Water layer first arrival traveltime tomography using multiples

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Abstract

Accurate acoustic velocity models of the water layer play a crucial role in reducing temporal errors between baseline and monitor surveys. One potential method to enhance the accuracy and resolution of these velocity models is by incorporating surface-multiple data. This study specifically focuses on investigating the impact of seasonal water velocity variations on the accuracy of these models using 2D tomography. The analysis employs two distinct approaches, utilizing ray tracing and an ocean bottom node acquisition geometry. The first approach utilizes only direct waves, while the second approach incorporates both direct and surface-multiples of the water layer. The eikonal equation was used to implement the ray tracing and to obtain the transit times of the acoustic wave. To solve the inverse problem, the conjugate gradient technique was used, in addition to Tikhonov regularization.

Introduction

Seismic monitoring effective in optimizing the recovery factor of hydrocarbon reservoirs and reducing drilling risks. The effectiveness of a seismic monitoring depends on highly repeatable acquisition parameters of the baseline and monitor surveys. However, unpredictable variations in seismic velocities within the water layer pose a challenge.

The water velocity variations can occur due to local and seasonal changes in salinity caused by saline outcrops and proximity to river mouths, as well as temperature fluctuations caused by ocean currents. Therefore, it is crucial to have an accurate velocity model of the water layer to minimize temporal errors between the baseline and monitor seismic data (Wang et al., 2012).

An accurate method for obtaining a velocity model of the water layer involves utilizing local salinity and temperature profiles. As described by the nine-term equation for water layer velocity presented by Mackenzie (1981). However, these profiles are one-offs and expensive measurements. In contrast, first-arrival seismic tomography is a cost-effective technique capable of supplying a highly accurate velocity model compared to direct measurements.

In first-arrival seismic tomography, results depend heavily on the data's quality, distribution, and quantity. The use of surface-multiple reflections can increase data volume and distribution. By incorporating these additional data, it's possible to enhance the subsurface's spatial coverage, thereby improving tomographic resolution and accuracy. Even though multiples are often treated as noise and removed, their strategic use can effectively elevate the seismic investigation's quality.

One such strategic use of surface multiples is represented by the ”Mirror” technique, introduced by Pacal et al. (2015). This method utilizes surface multiples to refine seismic images and uses the Mirror technique to generate seismic sections via Reverse Time Migration (RTM) of data derived from surface multiples. In the present study, the Mirror technique was integrated into the ray-tracing tomography framework, utilizing the Eikonal equation with the goal of modeling the rays and travel times associated with surface multiples.

This study aims to investigate whether adding surface-multiple data can help create more accurate velocity models for the water layer compared to models that only consider direct waves. Specifically, the research focuses on understanding how variations in water velocity due to seasonal changes can affect the models.

Theory

The eikonal equation (Equation 1) is a fundamental equation utilized in seismic tomography. It describes the propagation of seismic waves through a medium and relates the gradient of travel times (∇t) to the slowness of the medium (s). By solving the eikonal equation, the first-arrival times of seismic waves can be calculated. This study employed the algorithm proposed by Podvin & Lecomte (1991) to solve the eikonal equation. The algorithm operates through iterations, starting with initial time values at the source points (i.e., seismic sources) and advancing to neighboring points based on a slowness model. The outcome is a discretized grid containing the first-arrival times for a slowness model.

$$[\nabla t(x)]^2 = s(x)^2 \tag{1}$$

By obtaining transit times for a velocity model, ray tracing can be performed. It utilizes the gradient descent of the eikonal equation and follows these steps. Firstly, starting points (i.e., receivers) and initial arrival time values (i.e., zero time at the source position) are defined. Then, the algorithm iterates over neighboring points, advancing in the direction of the gradient descent of the eikonal equation. This means that the ray is traced in the direction where the arrival time decreases most rapidly. These iterations continue until the ray reaches the source.

