_m - x_0)^2}{R_N} + \frac{h^2}{R_{NIP}}\right]. \quad (2)
\end{aligned}
$$

Here, β denotes the angle the ZO ray makes with the normal at the measurement surface at x_0 and R_N and R_{NIP} are the radii of curvature of the N-wave and NIP-wave, respectively. Comparison of the NMO and hyperbolic traveltimes (1) and (2) provides

$$
v_{NMO}^2 = \frac{2v_0 R_{NIP}}{t_0\cos^2\beta}\,. \qquad (3)
$$

As introduced in Hubral (1983), the (normal) N-wave is the one that starts with the shape of the reflector in the vicinity of the reflection point of the normal ray that starts and ends at x_0 at the seismic line, and travels upwards with half the velocity of the medium until it is observed, also at x_0. In the same way, the (normal-incidence-point) NIP-wave is the one that starts as a point source at the reflection point of the normal ray to x_0 and travels upwards with half the velocity of the medium until it is observed at x_0. We also observe that the reflection point of a normal ray on a reflector is called normal-incidence-point (NIP).

The hyperbolic traveltime (2) depends on three attributes (β, R_N, R_{NIP}), called CRS parameters, defined for each ZO location, x_0 and traveltime, t_0. For a grid of preassigned points (x_0, t_0), and assuming that the near-surface velocity, v_0 is known at each x_0, the CRS method produces the parameter maps, $\beta = \beta(x_0, t_0)$, $R_N = R_N(x_0, t_0)$ and $R_{NIP} = R_{NIP}(x_0, t_0)$, as well as a corresponding simulated (stacked) ZO section $u = u(x_0, t_0)$. As we see, in the same way as the NMO method, one of the results of the CRS method is also a (simulated) ZO section. However, as opposed to the NMO method that produces one single parameter estimated from a CMP gather, the CRS method produces a triplet of parameters estimated from a multicoverage gather.

In the following, we consider that, for a given multicoverage dataset, the CRS method has already been applied. As a consequence, both the CRS parameter maps, as well as the CRS stacked section are available. We then consider the use of the obtained CRS parameters for the purpose of multiple attenuation.

Basic remarks on the CRS method

A. The general hyperbolic moveout gives rise to three parameters, (β, R_{NIP}, R_N), as opposite to the single-parameter, v_{NMO}, obtained by the NMO method. The three parameters allows for a better identification or discrimination of a (primary or multiple) reflection event. Note, moreover, that the simple relationship (3) determines the NMO-velocity by means of the the two parameters β and R_{NIP}. For the illustrative layered model containing primaries and multiples, Fig. 1) displays three panels, showing the behavior of the CRS parameters β, R_{NIP}, as well as the NMO-velocity, v_{NMO}, obtained by the combination of the two previous parameters.

B. As opposed to the NMO method in which the NMO-velocity, v_{NMO}, is estimated on a few user-selected events and interpolated at all the other points, the CRS method automatically estimates the parameters (β, R_{NIP}, R_N), at each point at the simulated ZO section. The CRS method is, thus, bound to yield more detailed and precise velocity maps. Due to the involved interpolations, the NMO method will in many case provide velocities that are incorrect for primaries and correct for multiples (see Fig. 2).

C. When the CRS parameters along a multiple are well identified, that multiple can be modelled and eliminated in any (pre-stack) domain. This is due to the fact that the hyperbolic equation (2) well adjusts, not only to the CMP, but to any measurement configuration. Moreover, in the case the amplitude of a primary is altered by the simultaneous arrival of a multiple, the correct amplitude of the primary can be recovered using the amplitudes of traces of nearby CMPs (see Figure 4).

