Streamer-tail Optimization for FWI

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Summary

Streamer-tails, an extended subset of the main streamer spread, are a pragmatic and cost-effective method to achieve longer offsets for refraction full waveform inversion (FWI). To our knowledge, there is currently no established best practice to design streamer-tail solutions. We present a new survey design workflow that finds the optimal streamer-tail geometry for towed streamer and source configurations.

The main objective of this workflow is to design a fit-for-purpose streamer-tail and source configuration, limited primarily by a finite streamer inventory, to provide the highest frequency supported by the survey setup. The main aspects of streamer-tail configurations are their length, or the maximum required offset, the number of streamer tails and their relative position within the main streamer spread. The design also depends on sail-line spacing and source separation, amongst other things. Wide-tow multi-source configurations perform superior compared to traditional narrow-tow source configurations. We also show a case study from the Norwegian Sea to demonstrate the benefits of using streamer-tails for FWI-based velocity model building.

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Introduction

It has become common practice to use full waveform inversion (FWI) for velocity model building (VMB) especially in geologically complex areas with, e.g., salt inclusions or carbonates present in the overburden. For such geological settings, refraction based FWI using long offset data provides additional information to better constrain the velocity model and to recover the lateral heterogeneities. Hence, the increased importance of long offset data for multiple exploration targets with complex overburden (Korsmo et al., 2016; Naumann et al., 2019; Oukili et al., 2020).

For optimal use of the finite streamer inventory, a pragmatic and cost-effective method to achieve longer offsets for refraction FWI is seismic acquisition with variable streamer lengths, i.e., a main streamer spread is designed for subsurface imaging and quantitative interpretation and then extended by a subset of longer streamers (Figure 1). We refer to the extended subset as “streamer-tails”. The general concept of variable streamer lengths for FWI was originally described, e.g., in Widmaier et al. (2019). To our knowledge there is no established workflow to determine streamer-tails solutions for FWI. In this paper, we present a new survey design workflow that finds the optimal streamer-tail solution for a towed streamer and source configuration and present a recent case study from the Norwegian Sea.

Figure 1 *Streamer configuration with sixteen streamers and three streamer-tails for a Barents Sea Survey in 2020 (Widmaier et al., 2021).*

Methodology

The main aspects of streamer-tail configurations are: (1) their length or the maximum required offset, (2) the number of streamer-tails, and (3) their relative position within the main streamer spread.

For a given target of interest, the length is determined by the minimum offset required to record the diving waves from the target interval. This is determined by the FWI sensitivity kernels (Figure 2): longer offsets result in greater penetration depths, which also depends on the velocity trend.

