## Introduction

Typical marine surface seismic profiles (SSP) consist of a number of towed airguns and streamers. The recorded SSP marine data suffer from trace gaps at the near offsets and result can be inadequate subsurface illumination and distortions in the migration image. To both trace gap problem, various interpolation algorithms have been suggested such as interpolation in the frequency domain (Gulunay, 2003 and Zwartjes and Sacchi, 2007) and in the time domain using multiples to fill in gaps (Berkhout and Verschuur, 2006; Ramirez et al., 2007; Curry and Shan, 2006).

Another approach is introduced by Dong and Hanafy(2008) where multiples are used to interferometrically interpolate the missing traces in 2D OBS synthetic and field data. In this approach a combination of a natural Green's function (OBS shot gathers) and a model-based Green's function for the water-layer model are used to generate virtual traces at the required offsets. Cao (2009) expanded this approach to 3D OBS surveys and Hanafy et al. (2009) used the same approach to interpolate for missing traces in 3D marine SSP case.

In this paper I follow the same approach introduced by Dong and Hanafy (2008) to extrapolate 3D marine SSP data by interferometry. This method transforms surface and seabed related multiples into primaries recorded at virtual receivers outside the receiver array; here, no assumptions and no velocity model for the deeper sediments are needed. The extrapolated data can be used for migration, velocity analysis, and tomography.

## Method

In this work, a two-layer model-based Green's function with a band-limited point source is used to extrapolate marine SSP data. Figure 1 shows how SSP traces can be correlated with other SSP traces to fill the near offset empty gaps. This correlation operation is required by the acoustic reciprocity equation of correlation type for a two-state system, where one state is the acoustic field associated with the multi-layered model shown in Figure 1b and the other state is associated with the sea-floor model in Figure 1a.

The far-field approximation to the reciprocity equation of correlation type yields the SSP → SSP far-field transform

$$G(B|A) = 2ik \int_{S_s} G(r|A) G_o(r|B)^* dr^2 + G_o(A|B)^*, \qquad (1)$$

where, $G_o(r|B)$ is the model-based up-going wave Green's function for a water layer model and $G(r|A)$ is the Green's function for the actual earth model (Dong and Hanafy, 2008). Here, $S_S$ is the integration boundary just below the sea surface. The integration along the free surface vanishes because both Green's functions are zero there. The contributions from the vertical boundaries at infinity to the left and to the right will be ignored (Schuster, 2009). Here, $A$ is just below the free surface and $B$ is just below the horizontal source line.

Only upgoing waves should be considered to minimize the artifacts in the virtual CSG. To implement this equation, the data are used to estimate the upgoing portion of $G(r|A)$ and a finite-difference solution to the wave equation is used to estimate the upgoing portion of $G_o(r|B)$ for the two-layer model that only contains the free surface and ocean bottom interfaces. This FD calculation is possible because the sea floor topography is well known beneath any exploration survey. The key idea for extrapolation is that the free surface acts as a perfectly reflecting mirror so that 2nd and 3rd views, i.e., free-surface related multiples can be used to fill in the trace gaps, as indicated by Figure 1.

In practice, it is not always possible to estimate the upgoing portion of $G(r|A)$, hence, more artifacts will be generated in the interferometric CSG due to using the total field of $G(r|A)$. However, a matching filter can be used to mitigate this problem and decrease the generated artifacts (Wang et al. 2009).

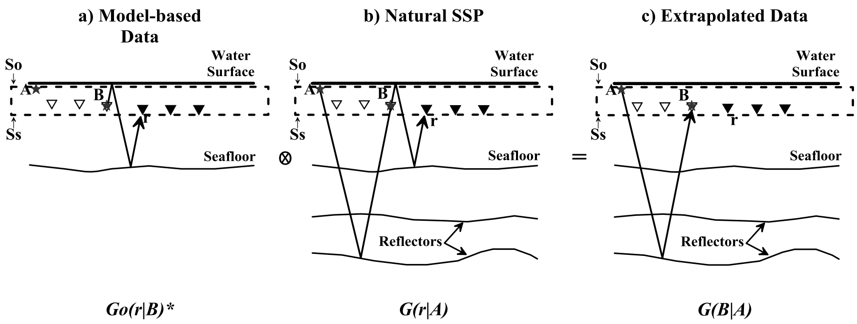


***Figure 1*** *Ray diagrams for transforming SSP data to SSP data. Here, the open geophones indicate the locations of virtual geophones where traces are created from the original SSP data recorded at the filled geophone positions.*

## Increase Accuracy with Virtual Shots

Generating virtual shots can be used to increase the density of CSGs in a survey, and this can lead to increased accuracy in the extrapolated virtual traces. Figure 2 shows two different gathers, in Figure 2a we have a shot gather with a physical source at *A* and a physical receiver at *r*. Equation 1 is used to interferometrically generate the virtual trace at *B* (*G(B|A)*), here, integration is along different receiver points *r*. Figure 2b shows a receiver gather with physical shot at *s* and physical receiver at *B*, here equation 1 is used also to interferometrically generate the virtual trace at *B* (*G(B|A)*), however, integration is along different source points *s*.

