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Seismic AVO and Inversion as a tool to assess the impact of cost-efficient environmentally responsible land 3D survey designs on AVO amplitude fidelity.

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Summary

To ensure comparable land 3D to 2D S/N quality, many authors advocate a dense receiver patch geometry for 3D acquisition to fully sample the 5D wavefield (Crewes 1991, Rigdon 1995). However complete sampling of the 5D wavefield through a “full patch” geometry with all shot and receiver stations live i.e., the 3D equivalent of the 2D stack-array (Anstey 1986) is economically and practically prohibitive due to surface restrictions and the environmental/ecological impacts from a dense grid of cut seismic lines. Consequently, land 3D’s are routinely acquired with variously coarse line cross-spreads, that have an extreme asymmetry between line and station dimensions where the receiver and shot line dimensions are generally 10 to 20 times larger than station spacings. This station to line asymmetry violates the concept of “symmetric sampling” (Vermeer 1994) by not reciprocating the regular areal sampling of receivers to equivalent shots resulting in extremely erratic offset and azimuth sampling within and between bins, thereby reducing the full 3D stack-array benefit for improved S/N, AVO fidelity and pre-stack imaging. Since the early 2000’s, 5D interpolation and regularization algorithms (Sacchi and Liu 2004, Trad 2009, Naghizadeh 2007, 2015) have been developed to overcome this coarse shot/receiver line cross-spread violation of the full 3D stack-array sampling requirement. However, despite the almost universal acceptance of both theoretical and practical implementation of 5D reconstruction beyond Nyquist, the question of why interpolation can overcome the stringent two samples per wavelength Nyquist restriction at all offsets, was not adequately justified until the concept of “Fresnel Zone Binning” (FZB) was introduced by Monk (2009, 2010, 2020). With Fresnel Zone Binning, an adequate three samples per Fresnel Zone sample rate provides an alternative spatial sampling that relaxes the strict Nyquist limit of two samples per wavelength for interpolation (Goodway et al 2024).

Understanding 5D Interpolation and Nyquist Limitations

Land 3D sampling design continues to be driven by the Nyquist limit as formulated by Shannon’s (1949) sinc interpolation theory. This theorem states that a wavefield can be exactly reconstructed by uniformly spaced samples when the sample rate is equal to or smaller than the Nyquist rate which is twice the spatial bandwidth of the wavefield, through Shannon’s 1949 interpolation formula.

However, this applies to the limited case of a 1D signal where there is no information available from other adjacent measurements and consequently is not applicable to the 3D seismic problem with a sampling distribution in four spatial dimensions. Satisfying the Nyquist-Shannon criterion in one or two spatial dimensions does not provide any clarity on adequate sampling in the remaining dimensions. As a result, a new criterion related to the full spatial distribution is needed to establish if the wavefield has been correctly sampled as introduced and described in the following section.

Furthermore, what has rarely appeared in the land 3D sampling discussion, is the concept of Seismic Wavefield Gradiometry to accurately reconstruct both the aliased signal and noise wavefields beyond Nyquist by factors of 2 to 6 times according to the multichannel signal sampling

theorem of Linden (1959). This sampling theorem of Linden is a Taylor series generalization of the 1st order truncated Nyquist-Shannon formula and shows how to accurately reconstruct the wavefield's aliased wavenumbers by simultaneously exploiting point sampling and its various higher order derivatives or gradients using sinc interpolation as a Taylor series expansion for half Nyquist sampling reconstruction (Goodway 2013, Poole et al 2019, Naghizadeh 2026).
This new technology for wavefield recovery and imaging through Seismic Wavefield Gradiometry was introduced by WGECO termed "IsoMetrix" to overcome coarse crossline marine data sampling, by enabling the accurate reconstruction of the seismic wavefield at fine spatial sample intervals (thus far only possible in the inline direction). The result is a reliable, continuous measure of the full seismic wavefield sampled at a finer point-receiver surface grid (Vassallo et al., 2010).
The sampling comb of the sinc functions proposed in the next section on "Fresnel Zone Bin Sampling" for alias protected seismic wavefield recording is representative of this multi-dimensionality of the 3D seismic dataset. Applying the 1D Nyquist-Shannon criterion to 3D sampling is analogous to a one-term NMO correction to seismic moveout, which is far too simple a model to be representative of the actual seismic wavefield.

