Multiple attenuation using Common-Reflection-Surface attributes

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ABSTRACT

Applied to multicoverage data, the Common-Reflection-Surface (CRS) method obtains, besides a clear stacked section, also a number of traveltime parameters or attributes defined at each point of that section. The CRS parameters provide useful information for a variety of seismic processing purposes. We consider the use of CRS attributes in multiple identification and attenuation. In the 2D situation, 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 these algorithms have the potential of favorably replace well-established multiple suppression methods.

INTRODUCTION

One of the main objectives of reflection seismics is to derive an image of the subsurface from multicoverage reflection seismic data. Stacking procedures, such as the conventional common midpoint (CMP) method, are thoroughly used, because of their ability to increase the energy of reflection signals, while attenuating coherent and random noise.

Stacking means summing seismic amplitudes along suitable traveltime curves or surfaces that are able to constructively interfere in the case of reflection or diffraction events, as opposed to other signals, such as noise, where they destructively interfere. The traveltime curves or surfaces are either provided by the user (under the use of a priori given velocity models) or derived from the input multicoverage data (by means of a direct application of coherence analysis methods).

In this work, we consider the construction of a 2D simulated zero-offset (ZO) section. The traces of that ZO section, generally referred here as central points are usually taken to coincide with CMP locations. In the CRS method, the stacking surfaces are designed to stack reflections from all source-receiver pairs around each central point. As opposed to the CMP method that uses the normal-moveout (NMO) traveltimes, the CRS stacking curves makes use of all source-receiver pairs, arbitrarily located around the central point. Moreover, the stacking operation is performed at each central point and also at each time sample of the ZO to be simulated.

One of the main benefits of the CRS method is the full use of the available data, leading to a significantly better signal-to-noise ratio, that makes it easier the identification of reflection events, both primaries and multiples. Another very important benefit of the CRS method is the extraction of the CRS parameters (three attributes in the present situation) that provide important information on the reflection event (primary or multiple) under consideration.

A clean ZO section, together with appropriate CRS stacking parameters, is the base of meaningful seismic processing procedures. Here we focus on the particular case of multiple identification and suppression. As a result of the stacking procedure, primaries and multiples become more pronounced. In many cases, multiples can be easily identified in the stacked section. Under the use of their associated CRS parameters, these multiples can readily be attenuated or suppressed in the original multicoverage data, allowing for better further imaging procedures such as migration. In other cases, the distinction between primaries and multiples are more difficult. In these cases, an analysis of the CRS parameters can be of help in the identification procedure, that will lead, again, to attenuation or suppression of the multiple in a next stage. In this work we present algorithms designed for each of the above situations.

THEORY

The normal-moveout (NMO) method is a routine processing step designed to produce a simulated zero-offset (ZO) section by means of a stacking procedure performed on CMP 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.

The NMO method is based in the following requirements: (a) the stacking operation is performed on CMP gathers only; (b) the stacking is performed over 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 at 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. For a general description and also practical considerations on the NMO method, the reader is referred to Yilmaz (2000) (see also more references therein).

NMO-traveltime

We consider the 2D situation, in which the given seismic dataset stem from sources and receivers located on a single horzontal seismic line and propagation occurs on the vertical plane below that line. 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 formula

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

As a function of half offset, h, the above-mentioned 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. Finally, v_{NMO} represents the NMO-velocity.

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).

CRS-traveltime

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 ones that do not conform to the original CMP condition. Traveltime moveouts that 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 formula can be written as

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

Here, β denotes the angle the ZO ray makes with the vertical 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 CRS TRAVELTIME ATTRIBUTES

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 the multicoverage gather.

