Hybrid Multiple Attenuation: Applications on Varying Acquisition Data Types and Their Challenges in Shallow and Deep Offshore Environments

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ABSTRACT

One of the main challenges in seismic data processing has long been the ability to accurately identify and effectively separate multiples from primary events, as one of the critical steps required for reliable reservoir characterization and subsurface geological mapping. In this study, we aim to contribute to the evolving landscape of multiple attenuation techniques by examining their performance across a spectrum of geological settings, ranging from shallow to deep-water environments. Our primary focus is integrating suites of fit-for-purpose demultiple methods, such as wave-equation-based techniques, deconvolutional methods, and transform domain approaches in different projects in order to achieve best results. Wave-equation-based methods, characterized by their high-resolution and accuracy, have been particularly effective in deep water settings. However, this class of demultiple techniques is often less effective in shallow water environments due to complexities and breakdown in the assumptions behind the algorithm, such as variable water depths, lack of proper near offsets, and seabed compositions. On the other hand, transform domain techniques, including but not limited to Radon, and Fourier domain (FK) works by transforming the data into a new domain where multiples and primaries map into different regions. Deconvolution method such as predictive deconvolution is a statistical-based technique which offers a more versatile yet less precise alternative, demonstrating efficacy in shallow water contexts. By combining these different methodologies, we aim to formulate a robust, adaptive demultiple algorithm approach that is both Amplitude Versus Offset (AVO) compliant and significantly enhances the signal-to-noise ratio. To validate the integrity of the processed signals, we employ a suite of quality control metrics. In this paper, we present an analysis of these different algorithms on some case studies from the Niger Delta's offshore regions spanning a variety of acquisition types. Through these real-world applications, we validate the proposed hybrid demultiple approach and offer a nuanced understanding of its applicability, advantages, and limitations in complex geological settings, thereby paving the way for more accurate and efficient seismic data processing in the future.

Keywords: Multiples, Attenuation, Wave equation, Deconvolution, Fourier Wave-Number, Hybrid Demultiples, Domains transformation, AVO, Signal- noise ratio

INTRODUCTION

The success of seismic reservoir characterzation is ultimately dependent on the level of noise suppression achieved during the processing of the data. One of such processes includes multiple attenuation which when done properly can provide clarity. In this paper, we focus on the multiple attenuation workflows that provide improvements to datasets in certain environments.

The water layer multiple is defined as one that has at least one upward bounce at the water bottom and one downward bounce at the surface (Figure 1). Each interval such as a reservoir level or air-water and water-seabed interfaces with high reflectivity will generate multiples. Figure 1 shows an example of the different types of multiples that can be generated with each shot and recorded by nearby receivers. This will pose a problem for the interpreter, as this will mask primary events, as will be shown in the case studies.

In the industry today, the use of algorithms varies based on water depths and complexities of the subsurface structures, and in most cases requires a cascaded approach to multiples removal. The most widely used of the multiple attenuation processes is the Surface Related Multiple Elimination (SRME), which is based on prediction of the multiples by convolving the data with successive estimates of the primaries recursively. The application of the SRME process has proven to be very

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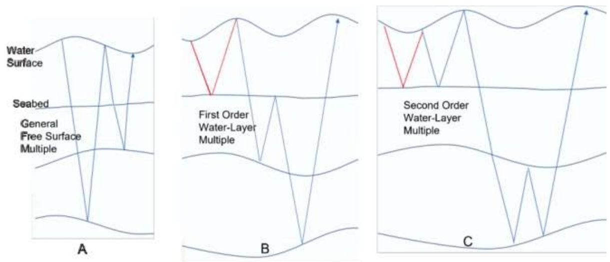

Figure 1: Schematic describing the definition of primary and multiple events. The red lines represent the primary event with one upward reflection. A multiple has at least 2 upward reflections. A represents a General free surface multiple. B is an example of a 1st order free surface multiple C represents a 2nd order surface multiple.

effective in the removal of free surface multiples in most marine situations, as will be shown in the examples. It is not, however, suitable for removal of multiples in shallow water environments, mainly due to poor recording of the water bottom reflection resulting from a lack of near offsets; and also the fact that the water-layer multiples can have significant amplitudes up to high orders, where the order of the multiple refers to the number of downward bounces from the sea surface. It is also worth noting that the SRME algorithm overpredicts shallow peg-leg multiples of higher order, and the peg-leg multiples from deeper events lie close to the water layer. This potentially leads to the failure of the adaptive subtraction step to simultaneously match all orders of multiple. To achieve a more precise prediction of the water-layer multiple in these shallow environments, primary energy at very near offsets would have to have been recorded, which is not done most of the time.

