Interferometric imaging with FreeCable™ geometry

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Summary

Seismic interferometry is an effective approach in solving the data redatuming problems. Through interferometric redatuming, the source-receiver array becomes closer to the interesting target. However, to ensure the redatuming results accurate, we must utilize a large amount of data in general. In this study, we develop a unique high-resolution interferometric imaging method based on a new marine FreeCable™ acquisition geometry that allows applying interferometric transformation for each individual shot gather. This survey geometry sets a flat recording cable in deep water, and airgun shots right below water surface. Using direct waves from a source to correlate with reflection data from the same source, we virtually place the source to the same level of receivers in the water. In a numerical example, we demonstrate that FreeCable™ interferometric imaging result shows enhanced resolution.

Introduction

Interferometry has been extensively studied and applied for redatuming and imaging purposes. As for the efforts of interferometry, Claerbout (1968) apply the interferometric method in seismology. Dong and Schuster (2008) develop an interferometric approach to extrapolate the OBS and SSP data, and Mallinson (2011) presents a supervirtual interferometric method to enhance the signal-to-noise ratio (SNR) for refractions. Zhang (2006) presents a refraction migration approach that can image multiple refractors without any manual picking involved. There are many other geophysical applications as well.

In this study, we develop an approach to generate interferometric gathers from marine data of FreeCable™ survey geometry and perform prestack-depth migration (PSDM) to image reflectors. This approach repositions the actual sources to the recording level, which helps produce higher resolution images for the subsurface structures. Also, this interferometric method can be applied to a single shot gather independently.

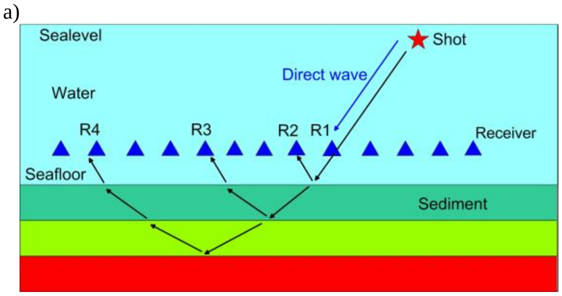
Method

FreeCable™ is a new seismic data acquisition approach, which is developed by Kietta SAS. One or more vessels are designed to provide acoustic sources. Meanwhile, a number of seismic sensors are attached to submerged cables to record the reflected waves at the same depth in deep water (Haumonté, 2017).

In the traditional reflection imaging, direct waves should be removed during preprocessing. However, in this study, we utilize both direct waves and reflected waves together to perform interferometric imaging.

The following figures explain the FreeCable™ acquisition geometry with only one shot and the idea of interferometry for this particular geometry:

a)



b)

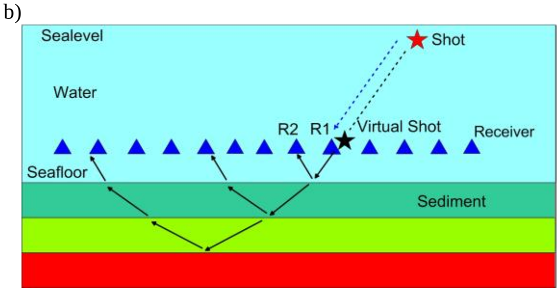


Figure 1: The schematic raypath of FreeCable™ with a single shot. a) Original raypath; b) Interferometric raypath.

As shown in Figure 1a, the total reflection traveltime from the shot (red star) to receiver R2 via R1 is T_{R2}. The direct wave traveltime from the shot (red star) to receiver R1 (blue triangle) is T_{R1}. Using interferometric method, we can derive the reflection traveltime from R1 to R2. As a result, the shot position is moved to a virtual position at R1 (see Figure 1b). This process is formulated as following:

$$T_{R1\,R2}=T_{R2}-T_{R1} \tag{1}$$

$$G_{new}(S_{R1}^{*},T_{R1\,R2})=G(S,T_{R1})\otimes G(S,T_{R2}) \tag{2}$$

where, $T_{R1\,R2}$ is the interferometric raypath traveltime from the virtual shot R1 to the receiver R2, $G(S,T_R)$ is the gather with the raypath from S to R, and $G_{new}(S_{R1}^{*}, T_{R1\,R2})$ is the gather with the raypath from virtual shot S_{R1}^{*} to R2.