Multiple Reflections

A multiple reflection can be defined as a seismic event that suffered more than one ascending reflection. A first classification of multiples can be stated as free-surface and internal multiples. A free-surface multiple is a typical event in marine data, namely a reverberation between the ocean floor and the free surface of the water. An internal multiple occurs within internal subsurface layers. The order of a free-surface multiple is defined as the number of reflections it has experienced at the free surface. In contrast, the order of a internal multiple is defined by the total number of downward reflections (see Weglein et al. (1997)). Currently, multiple-attenuation methods are divided into two main groups, namely (a) filtering and (b) prediction/subtraction. The first approach (filtering) exploits the different characteristics (e.g., traveltime, frequency) between primaries and multiples, trying to identify and eliminate the multiples by means of some filtering procedure. In this category, we cite the FK, Radon and slant-stack method as widely used schemes (see Yilmaz (2000)). The second approach (prediction/subtraction) tries to simulate the multiple to be suppressed, either from an a priori given model or from attributes directly derived from the seismic data. Well-known examples of that group include the inverse-scattering series and predictive deconvolution (see, e.g., Weglein et al. (1997) and Yilmaz (2000)). The above-mentioned two approaches can also be combined. An example of such an approach is provided in Landa et al. (1999a).

Multiples can also be attenuated by simple stacking operations. For instance, after NMO-correction using primary velocities, multiples can be naturally attenuated as a consequence of inadequate NMO-correction. Such an approach will be pursued below in the framework of the CRS stacking method.

MULTIPLE IDENTIFICATION USING CRS PARAMETERS

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. Before we describe our strategies, it is useful to recall some of the main characteristics of the CRS methodology.

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 CMP 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 two parameters β and

R_{NIP}. For a illustrative layered model containing primaries and multiples, Figure 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 CMP method, in which the NMO-velocity is estimated on a few user-selected events only and further interpolated at all the other points, the CRS method automatically estimates the parameters (β, R_{NIP}, R_N), *at every point* at the simulated ZO section. The CRS method is, thus, bound to yield more detailed and precise velocity maps.[1] Due to the involved interpolations, the NMO method will in many case provide velocities that are incorrect for primaries and correct for multiples (see Figure 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 gather. 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 5).

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 a very large R_N ($|R_N| >> 1$) and a very small β ($\beta \approx 0$), we can associate it with a planar, horizontal reflector. 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 sea 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.

PREDICTION OF MULTIPLE REFLECTIONS

In this section we consider some fundamental cases for which multiples can analytically expressed by means of the CRS attributes. These cases will serve as a guide for future procedures in more general situations.

[1] The NMO velocities obtained at all time samples by the CRS method represent, in fact, stacking velocities that need later to be smoothed, so as to be inverted for interval velocities. In this respect, see Perroud et al. (2002) and Perroud and Tygel (2003).

