Waveform tomography for areas of complex near surface

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ABSTRACT

We test the capability of waveform tomography in resolving a model in an area of very challenging near surface geology. The complex near surface of the model makes it difficult to image a low relief structure at depth. The goal of the inversion is to recover the near surface compressional velocity and to detect some indication of the of the low relief structure. We inverted the data using the a multi scale technique and the efficient approach of Sirgue and Pratt (2004). The resulting models contain substantially higher resolution than the initial models. We also compare statics provided by the estimated models. The statics of the estimated models agree with the statics of the true model to within +/- 15ms in most regions in the model. This statics correction is sufficient for a subsequent residual statics solution to be effective.

INTRODUCTION

Many methods exist for inversion of the near surface velocities. Refractions statics, travel-time tomography and others are robust and efficient methods for this purpose (Yilmaz, 2001, p. 370). However, in areas with complex near surface geology, conventional methods are challenged. We use frequency-domain waveform tomography to go beyond the travel-times, and extract the compressional velocity information of the near surface from the waveforms directly.

Waveform tomography has been applied to synthetic and real data. It also has been applied, in one case study, for the purpose of extracting near surface compressional velocities (Sheng et al., 2006). However, the areas that most need waveform tomography are the ones for which conventional methods fail. In this study, we apply waveform tomography to a model of complex near surface geology.

We have briefly discussed the theory in a previous report. We refer the reader to Hammad and Margrave (2008) and the references therein for further details on the theory. In this paper, we apply waveform inversion to a model from Saudi Arabia. The model bears some near surface challenges that obscure the subtle feature buried underneath, the low relief anticlinal structure.

We first describe the model and its complexity. Then, we generate synthetic data using the model and invert them. We first invert the data using a sequential scheme. Then, we test the efficient strategy of Sirgue and Pratt (2004). Finally, near-surface vertical traveltimes, or statics, are calculated from the estimated models and compared with the true statics.

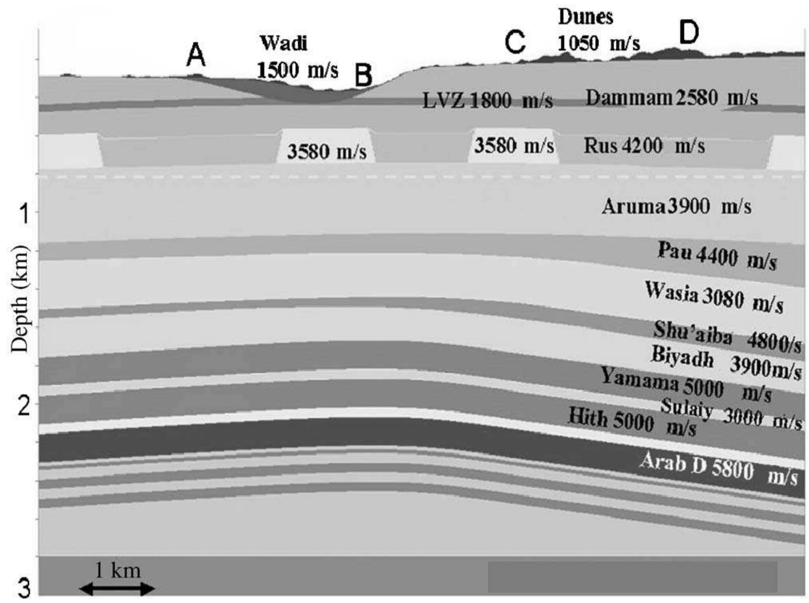


FIG. 1. The velocity model used in this study, from Alkhalifah and Bagaini (2006).

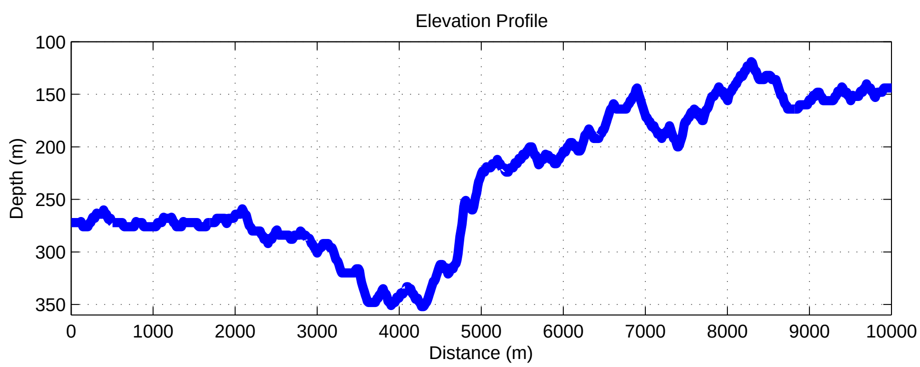


FIG. 2. The elevation profile of the model.