Predictive deconvolution can also be used for multiple attenuation in shallow water. It assumes the earth is made up of horizontal layers of constant velocity. However, it does not work effectively in complex structure areas, another thing to note is that the result of the predictive deconvolution can be quite unpredictable and should be used with caution.

In this paper, we propose a data-driven method for shallow water multiple removal to solve the problems faced by the SRME and predictive deconvolution, especially in complex shallow water depths. This multiple attenuation algorithm is known as the Deterministic Water-layer Demultiple, DWD (Moore and Bisley, 2006) and the Model-based Water-layer Demultiple, MWD (Wang *et al.,* 2011), these fall under the class of model-based multiple attenuation techniques. This method seeks to attenuate the water layer multiples using a hybrid wavefield extrapolation based on Green's function of the seafloor. Field data test results show that this method can obtain better results than the SRME and predictive deconvolution in shallow water depths. But to achieve an optimized solution it is best paired with SRME which requires a significant amount of computational power.

In this paper, we would elaborate more on the use of the DWD and show its applications in both streamer and OBC data, by applying these multiple attenuation algorithms in single and cascaded approaches, with a few practical examples taken from fields in the Niger Delta shallow and deep offshore environments.

METHODOLOGY

In medium to deep water environments (water depth > 200m), it is easy to discriminate between primary reflections and the multiples, this type of free surface multiples is easily addressed using techniques such as SRME (Dragoset *et al* 2010).

Shallow water environments (water depths < 200m) on the other hand, are more difficult as we have both the primary reflections and multiples interfering with each other. The multiple attenuation works better using a model-based approach, techniques such as Deterministic Water-layer Demultiple,

In our multiple attenuation sequence, for optimized results we followed DWD with a constrained 3D SRME (Moore and Bisley 2006), this is tailored towards attenuating the remaining long-period water layer multiples, this workflow is elaborated in Figure 3b. This would eliminate all the free surface multiples with bounces in the water layer on the shot or receiver side, as seen in Figure 2, followed by the multiples that are not related to the water layer. According to Moore and Bisley (2006), this basic work frame has been efficient in shallow water environments, Kostov et al. (2015) describes it in more details. For an OBC the receiver side ghost and multiples are removed during the process of wavefield separation.

For both first and second order multiples, as observed in Figure 1, each model is constructed by combining the water layer's Green's function (ray paths in black as seen in Figure 2) with a general ray path (dotted blue lines), which represent events in the recorded data. This uses Green's function of the water reflection, convolved with the field data to obtain a model of multiples that have experienced a water bottom reflection at both the receiver and the source side of the multiple path. A correction term is derived to avoid double prediction of the free surface multiples that experienced both source- and receiver-side reflections

After the DWD process is applied which has successfully removed the water-layer multiples by the wavefield extrapolation approach using the model of the water layer, the remaining free surface multiple will then be modeled and attenuated using the SRME process. This free-surface

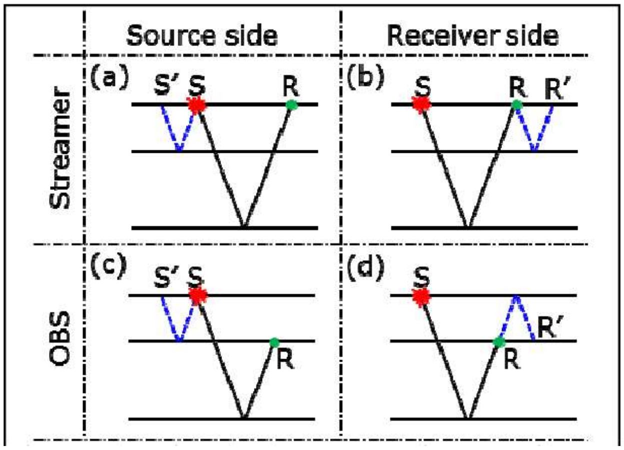

Figure 2: Illustrations show how DWD predicts source-side (a,c) or receiver-side (b,d) water-layer-related multiples for streamer (a,b) or OBS data (c,d). In each case, recorded data SR is convolved with the water layer Green's function (blue dashed line) to predict source-side (SR) or receiver-side (SR) multiples. Note that for the OBS case, the receiver-side ghost has the same kinematics as the receiver-side multiple.

prediction is modeled from data that is now free of all water-layer multiples with the aid of the DWD, workflow in Figure 3. In some of the examples, constraining the SRME model to only start modeling from a tested time, by muting the data above this time, has proven beneficial in the modeling of the free-surface multiples.