Fresnel Zone Bin Sampling theory for alias protected seismic wavefield recording and unaliased interpolation support

This paper will establish the theoretical basis for seismic wavefield interpolation through a new alternative proposed spatial sampling theory that relaxes Nyquist termed "Fresnel Zone Bin Sampling" for alias protected seismic wavefield recording and unaliased interpolation support. This proposed theory justifies the Fresnel Zone Binning (FZB) criteria of Monk (2009, 2020) and allows for the routine spatial reduction of sparse 3D sampling through 5D interpolation. This new "Fresnel Zone Bin Sampling" theory was motivated by the challenge in the following quote from Vermeer (2022): *"If true, this (our reference "Fresnel Zone Binning-FZB- Monk 2009, 2020") is an extremely important new law in (geo)physics. However, nowhere in the Monk papers can a proof of this law (FZB) be found, nor is there any research geophysicist who has taken up the challenge to prove it. Monk (2009, 2020) tries to assess the validity of the FZB idea using an illustrative example, but this really falls short of a proof."*
The new "Fresnel Zone Bin Sampling" interpolation theory is developed as a proof of the FZB concept of Monk (2009, 2010) and is based on Goodway et al EAGE Frist Break September 2024. Furthermore, this updated sampling criteria is needed to set clear limits on how far apart seismic lines can be before interpolation in processing begins to break down.
In this new theory the Fresnel Zone anti-alias filter (similar in function to a field array) for seismic wavefield sampling acts as the equivalent spatial gradient in the multichannel signal sampling theorem of Linden (1959).

Quantified AVO inversion assessment of various cross-spread versus parallel acquisition geometry decimations from a fully sampled patch 3D dataset

Having established this new "Fresnel Zone Bin Sampling" theory for 5D interpolation, the following portion of the paper will consider actual AVO fidelity and pre-stack imaging uplift from the un-interpolated "full patch" 3D stack-array geometry when compared to various 5D interpolated standard cross-spread geometries, as this remains untested in practice with a few exceptions (Goodway and Ragan 1996, Duncan et al 2014). These comparisons can be simulated using the concept of "full patch 3D stack-array acquisition decimation tests" that directly compare the "full patch" best 3D stack-array geometry to various 5D interpolated cross-spread and alternative parallel geometries (MegaBin; Goodway and Ragan 1996, EcoSeis™; Vermeulen et al 2022, Goodway et al 2024, Goodway et al 2025) through independent though identical processing flows.

One of the conclusions of these decimation tests was that 5D interpolation of the missing traces in the coarse cross-spread line geometries, was unable to recover the imaging and AVO fidelity of the “full patch” best 3D stack-array’s un-interpolated volume. This conclusion was evidenced by the persistent cross-spread geometry “footprint” contamination due to aliased high wavenumber surface noise and interbed multiple interference that contaminates the signal despite 5D interpolation. As a result of these simulated acquisition decimation tests, land 3D cross-spreads are now designed with a significantly reduced crossline dimension in the order of two to three times the station spacing (Duncan et al 2014, Vermeulen et al 2022).
This relatively recent dense 3D cross-spread line configuration requires cutting or clearing of trees from 10% to 25% of the total program area. The resulting orthogonal seismic cut-line surface footprint creates increasing environmental and ecological damage, which negatively affects sensitive species such as woodland caribou. Proposed changes to seismic regulations, to restrict line widths and reduce the seismic acquisition surface footprint, requires a new approach to acquiring seismic data driven by the 2017 COSIA Land Challenge, the 2020 Imperial Challenge – CleanTech Alliance, the 2021 COSIA- Foresight-Alberta Innovates Reducing Seismic Exploration Footprint challenge, and the recent CRIN Reducing Land Footprint Competition.

