Multiple suppression: A literature review

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ABSTRACT

Three basic methods for suppressing multiples exist in published literature. Deconvolution methods use the periodicity of multiples for suppression and are effective in suppressing short–period free–surface multiples generated at shallow reflectors. Filtering methods use differential moveout between primaries and multiples that are separate in the f–k, tau–p, or Radon domains. These filtering methods can successfully suppress multiples generated at moderate to deep reflectors where multiples are well–separated from their primaries. The third group of methods, wavefield prediction and subtraction, based on the wave equation, use recorded data to predict multiples by wave extrapolation and inversion procedures. These wavefield methods obtain multiple–free data by subtracting the predicted multiples and can suppress all multiples generated by any complex system of reflectors. This can be accomplished as long as the recorded wavefield has complete internal physical consistency between primaries and multiples. The most striking advantage of wavefield prediction and subtractions over other methods is its ability to suppress multiples that interfere with primaries without coincidentally attenuating the primaries.

Wavefield prediction and subtraction methods are the most promising methods for multiple suppression, but they have considerable cost and are limited by data acquisition and processing more than other methods. Therefore, the choice of multiple suppression methods should be based on the effectiveness, cost, and processing objectives, and depends on how well a particular data set fits the assumptions of each multiple attenuation method.

INTRODUCTION

The basic models in seismic processing assume that reflection data only consist of primaries (Hill, Dragoset, and Weglein, 1999; Weglein, 1999). So far, multiples are considered as noise in seismic data. We have to suppress these multiples prior to migration, inversion, AVO analysis, and stratigraphic interpretation. Otherwise, multiples can be misinterpreted as, or interfere with, primaries and dramatically change the results of migration, inversion, AVO analysis, and stratigraphic interpretation.

According to where the downward reflection of the raypath occurs, multiples can be divided into two types (Dragoset, 1998, 1999). One is free–surface multiples that are some times referred to as surface–related multiples or surface multiples. This type of multiple has at least one downward reflection at the air–water "free surface". Simple water–bottom multiples (or pure water–bottom multiples) and second–order water–bottom multiples (or seafloor peg–leg) or reverberation belong to this type of multiples. The other type is internal multiples that have all of their downward reflections below the free surface. This type of multiple gets more attention when the exploration target is a subsalt or sub–basalt layer.

Over the years, many techniques for suppressing multiples have been tried. In recent year, multiple–suppression techniques based on the wave equation have attracted attention because they seem to suppress all multiples without coincidentally attenuating the primaries (Dragoset, 1998). The choice of multiple–suppression methods does not only depend on the effectiveness of each method but is a compromise of the effectiveness, processing objective and cost of each method. Each method has its own assumptions, and it is useful when these assumptions are compatible with the data.

In this paper, we attempt to demonstrate that every multiple–suppression method has its own strengths and limitations, which are based on the underlying assumptions. Hopefully, this knowledge will lead to constructive conclusions.

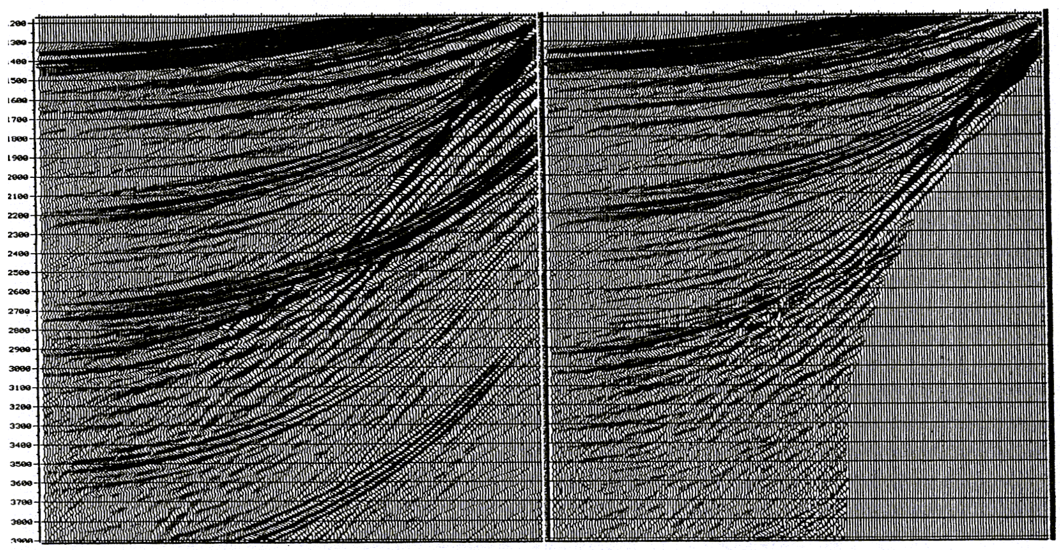
METHODS OF MULTIPLE–SUPPRESSION

Methods that are applied to suppress multiples can be placed in three basic categories: (1) deconvolution methods that assume that multiples have periodicity with respect to primaries; (2) filtering methods that assume that multiples separate from primaries in certain domains; and (3) wavefield predication and subtraction that use recorded data or models to predict multiples and then subtract them from the original data.