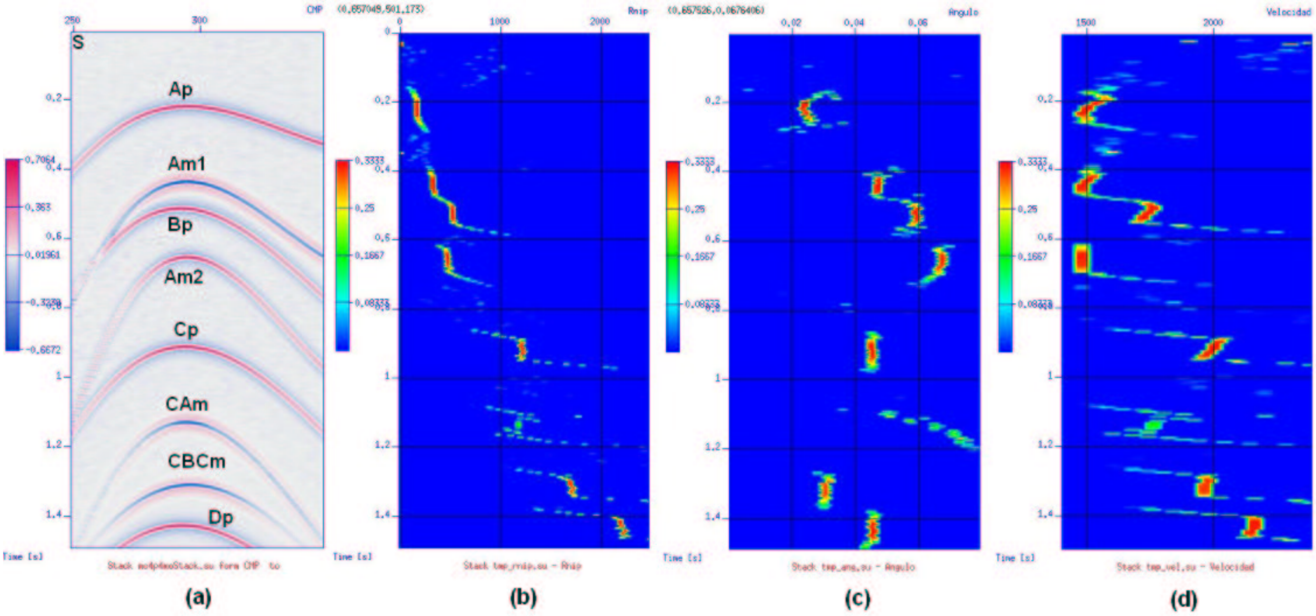

Figure 1: CRS attributes for primaries and multiples on a ZO section: (a) Identified primaries Ap, Bp, Cp e Dp and multiples Am1, Am2, CAm e CBCm; (b) Values of R_{NIP} for the trace (CMP) 300 of zero offset section (a); (c) Values of β for the trace (CMP) 300 of zero offset section (a), and (d) NMO-velocity for the trace (CMP) 300 as obtained from R_{NIP} and β.

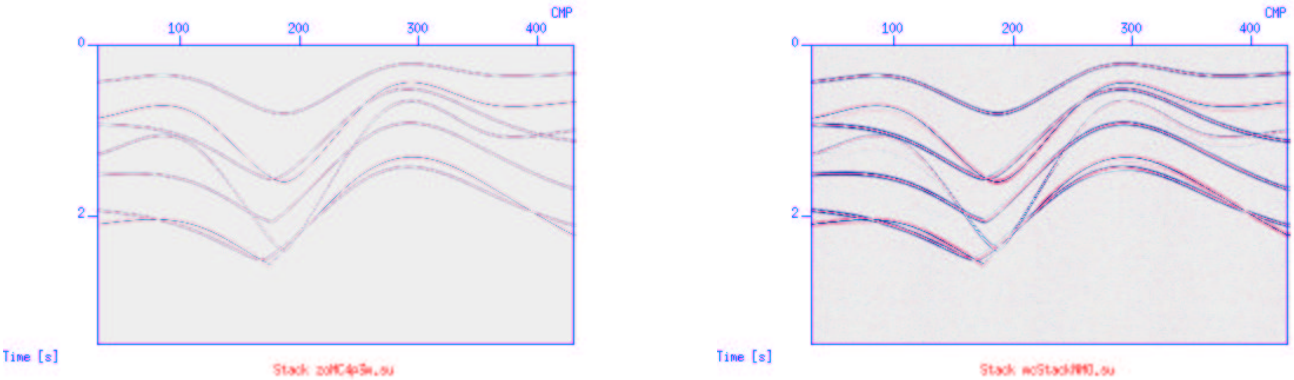

Figure 2: Left: Simulated stacked section with primaries and multiple; Right: NMO stacked section using primary-reflection velocities. Note that, even though multiples are not flattened by the NMO-velocity analysis, they are nevertheless also stacked.