MODEL DESCRIPTION AND SYNTHETIC DATA

The model

Figure 1 shows the model in detail. Alkhalifah and Bagaini (2006) describe the model fully. We give a brief description here. The model bears some of the near surface challenges observed in a complex near surface desert environment. The sand dunes with their relatively low velocity cover some parts of the surface. Some of them can be over 150 meters high. The wadi in the middle contains some relatively low velocity unconsolidated sediments. Below those features is a thin low velocity zone (LVZ) that is often very difficult to detect and properly correct for.

Below the LVZ are low velocity anomalies, which resemble the collapses within the Rus formation. The collapses result from the dissolution of carbonates within this formation. Below this complex burden is a structure with low relief. The complex near surface and the subtle relief of the structure makes imaging and delineating the structure a difficult task.

FIG. 3. An example area that shows how extreme the near surface and the topography can be in Saudi Arabia. Picture from Wikipedia (2009).

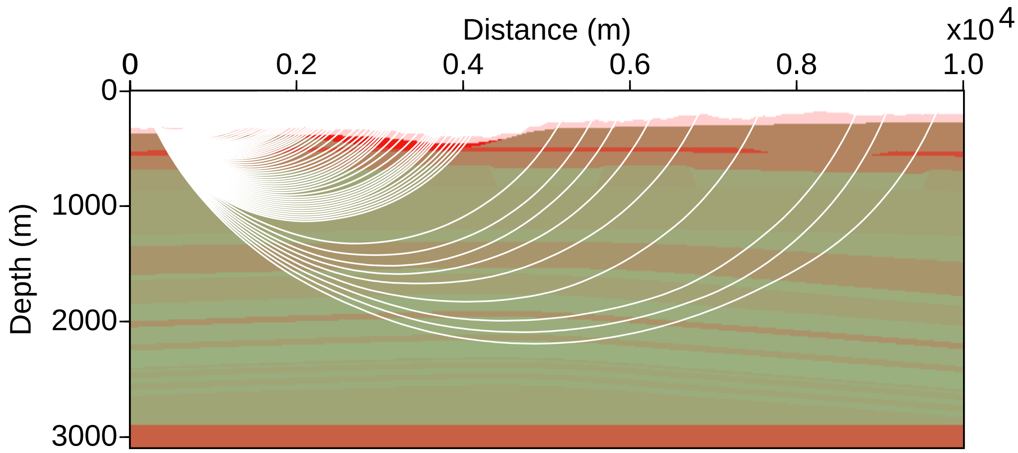


FIG. 4. Diving rays traced in a smoothed version of the model.

The elevation profile of the model is shown in Figure 2. The elevation can vary by over 200 meters. The picture in Figure 3 shows some of the complexity of the near surface in Saudi Arabia and the topographical challenges.

Waveform inversion is based on inverting mainly transmissions. In order to determine the maximum depth of the model that can be reliably inverted, we model diving waves. Figure 4 shows, the diving waves modeled in a smoothed version of the model. We can see that the diving waves could reach about 2 km of depth. Therefore we truncate the model to this depth, since there is no point of including the rest of the model that may not be recovered reliably.

Synthetic data

The original synthetic data has a fairly limited offset. To image the full near surface and some reflectors at depth, we have regenerated the data with a maximum offset of about 9500m. The receiver interval, for the new dataset is 25m and the source interval is 35m.

The entire spread is alive for this experiment. The source wavelet is a Keuper wavelet with 5.5 Hz dominant frequency. Figure 12a shows three sample shot records.