Method 1: Deconvolution methods

Deconvolution methods use periodicity to suppress multiples. In principle, this periodic assumption is valid only at zero offset in the time–space domain, and only when the interfaces generating the multiples are horizontal and have no lateral variations (e.g., a one–dimensional water layer). In practice, deconvolution methods can still be effective in the face of minor violations of the assumption of one–dimensional layers. In situations where the interface or layer generating multiples is not horizontal inline or cross–line direction or structure (e.g., a complex water bottom), deconvolution methods become less effective.

Assuming that the earth is sufficiently one–dimensional, the restriction to zero offset can be overcome by transforming the data to the tau–p or slant–stack domain (Calderon–Macias et al., 1997). In this domain, the multiples become periodic for each p value, and are then suppressed using deconvolution techniques (e.g. predictive deconvolution). In shallow water, where the water bottom is very flat, and peg–leg multiples are a key concern, tau–p deconvolution alone is often very effective. In general, deconvolution methods are less effective in deep water where the period of the multiples is longer, relative to the length of the record. This is because there may not be enough multiples, in the record length to satisfy the periodic requirements. Another problem is that long–period multiples require long operators. Since primaries can be periodic over long time windows, long operators have the potential to suppress primaries as well as multiples.



a) b)

FIG. 1. Real CMP gather in the tau–p domain a) before and b) after multlchannel deconvolution from an area with a strongly dipping water bottom (after Lokshtanov, 1999).

Deconvolution in the tau–p domain will be adversely affected by out–of–plane reflections. The missing near–offsets also adversely affect the predictability of the water–bottom multiples because their amplitudes cannot be properly predicted from postcritically reflected primaries. Even if the traveltimes are more or less correct, the amplitudes will be in error. Therefore, recording precritical near–offsets in shallow reflectors will enhance the performance of deconvolution methods.

Deconvolution methods include predictive deconvolution, adaptive deconvolution and multichannel deconvolution. Predictive deconvolution is a conventional deconvolution method. It suppress water–bottom multiples using a first–order deconvolution operator and suppress peg–leg multiples using a second–order deconvolution operator. Both of these operators fail if they are designed from a data window with both pure water–layer multiples and water–layer peg–legs (Lokshtanov, 1999). Adaptive deconvolution has successfully been applied to field data (Verschuur et al., 1992; Verschuur and Prein, 1999). This technique can be successful in suppressing multiples with a short time–varying period, but is expensive to apply, and can become unstable in the presence of noise (Hardy and Hobbs, 1991). Multichannel deconvolution has been proposed to take into account the effects of strong lateral inhomogeneity that are not considered by conventional deconvolution method (Lamont, Hartley, and Uren, 1999; Morley and Claerbout, 1983). It now has been extended to attack all free–surface multiples generated by the sea floor and a strong reflector below the water bottom (e.g., by the top of a salt or basalt layer) (Landa, Keydar, and Beyfer, 1999; Landa, Belfer, and Keydar, 1999; Lokshtanov, 1999).

Figure 1 is a CMP gather in the tau–p domain of real data before and after application of a multichannel deconvolution operator, from an area with a strongly dipping water–bottom. The water–bottom multiples and peg–leg multiples are easily identified in the raw tau–p gather. They are successfully removed to reveal reflection energy in Figure 1b.

Method 2: Filtering methods

Filtering methods use differential moveout between primaries and multiples that can be separated in tau–p, f–k, or Radon domains, to suppress multiples. They include stacking, slant–stack, f–k filtering and Radon filtering.

The filtering methods work effectively when multiples can be distinguished from the primaries based on the differences in moveout. However, this method fails for near–offset seismic data (Yilmaz, 1989). This is because differential moveout diminishes with near offsets; an inner mute is often applied to eliminate some traces in that range. In the case of a large water column, NMO hyperbolas tend to flatten, thus increasing (sometimes substantially) the number of near traces to be discarded. But, since the near–offset traces contain the highest resolution, removing them is not an optimal solution (Filpo and Tygel, 1999).

Radon filtering is able to separate the primary and multiple energy in the transformed space because of their different moveout velocities. A velocity function is estimated and used to flatten the primaries on common midpoint gathers. The moveout–corrected gathers are then transformed to the Radon domain. This transformation maps the flattened hyperbolic primaries in time and offset space to points (or more accuratedly to local areas) in Radon space where the multiples are separated from the primaries. Because the forward and inverse transforms produces distortions, the multiples are estimated in Radon space, transformed back to the time/space domain, and then subtract from the original data, leaving only the primary data (Berndt and Moore, 1999).

Figure 2 shows the basic principle of Radon filtering. Like all transform filter pairs, the Radon transform first “forward” transforms the data (Figure 2a) into a model parameter space (Figure 2b) where primaries and multiples will be better separated. Unlike Fourier transform, Radon transform is not a perfect transform. Therefore, In order to avoid the distortion of primaries introduced in the forward and inverse Radon transform, a mute is usually selected to remove the portion of Radon space that contains the primaries (Figure2 c–d). These multiples are transformed back to time and offset (Figure 2e) and then they are subtracted from the original untransformed data set to obtain primaries (Figure 2f).

Filtering methods can suppress peg–leg multiples generated in moderate to deep water where peg–legs are well separated from their primaries. It can not suppress peg–leg multiples generated in shallow water where peg–leg multiples have little differential moveout compared with their own primaries.

Figure 3a is a raw CMP gather, and the estimate of the multiples in the gather is displayed in Figure 3c. The primaries after Radon filtering are shown in the Figure 3b.

