What Does 'Sparse' Really Mean Anyway? Ocean Bottom Nodes, Towed Streamers and Imaging

Towed streamer acquisition is drawing closer to the spatial sampling quality of the 'ideal' seafloor seismic survey, and the cost of seafloor seismic continues to attract considerable debate—particularly with respect to whether and how receiver spacing might be decreased to reduce cost ('Sparse Ocean Bottom Nodes' or 'Sparse OBN'). I consider the general topic of spatial sampling during marine seismic survey design and revisit some of the Least-Squares Migration (LSM) concepts introduced in my previous article.

Ideal 3D Sampling

It is well known that the 'perfect' 3D seismic survey would densely sample both the source and receiver wavefields as shown in Figure 1 (refer to Vermeer, 1998). On land, the vision of many vibroseis trucks operating simultaneously with encoded sweeps and recorded by large patches of receiver nodes is coming close to reality (e.g. Manning et al., 2019); with recent surveys acquiring in excess of 100 million traces per square kilometer. In the marine environment, the engineering challenge to efficient node acquisition remains high, so ocean-bottom node (OBN) surveys are typically acquired with a regular grid of 'sparse' nodes (400-1000 m separation) and dense shots (e.g. 50 x 50 m grid). Although the offset-azimuth coverage may be uniformly sampled at each receiver node location, the large receiver separation means that the offset-azimuth coverage will vary considerably throughout the shot grid that will typically be used for pre-stack depth migration (PSDM), and the seismic image quality will become unacceptably compromised in a manner that depends upon the local geology for a certain receiver separation.

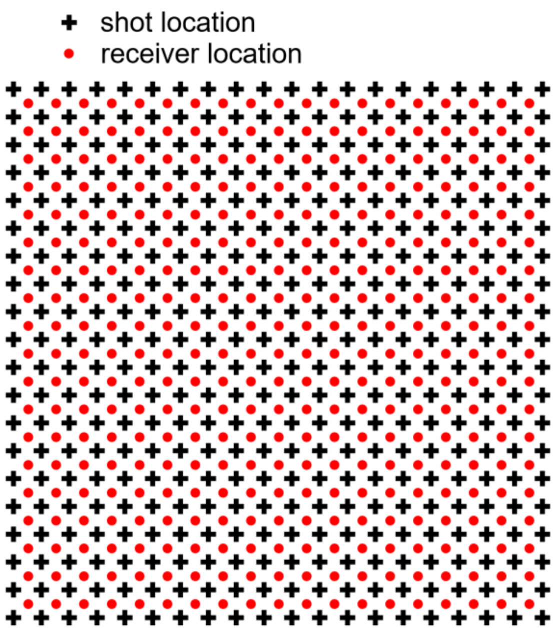

Figure 1. Ideal 3D spatial sampling of the source and receiver wavefields.

The geophysics of towed streamer acquisition is better understood—primarily because the much lower cost has translated to the methodology being the industry workhorse for the past three decades. Improvements in vessel towing capabilities made dense receiver sampling practical two decades ago, and an elongated receiver patch is typically towed along sparsely separated sail lines. Most commonly, there will be two or three source lines separated by about 50 m for each sail line when using dual-source or triple-source shooting, respectively (refer to Figure 2A). Most seismic vessels carry six source sub-arrays, so it follows that the maximum number of sources is correspondingly also six. Figure 2B shows a conceptual example where the sub-arrays have been laterally separated by a distance that yields uniformly spaced source lines using the same sail line separation (in the 18 streamer example, lateral source separation = 1.5 x streamer separation).

Note that a towed streamer geometry such as Figure 2B would have a relatively narrow-azimuth coverage for most offsets by comparison to an OBN survey. However, the ‘minimum data set’ concept of Padhi and Holley (1997) can explain how smoothly-varying changes in acquisition geometry will translates to reduced artifacts being introduced during migration. In the case of Figure 2B, the acquisition geometry is constant along each source and sail line, and because the source line separation is constant, the source-receiver geometry is more smoothly varying in the cross-line direction. Widmaier et al. (2019) describe how a combination of dense source and receiver wavefield sampling, complemented by wide-source geometry and multi-azimuth acquisition, yields an overall acquisition geometry that is comparable to OBN geometry, but at a fraction of the cost. The strategic use of a couple of long streamers within an otherwise conventional streamer spread also provides the platform for Full Waveform inversion (FWI) to yield deep velocity updates. The point here though is that we are getting much closer to the ideal 3D sampling criteria with both OBN and towed streamer survey designs.

