A MULTIPLE SUPPRESSION METHOD VIA CRS ATTRIBUTES

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keywords: *Multiple suppression, Imaging*

ABSTRACT

Multiple identification and attenuation are one of the most challenging tasks in the seismic data processing chain. We are presenting two approaches for identification of surface related multiples within the CRS workflow, since that a complete workflow from time to depth imaging with the CRS technology is possible. One approach focusses on the multiple identification with CRS attributes (i.e. the angle of incidence). The second one is based on the multiple prediction by autoconvolving each stacked trace with itself (hybrid SRME-CRS approach). The implementation of both methods is done with focus on automating the process. After the multiples are identified/predicted they are modelled with the CRS attributes, adaptively filtered, and subtracted from the prestack data. Initial tests are performed on two synthetic data sets. For both methods the results are quite promising. The identified/predicted multiples could be successfully removed from the data sets. The identification of multiples with CRS attributes has the potential to handle also quite noisy data and can also be extended to internal multiples. The prediction with the autoconvolution is simple and robust, but also produces some prediction errors due to theoretical assumptions involved in this concept.

INTRODUCTION

With the help of the CRS technology (Mann, 2002; Duveneck and Hubral, 2002) a complete workflow for imaging seismic data is possible. With the necessary preprocessing applied, we can directly go from time to depth imaging with the help of the CRS stack, the NIP-wave tomography and a corresponding prestack depth migration algorithm. This workflow is also called the 'CRS-workflow' (Hertweck et al., 2003). One of the aspects that reduces the applicability of this workflow are multiple reflections present in the data, since they provide information of the subsurface that can not be used directly in the above mentioned technologies (i.e. most migration methods rely on primaries only). The multiples have to be removed in one of the preprocessing steps. This is a quite challenging task, since the success of the removal strongly depends on the methods and the geological situation that has to be dealt with.

The most prominent methods available are Surface Related Multiple Elimination (SRME) after Verschuur et al. (1992), the inverse scattering series after Wegelein et al. (1997), and the hyperbolic radon transform, see for example Ryo (1982). For shallow water environments the predictive deconvoluton is also widely used. All of these methods have theirs advantages and disadvantages, for several reason (data density, regularization of the data, wavelet knowledge, computational efforts, etc.).

In the frame of this paper we will discuss, some ideas to incorporate multiple suppression within the CRS workflow. For this reason we will present results of two implementations for identifying multiple reflections in stacked data and removing them with the help of CRS attributes.

The first concept follows basically the work of Zaske et al. (1999) and is based on the general assumption that multiple reflections can be constructed from primary reflections. For surface related multiples, the point where both primaries are connected has to fulfill Snell's law. This means that the angles of incidence and emergence have to be equal at this point. The angle of incidence for the ZO situation is directly determined by the CRS stack and can be calculated with respect to the offset cordinate. This can be used to

detect a possible multiple ray-paths.
The second approach is based on the work from Kelamis and Verschuur (1996). The basic idea is that the autoconvolution of a seismic trace with itself predicts multiple reflections. This concept is applied in the poststack data domain and provides a direct prediction of the ZO traveltimes of the multiples.
After detecting the possible multiple reflections, for both methods prestack spike seismograms are calculated with the help of the corresponding CRS attributes. These seismograms are then adaptively filtered, so that the wavelet is matched to the original data. Afterwards the shaped seismograms are subtracted from the original data, to obtain multiple attenuated data sets.

THEORY

In this chapter both above mentioned methods will be discussed in detail. For the initial tests only surface related multiples will be addressed. Due to the limitations of each method, both could be used complementary in the future, but for now each approach is used on its own.
The methods first identify/predict the multiple reflection and afterwards model the corresponding prestack seismograms with the help of the CRS attributes. Then the modeled seismograms are adaptively subtracted from the original prestack data to obtain multiple attenuated data sets.
A full CRS stack needs to be performed on the data and also the multiple reflections are stacked during this procedure. We need the kinematic wavefield attributes of these reflections to remove them later on. We also have to identify the possible multiple generating horizons in the data set. This is done by an automatic picking procedure, similar to the one presented in Müller (2007). An initial seed pick has to be given and the algorithms performs an automated picking basically on the second order hyperbolic ZO traveltime formula and the corresponding coherency section of the CRS stack. This works quite well for shallow horizons (i.e. the water bottom) because they yield high coherency values. After picking we have a spike ZO section of the main multiple generating horizons.