Note that the above discussion assumes only one shot. When the geometry contains two or more shots, the final interferometric image result should be generated by stacking the image from each shot:

$$image = \sum_{i=1}^{M} image\ (i) \qquad (3)$$

Where, M is the total number of shots, $image\,(i)$ is the migration result from shot i .

Above equations suggest that we can create interferometric gathers by applying cross correlation. First, for each shot gather, all reflected waves are correlated by the direct wave in each trace, which will create N virtual shots at each receiver location, where N is the number of receivers. And then applying correlation with each shot should create $M \times N \times N$ interferometric traces in total.

After the above procedure, we create the interferometric gathers that include both effective and noneffective reflection events. Applying PSDM with the interferometric gathers and stacking the images should cancel the noneffective events because of stationarity condition, then a correct image should be produced.

Numerical Examples

First, we demonstrate the method with a flat velocity model (Figure 2). As shown in Figure 2, we set 1 shot (red star) at depth of 10 m and 71 receivers (white points) at the depth of 700 m under the sea surface. The total water depth is 1200 m.

Figure 3 shows the original gathers of direct waves and reflections, which are generated from finite difference (FD). After the cross correlation is applied, we create 71 interferometric gathers, among which fifteen gathers are displayed in Figure 4. These virtual gathers are ready for prestack-depth migration with the new virtual source locations.

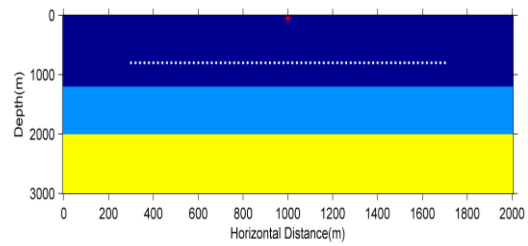


Figure 2: A 3-layer model for FreeCable™ geometry.

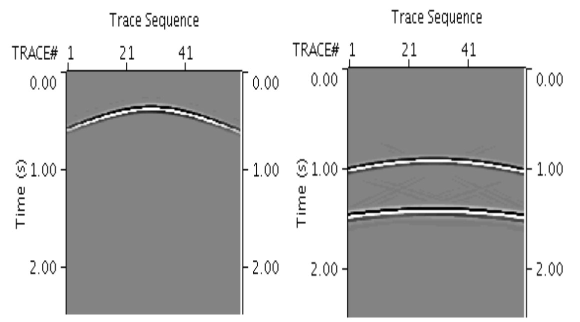


Figure 3: Original direct wave gather (left) and reflection gather (right).

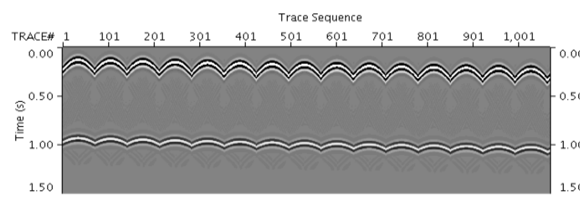


Figure 4: Interferometric gathers for the 3-layer model.

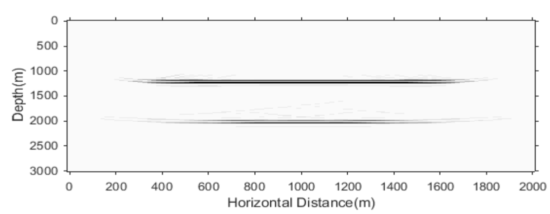


Figure 5: PSDM result from 71 interferometric gathers.