CRS parameters of primaries and multiples

Useful insight for the geometrical meaning of the CRS parameters can be gained by the consideration of a single reflector in a homogeneous medium. In this simplest situation, we see that the CRS parameters, β, R_{NIP} and R_N (roughly) inform us about the reflector's dip, depth and shape, respectively. We use this very qualitative observation to guide us on how to use the CRS attributes to identify or discriminate multiple and primaries. For example, if we have at point (x_0, t_0) on the CRS-stacked section the parameter values $R_N = \infty$ (very large R_N) and $\beta = 0$, we can associate it with a horizontal and planar re-

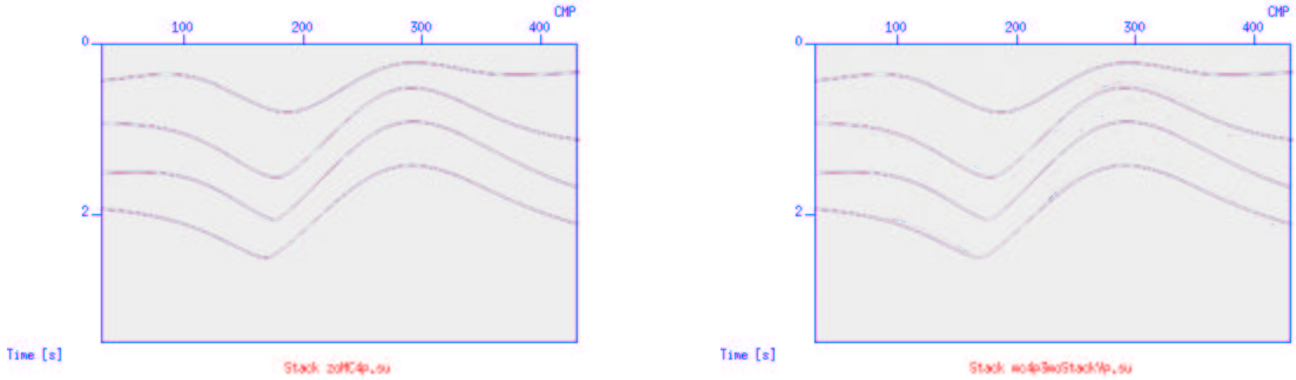

Figure 3: Left: Simulated ZO section; Right: CRS stacked section otained under the use of parameters of primaries only. Note the good attenuation of the multiples.

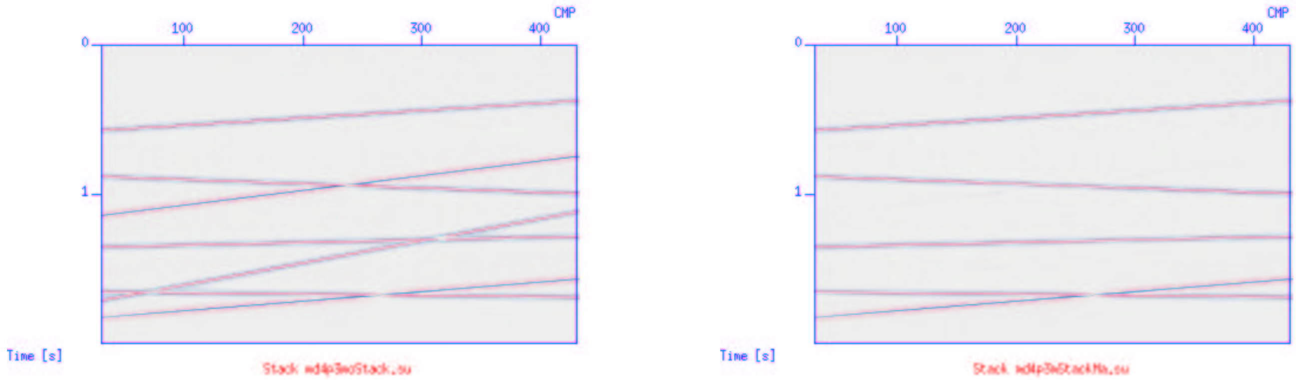

Figure 4: Left: ZO section containing primaries and multiples; Right: ZO section after removal of multiples by modelling.

flector. As a second example, suppose for the same trace location, x_0, we have two events at traveltimes $t_{0,1} < t_{0,2}$ for which the corresponding R_{NIP} parameters satisfy $R_{NIP,1} > R_{NIP,2}$. This would indicate that the second event would be a multiple.