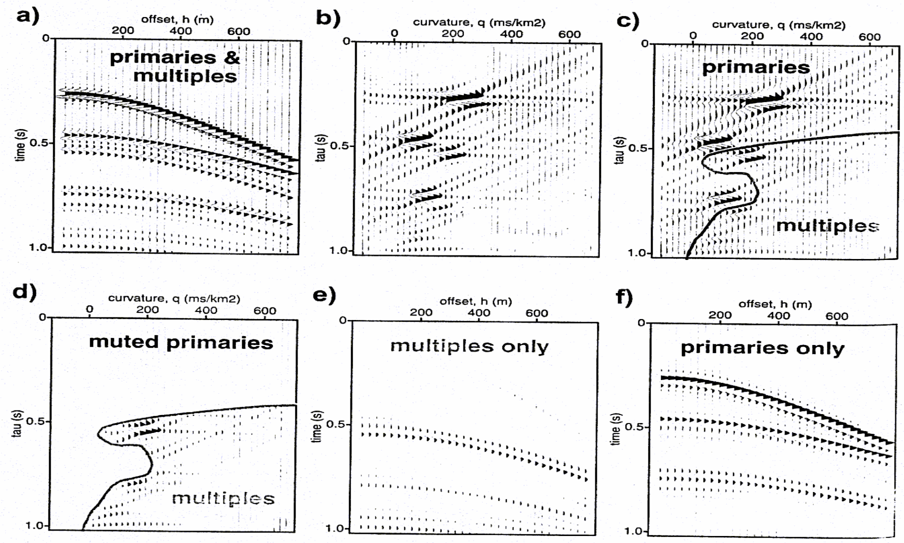


FIG. 2. Multiple–removal using the parabolic Radon transforms. (a) Original data. (b) After forward transformation. (c–d) Primaries are muted. (e) Inverse transformation. (f) Estimated primaries after (e) are subtracted from (a). (After Kabir and Marfurt, 1999.)

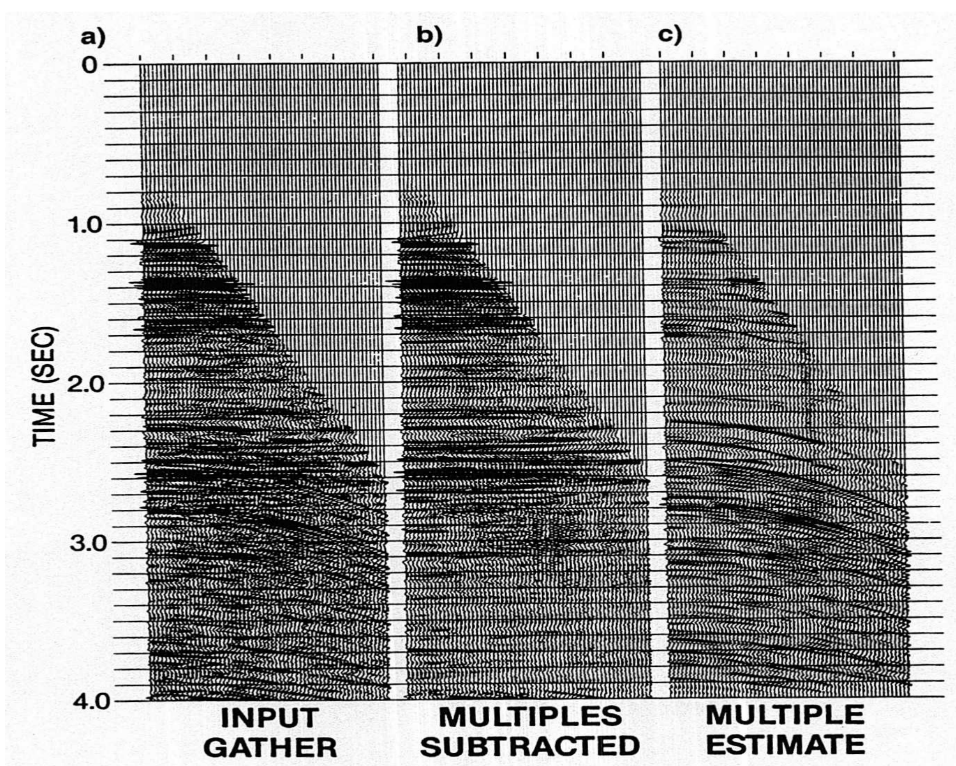
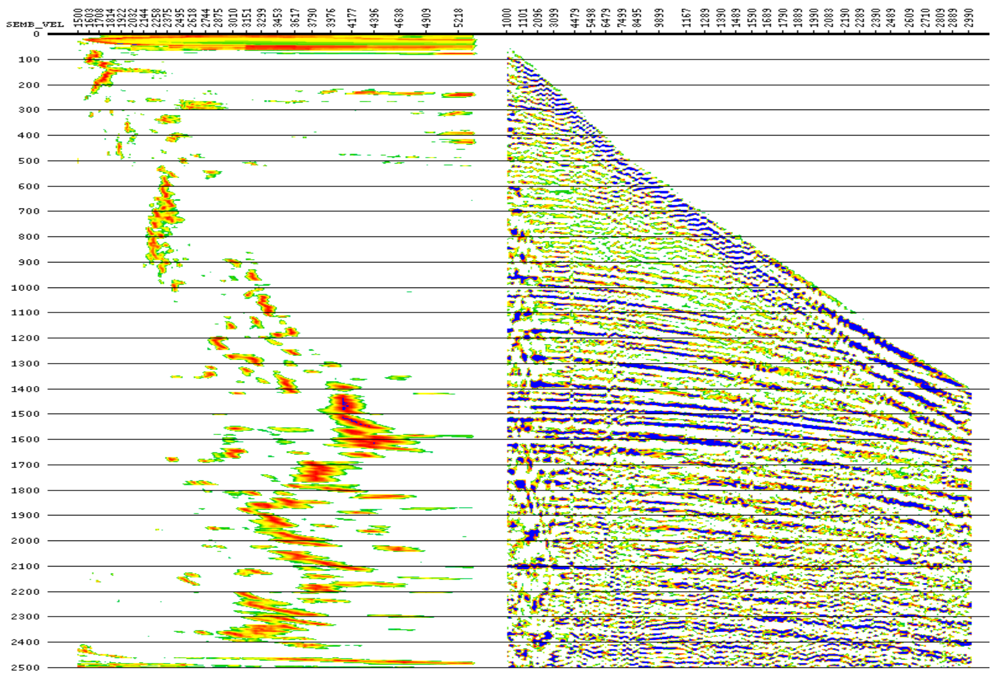