The challenge is that the mentioned method only traces direct and refracted waves, ignoring the reflection phenomenon. However, the surface multiples used have two reflection points, one on the sea floor and another on the water surface. To overcome this, the "mirror" technique was used. It involves mirroring the water layer and relocating the receivers to virtual positions, considering the water/air interface as a mirror. This ensures that surface multiples have a single reflection point at the sea floor. Determining the exact location of this reflection point is crucial for accurate ray tracing. The technique involves solving two eikonal equations, one with the original slowness model (Figure 1) and another with the mirrored model (Figure 2), to find the reflection point where the sum of the two transit times is minimized along the seafloor horizon. The rays are then traced using the gradient of travel times from both models, generating two parts of the ray corresponding to the surface multiples. These parts are combined, and the depth information for the mirrored model is converted to the real position. The resulting ray can be seen in Figure 2.

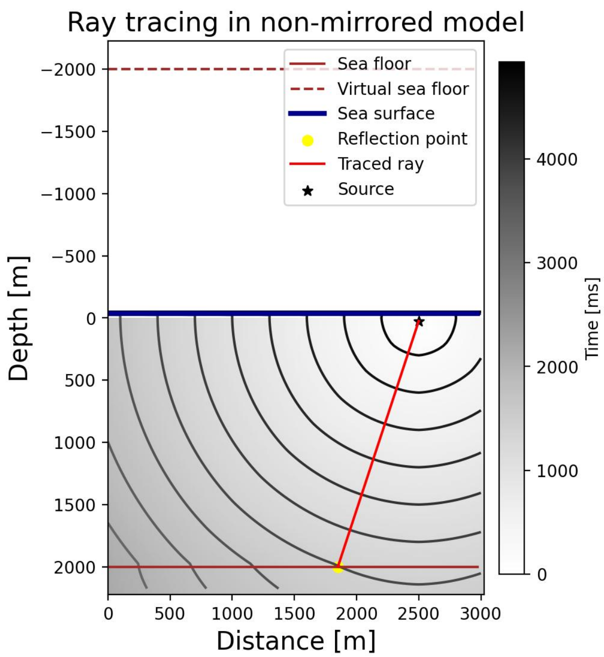

Figure 1 – Calculated ray for the non-mirrored model. The source is in the original position, and the ray is traced from the reflection point to the source.

The advantages of using surface multiples in addition to direct waves include their capacity to propagate through the upper section of the water layer above the seismic sources and their triple path through the water column, which increases the illuminated area by the rays.

This work uses travel-time tomography. which aims to solve the inverse system presented in Equation 2, where G is the sensitivity matrix, s are slowness values, and t are the acoustic wave travel times. As slowness is the inverse of velocity, the velocity model of the desired water layer can be easily calculated.

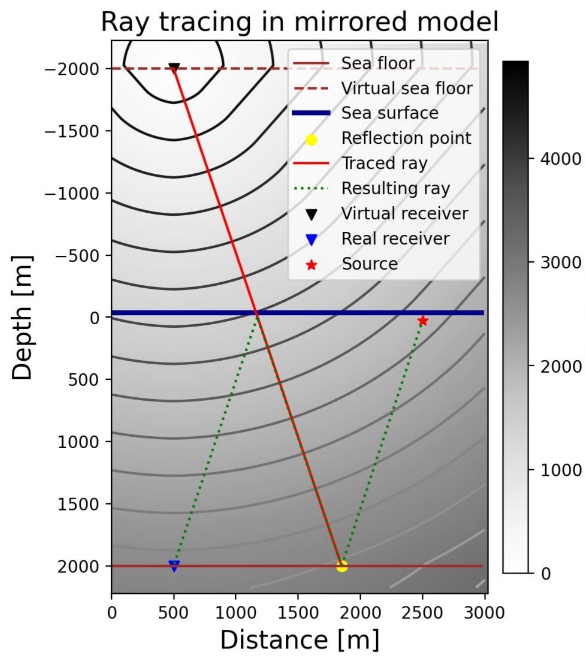

Figure 2 – Calculated ray for the mirrored model (red line). The receiver is in the virtual position, and the ray is traced from the reflection point to the receiver. The green line represents the resulting ray of the surface multiple.