Identification with CRS attributes

To identify multiple reflection with the help of CRS attributes we are basically following an approach suggested by Zaske et al. (1999), who used this concept in the frame of the homeomorphic-imaging method (Gelchinsky, 1989). The general idea is that every multiple reflection can be constructed from two primary reflections, thus we are searching for so called multiple reflection constructing primaries (multiple constructors).
In the case of a surface related multiple reflection, the ray of the multiple is at least once reflected at a surface point BP (see Fig. 1). Following Snell's law the angle of incidence α_1 is equal to the angle of emergence α_2. Due to the reciprocity of the ray path the multiple can be constructed from a primary reflection originating at the source (orange ray in Fig. 1) and a second ray that originates at the receiver (red ray in Fig. 1). Both coincide at point BP, where the multiple is reflected at the surface. In this way the complete multiple traveltime can be identified, by finding the corresponding rays, that fulfill Snell's law at the surface. Afterwards the multiple traveltime can be calculated with $t_m(h_m) = t_1(h_1) + t_2(h_2)$. This concept can also be extended for internal multiples, i.e. multiples that are not reflected at the surface. For further details see Zaske et al. (1999). The transformation of this approach to the CRS case is straight forward. To identify the possible multiple constructors in the data all possible angles of incidence have to be compared with all possible angles of emergence. Since we determine the angle of incidence for the ZO case during the CRS processing, we can also calculate the angle of incidence for a certain offset with the help of the following expression, which follows from simple geometrical considerations and a locally spherical wavefront assumption.

$$\sin\beta(h) = \frac{h + R_{NIP0}\sin\alpha_0}{\sqrt{R_{NIP0}^2 + 2R_{NIP0}h\sin\alpha_0 + h^2}} \qquad (1)$$

Here $\beta(h)$ is the angle of incidence for a certain offset, R_{NIP0} and α_0 are the radius of the NIP-wave and the ZO incidence angle. h represents the half offset cordinate.
This is done for every shot position in the data, so a complete data set of angle variations is available. To obtain the angles of emergence we simply make use of the reciprocity of the ray path.

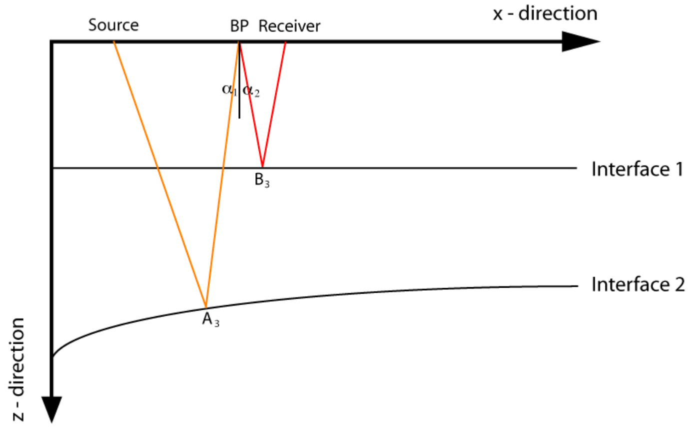


Figure 1: Ray path of a surface related multiple. It can be constructed from two primary reflections (after Zaske et al. (1999)). Following Snell's law the angle of incidence and emergence at point BP have to be the same.

The implemented procedure works as follows: For the considered shot position all angles with offset are compared to the angle variation with offset of all corresponding receivers within the aperture. If a possible multiple constructor is found, the corresponding multiple traveltime is calculated and stored together with the considered offset (see Fig. 2). This procedure is repeated for all shot positions. Afterwards the higher order water bottom reverberations are constructed from the detected first order reverberations by combining their raypaths. This means a second order water reverberation can be constructed from two first order ones, if the source of the second multiple coincides with the connecting point of the first one and the connecting point of the second coincides with the receiver of the first. This can be done up to n-th order of the water reverberations.

To determine the corresponding CRS attributes (i.e. ZO attributes), we have to determine the t_0 traveltimes

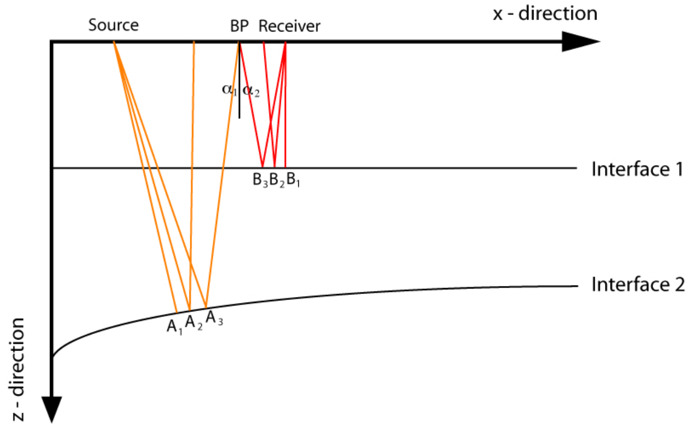


Figure 2: Comparison scheme: Each angle of incidence/emergence is varied over a certain offset range and compared to the corresponding angle variations of each receiver position within the aperture.