FIG. 3. (a) A raw CMP gather after a normal moveout correction; (b) the primaries after Radon filtering; (c) estimate of multiples in the gather (a). (After Foster, 1992.)



(a) (b)

FIG. 4. (a) A hyperbolic Radon transform of the attached CSP gather (b). (After Bancroft, 2003.)

The high–resolution semblance plot in Figure 4a is a hyperbolic Radon transform of the attached CSP gather (b). Note the fidelity and separation of the primary and other energy that includes multiples and possibly converted–wave energy. Multiple energy can be identified in vertical bands that have the same velocity.

Method 3: Wavefield predication and subtraction methods

Wavefield prediction and subtraction methods, based on the wave equation, use recorded data or models to predict multiples. Wave extrapolation and inversion procedures then subtract the predicted multiples from the original data to obtain multiple–free data. The most striking advantage of wavefield predication and subtractions over other methods is its ability to suppress all multiples, especially the multiples that have stacking velocities close to the primary reflections without coincidentally attenuating the primaries. If one is interested in prestack analysis of the data, for example, amplitude–versus–offset analysis, then prediction and subtraction may be the only suitable multiple–attenuation method.

The source wavelet or the reflectivity are not usually known from separate observations and must be estimated from seismic data by minimization of energy. Wavefield prediction and subtraction methods define a multiple–suppression algorithm as an optimization problem in which the data with minimum energy are considered to be multiple–free.

These methods seek data with minimum energy by adaptive subtraction of the predicted multiples, given the knowledge of the source function or the reflectivity. Accordingly, these methods are broadly classified into two categories: one based on the estimate of the source function, referred to as source–related multiple–suppression methods, and the other requiring knowledge of the reflectivity of the structure, referred to as reflectivity–based multiple–suppression methods (Liu, 2000).

At present there are three different wavefield prediction and subtraction techniques. They are wavefield extrapolation, feedback, and inverse–scattering series techniques (Weglein, 1999). Wavefield extrapolation techniques belong to reflectivity–based multiple–suppression methods (Lokshtanov, 2002; Wiggins, 1999; Wiggins, 1988). Feedback and inverse–scattering series techniques belong to source–related multiple–suppression methods (Verschuur et al., 1992; Weglein et al., 1997).

REFLECTIVITY–BASED MULTIPLE–SUPPRESSION METHODS

Wavefield extrapolation is a reflectivity–based multiples suppression method and mainly suppresses surface–related multiples generated at water layers and ocean bottom. We will take wavefield extrapolation methods as an example to show how a reflectivity–based multiple–suppression method predicts multiples.

Figure 5 shows the relationship between water–bottom multiples and primaries at the water bottom. The upgoing wave just above the water bottom consists of both the primary reflections transmitted through the water bottom and the reflected downgoing wave, gives (William, 1988):

$$u^{ABOVE} = u^{BELOW} + r_B \bullet d$$

where

u^{ABOVE} is the upgoing wave above the water bottom,

u^{BELOW} is the upgoing wave below the water bottom, and

d is the downgoing wave above the water bottom.

It is obvious that u^{BELOW} is the water–bottom multiple–free signal that we want to obtain.

$$u^{BELOW} = u^{ABOVE} - r_B \bullet d$$

Where u^{ABOVE} can be obtained by backward wavefield extrapolation to water bottom; d can be obtained by forward wavefield extrapolation to water bottom, and the water–bottom multiple–free signal u^{BELOW} are calculated by seeking data with minimum energy by adaptive subtraction of the predicted multiples.