This situation is well illustrated in the marine-data synthetic example of Figure 1. The depth model (not shown in the figure) consists of four curved interfaces, A, B, C and D, below the see surface, denoted by S. The primaries of all interfaces are denoted Ap, Bp. Cp and Dp, respectively. The events Am1 and Am2 are first- and second-order (surface) multiples of first interface A. Also, CAm is the first-order multiple, SCSAS, of interface C with respect to the water surface S. Finally, CBCm represents the internal multiple, SCBCS, that starts at S, reflects at C, reflects at B, reflects at C and returns to S.

Looking at the events Ap, Am1 and Am2, we can readily verify their periodicity and almost constant increment of the values R_{NIP} and β. This, in turn, leads to very close NMO-velocity values for these events, in agreement with the expected behavior as free-surface multiples (see next section). We now note that the R_{NIP} values of the multiples Am2 and CAm are significantly smaller than the R_{NIP} values of the previously identified primaries. In both cases, we observe the combination of an increasing arrival time together with a decreasing value of R_{NIP}, an expected behavior of a multiple. We finally consider the multiple CBCm. Although their CRS parameters R_{NIP} and β do not present any particular behavior, the NMO-velocity (as obtained by the combination of these parameters) is smaller than the NMO-velocity of the primary Cp, also a characteristic behavior of a multiple.

Free-surface multiples for a dipping sea bottom

We consider the typical marine situation of free-surface multiple reflections from the sea bottom. As shown by Levin (1971), in the situation for a planar dipping sea bottom and a CMP gather, traveltime of a primary reflection can be written as

$$t_p^2(h) = \left(t_{0,p}^2\right)^2 + \frac{4h^2}{V_{NMO,p}^2} \ , \tag{4}$$

where t_0, p is the ZO traveltime of the primary at the CMP location and V_{NMO}, p is its NMO-velocity. Note that, in the present situation, the CRS emergence angle and NIP-wave curvature parameters, β_p and $R_{NIP,p}$, posses the simple interpretations

$$\beta_p = \phi \ , \quad \text{and} \quad R_{NIP,p} = v_0 t_{0,p}/2 \ , \tag{5}$$

in which ϕ is the reflector's dip, and v_0 is the medium (water) velocity. For the same CMP gather, the traveltime of any multiple of the previous primary has an analogous expression

$$t_m^2(h) = t_{0,m}^2 + \frac{4h^2}{V_{NMO,m}^2} \ , \tag{6}$$

in which t_0, m and $N_{NMO,m}$ have analogous meanings of their primary-reflection counterparts. Let us assume that $(\beta_m, R_{NIP,m})$ represent the CRS emergence angle and NIP-curvature parameters multiple. Denoting by N the order of the surface multiple, one can the write that (see Levin (1971))

$$\begin{aligned} t_{0,m} &= \frac{\sin\beta_m}{\sin\beta_p}\, t_{0,p} \quad v_{NMO,m} = \frac{\cos\beta_p}{\cos\beta_m} v_{NMO,p} \ , \\ \beta_m &= (N+1)\beta_p \ , \quad R_{NIP,m} = \frac{\sin\beta_m}{\sin\beta_p} R_{NIP_p} \ , \end{aligned} \tag{7}$$

Interbed multiples in horizontally layered media

In the case of plane horizontal homogeneous layers ($\beta = 0$ for all interfaces), the NIP-curvature parameter of a primary reflection at the N-th interface, $R_{NIP,p}$, can be expressed as

$$R_{NIP,p}^N = \frac{1}{v_0} \sum_{i=0}^{N} v_i^2 t_i \ . \tag{8}$$

We consider a *symmetrical multiple* (Hubral and Krey (1980)) between the interfaces N and n, $(n < N)$ that corresponds to the previous primary. To compute its NIP-parameter, $R_{NIP,m}$, we have to take into account the extra propagation between the interfaces n and N. From simple geometrical arguments, we can show that

$$R_{NIP,m}^{N,n} = R_{NIP,p}^N + \frac{1}{v_0} \sum_{j=n}^{N} v_j^2 t_j \ , \tag{9}$$

With the knowledge of $R_{NIP,m}^{N,n}$ and also taking into account that $\beta = 0$, we can determine the NMO-velocity of the symmetric multiple by

$$V_{NMO}^2 = \frac{2v_0}{t_0} R_{NIP,m}^{N,n} \ . \tag{10}$$

It is to be noted that, in the case of dipping planar interfaces, analogous expressions for $R_{NIP,m}^{N,n}$ and v_{NMO} can be readily obtained. These depend, however, also on the reflector dips and will not be shown here.