of the multiple reflections. At the moment only multiple traveltimes at a certain offset $t(h)$ are determined. To obtain the ZO traveltimes and thus the CRS attributes of the multiples, a minimum energy fit of all stacking operators found during the CRS stack and the detected multiple traveltimes is perfomed. The determined traveltimes of the multiple reflection are compared with the traveltime predicted by the CRS stacking operators, and thus also to the stacking operator of the considered multiple reflections. The t_0 of the multiple reflection is determined by the best fitting stacking operator:

$$E = \Sigma_i (t_{DETECi} - t_{CRSi})^2 \longrightarrow Min \tag{2}$$

Afterwards all CRS attributes (idicated by the ZO traveltime) of the multiple reflection are determined and we can model prestack spike seismograms for the multiple reflections. These will be adaptively shaped and subtracted from the original prestack data set.

Prediction with PSRME

The multiple prediction with poststack SRME (PSRME) is based on the work of Verschuur et al. (1992) and the ideas presented in Kelamis and Verschuur (1996). Here the SRME process is simplified to the case that it can be applied to a single trace (i.e. 1-D earth model) or stacked data. In this approach the assumption is made that the stacked data can be considered as plane waves and a local homogenous medium is assumed. This is not fulfilled in reality and results in prediction errors, but for moderate inhomogenous media the PSRME process can still predict multiples quite well.
The idea is that an autocovolution of a seismic trace $x(t)$ with itself results in a first order surface related multiple prediction $M_1(t)$ (after Verschuur (2006)):

$$M_1(t) = x(t) * x(t) \tag{3}$$

Next the first order multiples can serve as a source for the second order multiples:

$$M_2(t) = M_1(t) * x(t) = x(t) * x(t) * x(t) \tag{4}$$

This can be repeated until n-th order (see Fig. 3). This is all we need from the actual SRME process, since we have a ZO spike seismogram from the automated picking algorithm, there is no need for us to care about the wavelet of the multiples. We just autoconvolve the ZO spike section with itself and repeat this until we reach the desired order of multiples. We than have a ZO traveltime prediction of our multiples and thus determined the corresponding CRS attributes. Afterwards we can directly model the multiple prestack spike seismograms from the CRS attributes and again apply the adaptive filtering process which will be discussed in the next chapter.

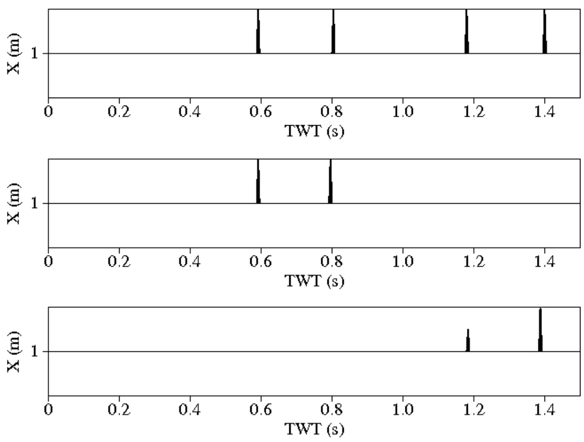


Figure 3: Basic principle of poststack SRME. The upper figure shows all reflections including the multiples, the image in the middle displays the autopicked horizons and the last figure presents the predicted multipes. Note that the amplitude of the prediction is not taken into considerations.