INVERSION

Sequential inversion

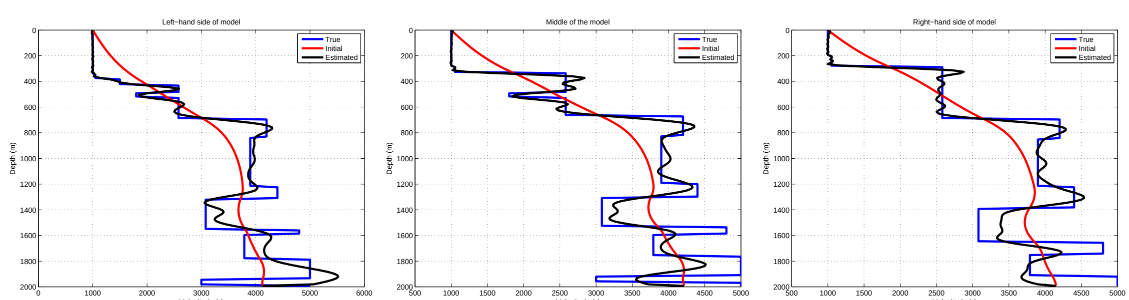
We inverted for the model using an initial model that is a smooth version of the true model. The smoother used is about 480x480 m. We inverted sequentially each frequency from 2-14.8 Hz, with an interval of 0.2 Hz. We used 5 iterations per frequency. The preconditioning used is based on filtering the gradient of the misfit function in the wavenumber domain.

We can see that the estimated result in Figure 7 matches closely the true result. The near surface is recovered accurately and more details about the curvature of the structure are recovered. Note that the thin low velocity layer, which is a very hard feature to recover, is almost fully recoved, including the truncations. Note also that the feature within the wadi and the low velocity zones within the Rus formation are also recovered.

Figure 7d shows absolute value of the difference between the estimated and the true model. Most of regions of the model are recovered within less than +/- 500 m/s. Note that the feature in the bottom of the model is caused by the thin layer at the very edge of the model. Edge effects combined with this thin layer caused this sort of artifact. Understanding such artifacts is crucial in assigning confidence levels to each region of the model and subsequently smoothing or keeping such features.

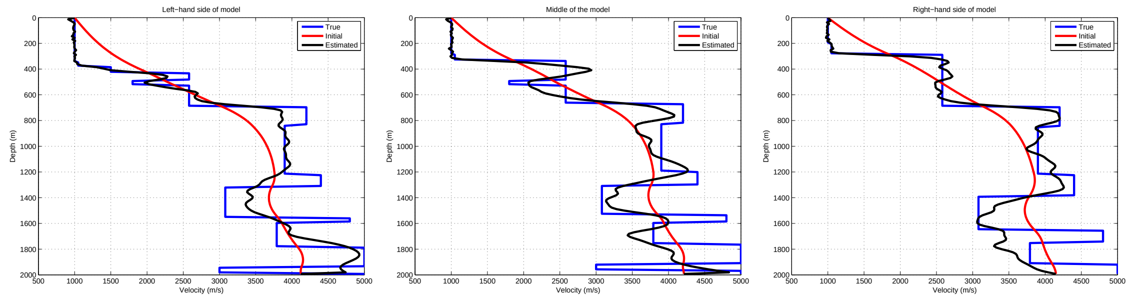
One-dimensional profiles of the models in three locations are shown in Figure 5. You can see that the initial model is an averaged version of the true model. Note how closely the estimated result matches the true result. The estimated models are less accurate in the thin layers. Recovering such small details would require inverting higher frequencies.

We have calculated the one way vertical travel times from the acquisition surface to the datum shown in Figure 9. Figure 9 shows the statics calculated in the models. Figure 9b shows the improvement we are able to achieve. The statics in the initial model can be higher than +/- 40 ms. The statics calculated in the estimated model are less than +/- 10 ms. With this much accuracy of estimating the statics, residual statics methods would not have difficultly correcting for the rest of statics.



(a) (b) (c)

FIG. 5. 1D velocity profiles from the sequential experiment shown from 3 different locations.



(a) (b) (c)

FIG. 6. 1D velocity profiles from the efficient experiment shown from 3 different locations.

Efficient Strategy

In this experiment, we use more efficient strategy of (Sirgue and Pratt, 2004). The efficient strategy suggests inverting only four frequencies: 2, 4.5, 10, 22.4 Hz. We used 30 iterations per frequency. The total number of iterations is 120. Figure?? shows the frequencies selected and their relation with the wavenumber. The selection strategy is based on selecting those frequencies whose wavenumber range in total would span the wavenumber domain. The redundancy of the data is fully utilized through the efficient strategy.