Methods for multiple attenuation or elimination

1. CRS stacking using primary-reflection parameters

The method consists of performing the CRS stacking using only the CRS parameters that pertain to previously-identified primaries. An application of this procedure is shown in Figure 3.

2. Elimination of a multiple by modelling

If the three parameters of a multiple are known (e.g., using the methodology as in Figure 1), its moveout, in any configuration, is well described by hyperbolic equation (2). This permits a more precise traveltime determination of the multiple and, as a consequence, a better discrimination from concurrent events. We observe that the CRS parameters of a multiple can be obtained either by inspection on the CRS-stacked section or by the use of suitable parameter relationships. Examples of the latter are the above-derived formulas for the specific cases of free-surface or interbed symmetrical multiples.

Extension for inhomogeneous layered media with curved interfaces

In the case of a general model with inhomogeneous layers and curved interfaces, the modelling and suppression of a multiple reflection can be performed in an analogous manner as before. If the multiple has been already identified (i.e., its CRS parameters are known) then its elimination can be done by the above-described modelling procedure. In the case the primaries are well identified (i.e., their CRS parameters are known), then the CRS parameters β_m, $R_{NIP,m}$, and consequently, the NMO-velocity, $v_{NMO,m}$, of the corresponding multiples can be approximated by means of equations (7) and (3). Note that, although these equations were derived under simplifying assumptions, they can provide useful initial parameter values in some optimization scheme.

Multiple elimination in the common-shot domain

A very interesting and promising multiple elimination method has been proposed by E. Landa and coworkers (see Landa et al. (1999)) in the framework of the multifocus method. Similar to CRS, the multifocus method uses a different traveltime moveout formula, that also depends on the the same three parameters β, R_{NIP} and R_N. For a description of the multifocus method, and moreover to its relationship to the CRS and other imaging methods, the reader is referred to Hubral (1999). In Landa et al. (1999), it is shown that the traveltime of each multiple can be decomposed as a sum of traveltimes of a number of primaries. The CRS (or multifocus) parameters of each these primaries are seen to satisfy a so-called multiple condition (namely a relationship between the emergence angles of the primary components of the multiple). The procedure is carried out in the common-shot or common-receiver domains and, in the same way as the proposed methods in this paper, does not require any knowledge of the subsurface velocity model.

Conclusions

The CRS method offers a good alternative to treat a number of sesimic processing tasks. The main reasons are the consistent use of the full available data and also the automatic extraction of several parameters that are related to the involved seismic propagation. In the case of a single seismic line (the so-called 2-D situation) the number of parameters is three. This is to be contrasted to the single-parameter that the NMO method extracts from CMP data. Here, we have discussed the used of parameters and stacked sections obtained by the CRS method to identify and eliminate multiples. We have considered two situations, namely (a) the elimination of a multiple that has been already identified in the CRS stacked section and (b) the identification and elimination of a multiple by means of the behavior of its CRS parameters. The latter case was restricted to the particular cases of free-surface multiples and symmetrical interbed multiples. As it is very often in geophysics, the full theoretical analysis can be carried out on simple models (homogeneous layers separated by planar horizontal or dipping interfaces) only. In these situations, our results were very encouraging. It is expected, however, that, under suitable approximations, the results of this paper can be extended to more realistic cases or real datasets. This we intend to do in future work.

Acknowledgments

We acknowledge the following organizations for financial support: Research Foundation of the State of São Paulo (FAPESP), grant 01/01068-0, and The National Council for Scientific and Technological Development, grant 300927/82-7. All algorithms developed in this work use the Seismic Unix (SU) software, release 35.3, provided by the Center for Wave Phenomena, Colorado School of Mines.

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