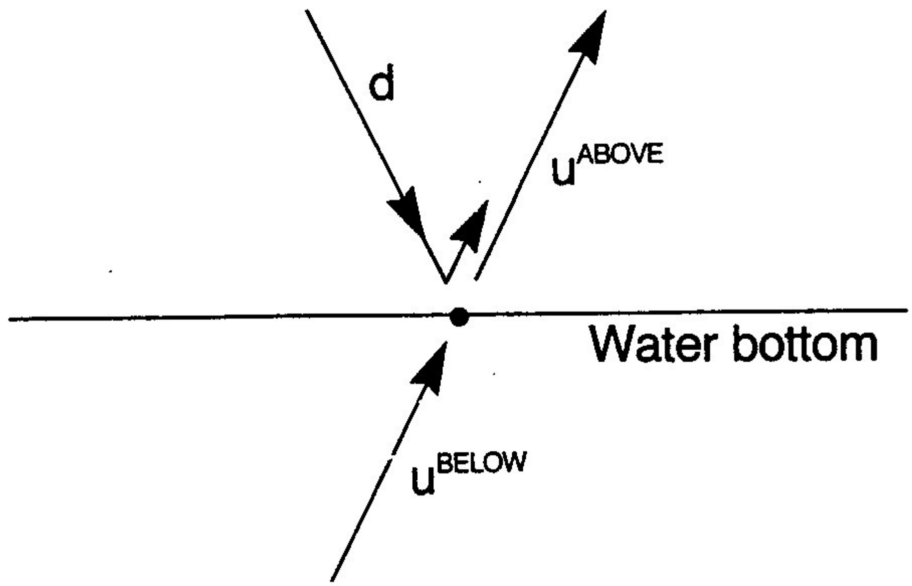


FIG. 5. The relation between downgoing and upgoing waves at the water bottom (after William, 1988).

The process above predicts and remove the water–bottom multiples, but the result represents the wavefield just above the water bottom as shown. To recover the wavefield at the recording datum, another wave extrapolation is required to move forward in time and upward to the surface. This third extrapolation completes the water–bottom multiple–attenuation process for one shot gather.

For a near–horizontal seabed, an f–k domain extrapolation operator is the most efficient method to use in CMP gathers. For a dipping or complex water bottom, Kirchhoff operators are used for wavefield extrapolation in shot gathers as illustrated in Figure 6.

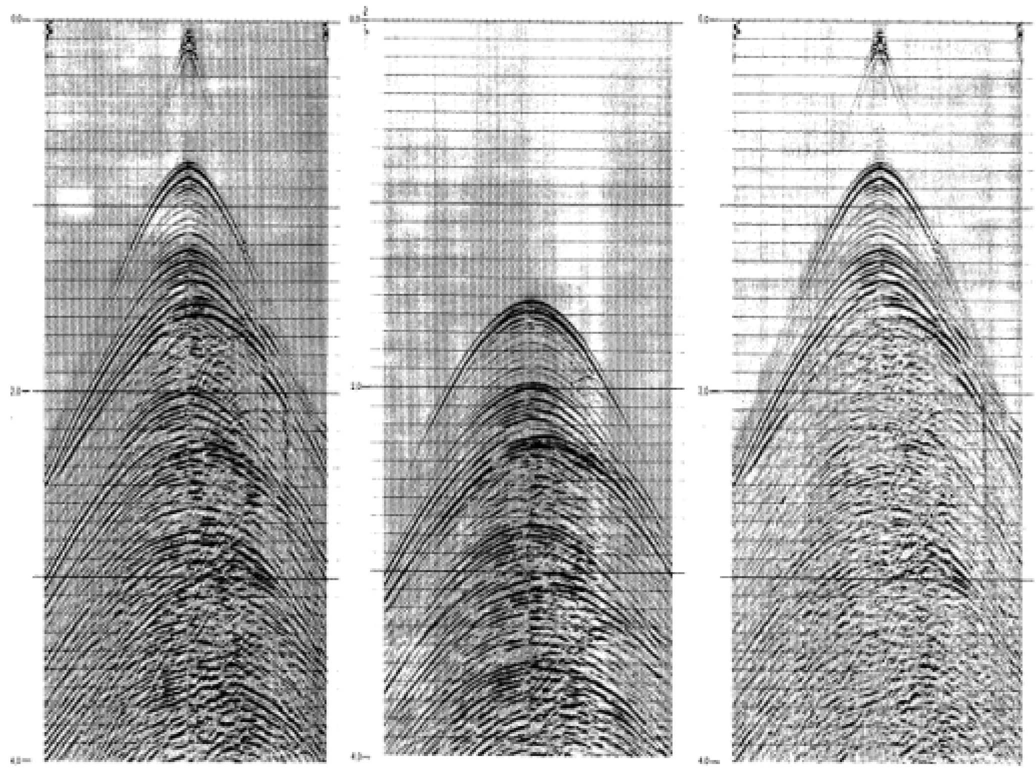


FIG. 6. The left panel is a split–spread, common–source ensemble of seismic traces as input. The middle panel is the result of performing wavefield extrapolation forward in time to water bottom and then forward in time to the recording datum. The right panel is the result of subtracting the predicted multiples (middle) from the original input (left)—removal of deep–water peg–legs and multiples. (After Berryhill, 1986.)