Also, spatial interpolation is required to ensure an accurate multidimensional convolution scheme for the prediction of multiples. Post prediction of the water-layer multiples

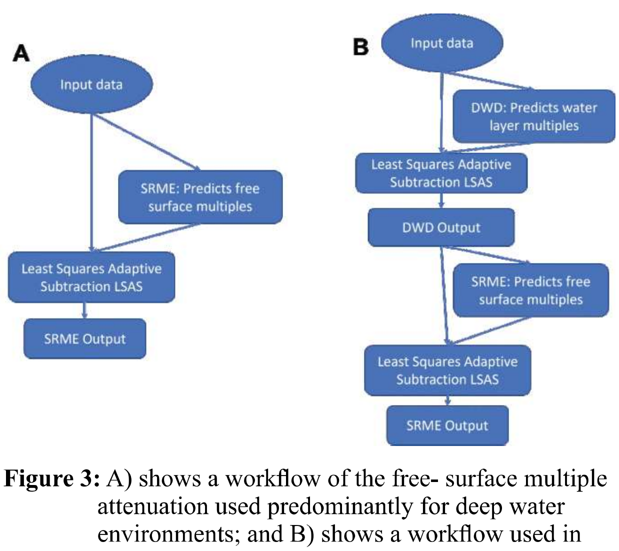

Figure 3: A) shows a workflow of the free- surface multiple attenuation used predominantly for deep water environments; and B) shows a workflow used in shallow water environments using DWD to attenuate water layer multiples followed by SRME to attenuate the free surface related multiples

and the free-surface multiples, the modeled data would need to be adaptively subtracted from the input data. One of the challenges during the subtraction is the inaccuracy of the arrival time, due to the errors in the water layer model used during the prediction, hence the need for an effective subtraction that combines the global and least-squares subtraction. The subtraction can either be done in the common shot or common channel domain.

In conventional to deep water settings, the demultiple workflow is quite different Figure 3A, the first pass of demultiple is done using SRME, followed by diffracted multiple and subsequently pre and post migration radon demultiple depending on the level of residual multiple left in the data. However, for deep water Ocean bottom survey (OBS), the receiver side ghost and multiple energies are removed by means of wavefield separation, follow by DWD model-based demultiple technique, this is often followed by SRME and a pass of Radon.

CASE STUDY

In the Niger Delta, we have applied this methodology to different datasets acquired using both streamer and OBC acquisition types, in both shallow and deep-water environments. The application of the SRME only in the data examples will demonstrate the efficiency it brings to the deep water data, especially in areas with complex geology. We also show shallow water datasets where we have applied the DWD to the shallow water data followed by the SRME in a cascaded manner on the shallow water data examples with successful results.

Figure 4A shows the location map of field A, acquired using towed streamer acquisition type in water depth of about 1500m, 200km south from the shore, the data was acquired using 8 streamers, each 5km long, separated by 50m in the crossline direction, and towed at a depth of 8m. The minimum offset is about 150m from the source array. The source depth is about 6m. The input data was deghosted and reconstructed to a spacing of 6.25m in both shot and receiver directions.

Figure 4B shows the location map of field X & Y both acquired in a shallow water environment about 65km away from the shore. Field X is a towed streamer data in a water depth of about 150m, which was acquired using 8 streamers, towing 480 receivers 6km long, separated by 50m in the crossline direction, and towed at a depth of 7m. The minimum offset is about 140m from the source array. The source depth is about 6m.