Subtraction of multiples

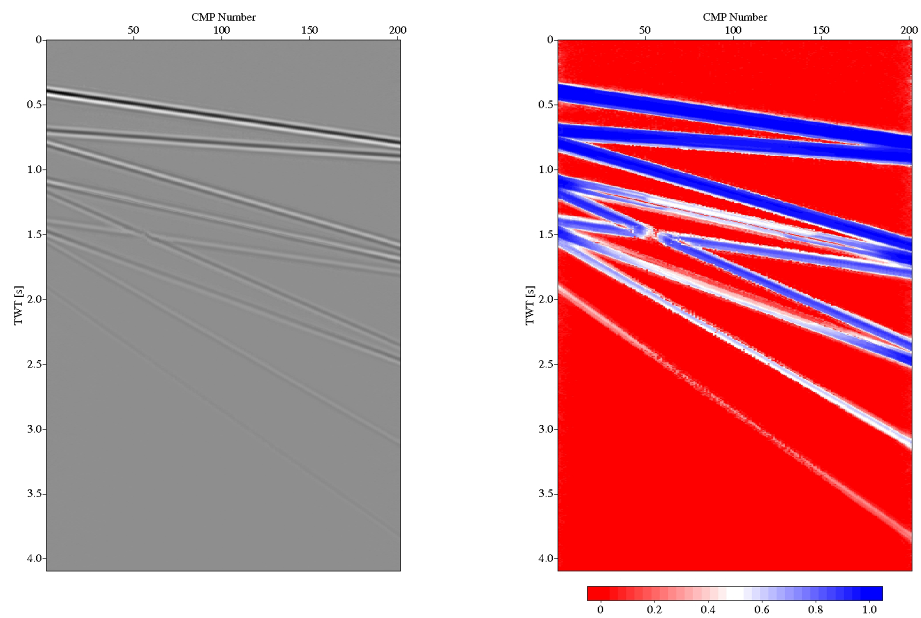
The subtraction of the modeled multiple prestack data sets from the original data set is done by adaptively filtering the spike data set. The adaptive filtering part in this work uses the implementation of Gamboa et al. (2003). The spike seismograms are shaped to match the source wavelet of the original data set.
In the implementation a Wiener optimum filter is used to fit the input seismograms to the desired original data, during this a linear set of equations is solved. It contains a Toeplitz matrice with the autocorrelations of the input signal as elements, the desired filter coefficients and the autocorrelations of the output signals (see Yilmaz (2001) for further details). The systems is solved and the best filter coefficients are determined to fit the input data to the desired output. After the adaptive filtering process the shaped seismograms are subtracted form the original data to obtain the multiple attenuated data set.

SYNTHETIC DATA EXAMPLE

In this section the first results of the above mentioned implementations will be presented. The multiple suppression was performed on two synthetic data sets, where the first one (MulMod) is less complex than the second one (Bastard). Currently both methods address surface related multiples. In the case of the identification with CRS attributes only water column reverberation are considered, in the second case of PSRME all kinds of surface realted multiples can be addressed.

MulMod data set

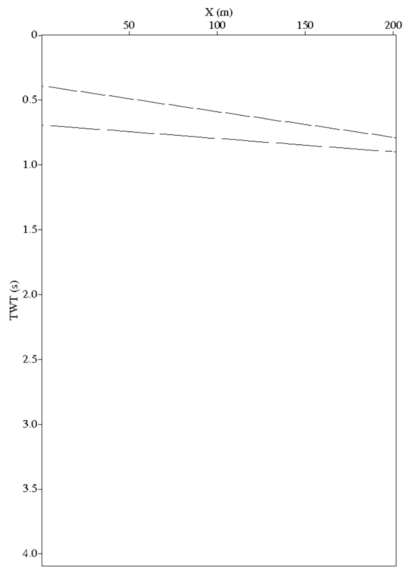
The MulMod data set consists of 201 CMPs and two primary reflections, all other reflections are multiples. Two are internal multiples and will remain after the multiple subtraction since they are not considered. The data set was processed by means of a CRS stack, where all multiple reflections were also stacked, in Fig. 4(a) and Fig. 4(b) we can see the stack result and the corresponding coherency section, respectively.



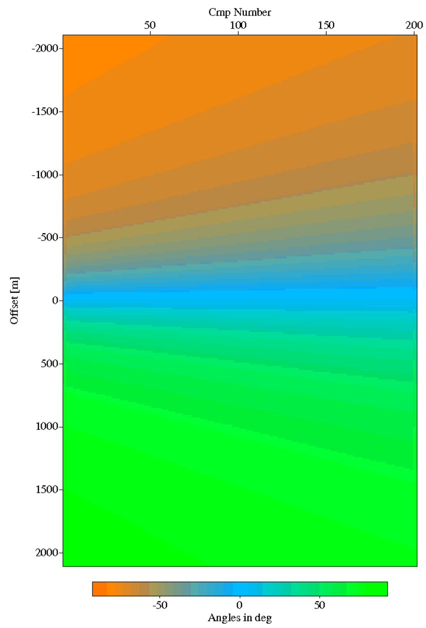
(a) CRS stack. **(b)** Corresponding coherency section.

Figure 4: The result of the CRS stack applied to the MulMod data set. In the left figure the stacking result is shown and in the right figure the corresponding coherency section is presented. Only the first two reflections are primaries.