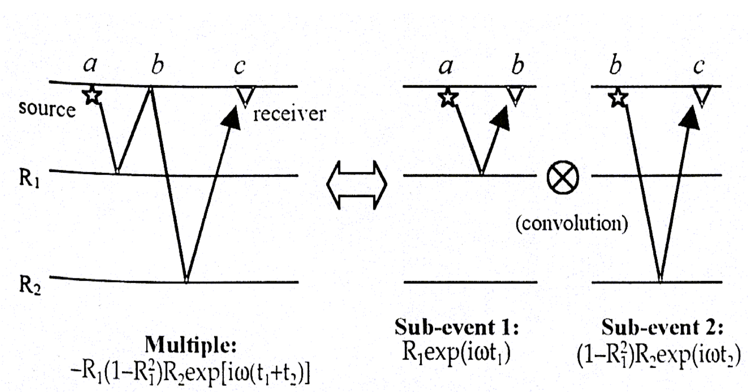


FIG. 7. Subevent construction of a free–surface multiple (After Matson, 1999).

SOURCE–RELATED MULTIPLE–SUPPRESSION METHOD

Inverse–scattering series and feedback techniques belong to source–related multiple–suppression methods and they can suppress both free–surface multiples and internal multiples. Inverse–scattering series suppress one–order multiples generated at all interfaces simultaneously (Ikelle, Amundsen, and Eiken, 1997; Ikelle, 1999) while feedback methods can suppress all order multiples generated at one complicated interface at a time (Berkhout and Verschuur, 1997; Berkhout, 1999).

For free–surface multiples, feedback methods need no additional information. For internal multiples, feedback methods need a prior velocity model and an *a posteriori* interpretation decision at each reflector. Inverse–scattering series need no additional information for either free–surface multiples or internal multiples. The difference between inverse–scattering series and feedback techniques is that the formatter is a free–surface and scatterpoint model with a monopole source while the latter is free–surface and interface model with a dipole source. Feedback and inverse–scattering series treat free–surface multiples in a similar fashion. Their major strength is that they can suppress free–surface multiples and do not make any assumption about the subsurface. Inverse–scattering series removes multiples through wavefield prediction and subtraction. It does not require subsurface information to suppress internal multiples. The multiples are predicted by spatial and temporal convolution of the original prestack data.

How does this type of multiple–suppression methods predict multiples? Suppose we have a multiple as shown in Figure 7. This multiple is generated at source *a* and received at the receiver *c* as shown on the left of this figure; it can be taken as the convolution of two subevents as shown on the right of this figure, but they have two differences: they have the opposite sign, and the actual multiple contains one source wavelet while the convolution result contains two source wavelets. The construction of free–surface multiples by convolution of subevents works for any event that strikes the free surface one or more times regardless of the path of the event in the subsurface (after Matson, 1999). Just as the temporal convolution acts to predict the proper traveltime of the multiple, the spatial convolution acts to predict the proper offset because the sum of the offsets of the two subevents will equal the offset of the multiple.

Following this logic, every event in the record can be thought of as a subevent for a free–surface multiple somewhere in the data. By convolving all the data with it, all the subevents are convolved together, thus constructing all the free–surface multiples. The input to the algorithm is just the multiple–contaminated prestack data sets. The output is a second prestack data set that contains just the predicted multiples. By subtracting this second data set from the original input data, the multiples are removed while the primaries remain intact (Matson, 1999).

The great advantage of the algorithm is that no subsurface information is required, but it does have two requirements. The first requirement is that all the needed subevents must be recorded or estimated to properly predict the multiples. The second requirement is that the source wavelet must be removed from the multiple estimates before the multiples can be subtracted from the data. If subevents are missing or contain errors, free–surface multiples that contain those subevents will not be predicted accurately. Consequently, missing near–offsets is an important issue since all free–surface multiples that contain subevents in the missing offset range cannot be predicted. In practice, the near offsets must be extrapolated or in filled. In addition, the actual recorded multiple contains only a single source wavelet while the multiple estimates, which are formed by convolving shots together, contains two source wavelets. Therefore, one of the source wavelets must be removed from the multiple estimates so that the estimate can properly present the multiple in the data. Figure 8 shows the result for surface–related and internal multiples suppression.