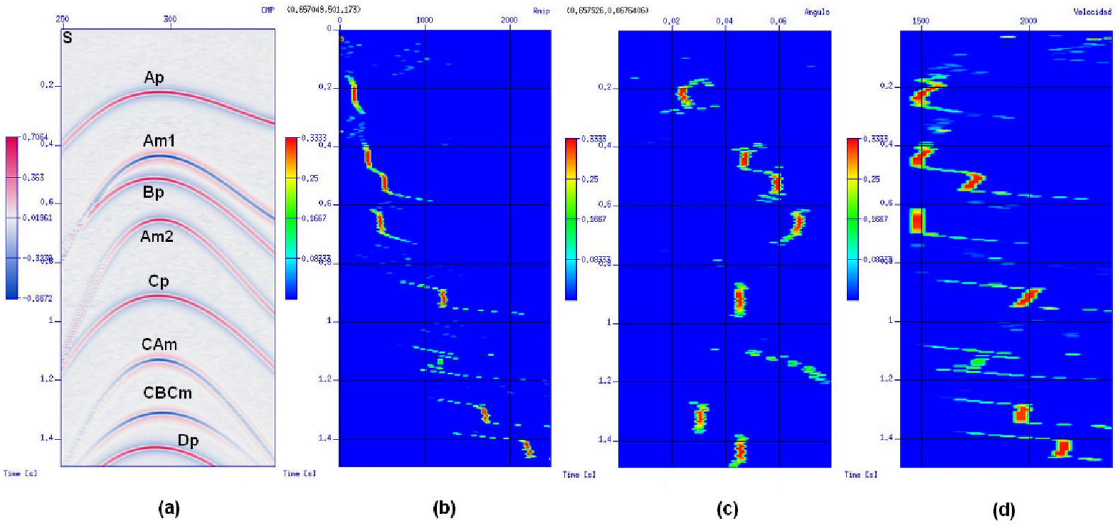

Figure 1: CRS attributes for primaries and multiples on a ZO section: (a) CRS stack section with primaries Ap, Bp, Cp e Dp and multiples Am1, Am2, CAm e CBCm; (b) Coherency maps for R_{NIP} for the trace CMP=300 of section (a); (c) Coherency map for β for the trace CMP=300 of section (a) and (d) Coherency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

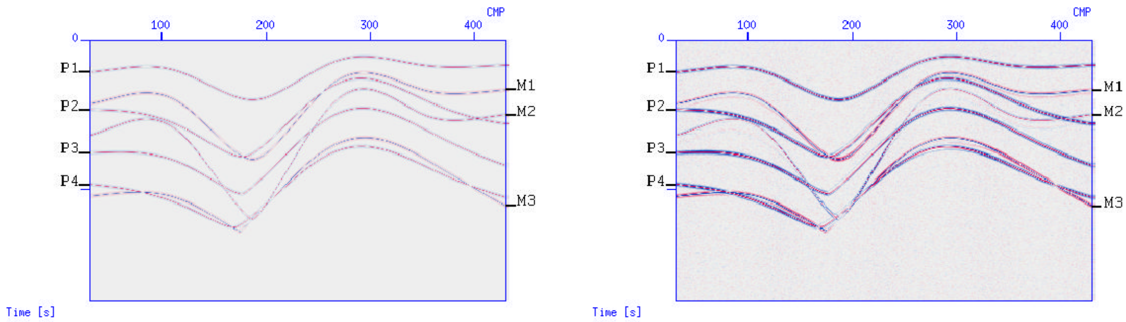

Figure 2: Left: Simulated stacked section with primaries and multiples; Right: NMO stacked section using primary-reflection velocities. Note that, even though multiples are not flattened by the NMO-velocity analysis, they are nevertheless also stacked.

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), for a planar dipping sea bottom and a CMP gather, the traveltime of a primary reflection can be written as

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

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

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

in which α 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 $v_{NMO,m}$ 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 for the multiple. Denoting by N the order of the surface multiple, one can write (see Levin (1971))

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

Internal multiples in horizontally layered media

In the case of a model of 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 (see, e.g., Hubral and Krey (1980))

$$R_{NIP,p}^N = \frac{1}{v_0} \sum_{i=0}^{N} v_i^2 t_i \; . \tag{7}$$

We consider a *symmetrical multiple* (Hubral and Krey (1980)) between 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

$$R_{NIP,m}^{N,n} = R_{NIP,p}^N + \frac{1}{v_0} \sum_{j=n}^{N} v_j^2 t_j \; . \tag{8}$$

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

$$v_{NMO}^2 = \frac{2v_0}{t_0} R_{NIP,m}^{N,n} \; . \tag{9}$$

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

Based on the considerations made in the last section, we proceed to describe our proposed methods for multiple elimination using the CRS attributes. As explained earlier we assume that these attributes are already available from a previous application of the CRS method.

1. CRS stacking using primary-reflection parameters

The method consists of performing the CRS stacking using the CRS parameters that pertain to previously-identified primaries only. As a consequence, we obtain a stacked section with those primaries only. An application of this procedure is shown in Figure 3.