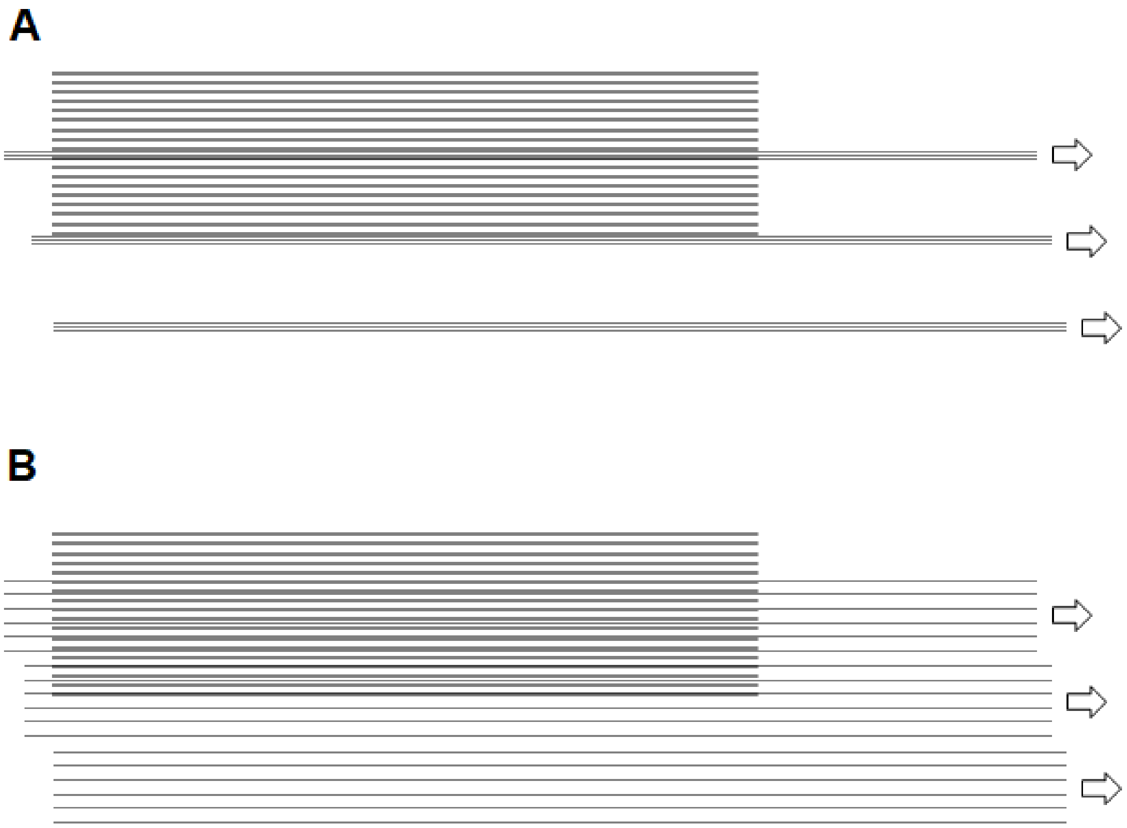

Figure 2. (A) Schematic acquisition geometry for conventional triple-source shooting with an 18-streamer spread; and (B) the same streamer spread with uniformly separated source lines. In both cases, three adjacent sail lines are shown, and the streamer spread is superimposed to scale upon the uppermost sail line.

The methodology of Widmaier et al. (2019) only requires coarsely separated long streamers because FWI only requires low frequency data. This leads to the next section on 'sparse' OBN survey designs wherein the OBN separation is so coarse that the data is only fit for FWI applications, and the data are so undersampled that traditional imaging is probably impossible.