Field Y is an Ocean Botton cable (OBC) data in water depth of about 40m with a configuration of 6000m cable length laid on the seabed, 300m cable separation, with a spacing of 25m between receivers and 240 receivers on each cable. The source depth is about 5m. Both datasets were deghosted and reconstructed to a spacing of 6.25m in

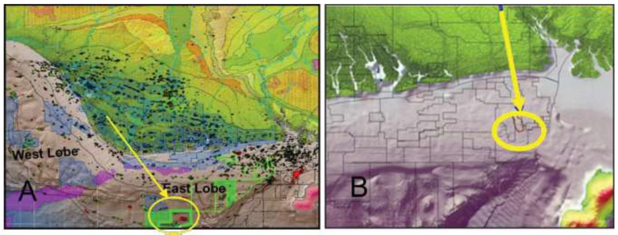

Figure 4: A)image shows a deep water environment where field A example is derived from, and B) shows a shallow water environment where fields X and Y were selected.

both shot and receiver directions.

Figure 5 shows the data from Field X, with extracted near, mid, and far channels. The input data in Figure 5A shows the multiples masking all the primary events, applying the SRME only to this data eliminates the general multiples in the data, and allows for a clearer view of the subsurface structures seen in Figure 5B. This coherent noise eliminated from the data, shoZZZwn in Figure 5C shows that no primaries have been taken out, and the water bottom multiples taken out mimic the shape of the sea bed (not shown in this paper). The NMO corrected CMP gather in the far left of each image shows the moveout can easily be discriminated, looking at the gathers is one of the QC's used to analyze the efficiency of the SRME process applied to ensure no primary reflections were damaged.

From the shallow water environment, comparisons are made between the input deghosted data, the attenuated water-layer multiples and the free surface multiple data, based on the results from the DWD and the SRME approaches applied to the data, including their differences post adaptive subtraction, which in this paper we refer to as LSAS (Least Squares Adaptive Subtraction). The DWD targets the water-layer multiples and attenuates them, leaving only the free surface multiples, therefore the SRME does not predict any water-layer related multiple that has already been addressed by the DWD. As mentioned earlier all modeled multiples from both the DWD and the SRME have been subtracted using the least squares adaptive subtraction LSAS to reduce any timing errors during prediction.

Figure 6 and 7 from the shallow water environment show results on a stack where the input, the DWD, and the cascaded SRME approach was followed, and their subtractions to show how much multiples were eliminated.

Figure 6 shows a Full stack where Water-layer multiples are dominant in the data and the DWD was able to attenuate most of the strong reverberations. The SRME shows the elimination of the remaining free surface multiples. Highlighted areas show the portions of the stack where most of the strong reverberations have been eliminated. The lower section of Figure 6 shows the zoomed sections and their differences in the same way they were applied.

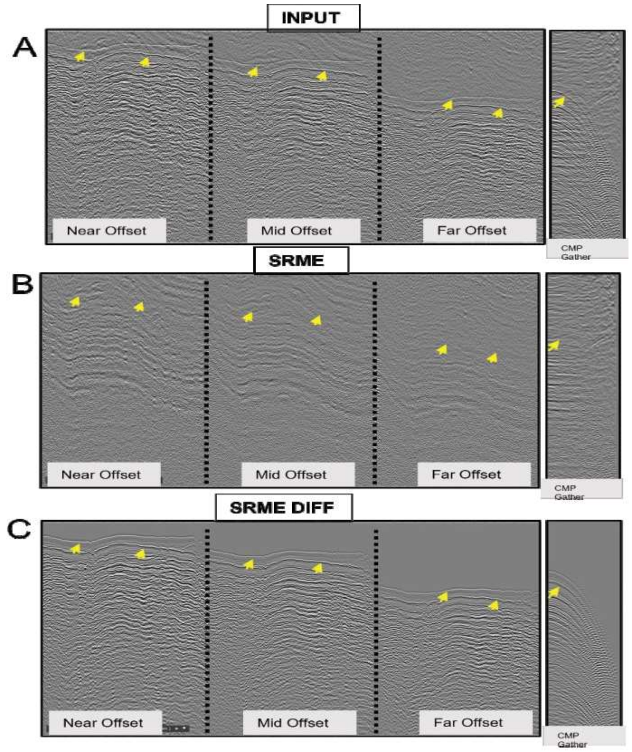

Figure 5: Field X from a deep water environment, showing near, mid, and far offsets A) pre-, B) post SRME and C) the adaptive subtraction difference. The multiple elimination using only SRME shows its efficiency. Annotations with the yellow arrows indicate areas where the multiple removal improves structural clarity, and event continuity can be appreciated.

One of the points to note is the clarity of the events after the removal of the water-layer multiple and the free surface multiples. Though most of the free-surface contaminations are due to the strong water layer reverberations, the remaining unrelated water-layer related multiples were taken out by the cascaded pass of SRME.