Figure 8 shows the results. Note that we are able to recover the low velocity zone, the wadi's low velocity zone and in a bit less detail the Rus collapses. Note also that low relief structure especially at Wasia formation is recovered in more details.

Although the result here seems to be less accurate, a closer look at the difference plot shows that the resulting model is almost within +/- 500 m/s in many areas. A closer look at the 1D profiles in Figure 6 shows how close the match is. The resolution of the recovered model is comparable to that of the sequential approach for almost 37.5% of the cost.

Obtaining more accurate models using the efficient strategy can be accomplished. However, it would require more human input and interpretation through the application of a more aggressive preconditioning scheme. A big advantage of the efficient strategy is that it can be used as a tool for quick testing of an array of parameters. For such a computationally intensive process, the efficient strategy can make a big difference.

We have calculated the statics for the models as shown in Figure 10. Note that the statics are less accurate than the previous experiment. Nevertheless, in most regions they are less than +/- 15 ms, which is accurate enough for residual statics to be effective when applied afterward.

Figure 12 shows three shot records in different left, middle and right-hand side of the model. The shots generated using the true model (observed data), the estimated and the difference between them. Note how close the match is between the observed and the predicted data. The difference between them seems to be a scaled version of the observed data. This kind of match is what should look for when using real data.

CONCLUSIONS AND DISCUSSION

We have applied waveform tomography on a model of an area of complex near surface and low relief structure. Frequency domain waveform inversion successfully recovered the compressional velocity of the model using a smooth initial model. Waveform inversion was able to recover the true model in using a sequential approach and less accurately using the efficient strategy. The statics corrections in both cases are accurate enough for residual statics to be effective.

ACKNOWLEDGMENT

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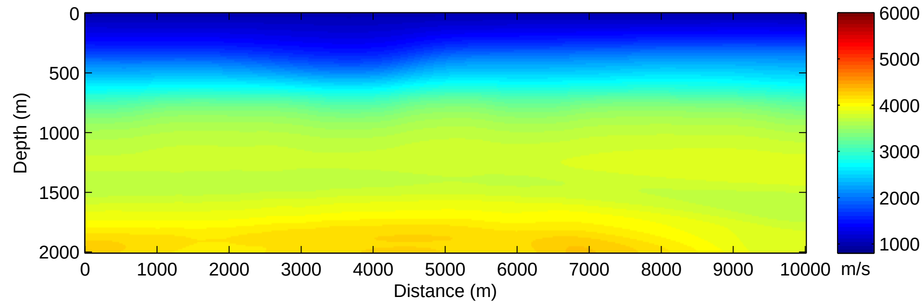
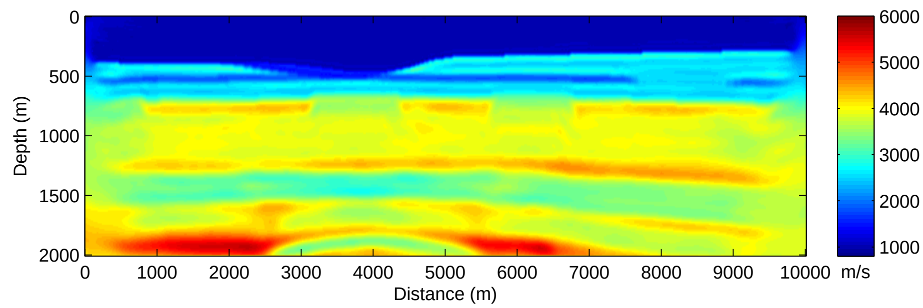
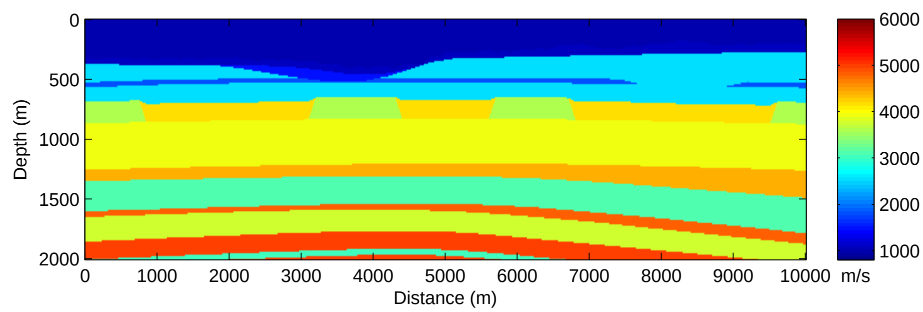