Velocity Surveys

The recovery of ultra-long offsets for FWI is often quoted as a motivation to acquire OBN surveys. A traditional rule-of-thumb for the maximum depth for velocity updates from transmission FWI (diving waves and refractions) is one-sixth to one-third of the maximum offset, and one-third to one-half of the maximum offset for scattering FWI (reflections). It follows that a typical maximum streamer length of 10 km may prohibit FWI from application to deep targets—particularly in deepwater areas with thick and rugose salt. However, it is noted that Simultaneous Long Offset (SLO) acquisition with a dedicated source vessel will effectively double the offsets recovered from the streamers being towed (Long et al., 2013a), so offsets up to 20 km can be efficiently recorded with the SLO methodology. If a geophysical argument to record 30+ km offsets can be made, it follows that OBN is a candidate solution. Note that a variety of surface buoy or semi-stationary floating receiver solutions are also starting to emerge for the recovery of ultra-long offsets for FWI.

Higher signal-to-noise ratio (SNR) at ultra-low frequencies (less than 3-4 Hz) is also often quoted as a motivation to acquire OBN surveys as a platform for FWI, although it has been difficult for authors to demonstrate this. The ambition of ultra-low frequency recovery for FWI has also spawned the renewed interest in recent years for alternative 'low frequency' air gun and marine vibrator source concepts—neither of which have been commercialized yet.

Are such long offsets or low frequencies justifiable? On one hand, the sophistication of FWI software is rapidly advancing. Improved regularization terms and handling of the misfit function have relaxed the traditional dependency of FWI upon the availability of ultra-low frequencies to converge without cycle skipping, as well as being able to exploit the scattered wavefield energy (e.g. Ramos-Martinez et al., 2019). On the other hand, there is emerging evidence that for sub-salt imaging challenges in parts of the Gulf of Mexico (GOM), dense OBN surveys facilitated by improvements in OBN survey efficiency have contributed to improved seismic images (e.g. Li et al., 2019). An obvious contributor to the imaging uplift is the richer offset-azimuth coverage and the related attenuation of scattered and coherent noise (Regone, 1998). Li et al. (2019) also demonstrated that the OBN data could be decimated from the natural 426 x 369 m sampling to 852 x 738 m sampling (with the same source sampling of 54 x 47 m) without compromising FWI.

It is still early days, but the concept of 'velocity surveys' has emerged wherein the spatial sampling between OBN receivers is relaxed to the point where FWI may be successfully run to low frequencies that adequately recover salt boundaries and other major features of interest. As intimated by Li et al. (2019) and Mei et al. (2019), the current thinking is that 800-1000 m OBN separation is probably reasonable for 'exploration' grade resolution. So one commercial concept is that a regional sparse OBN survey is used to recover a reasonably high quality FWI model that is then used to reprocess existing data—probably towed streamer data. OBN spacing in the range of 300-400 m is probably necessary to satisfy the velocity model accuracy required by reservoir production teams; although Schneider and Docherty (2016) show that useful angle gathers may be processed when OBN separation exceeds 400 m.

Can We Recover From Sparse Sampling?

The effects of OBN decimation upon seismic image quality are well known (e.g. Olofsson et al., 2012). Compressive Sensing (CS) concepts have been successfully applied to a variety of seismic survey styles, wherein the acquisition effort and cost can be strategically reduced whilst data resolution is preserved (e.g. Li et al., 2017; Mosher et al., 2017). Non-uniform spatial sampling is a key element of CS, and Zhang and Lumley (2019) correspondingly show that by arranging OBNs randomly, a sparse under-sampled volume is acquired, and the seismic data can subsequently be reconstructed using CS. The ambition is that one may maintain a similar resolution in images by using fewer OBNs, or obtain higher-resolution images from the same number of OBNs.