To solve the system, the Linear Conjugate Gradient method proposed by Hestenes & Stiefel (1952) is utilized. This method offers advantages such as low memory consumption and efficient computational processing (Wright et al., 1999).

The sensitivity matrix G is constructed through the application of ray tracing. It records the paths traversed by the rays within the model, where each row represents the distances covered by a specific ray across the individual cells of the slowness model. Since rays typically traverse only a small fraction of the total number of cells, the resulting matrix G often exhibits sparsity, indicating an ill-posed problem. To address this issue, first-order Tikhonov regularization is employed.

The solution of the eikonal equation is utilized to simulate the observed data d_{obs} and the calculated data d_{calc}, thereby obtaining the term Δd in Equation 2.

$$\Delta s = [G^T G]^{-1} G^T \Delta d \tag{2}$$

The tomography algorithm applied in this study follows a step-by-step iterative approach. In each iteration, the main goal is to update the slowness model s_i by obtaining Δs using the inversion process described in Equation 2. The updated model s_{i+1} aims to minimize the difference between the observed and calculated data ($\Delta d = d_{obs} - d_{calc}$). The algorithm continues until a certain number of iterations δ is reached. Once this happens, the process illustrated in Figure 3 stops, and the final velocity model is obtained.

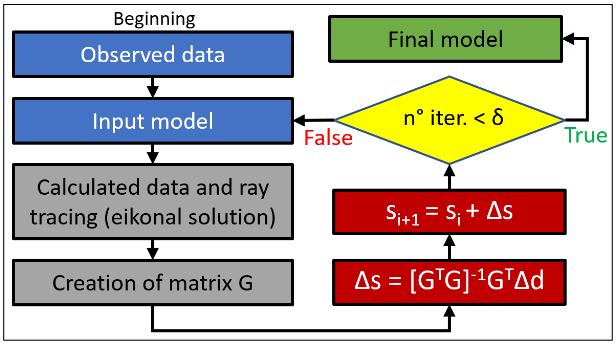

Figure 3 – Tomography flow used. Source: adapted from BULHÕES (2020)

Water Layer Velocity Model

This section discusses the creation of the velocity models used in the study. The initial model represents the acoustic wave velocity conditions in water during the winter, while the reference model represents the conditions during the summer. Both models were generated using the Mackenzie equation, which describes the acoustic wave velocity in water as a function of salinity (s), temperature (T), and depth (z). The Mackenzie equation (Equation 3) includes empirical constants, represented by Greek letters as shown in Table 1. Actual temperature and salinity data obtained from the WOA database were utilized in this study. It is important to note that during the summer, the water layer in the shallow region exhibits higher velocity values compared to the winter conditions. As the depth increases, the difference in velocities between the two seasons decreases. For each model, a salinity profile and a temperature profile were employed.

It is crucial to note that the main objective of this study is to investigate temporal variations in velocity rather than spatial variations. As a result, the models were specifically designed to capture temporal changes and do not feature lateral variations in velocity. Furthermore, it is worth highlighting that the reference model was specifically utilized to simulate the observed field data in this study.

$$\begin{aligned} v(T,s,z) = {} & \eta + \chi T + \delta T^2 + \varphi T^3 + \sigma(s-35.0) \\ & + \mu z + \gamma z^2 + \alpha T z^3 + \beta T(s-35.0), \end{aligned} \tag{3}$$

Results

Two sets of results were obtained in this study: one using just data from direct waves and another incorporating both direct and multiple waves. In both cases, the initial model shown in Figure 5a was utilized. The acquisition geometry aimed to represent parameters resembling an Ocean Bottom Node (OBN) configuration commonly employed in the oil and gas industry. For this purpose, the shots were spaced at intervals of 24 meters and positioned at a depth of 8 meters. The receivers were deployed on the seabed at a depth of 1696 meters, with a spacing of 400 meters.

Table 1 – Values of the empirical constants of Mackenzie (1981) formula, which relates acoustic velocity to salinity, depth and temperature of ocean water.