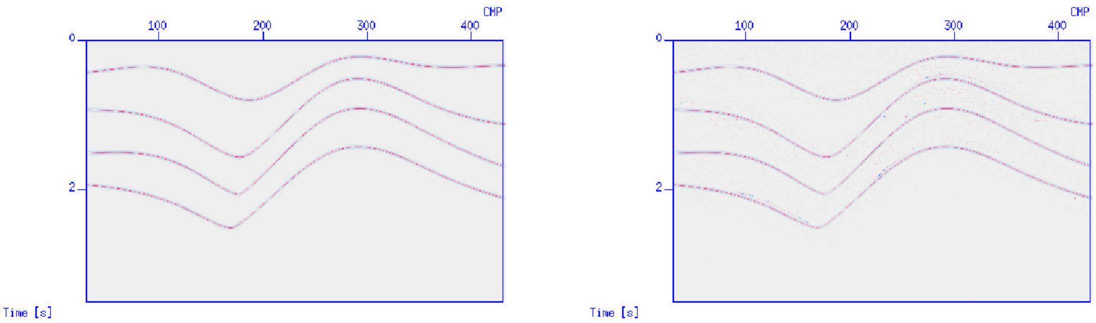

Figure 3: Left: Simulated ZO section; Right: CRS stacked section obtained using parameters of primaries only. Note the good attenuation of the multiples.

2. Elimination of a multiple by modelling

Multiples can also be eliminated by means of a process that consists of a few steps, as depicted in the flowchart of Figure 4. The key steps in the above multiple-suppression algorithm are:

- **Identification of multiples:** The CRS parameters of a multiple can be obtained (a) by a priori knowledge or direct inspection on the CRS-stacked section or (b) as a suitable use of parameter relationships, such as the above-derived formulas for the specific cases of free-surface or internal symmetrical multiples.

- **Traveltime extrapolation:** 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 allows a more precise traveltime determination of the multiple and, as a consequence, a better discrimination from concurrent events.

- **Modelling of multiples:** After the traveltime of the multiple is well determined, an estimation of the source wavelet and an adjustment with the amplitudes in the data can be carried out by means of a suitably designed shaping filter. Se do not enter here in the details of the construction of that filter. We remark, nevertheless, that such filters constitute a well-known part of many modelling schemes. As a result, the multiple is modelled. Having obtained the modelled multiples, we can next produce a dataset having multiples only or subtract the multiples from the multicoverage data, producing a dataset with primaries only.

Results of the multiple elimination method using the automatic approach are shown in Figure 5.

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 can be performed in an analogous manner as before. As it is often the case in geophysics, a full theoretical analysis is carried out on simple models (e.g., homogeneous layers separated by planar horizontal or dipping interfaces) only. Although derived under simplifying assumptions, it is reasonable to expect that the obtained expressions still provide useful initial approximations in some optimization scheme. The actual validity of the multiple-suppression schemes proposed here is still a topic of ongoing investigation.