The past decade has seen steady progress in the incorporation of the full wavefield into both FWI (Ramos-Martinez et al., 2019) and into imaging (Lu et al., 2018). Separated Wavefield Imaging (SWIM) has been applied to mitigate the acquisition footprint on towed streamer data (Long et al., 2013b), imaging OBC/OBN data (Lecerf et al., 2015), and for improving the 4D monitoring of Permanent Reservoir Monitoring (PRM) data (Lecerf et al., 2017). By using the Jubarte PRM dataset acquired by Petrobras, a decimation test by Lecerf et al. (2017) selected all receivers in consecutive sub-sections of 600 m length along each PRM cable, effectively splitting the receivers into circular patches with a 600 m diameter. The number of sensors is then reduced by a factor of two. Their results demonstrate that it is possible to increase the sparseness of seabed sensor locations without compromising the resolution of 3D/4D imaging. van der Burg et al. (2018) also tested the sensitivity of SWIM to the decimation of OBC data with very encouraging results (see Figure 4). More recently, Full Wavefield Migration (FWM: Lu et al., 2018) has combined SWIM and imaging of primaries into one solution that is implemented as a Least-Squares Migration (LSM: see also Long, 2019). Lecerf and Basselievre (2018) and Lecerf (2019) correspondingly use LSM principles to accommodate significant differences in the acquisition geometry of baseline and monitor surveys during 4D imaging.