Parameters	Empirical constants
η	$1448,96$
χ	$4,591$
δ	$-5,304 \times 10^{-2}$
φ	$2,374 \times 10^{-4}$
σ	$1,340$
μ	$1,630 \times 10^{-2}$
γ	$1,675 \times 10^{-7}$
α	$-7,139 \times 10^{-13}$
β	$-1,025 \times 10^{-2}$

Figure 5c displays the model obtained solely from direct waves, while Figure 5d illustrates the model derived from the inclusion of multiple waves. Notably, the model generated without considering multiples exhibited minimal changes, remaining remarkably close to the initial model (notice that the reference model on Figure 5b has a reddish coloration in the shallow region). This can also be observed in Figure 4, where the profile of the initial model (represented by the orange curve) and the model obtained solely from direct waves (indicated by the red curve) closely align. Conversely, the model incorporating multiples successfully detected the presence of a high-speed anomaly situated in the shallower regions. Figure 4 demonstrates the convergence of the green curve (representing the model obtained with the inclusion of multiples) toward the blue curve (representing the reference model).

To quantitatively compare the models, Pearson's correlation coefficient was employed. This coefficient measures the degree of linear relationship between matrix elements, ranging from -1 to 1, where -1 signifies a perfect negative linear relationship, 0 indicates no relationship, and 1 reflects a perfect positive linear relationship. The Pearson coefficient between the initial model and the reference model was determined to be 0.99468. Moreover, the coefficient between the model obtained solely from direct waves and the reference model was calculated as 0.99478, indicating a slight approximation between the models. Notably, a significant approximation between the models was observed when the multiples were incorporated, as evidenced by the coefficient of 0.99839 between the reference model and the model obtained with the inclusion of multiples.

Conclusions

The addition of multiples presents a great result in models with shallow velocity variations, significantly approaching the reference model to the initial model. This is due to the fact that multiples are capable of illuminating areas between 0 and 8 meters deep, areas where direct waves cannot travel.

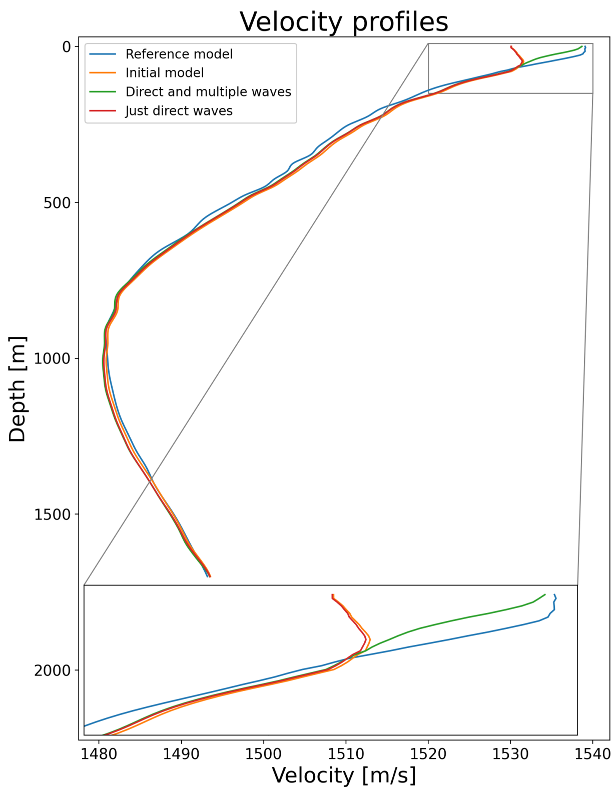

Figure 4 – Velocity profiles taken from the 2D models used. They represent the entire model well as there are no large lateral variations in the model.

It is possible to highlight other suggestions to apply in future works. These are: using real data to verify the likelihood of the synthetic models used and whether the results will be equally promising; to analyze whether the use of multiples is capable of reducing noise in real 4D data.

