Spatial Sampling Dilemma in Seismic Acquisition: Regular (Deterministic) vs. Irregular (Random)

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Summary

The search for optimal spatial sampling scenarios compatible with sparse Fourier seismic reconstruction algorithms (also known as 5D interpolation methods) will often lead to random sampling functions. The spectral responses of random sampling scenarios contain low amplitude leakages which are spread over the entire spectral domain. This property, combined with the sparse recovery conditions, can be utilized to successfully reconstruct the seismic records. However, designing seismic surveys based on a random distribution of shots and receivers can be operationally challenging, impractical, and confusing. Here I discuss two alternatives to random sampling scenarios consisted of regular and pseudo-random sampling functions with semi-optimal and ultra-optimal Fourier recovery properties, respectively.

Introduction

Seismic acquisition design can be posed as an optimization process to strike a balance between geophysical, operational, and cost constraints (Liner *et al.* , 1999). This is achieved by determining design parameters which minimizes a cost function that is properly weighted based on geophysical targets. These optimization processes were often carried out for traditional orthogonal surveys to obtain optimal shot and receiver spread lengths, uniform fold distribution, and desired offset range. In traditional orthogonal geometries, there are two sparse (shot-line and receiver-line intervals) and two dense (shot and receiver intervals) spatial dimensions. It is also important to have shot and receiver symmetry for these 3D acquisition designs (Vermeer, 2010). The ideal scenario, however, would be to acquire densely sampled seismic data in all spatial dimensions but often the problem is this might not be feasible due to economical considerations and natural barriers. further, seismic data interpolation algorithms (Ronen, 1987; Spitz, 1991; Liu and Sacchi, 2004; Naghizadeh and Sacchi, 2010) can be used to transform sparsely sampled seismic data into densely sampled seismic data. Therefore, it might be beneficial to take into account the interpolation compatibility of various seismic surveys by adding a new term into the cost function of the survey optimization problem.

The interpolation compatibility parameter could influence both operational costs and geophysical illumination constraints, hence, changing the shape of the cost function for the survey design optimization problem. In this paper, I introduce a new sampling scheme, named weave sampling pattern, which is suitable for sparse Fourier reconstruction. I also examine some pseudo-random/deterministic sampling functions with Fourier optimal recovery properties superior to random sampling scenarios.

Spectral Responses of Sampling Functions

Figure 1a shows a full sampling function on which all of the samples on a 16×16 spatial grid are available. Figure 1b is a typical regular decimation function in both X and Y directions. Filled and empty circles represent the available and missing samples, respectively. Figure 1c depicts another regular decimation function resembling a hexagonal sampling pattern. Figure 1d represents a diagonal regular decimation scenario. Figure 1e is a special kind of regular sampling operator which has been derived from Figure 1d. In order to create Figure 1e, one can pick any diagonal line of available samples from Figure 1d and flip every other pair of available samples by 90 degrees. This is a weave