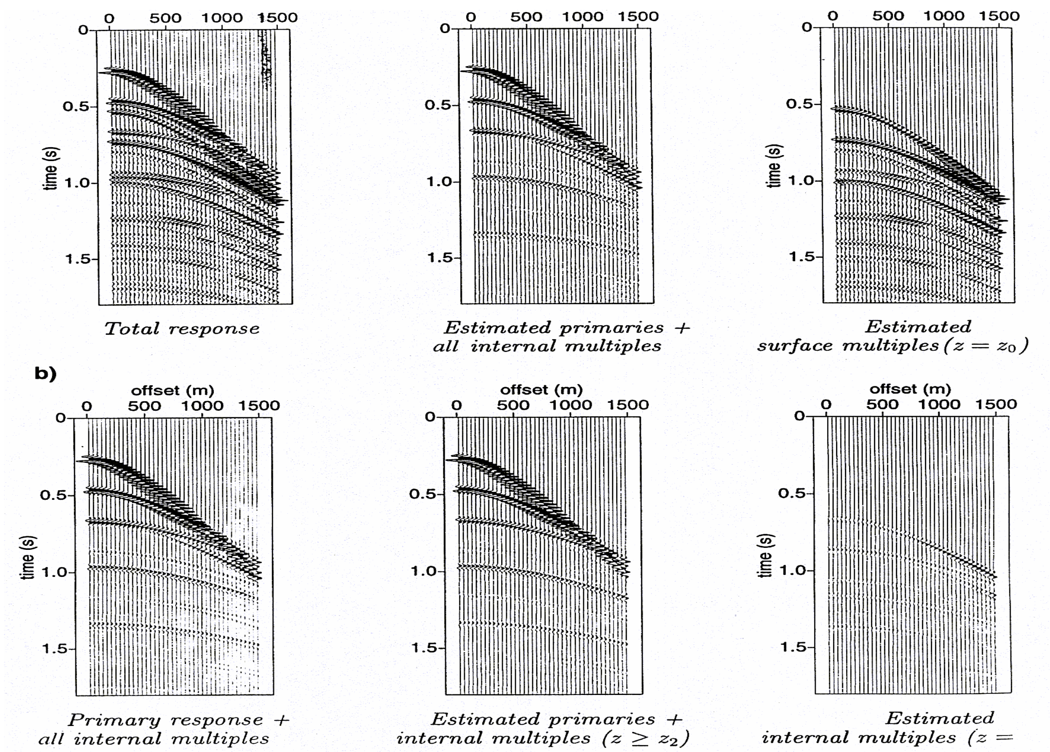


FIG. 8. (a) Surface–related multiples and (b) elimination of the internal multiples related to the sea bottom (*z*=*z*1) (after Berkhout et al., 1997).

PRACTICAL ISSUES FOR WAVEFIELD PREDICTION AND SUBTRACTION METHODS

Wavefield prediction and subtraction methods are the most promising methods of multiple–suppression, but they cost considerably, and are limited by data acquisition and processing more than other methods.

A major disadvantage of these algorithms is the need for good estimates of source wavelets and reflection coefficients. Theoretically, if one knew the acquisition wavelet, its effects could be removed completely from predicted multiples by deterministic deconvolution. If the acquisition wavelet is unknown and nonstationary, then some kind of minimization procedure is necessary to find a wavelet that makes predicted multiples a best match to the actual multiples. This is a costly procedure.

The most serious limitation of wavefield prediction and subtraction method is the relatively long time required for the computation because of the greater trace lengths involved in deep–water data. Wave extrapolation to an arbitrary shallow reflector (water bottom), when carried out as a Kirchhoff summation, requires a time that is approximately proportional to the square of the number of traces in a shot gather. In contrast, if one assumes that the shallow reflector (water bottom) is flat, a simple phase shift in the f–k domain can be used in extrapolation, therefore reducing computation time to an amount comparable to that of other multiple–attenuation methods. Widespread use of this method for irregular reflectors such as water–bottom will require either more efficient extrapolation algorithms or further dramatic advances in computing economics.

Other limitations in the quality of predictive multiple attenuation arise from out–of – plane reflection, cross–line dip, lack of near–offset data, cable feathering, inadequate dynamic range, and wavefield spatial sample (Dragoset, 1999).

Out–of–plane reflection

It should be noted that with data collected in the usual way, the wavefield prediction and subtraction methods could be applied only as a 2D process. To predict multiples reflected from outside of the vertical plane of the survey, one would have to collect the wavefield from a given source position with a 2D array rather than a linear streamer.

Cross dip issue

Wavefield prediction and subtraction is strictly 2D; it will not attenuate multiples that have a significant cross–line component in their raypaths. As shown in Figure 9, the two primary legs of left–hand multiple in Figure 9 are not separately recorded in the 2D data set, even though the multiple itself is recorded. The multiple cannot be predicted from information inherent in the data. On the right of Figure 9 is the opposite situation: a primary event is recorded but its matching multiple is not recorded. Wavefield prediction and subtraction will predict a multiple which not was recorded. Thus, wavefield prediction and subtraction methods would fail because the wavefield is missing crucial information. The obvious solution to this problem, widening the cross–line aperture, may be practical for ocean–bottom cable acquisition but may never be practical for streamer acquisition. Shooting in the dominant dip direction of the reflectors, which is the major source of surface multiples can, however, minimize the effects of cross–dip.

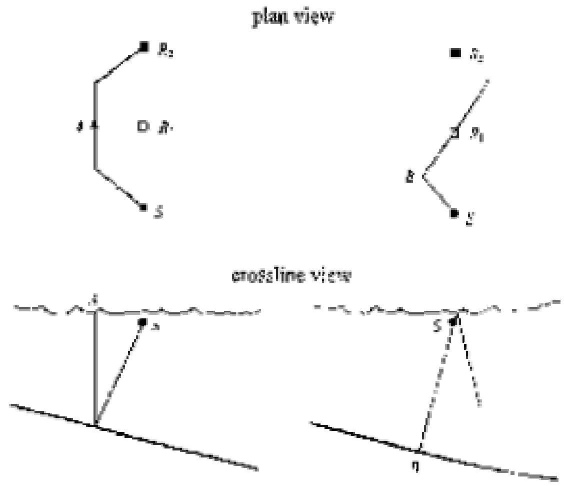


FIG. 9. Problem caused by cross–dip. On the left is the raypath of a record surface multiple whose primary piece is not recorded. The opposite situation is shown on the right. (After Dragoset, 1999.)

Lack of near–offset trace

Lack of near–offset data prevents accurate prediction of the multiples at the nearest nonzero offsets that are actually present. If wave–equation prediction were to be used, a near–offset of zero would be best, while long offsets may not be as important.