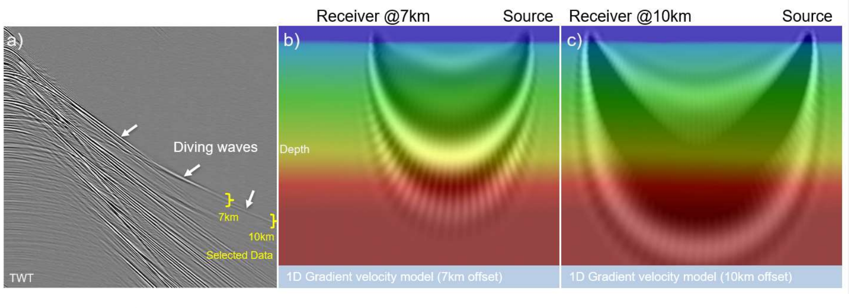
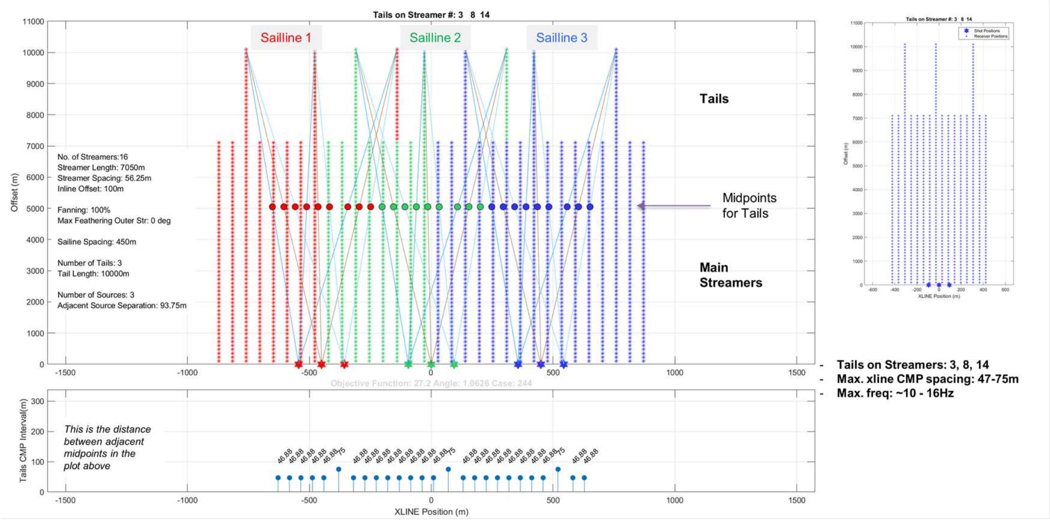


Figure 2 *An example of real shot gather (a) and the corresponding FWI sensitivity kernels showing penetration depths for 7km offset (b) and 10km offset (c). The maximum offset for the main streamer spread was 7km and the streamer-tails were 10km long (modified from Naumann et al., 2019).*

The number of streamer-tails depends on their length, streamer inventory, and the maximum frequency desired for refraction FWI. The latter depends (amongst other factors) on target depth and subsurface properties. For low frequency FWI, as typically used for long wavelength velocity updates, sparser sampling using few streamer-tails is adequate.

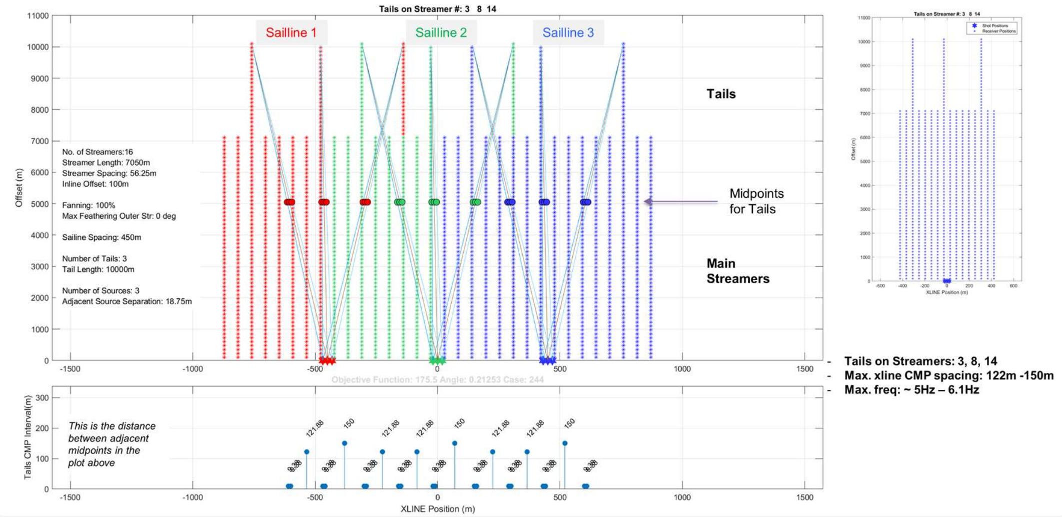
Next, we optimize the positions of the streamer-tails based on the proposed nominal survey geometry. This is done by an optimization process that seeks to obtain uniformly distributed and adequate xline sampling for the streamer-tails in the FWI forward modeling grid to meet the desired frequency. A cost function is calculated using the distribution of CMP intervals in the xline direction. To simulate 3D acquisition for a 16-streamer spread with a wide-tow triple source, three adjacent sail-lines each comprising three consecutive shots are used. For a given number of streamer-tails, all possible combinations are scanned to determine the optimal positions for the tails. For the setup with 16 streamers and three streamer-tails shown in Figure 1, there are 560 possible combinations.