Virtual trace from Figure 2a will be added to the virtual trace from Figure 2b. The same steps will be repeated for all possible locations in the recorded data that will interferometically generates *G(B|A)* and results are stacked together, which will increase the accuracy of the final virtual traces.

$$G(B|A) = 2ik\left[\int_{S_s} G(r|A)G_o(r|B)^* dr^2 + \int_{S_s} G(B|s)G_o(A|s)^* ds^2\right] + G_o(A|B)^*, \qquad (3)$$

where, $G_o(r|B)$ and $G_o(A|s)$ are the model-based Green's functions for the water layer model and *G(r|A)* and *G(B|s)* are the Green's functions for the actual earth model. Here, $S_S$ is the boundary just below the sea surface. The integration along the free surface vanishes because both Green's functions are zero there. The contributions from the vertical boundaries at infinity to the left and to the right will be ignored. Here, *A* and *s* are just below the free surface and *B* and *r* are just below the horizontal source line.

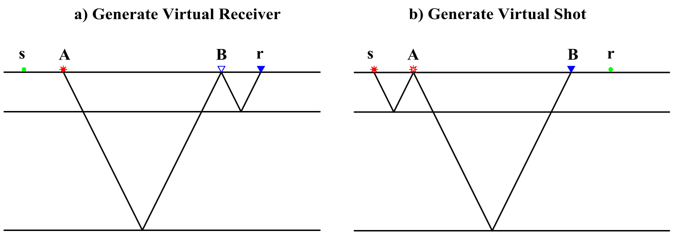


***Figure 2*** *Using virtual shots to improve the accuracy of the virtual traces. (a) "A" is a physical shot, "r" is a physical receiver and "B" is a virtual receiver, here, only one shot gather may satisfy this condition. (b) "s" is a physical source, "B" is a physical receiver and "A" is a virtual receiver, here, many shots could satisfy this condition. In both cases, trace G(B|A) is generated by interferometry and they are stacked together to enhance the signal-to-noise ratio.*

## Numerical Test

A 3D synthetic example is used to test the validity of the proposed approach. Figure 3 shows the SEG/EAGE 3D velocity model used to generate 40 CSGs with shot interval of 30 m; each CSG contains 13 streamers, streamer interval is 150 m and 134 traces per streamer at a trace interval of 30

m. One CSG is selected (Figure 4a) and the first 33 traces are removed (Figure 4b). The CSG shown in Figure 4b is used as the input data for Equation 1, where traces are interferometrically extrapolated to fill the near offset gap. Here, virtual shots are not used here and the result (Figure 5a) shows the virtual CSG after 4 iterations of a matching filter. Artifacts are not totally removed from the final virtual CSG even after using matching filter. Virtual traces obtained by using virtual shots (Equation 3) are then calculated and stacked together, the results after 4 iterations of a matching filter (Figure 5b) show that more artifacts are removed and later arrivals are better represented. Using both virtual traes and virtual shots enhanced the virtual CSG by increasing the signal components relative to the artifact components in the virtual CSG, hence, the matching filter gives better results.

Figure 6a shows a trace-to-trace comparison between the true and virtual traces before using virtual shot (Figures 4a and 5a), while Figure 6b shows the same comparison after using virtual shot (Figures 4a and 5b). With virtual shots, a better match between the true (blue) and virtual (red) traces is shown; however, artifacts are not totally removed. We believe that migrating these virtual CSGs will eliminate many of the remaining artifacts and produce a better subsurface image.