The finite extent of marine 2D recording geometry causes problems for surface–multiple attenuation similar to those just described, even when cross–dip is not an issue. Figure 10 shows a sketch of the near–offset end of a typical 2D recording geometry. In the sketch a water–bottom multiple is present in the near–offset trace, but the two primary legs of that multiple are not recorded because they occur at offsets smaller than the near offset. Thus, the recorded wavefield is not internally consistent; it contains multiples for which there are no corresponding primaries.

There are two possible solutions to the finite near–offset by either better field recording, or wavefield extrapolation. In the field, positioning the source as near as possible laterally to the first receiver group can minimize the near offset. The other solution is to numerically extrapolate the field after recording. At present, the extrapolation method has been the more satisfactory (Berryhill, 1986). Nevertheless, field geometries should be designed so that only a few missing near–offset traces have to be extrapolated. Therefore, recording precritical near–offsets in shallow reflectors will enhance the performance of multiple–suppression algorithms and allow them to reach their full potential.

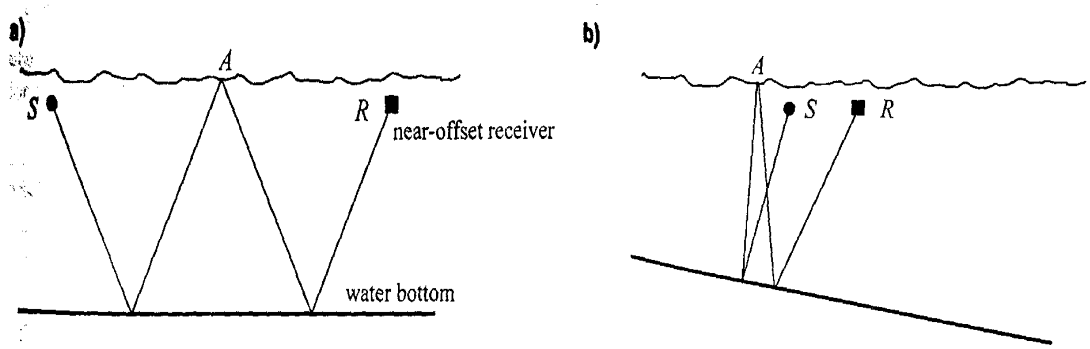


FIG. 10. Problem caused by a finite recording aperture. (a) The primary events that make up surface multiple SAR are not recorded because their offsets are shorter than the cable' near offset. (b) Even if the near–offset is zero, some surface multiples are not recorded because receivers are not positioned upstream of the shot. (After William, 1998.)

Having an offset range that begins at zero does not eliminate all aperture effects at the near–offset edge of a recorded wavefield. Figure 15b shows a water–bottom multiple SAR is recorded, as is its second leg, primary AR. The first leg, SA, is not recorded because at no time during the field recording is a shot located at position S when a receiver is located at position A. If the effect is ignored, surface multiple–attenuation does a poor job of removing multiples at near offsets.

A simple solution to this problem is to assume that source–receiver reciprocity is valid. Then, missing event SA could be recovered by primary event AS, which is recorded when a source is at A and a receiver is at S. In other words, source–receiver reciprocity can be used to make the usual marine end–on spread geometry look like a split–spread geometry.

Cable feathering

Cable feathering is a troublesome cause of distortion between primaries and multiples in a 2D data set. Figure 11, a simplified plan–view sketch of a marine acquisition system, shows how cable feathering produces such distortion. Suppose the dashed line represents a vertical plane containing raypath SAR of a first–order surface multiple. It can be seen from the figure that the actual primaries are never recorded because at no time there is a source at S with a receiver at A and a source at A with a receiver at R.

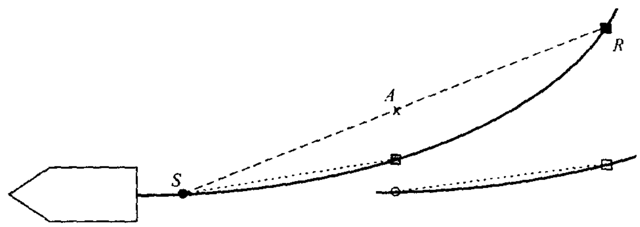


FIG. 11. Problems caused by cable feathering (after Dragoset, 1999).

Inadequate dynamic range

If the data acquisition recording system has an inadequate dynamic range, then the resulting amplitude distortion makes that event unsuitable for predicting multiples. This problem is most likely to happen in shallow–water areas, where the near–offset amplitudes of the water–bottom primary event can be unusually large because of the short travel path.

Wavefield spatial sampling

As with Kirchhoff migration, the spatial sampling should be dense enough to avoid aliasing of dipping events in the bandwidth of interest. In addition, the spatial sampling of the wavefield on one side of the aperture may differ from that of the wavefield on the opposite side, causing some problems. If spatial aliasing is an issue, interpolation is a better solution than decimation to the problem of mismatched wavefield sampling in the Kirchhoff integral aperture.

CONCLUSIONS

There is no optimum method for multiple–suppression. The performance of each technique depends on the particular data example under consideration, and on how well a particular data set fits the assumptions of each multiple attenuation algorithm.

Alternative methods of multiple–suppression should not be used before wavefield prediction and subtraction methods are applied because these multiple–suppression methods require the complete wavefield.

The choice of multiple–suppression methods is based on the effectiveness, cost, and processing objectives.

Recording precritical near–offsets in shallow reflectors will enhance the performance of multiple–suppression algorithms and allow them to reach their full potential.

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