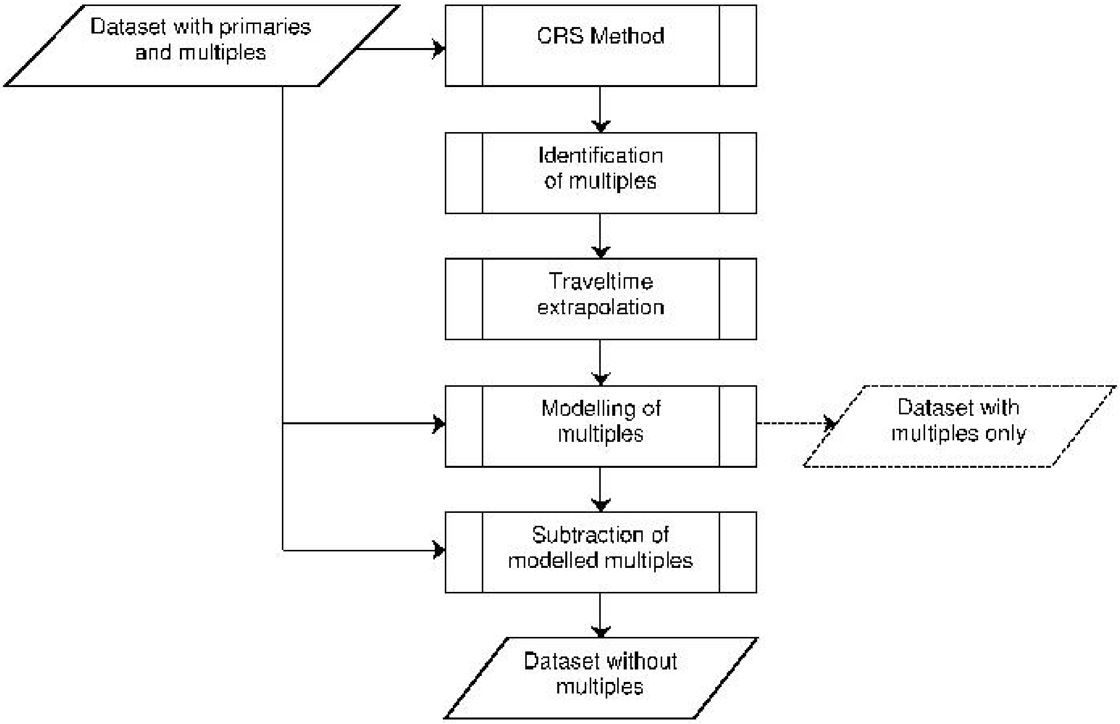

Figure 4: The method considered for the multiple attenuation by modelling, using CRS parameters, involves: (a) Identification of multiples, (b) modelling of multiple in any domain and adjusted the amplitudes, and (c) subtraction of multiples.

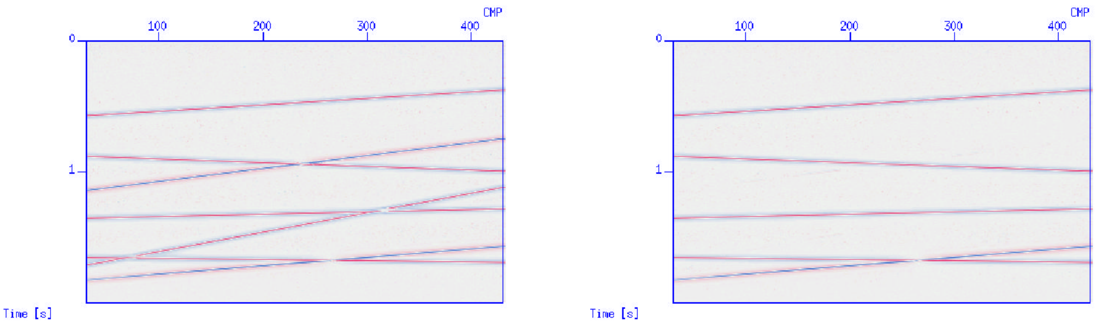

Figure 5: Left: ZO section containing primaries and multiples; Right: ZO section after removal of first and second order free-surface multiple by modelling.

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. (1999b)) in the framework of the Multifocus method. Similar to the CRS method, 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. (1999b), 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 of 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 seismic processing tasks. This can be explained by 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 2-D situation considered here, the CRS method depends on three parameters that need to be inverted from the full multicoverage. This is to be contrasted to the single-parameter, NMO-velocity, involved in the conventional CMP method. In this paper, we have discussed the use of the CRS parameters, as obtained from the application of 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 a suitable behavior of its CRS parameters. Our investigation of the latter case was restricted to the particular cases of free-surface multiples and symmetrical internal multiples. In these simple and initial situations, our results have shown to be very encouraging. More realistic applications are achieved by means of suitable approximations. This we intend to do in future work.

ACKNOWLEDGMENTS

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