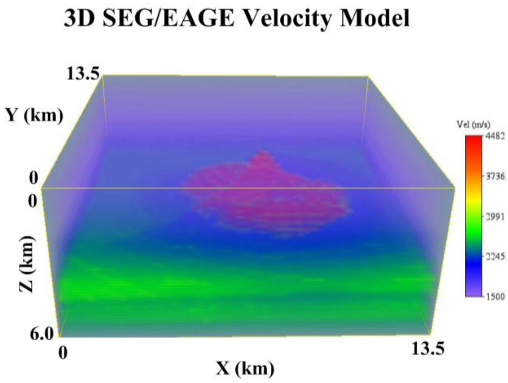


***Figure 3*** *SEG/EAGE Velocity model used to generate the 3D synthetic SSP data.*

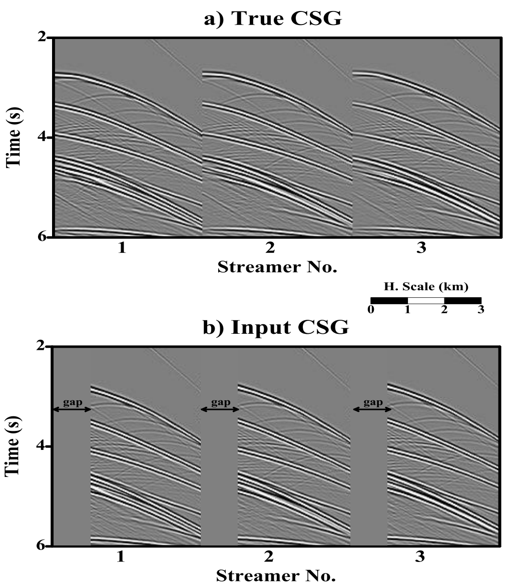


***Figure 4*** *Three selected streamers of (a) The true CSG, and (b) the same CSG with gap at the near offsets.*

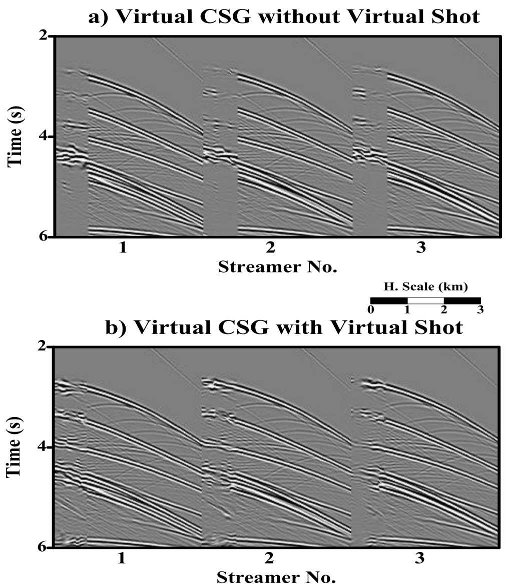


***Figure 5*** *(a) The virtual CSG after matching filter and without using virtual shot. (b) Virtual CSG after matching filters and with virtual shot.*

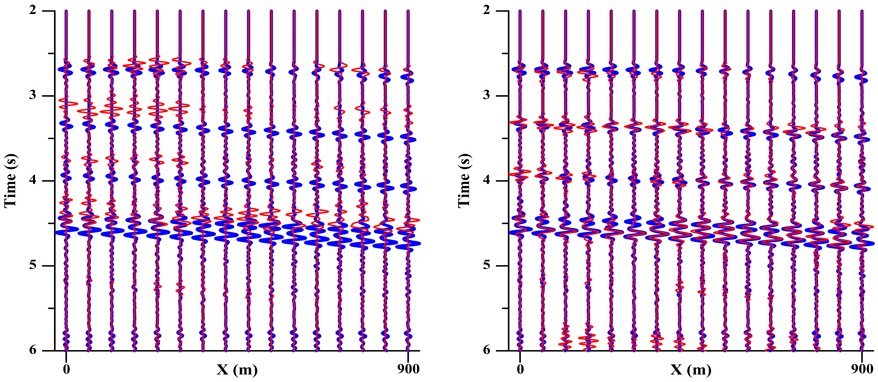


***Figure 6*** *Left: Trace to trace comparison between true and virtual traces before virtual shot. Right: after virtual shot. Blue traces are true ones while red traces are virtual ones.*

## Conclusions

An interferometric method for extrapolating marine SSP data is tested on synthetic traces generated from 3D velocity model. Results show that this method can kinematically extrapolate the traces to fill the gaps between source and receiver arrays. I used virtual shots to generate virtual traces at other CSGs that share the same shot and receiver locations and stacked them together to improve the quality of the final virtual traces. The least squares image matching filter is shown to partially suppress artifacts and correct for amplitudes. This procedure is repeated several times to enhance the final results.

Only the sea floor topography is required and a rough estimate of the sediment velocity is desired. The interpolated data can be used for migration, velocity analysis, tomography, and the multiples can also be used to illuminate much wider areas of the subsurface.

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