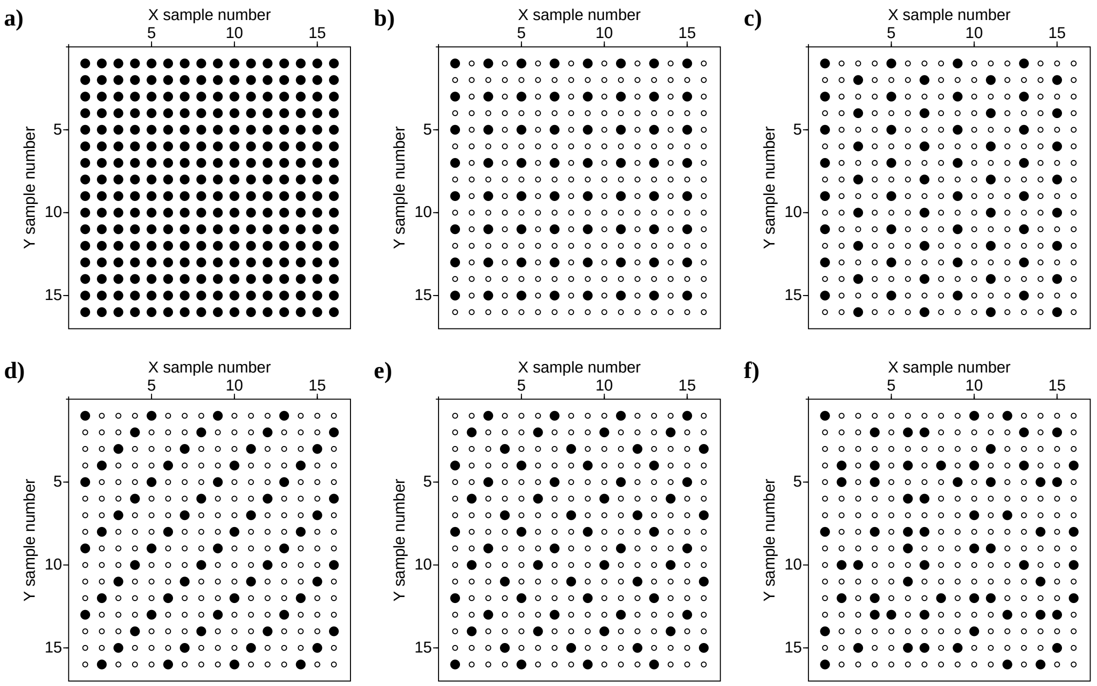

Figure 1 *a) Full sampling operator. b) Regular decimation. c) Regular hexagonal sampling. d) Regular diagonal sampling. e) Regular weave pattern sampling. f) Random sampling. Filled and empty circles represent the available and missing samples, respectively.*

sampling pattern with paring factor of $\delta = 2$. Figure 1f shows a random sampling function. All of the sampling functions in Figures 1b-1f contain only 25% available samples. These sampling scenarios could represent the distribution of active shots or receivers in a seismic survey.

Figures 2a-2f show the Fourier responses of the sampling functions in Figures 1a-1f, respectively. The spectral domain representations are portrayed in terms of normalized wavenumbers. Normalized wavenumber axes are obtained by assuming a unit spatial increments of $\Delta x = 1$ or $\Delta y = 1$. This means that to obtain wavenumber axes in cycles/m, one must divide the normalized ones by the desired Δx or Δy. The Fourier response of full sampling function is a single spike at origin $(k_x, k_y) = 0$ (Figure 2a). The Fourier responses of three regular sampling functions in Figures 2b-2d contain three extra spikes in addition to the original spike at the origin. The amplitudes of these extra spikes are also equal to the amplitude of the spike at the origin. This could be detrimental for sparse Fourier recovery methods since a sparsity measure will not be able to distinguish between the original signal and artifacts. Figure 2e shows the Fourier response of the weave sampling function in Figure 1e. The spectral response contains eight extra spikes in addition to the spike at the origin. However, their amplitudes are less than the amplitude of the spike at the origin. Figure 2f shows the Fourier response of the random sampling function in Figure 1e. The spectral response contains spikes over the entire wavenumber domain but their amplitudes are significantly less than the amplitude of the spike at the origin. These low amplitude spikes in Figures 2e and 2f are beneficial for sparse Fourier recovery.

Double-Weave Sampling functions

To design a 3D seismic acquisition, one can use weave patterns with even δ values to distribute shots and receivers (Naghizadeh, 2015a,b). This leads to a *double-weave 3D seismic acquisition* design. Figures 3a, 3b, and 3c show three possible double-weave acquisition layouts. Figure 3a is a double-weave design with weave pattern of $\delta = 6$ for shots (red asterisks) and $\delta = 4$ for receivers (blue filled squares). The shot and receiver weave patterns can be shifted relatively to prevent coinciding shot