Figure 7 shows an inline stack of the upgoing wavefield of the OBC data before multiple attenuation, after DWD, and after DWD+SRME (top section of Figure 7). The water layer multiples are quite dominant given the sharp contrast, and the DWD was able to eliminate most of the strong reverberations because we observe that the remnant free surface multiples, which are much weaker (not as strong as the water layer multiples, but can still be seen in the difference), have been addressed by the SRME which followed. Highlighted window on the input stack have been zoomed into to give a better view of the area highlighted in yellow (zoomed sections at the bottom of the image). The zoomed displays are deghosted input, post-DWD, least squares adaptive subtraction LSAS of the input and the DWD only, followed by the application of the SRME over the DWD output DWD+SRME and finally, the LSAS subtract of the DWD and the DWD+SRME. The red arrows also highlight the preserved primaries that have not been attenuated by the demultiplex processes applied. In the images of the LSAS, we see the step differences of the multiples attenuated.

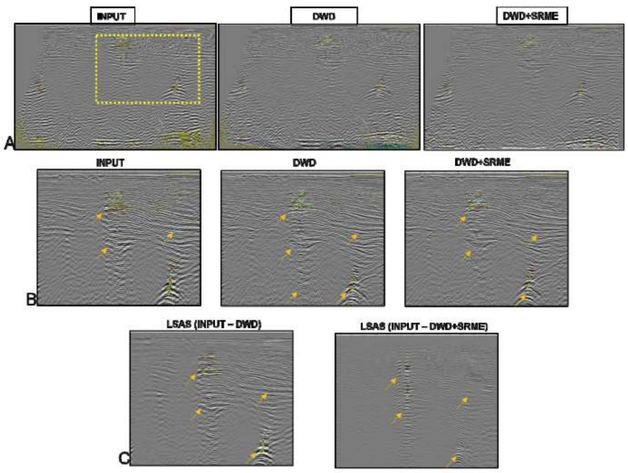

Figure 6: A) Field X from a shallow water environment, showing structural stacks pre and post-application of the DWD and SRME Cascaded approach. B) & C) show the zoomed section. Annotations with the orange arrows indicate areas where the multiple removal improves structural clarity post-application of the workflow.

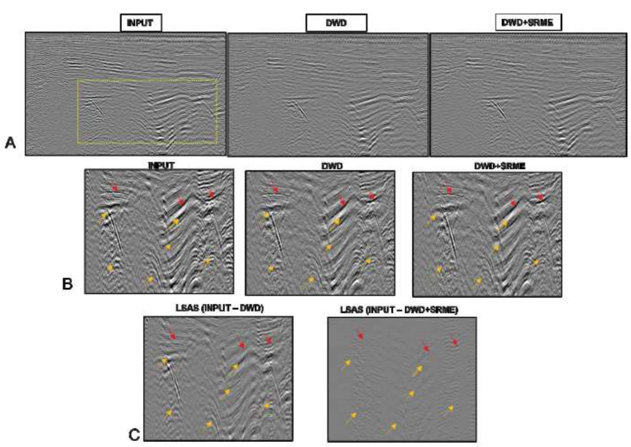

Figure 7: A) shows the stacked section of the deghosted input, DWD attenuating the free surface multiples and the cascaded approach where the SRME immediately after. B) & C) sections show the zoomed display and their step changes in terms of what each application is taking out. Red arrows indicate areas where primary reflectors have been preserved, while the orange lines show multiples of events that have been attenuated.

CONCLUSION

In our first example, we illustrated the removal of the water bottom multiples using only the SRME process, with very good results which enhanced the clarity of the structural continuity being masked by the multiples. In our second example, we see that using only one approach in a shallow water environment still leaves the remaining free surface multiples in the data.

In our second example, in water depths less than 200m, the cascaded approach of utilizing the DWD first to remove the water-layer multiples followed by the SRME to remove the remaining free-surface multiples, has proven to be the most efficient way of attenuating the multiples in the data.

These multiple attenuation algorithms also benefits from the spatial interpolation of the input dataset in both the inline and crossline directions, to model the multiples in the datasets and the adaptive subtraction which eradicates any timing errors that can pose a problem during the subtraction. Results on the near, mid, and far channels and stacked sections and CMP show that the workflow was successful at eliminating the multiples, especially the strong reverberations we see in both shallow water dataset examples.

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