Identification with CRS attributes The first step in the application of this method is to trace the multiple generating horizons. In this case it can be done quite easily, since only the first two reflections are primaries. Given two initial seed picks the algorithm automatically traces the horizon along the coherency section and produces a ZO spike section of the primaries (Fig. 5(a)) and a section in which all angle of incidence variations according to equation (1) are stored (Fig. 5(b)). Since the implementation of this approach can only handle ocean floor reverberations at the moment, only the first picked reflection is taken into account.
Next all angle variations with offset are compared with all other angle variation from receivers within the



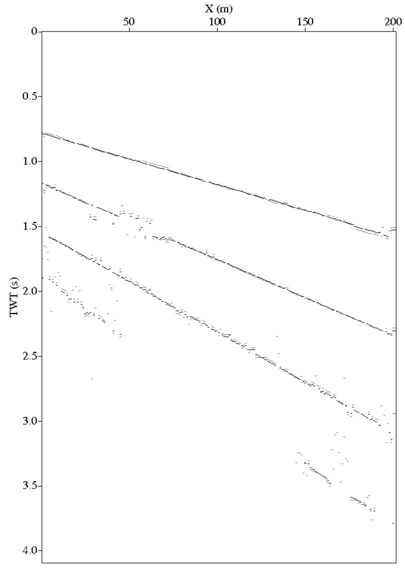
(a) Autopicked primary reflections



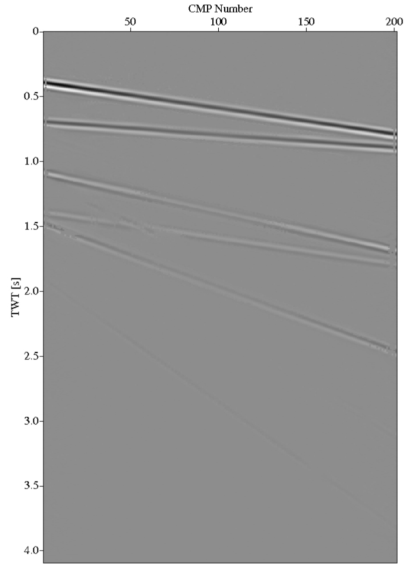
(b) Variation of angle of incidence

Figure 5: Autopicked multiple generating horizons (left) and angle of incidence variations with offset (right). The vertical axis is the offset and on the horizontal axis is CMP location.

aperture. If the angles are equal a possible multiple constructor is found and the corresponding traveltime and offset are stored. Then the corresponding t_0 traveltime is determined by the best fitting stacking operator (as described in the theory section).
In Fig. 6(a) the resulting multiple prediction for the ZO case is imaged. We see that the first, second, and third order water column reverberations are quite good estimated. In the second one, we see some problems with the conflicting dip situation. Here we have low coherency values, thus also the CRS attributes are not reliable and the identification fails. This is still an unsolved issue and has to be considered in the future work. For the fourth order reverberation we see a gap in the prediction. This is due to the fact that we need a certain offset to predict the fourth order reverberation in the data. But since the acquisition of this data set was performed in a 'moving source' geometry, we do not have sufficient offset in the middle parts of the model to detect the multiple.
Now the CRS attributes related to the multiple reflection are detected and the multiple prestack spike data set can be calculated. These are adaptively filtered and subtracted from the original data. In Fig. 6(b) the resulting CRS stack after multiple attenuation is imaged. It is clearly visible that the first, second, and third order ocean floor reverberations are removed fairly well, the fourth one shows some residuals, especially in the middle part of the section, where no prediction was available. We also see a little residual for the second order reverberation in the conflicting dip situation. This is again related to an imperfect prediction in that area.
Generally the initial tests are quite successful in suppressing the ocean floor reverberation for this synthetic data set. There are still some problems in conflicting dip situations, but generally the multiples are identified and attenuated well. Further implementation work has to be done to implement more ray-paths for other