As shown in Figure 3, the method has found the optimal positions for three streamer-tails are on streamers #3, #8, and #14. These positions will result in the optimal resolution for the velocity model in the xline direction.



- Tails on Streamers: 3, 8, 14
- Max. xline CMP spacing: 47-75m
- Max. freq: ~10 - 16Hz

Figure 3 Top panels show the survey geometries for three shots from three adjacent sail-lines shown by red, green, and blue dots. The lower panels show CMP-distance plotted vs. xline position. The maximum CMP-distance and its corresponding frequency are listed. The optimal streamer-tail positions with wide-tow source for the setup in Figure 1 is shown here.



- Tails on Streamers: 3, 8, 14
- Max. xline CMP spacing: 122m -150m
- Max. freq: ~ 5Hz – 6.1Hz

Figure 4 Standard narrow-tow source setup for comparison with wide-tow in Figure 3. The frequencies for the narrow-tow and wide-tow triple source are ~5Hz and ~10 Hz, respectively.

The cost function favors the smallest CMP interval, having uniform distribution, and symmetry of the streamer-tails around the source; this will generally result in the highest frequency. Three key acquisition parameters that affect the cost function are sail-line spacing, source separation, and streamer-tail positions. During optimization of the streamer-tail positions, the parameters sail-line spacing, source separation, and number of streamer-tails are kept unchanged.

Comparing Figure 3 with Figure 4 shows that the wide-tow triple source configuration performs superior to the traditional narrow-tow triple source configuration. The highest frequency is doubled by using a wide-tow source configuration without significant increase in survey cost. On the contrary, reducing the sail-line separation or increasing the number of streamer-tails to achieve a similar result as with the wide-tow source configuration would result in a cost increase. Note that the source positions are considered wide-tow for the main dense streamer spread but could be viewed as a traditional narrow source setup from the perspective of the streamer-tails.

Norwegian Sea case study

During a multi-azimuth seismic program in the Norwegian Sea in 2022, we acquired new multisensor streamer data perpendicular to legacy data from 2011. The survey configuration for the new azimuth consisted of 14 streamers with 75m streamer separation and 7km streamer length. In addition, it included two 10km long streamer-tails placed at streamer #4 and #11. A wide-tow triple source configuration with a source separation of 125m was used. The design of the streamer-tails, i.e., number and length of streamers as well as location, followed the same recipe as explained above. The 2011 legacy data were acquired using standard dual source, and 10 streamers with 100m separation and 7km long.

The study area is characterized by complex geology comprising high velocity contrast features in the overburden and a high velocity layer at BCU with variable depth. One key objective was to use FWI to refine the subsurface velocity model and the corresponding image.

Comparison of real and modelled refractions recorded by the streamer-tails suggested the presence of a high velocity feature (layer) below BCU. This high velocity interface at the BCU was not present in the legacy model, thus requiring a modification of the initial model for FWI to avoid cycle skipping during FWI.

Subsequently, refraction FWI using a narrow data selection around first arrivals was run up to 12Hz and offsets up to 10km. PGS' implementation of FWI is described in Ramos-Martinez et al. (2016). Figure 5 compares the initial velocity model with the 12 Hz FWI velocity model. For shot gathers, the real-to-modelled data fitness has improved for the first arrivals from *(a)* to *(d)* up to 10km offset. This improvement in data domain has resulted in structurally consistent velocity updates below BCU (green arrows) to produce a more detailed velocity model.