The final PSDM image (Figure 5) shows that our interferometric imaging method can be applied with one shot only.

Second, we perform the FreeCable™ interferometric imaging method with a complex seabed model (Figure 6). We set 14 shots (red stars) at depth of 5 m and 110 receivers (black points) at depth of 250 m below the sea surface.

Figure 7 and Figure 8 show six original gathers of direct waves and reflections, respectively. After correlations and stacking, we produce 14×110 interferometric gathers and six of them are shown in Figure 9. Then we perform PSDM with the original reflections and the interferometric gathers separately.

As shown in Figure 10, the image of interferometric gathers is in a much higher resolution than the image generated by the traditional method. Figure 10b shows improvements in the lateral continuity of all flat three reflectors.

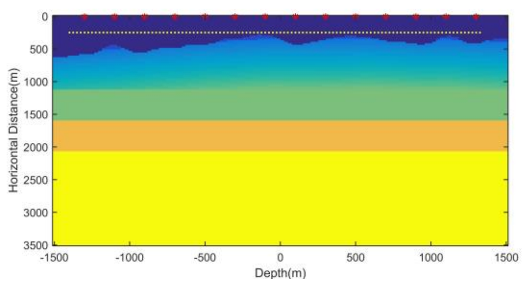


Figure 6: A numerical model with a complex seabed.

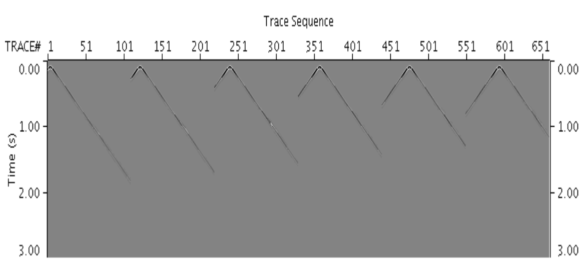


Figure 7: Original direct wave gathers

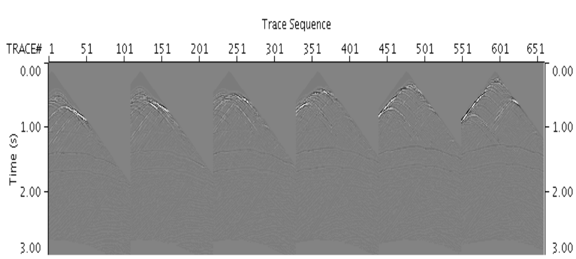


Figure 8: Original reflection gathers

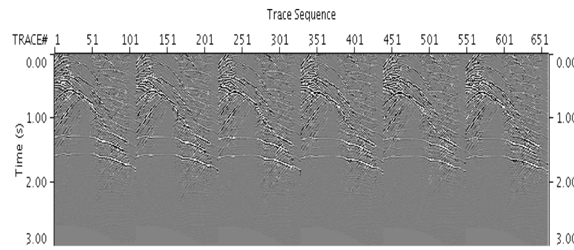
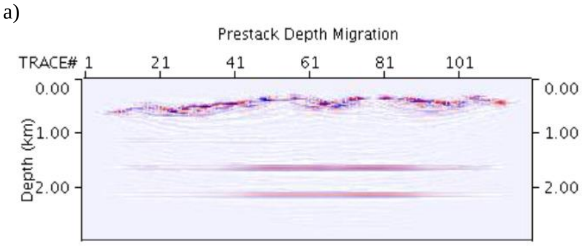


Figure 9: The interferometric gathers.

a)



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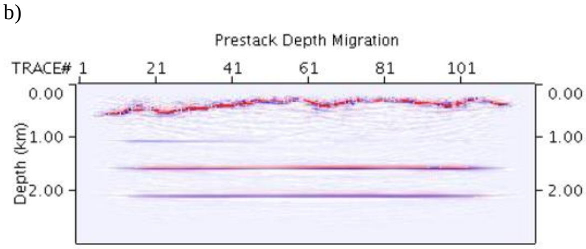

Figure 10: The prestack-depth migration results from the original reflection gathers (a) and interferometric gathers (b).