(a) Predicted multiple reflections



(b) Resulting CRS stack after multiple suppression

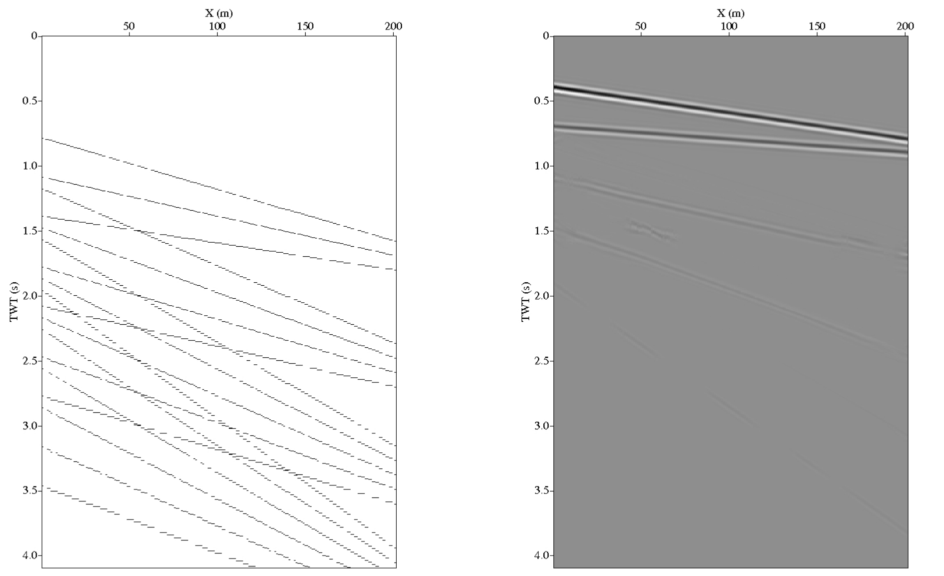
Figure 6: Predicted ZO traveltimes of the multiple reflections (left) and the CRS stacked section after the removal of the water column reverberations (right).

kinds of multiples (i.e. peg-leg multiples).

Prediction with PSRME To apply the poststack SRME prediction to the data set, we used the same ZO spike section as before (see Fig. 5(a), this time all picked reflections can be taken into account) and afterwards applied the trace by trace autoconvolution to obtain a prediction for all kind of surface related multiples. The result of the prediction is imaged in Fig. 7(a). We see that much more multiples were predicted than before. We applied the prediction up to fourth order. The prediction errors resulting from the assumptions made to derive this method, are moderate. We can immediately use this prediction to model the prestack data with the help of the corresponding CRS attributes.

The CRS stacked results after the multiple attenuation process is shown in Fig. 7(b). We observe that all multiples that were predicted are fairly well attenuated, except the fourth order water bottom reverberation. At the moment we do not know why the shaping filter fails to form the wavelet correctly. We see some residuals at the conflicting dip situation, but again this is related to the low coherency values in that area. Coherency values below a certain threshold are automatically rejected from the modeling. Still two dipping multiple reflections are present with a lower amplitude than in the result (Fig. 6(b)) before. Here the surface related multiples were removed but some internal remain. They are not processed by the method. In these cases the surface and internal multiples have almost the same ZO traveltime.

Generally we can say that the prediction and attenuation works quite good, for this data set. There are still problems in conflicting dip situations and shaping the fourth order water reverberation.



(a) Predicted multiple reflections

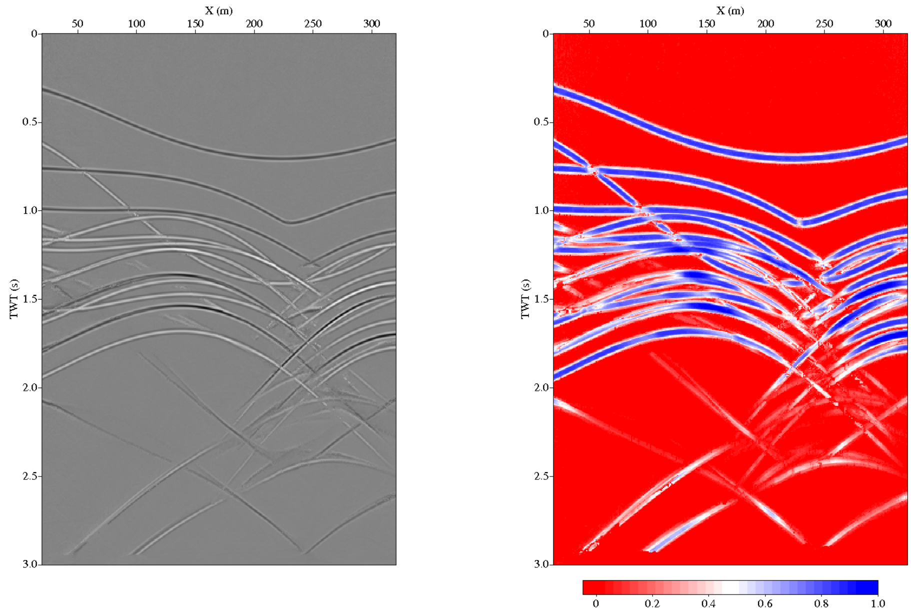
(b) Resulting CRS stack after multiple suppression

Figure 7: Predicted ZO traveltimes by PSRME of the multiple reflections (left) and the CRS stacked section after the removal of all surface related multiples (right). Only a residual multiple event from the conflicting dip situation and two internal multiples are visible.