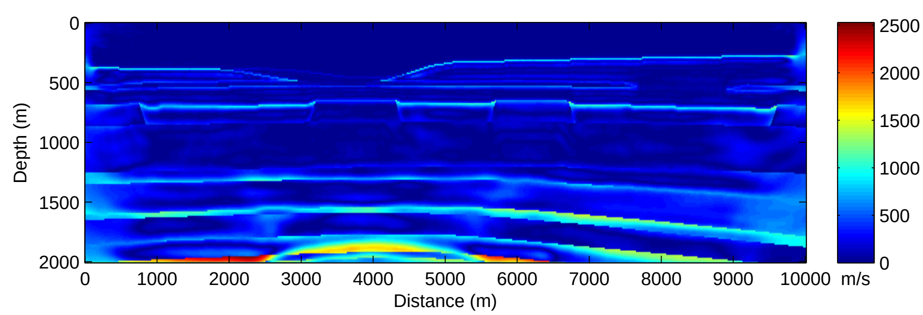
(a) Initial Model



(b) Estimated Model

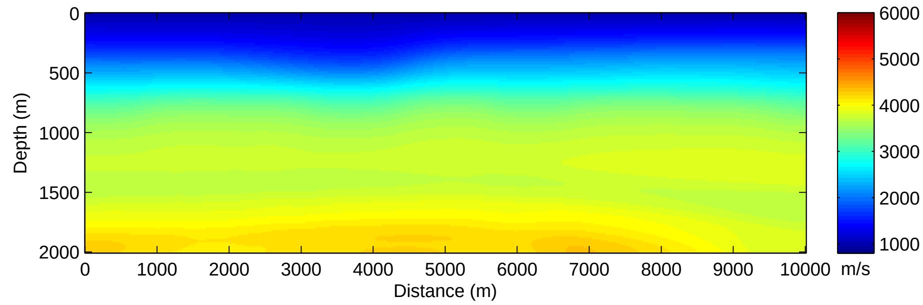


(c) True Model

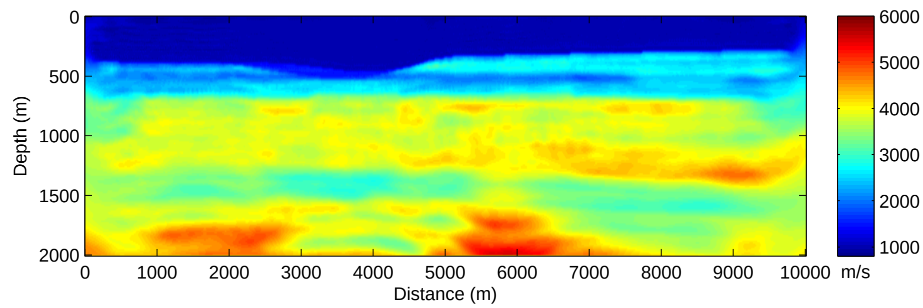


(d) Absolute Value of the Difference

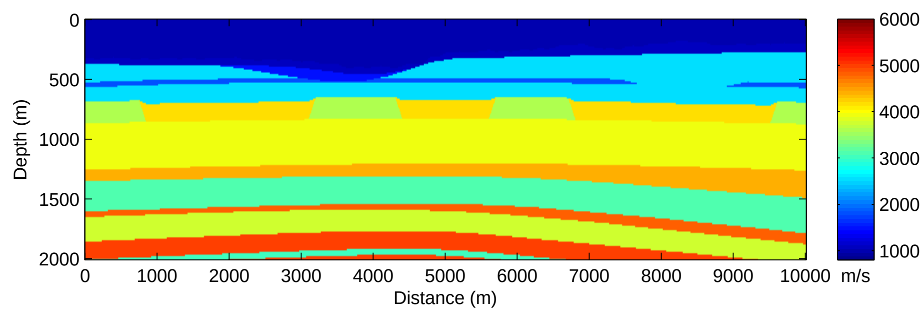
FIG. 7. The models for the sequential experiment.