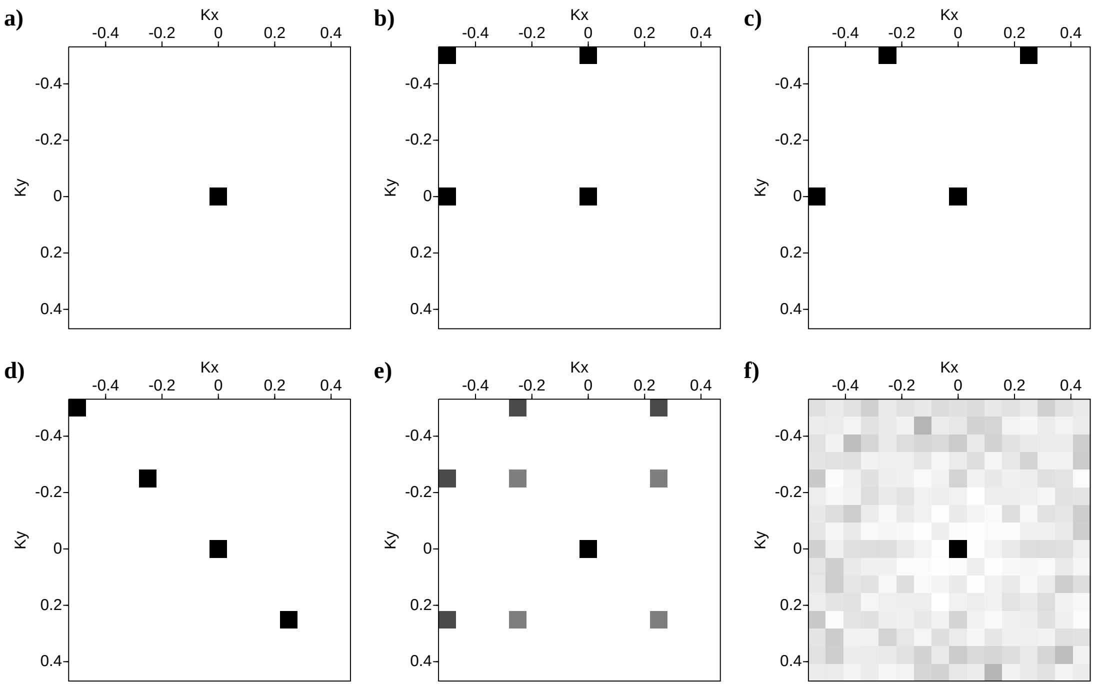

Figure 2 *a-f) Fourier responses of the sampling functions in Figures 1a-1f, respectively.*

and receiver locations. The 5D Fourier interpolation algorithms can be used to reconstruct shots and receivers on all grid locations. Figures 3b and 3c show two other double-weave acquisition patterns with paring factor $\delta = 4$ for both shots and receivers. The double-weave layout in Figure 3b creates a zigzag pattern with alternating shots and receivers along the zigzag lines. This provides an opportunity to deploy seismic survey cut-lines by following the zigzag patterns rather than straight orthogonal lines. This also leads to a 3D land acquisition survey design with slightly shorter length of cut-lines and hence minimizing environmental footprint. The double-weave layout in Figure 3c resembles an acquisition similar to traditional orthogonal acquisition but with a weave pattern distribution of shots and receivers. The orthogonal double-weave acquisition can be acquired on similar cut-line layouts from a past traditional orthogonal survey.

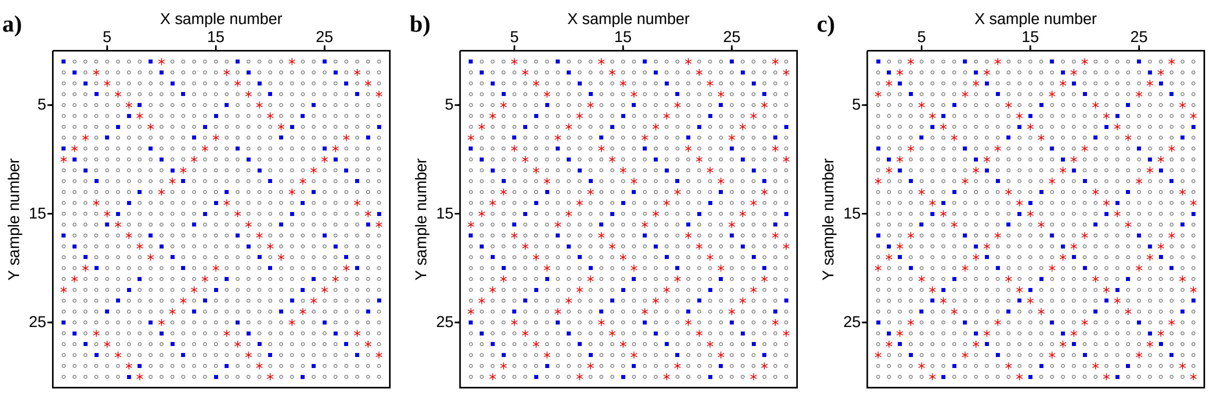

Figure 3 *a) An asymmetric double-weave acquisition layout. b) Zigzag double-weave acquisition layout. c) Orthogonal double-weave acquisition layout. Red asterisks and blue filled squares represent shots and receivers, respectively*