Bastard data set

The Bastard data set consists of 301 CMPs. Four primary reflections and all kinds of multiple reflections are present. First a CRS stack was applied on the data set to obtain all necessary parameter for the multiple reflections. The CRS stack result and the corresponding coherency section are imaged in Fig. 8(a) and Fig. 8(b). In the coherency section we see that low coherency values occur in conflicting dips situation, so we expect that the algorithms will not perform well in these areas. We can also observe in the stacked section, that the primary reflections are overlying the multiples without a convolution of the wavelets (the multiple reflection seems to be interrupted), so we also expect some problems in applying the adaptive filtering routine.

Identification with CRS attributes To identify the multiple reflections by comparing the CRS attributes, we perform the automated picking algorithm. Only the ocean floor reflection is considered as a possible multiple generator, since the only visible ocean floor reverberation in this data set is the multiple of first order. The angle of incidence was varied for every identified event, to obtain the data for the comparison. Afterwards we identified the ZO traveltimes of the ocean floor reverberation (see Fig. 9(a)). Again we observe prediction errors next to conflicting dip situations. But we can also see from the stacked section in Fig. 8(a) that in the conflicting dip situations the identification has to stop since only the primary is left there i.e., the algorithm performs right to stop the identification in these areas.
After prediction we modelled the prestack data set with the corresponding CRS attributes, shaped them adaptively and subtracted the result form the original prestack data set. In the modelling process, we applied a small shift of the spikes towards the coherency maximum next to the spike location, to model with the best CRS attributes. This has to be applied very carefully, since we do not want to shift the spikes into an other reflection.
The resulting CRS stack section is shown in Fig. 9(b). We can observe that most of the ocean floor reverberation is removed and also that some of the conflicting dip situations are resolved quite well. But we can also see that some of the other multiples are attenuated unintentional. We have to further investigate

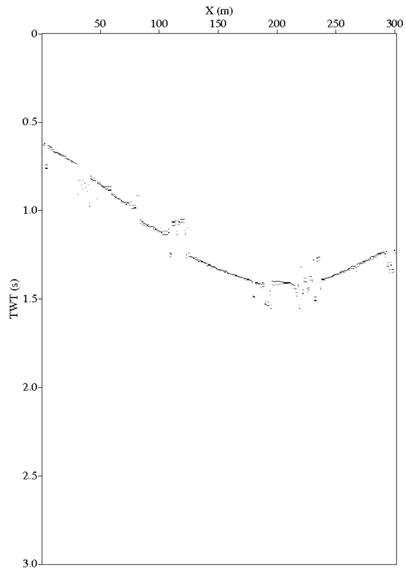


(a) CRS stacked section **(b)** Corresponding coherency section

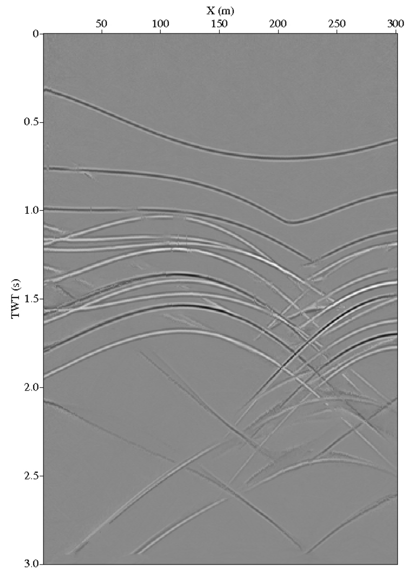
Figure 8: CRS stacked section of the Bastard data set (left) and the corresponding coherency section (right). Low coherency values occur at conflicting dip situations.

the identification of the multiple events in conflicting dip situations, but in general a quite promising first result is obtained.

Prediction with PSRME To predict the surface related multiples with PSRME, we autoconvolved the autopicked ZO section with itself. This time we applied the automatic picking algorithm to the first three horizons. The resulting prediction shows quite big errors in the area of the syncline structures and their related multiples, also for the steep dipping reflections we can observe some errors. Nevertheless, the estimate for the ocean floor multiples and some peg-leg multiples are quite good (see Fig. 10(a)).
To optimize the prediction, we also applied a small shift of all prediction to the next coherency maximum, this step has to be applied with care, so that the prediction will not get worse. We only used this within some samples, so large timing errors will not be corrected by this refinement.
The result after multiple subtraction and CRS stacking is displayed in Fig 10(b). The first ocean floor reverberation is removed quite well, also some of the peg-leg multiples are fairly well attenuated, but we also see that we got some problems in conflicting dip areas, where the subtraction also attenuated the primaries, or other multiple events that are crossing the considered event. Again this is not surprising, since we have no conflicting dip handling here and the time prediction of the multiples also affects other events in these situations.
Generally we can say that the initial tests with this method are promising, but especially in complex geological situations, we have to add some correction to the prediction of the multiples. Also the conflicting dip handling has to be improved, to not remove primary information from the data.