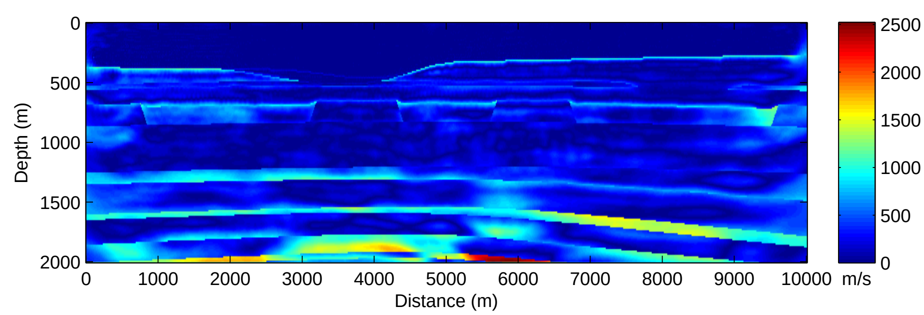
(a) Initial Model



(b) Estimated Model



(c) True Model



(d) Absolute Value of the Difference

FIG. 8. The models for the efficient experiment.

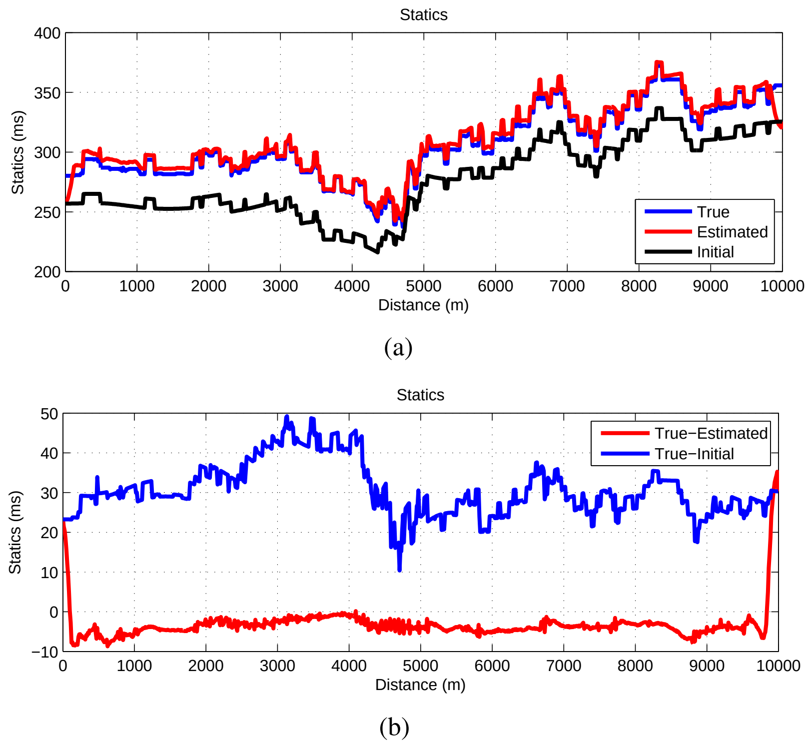


FIG. 9. Statics for the sequential experiment. a) shows all the statics b) shows the differences.