The above examples demonstrate the idea of FreeCable™ interferometric imaging method, which can be applied with a single shot independently, and the final result also shows a much higher-resolution image for the seabed structures.

Comparison with the Interferometric Redatuming

Traditional interferometric redatuming method is linked with the Green's function. The acoustic Green's function for a homogeneous medium is given by (Morse and Feshbach, 1953):

$$G(\mathbf{g} \mid \mathbf{s}) = \frac{1}{4\pi} \frac{e^{ikr}}{r} \quad (4)$$

Where k is the wavenumber, r is the distance from shot $\mathbf{s}$ to receiver $\mathbf{g}$.

And then the reciprocity equation of correlation type is proposed. After applying the far field approximations (Goertzel and Tralli, 1960), the equation can be expressed as:

$$\mathrm{Im}[G(\mathbf{B}\,|\,\mathbf{A})] \approx k\int_s G(\mathbf{x}\,|\,\mathbf{B})^* G(\mathbf{x}\,|\,\mathbf{A})\,d^2x \qquad (5)$$

Where $G(\mathbf{x}\,|\,\mathbf{A})$ is the Green function, which can be interpreted as the gather excited by A and recorded at x, $G(\mathbf{x}\,|\,\mathbf{B})^*$ is the conjugate type of $G(\mathbf{x}\,|\,\mathbf{B})$, and S is the boundary for integral. After performing inverse Fourier transform, the above equation becomes correlation in time domain.

Obviously, the redatuming method is focused on the data reconstruction, which devotes to create an accurate record from A to B by stacking all shots on the boundary. But the accuracy of this virtual record is affected by many parameters (Barala, 2015).

Our interferometric method is applied for reflection imaging purpose. After cross correlations, each virtual shot is created at the receiver location. Although each virtual shot gather includes a number of invalid traces that do not satisfy the raypaths as shown in Figure 1, we perform PSDM to eliminate these invalid traces, and then the valid events are migrated to the true locations. After stacking, the real structure image is produced.

Our method combines the interferometric redatuming with the PSDM method for imaging. Therefore, we can get the correct image (Figure 5) when we apply the interferometric method for only one single shot.

Effect of Receiver Spacing

FreeCable™ interferometric imaging result is also affected by different geometry parameters. Receiver spacing is a significant factor in generating the interferometric gathers. As shown in Figure 11, the receiver spacing is three times wider than that shown in Figure 1. We also apply cross correlation to create a virtual shot gather with the raypaths from R1 to R2, R3, and R4. However, in this case, this interferometric gather contains only four invalid traces due to different raypaths from the actual reflections (black solid lines). As a result, these invalid traces should lead to an incorrect image.

Therefore, choosing a reasonable receiver spacing is necessary when we perform FreeCable™ interferometric imaging method.

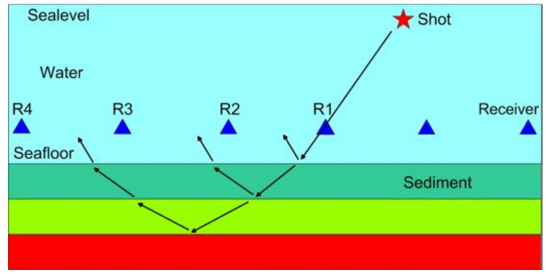

Figure 11: The schematic raypath of FreeCable™ with a large receiver spacing.

Conclusions

In this study, we develop the FreeCable™ interferometric imaging method, which can image the structure under the seafloor with high resolution. Meanwhile, the velocity anomalies between shot and receiver will be removed automatically during the computation process, and there's no limit on the number of shots needed when performing interferometry.

Similar to other marine seismic exploration, the ghost and multiples also exist in FreeCable™ data, which should lead to undesirable imaging in the final result. However, these waves also contain different raypath information, which should be useful for more interferometric applications.

Acknowledgments

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