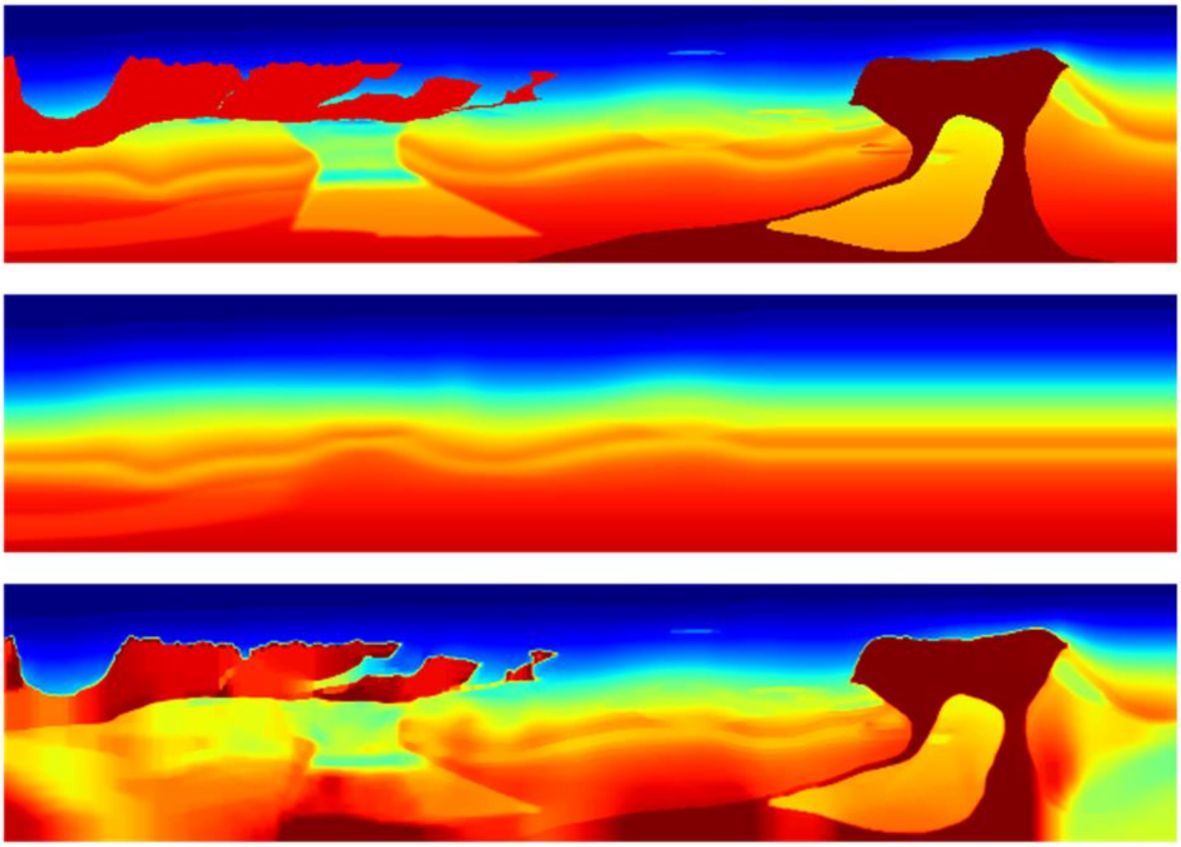

Figure 3. Synthetic full wavefield FWI result. (upper) Desired model; (middle) Starting velocity model; and (lower) Inverted velocity model. The scattered wavefield (reflections) can usefully contribute with the use of appropriate misfit functions; regularization terms and imaging conditions (refer to Ramos-Martinez et al., 2019).

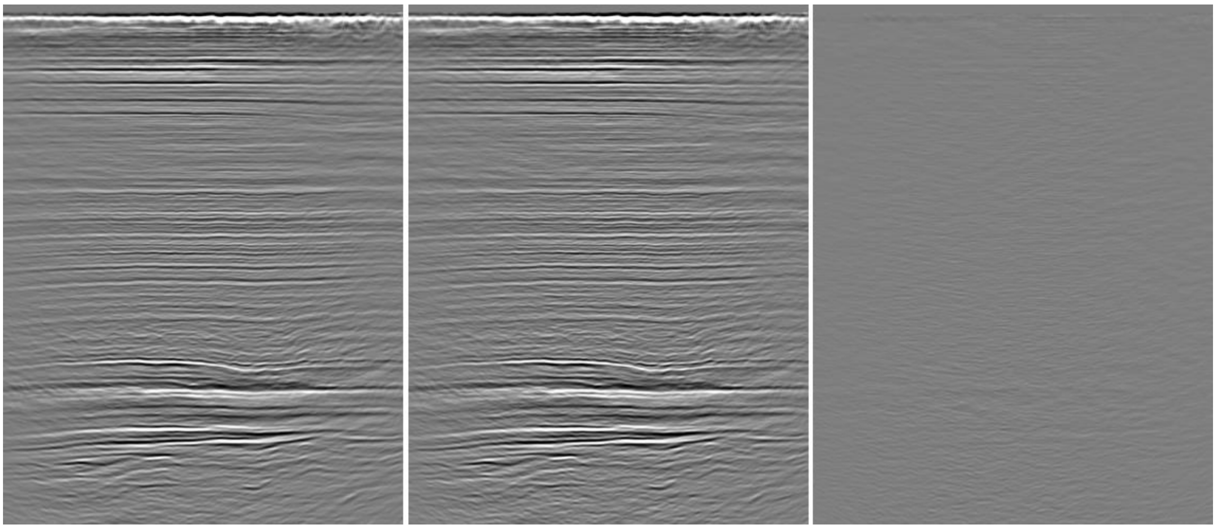

Figure 4. (left) Cross-line SWIM stack of OBC data decimated from 350 m to 700 m cable spacing; (middle) Undecimated SWIM stack; and (right) Difference. From van der Burg et al. (2018).

Summary

The high cost of OBC and OBN acquisition has encouraged several creative approaches to the design of associated velocity model building and imaging solutions. On one hand, 'sparse' OBN survey design with 800+ m between receivers may allow so-called 'velocity survey' concepts wherein a high-quality velocity model can be recovered that enables an uplift in the reprocessing of existing seismic data. On the other hand, advances in Least-Squares Migration with the full wavefield may enable reservoir-scale imaging and characterization pursuits with sparse OBN data anyway. At the same time, improvements in towed streamer design coupled with the ability to tow sources with large lateral separation now enable the long offset capabilities of OBN up to about 20 km, and with the established high resolution imaging capabilities of towed streamer 3D data—and at much lower cost. It is clear that improvements in acquisition engineering coupled with creative survey designs and new imaging solutions still have substantial room for improving the cost and quality of seismic data.

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