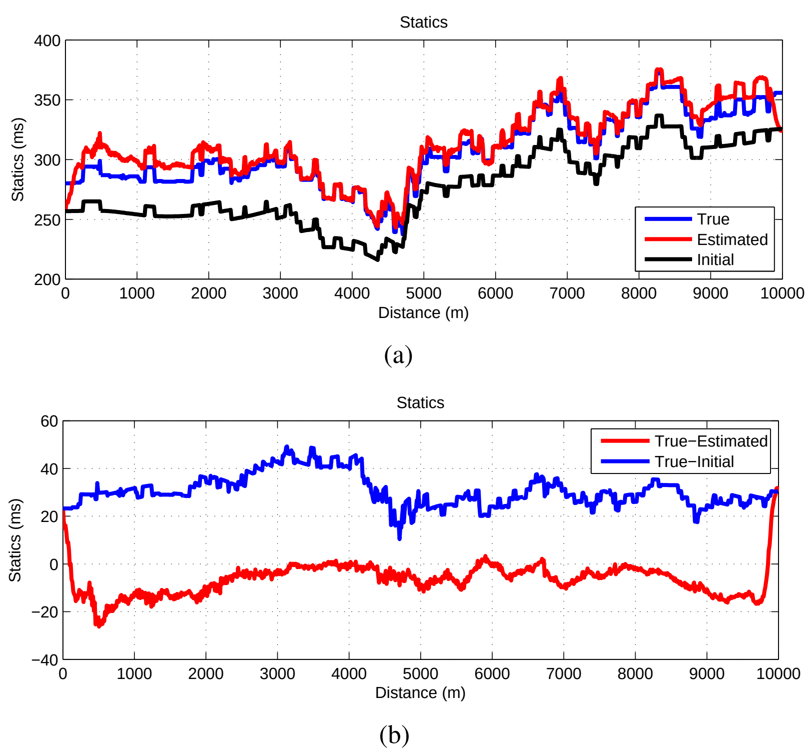


FIG. 10. Statics for the efficient experiment. a) shows all the statics b) shows the differences.

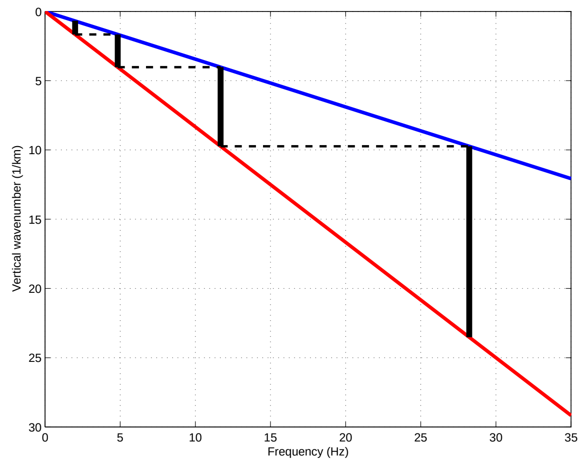


FIG. 11. The frequencies selected for the efficient strategy.

a)

b)

c)

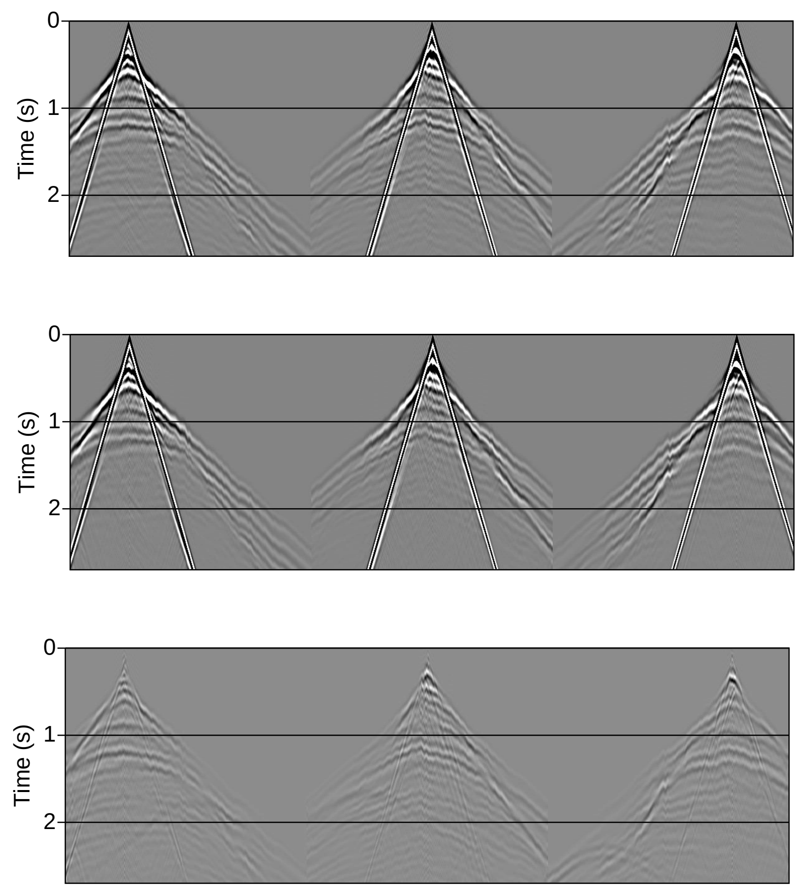


FIG. 12. Sample shots for a) the true model, b) the estimated model from the sequential experiment and c) the difference between them.