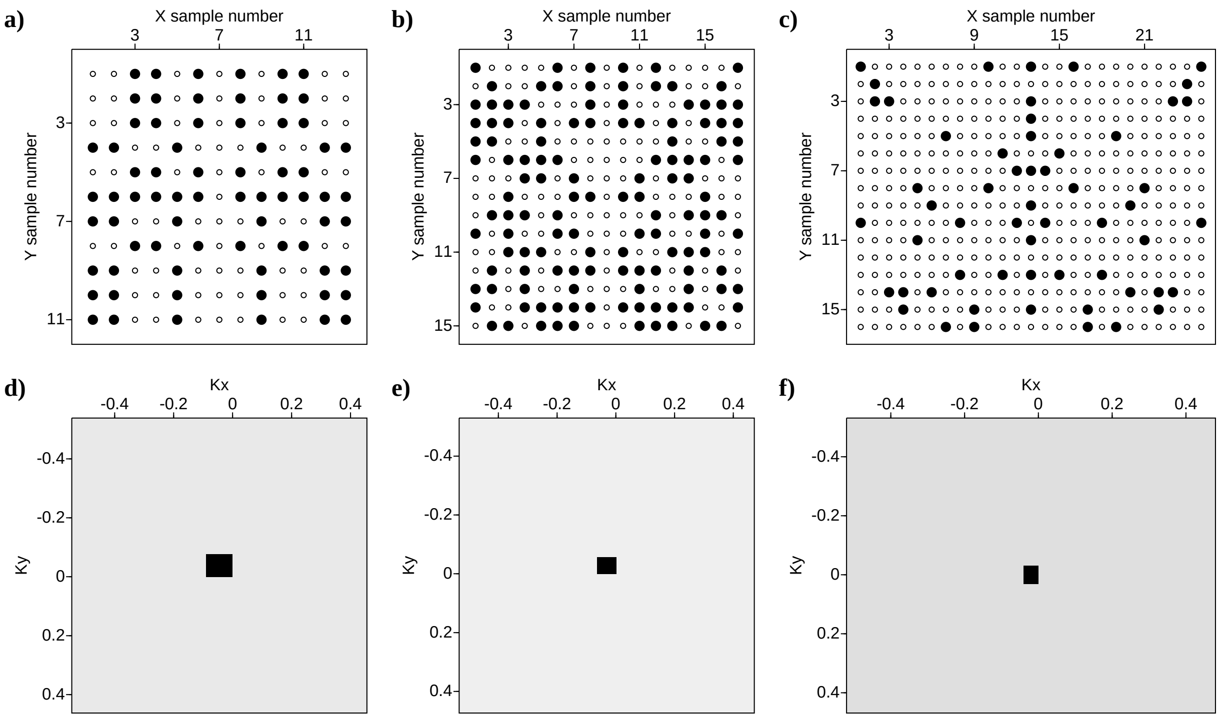

Figure 4 *a, b , and c) Three 2D sampling functions created using difference sets. d, e, and f) Spectral responses of sampling function in a, b, and c, respectively. The Fourier response leakages in each spectral response have equal amplitude over full spectrum.*

Pseudo-Random Sampling functions

Recently, Jamali-Rad *et al.* (2016) have proposed using sampling functions created using difference sets. These sampling functions, also known as pseudo-random sampling functions, lead to spectral responses with equal amplitude Fourier leakage over the entire components of the spectrum. Figures 4a, 4b, and 4c show three examples of pseudo-random sampling functions and Figures 4d, 4e, and 4f show their corresponding spectral responses, respectively. The equal amplitude leakage response of pseudo-random sampling functions could lead to faster convergence in data reconstruction applications. The synthetic seismic data reconstruction tests using double-weave and differences sets sampling functions show successful recovery of missing samples.

Conclusion

The spectral responses of weave and pseudo-random sampling functions were compared to random and regular decimation sampling functions. Double-weave 3D seismic acquisition was proposed as an unsophisticated alternative to random sampling scenarios. Weave sampling functions show a sub-optimal sparse Fourier recovery in comparison to random sampling functions. Meanwhile pseudo-random sampling functions outperform pure random sampling functions in sparse Fourier reconstruction applications.

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