Conclusions

We presented a workflow to optimize streamer-tail configurations for FWI. The streamer length or maximum offset is determined by the penetration depth of the FWI sensitivity kernels. The position of the streamer-tails is optimized using a cost function based on the xline CMP intervals provided by the tails. Wide-tow source configurations that are designed for the main streamer spread, enable a more optimal xline CMP sampling from sparse streamer-tails compared to a scenario using traditional narrow-tow sources.

Velocity model building and imaging results from a recent Norwegian Sea seismic survey in 2022 which included streamer-tails that were designed following the workflow presented here, demonstrate the benefits of using streamer-tails for FWI.

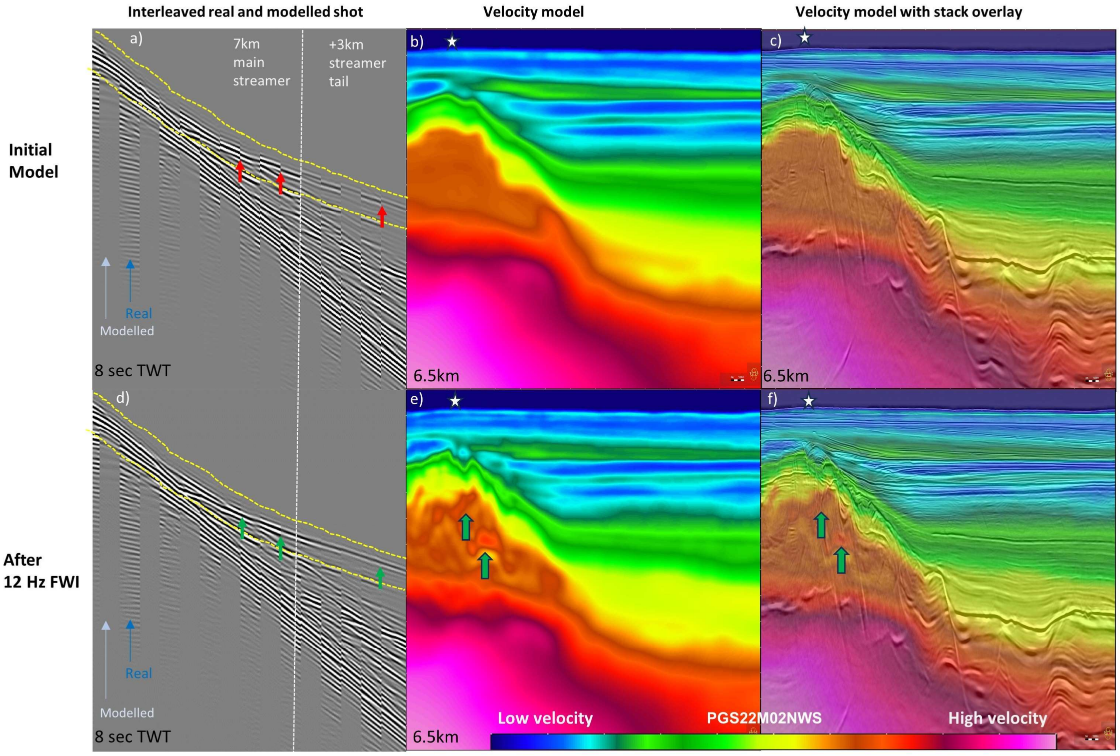


Figure 5 Comparison of interleaved real and modelled shots before (a) and after refraction FWI up to 12 Hz (d). Note the improvement in data fitness after the FWI updates within the data selection window (yellow dashed lines). The initial velocity model is shown in (b) while (e) shows the updated model after FWI. The corresponding stack overlays are shown in (c) and (f). It can be observed that improvement in data fitness in shot domain has produced structural consistent velocity updates resulting in a more detailed velocity model below BCU.

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