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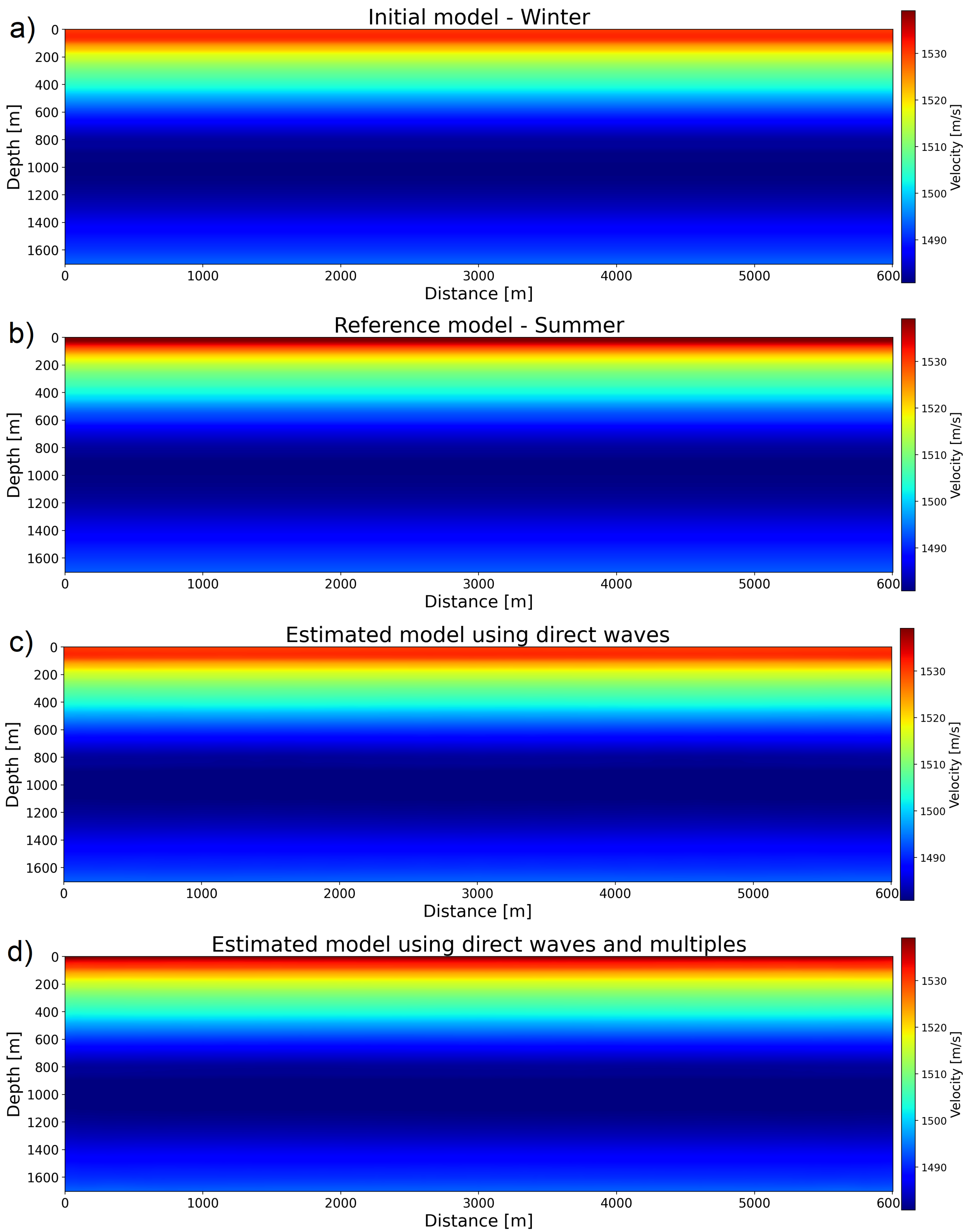

*Figure 5 – Water layer velocity models: **a)** initial model used as input in the tomography flow; **b)** reference model; **c)** model calculated using only direct waves; **d)** model calculated using both direct and multiple waves.*