(a) Predicted ZO multiple times



(b) CRS stack of the multiple removed data set

Figure 9: Predicted ocean floor reverberation (left) and the corresponding CRS stacked section (right). The conflicting dip situations are partly resolved.

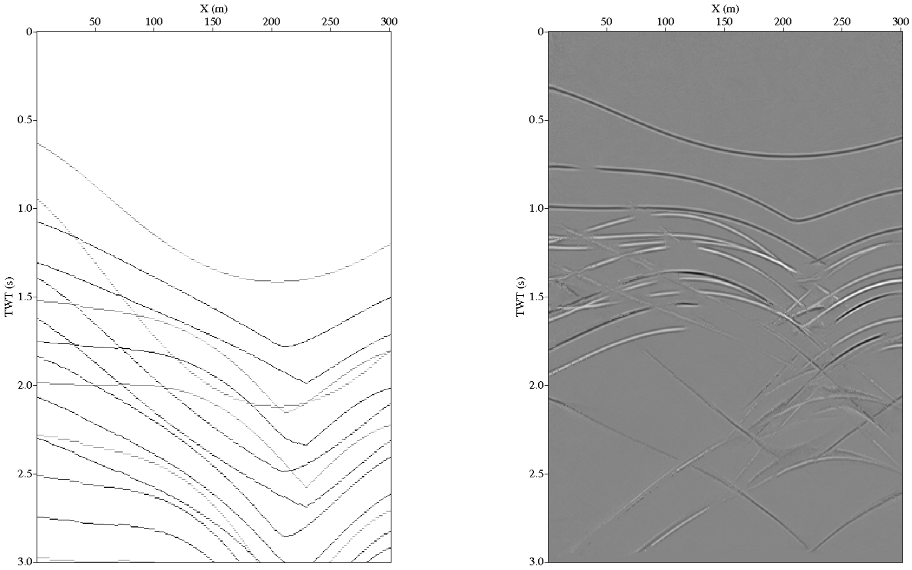
SUMMARY AND CONCLUSIONS

We have presented two implementations of multiple prediction approaches, that could be used complementary in the future within the CRS workflow. So far we could only present initial test results, but these show the potential of these methods used within the CRS frame work. Both methods are not dependent on the regularity of the data. Since they are both applied in the poststack data domain they can also handle sparse data, if the CRS stacking result is of sufficient quality. A disadvantage of both approaches is the dependency on the automated picking procedure and the related picking problems at fault zones.

The identification with CRS attributes has the potential to handle all kinds of multiple reflections, no velocity discrimination between multiples and primaries is necessary and it can also handle quite noisy data, because it is based on the good quality of the CRS attributes. The disadvantages of this approach are the huge implementation work for handling all kinds of multiples, the strong dependency on the quality of the CRS attributes and the identification errors in conflicting dip situations.

The prediction with the poststack SRME process is restricted to surface related multiples, but convinces with its robustness and simplicity. It is easy to implement and instantaneously predicts all surface related multiple reflections. The disadvantages are the assumption made to derive this approach and the related prediction errors. Again conflicting dip situations are a problem to be taken care of. The combination of both methods would be desirable to overcome some of the issues mentioned above.

The modelling and adative filtering process could also be optimised. With the help of the CRS attributes found for the multiples reflections we are also able to introduce some dynamics into the adaptive filtering problem. For example we could directly predict the amplitude of the multiple reflection from the CRS attributes. This would lead us closer to a solution of the wavelet shaping problem.



(a) PSRME multiple prediction

(b) CRS stack of multiple attenuated data

Figure 10: The PSRME prediction (left) and the corresponding CRS stacked section (right). Some events are attenuated unintentional.

ACKNOWLEDGMENTS

The authors would like to thank:

- *Eric Verschuur* for kindly providing the MulMod data set and the fruitful discussion
- *Paolo Marchetti* for kindly providing the Bastard data set and the fruitful discussion
- The *Wave Inversion Technology consortium* (*WIT*) for the finacial support
- The *Deutsche Forschungsgemeinschaft* (*DFG*), the *Integrated Ocean Drilling Project* Germany (*IODP*) and the *Wave Inversion Technology consortium* (*WIT*) for the financial support

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