Initiated and motivated by Optiseis Solutions’ 3D design study (Vermeulen et al 2022, Naghizadeh et al 2022, Goodway et al 2024, Goodway et al 2025) to meet the 2017 COSIA Land Challenge, this paper describes and presents the results from a series of “full patch 3D stack-array acquisition decimation tests” to advance land 3D design towards environmental and ecologically responsible seismic surveys resulting in the recent Optiseis parallel zigzag EcoSeis™ design. The 3D acquisition design goal in this study is to maximize post 5D interpolated pre-stack migration resolution and AVO fidelity preservation, while minimizing the surface footprint.

An oversampled “full patch 3D stack-array acquisition” enables a comparison of ten pseudo-decimated cross-spread designs (40m, 60m and 80m line spacings) and parallel 3D geometries (40m MegaBin, 60m zigzag EcoSeis™ and 80m parallel sinusoidal design) through a controlled and quantifiable AVO inversion assessment of the decimated acquisition geometries. The assessment methodology was developed using Qeye's pre-stack AVO elastic inversion, to compare the accuracy of the various decimated 3D volumes through a relative correlation to the fully sampled un-decimated un-interpolated input, using AVO and QI attributes. The results illustrate the sensitivity of each inverted AVO parameter to offset/incidence angle distributions for each decimated survey. Inversion results obtained for acoustic impedance (AVO intercept) are less sensitive to intra-bin offset distribution but are strongly affected by the quality of the near-offset data which is a function of the “largest minimum offset” as well as the sparse acquisition footprint. By contrast inverted parameters like AVO gradient and Vp/Vs are not only strongly affected by intra-bin offset distributions especially from the sparse cross-spread geometry, but the inverted values change with a systematic 5D interpolation AVO gradient error depending on the decimated 3D design impact on near to mid-angle range sampling.

Conclusions

This paper establishes the theoretical basis for seismic wavefield interpolation through a new “Fresnel Zone Bin Sampling” theory for alias protected seismic wavefield recording that justifies the FZB criteria of Monk (2009, 2010) and allows for routine spatial reduction of sparse 3D sampling through 5D interpolation. Consequently, wavefield reconstruction (pre-migration) through interpolation of the Parallel geometry’s asymmetric bin in the crossline direction, reduces the coarser bin dimension through de-aliased “Fresnel Zone Bin Sampling” interpolation and 3D PSTM that recovers the fully sampled 3D patch/grid geometry’s spatial resolution. By contrast orthogonal cross-spread 3D geometries designed specifically without the need of pre-stack

interpolation that was rejected as a viable process (Vermeer 1994, 1995, 2002) suffer from aliasing of noise/multiples with footprint pattern interference artifacts that are generated by PSTM and AVO processing steps that require fully sampled shots and receivers.

References

Anstey N. “Whatever happened to ground roll?”; TLE March 1986, 40-45.

Crews G., Musser J. and Phillips H., “Economical high-resolution 3D seismic survey technique without interpolation”; 1991 SEG Ann. Mtg. Abstracts, 754-756.

Duncan E., A. O’Byrne and J. Dalsin, “Real vs. ‘5D’ Data: An analysis of acquired vs. interpolated data in both the post-stack and the pre-stack domains for parallel and orthogonal geometries”; CSEG Recorder 2014 Vol. 39 No. 03.

Goodway, W., and B. Ragan, 1996, “Mega-Bin”: Toward a cost effective “near symmetric patch geometry” for improved S/N & resolution from regular acquisition sampling and co-operative image processing”; CSEG convention abstracts p 99-102.

Goodway, W. 2013. Cost-efficient acquisition to reduce coarse land 3D line spacings through beyond Nyquist interpolation and wavefield reconstruction for signal and noise. CSEG Convention Abstracts.

Goodway B., R. Cova, W. Pardasie, A, Crook, M. Naghizadeh, C. Crook, M. Hons, Land 3D acquisition design: Theory of wavefield sampling and case study of AVO and Inversion as a tool to assess the impact of sparse cost-efficient environmentally responsible land 3D survey designs on AVO amplitude fidelity. Part 1: Past 3D design testing and assessment of cross-spread and parallel geometries. EAGE Frist Break September 2024.

Goodway B., R. Cova, W. Pardasie, A, Crook, M. Naghizadeh, C. Crook, M. Hons, Seismic AVO and Inversion as a tool to assess the impact of cost-efficient environmentally responsible land 3D survey designs on AVO amplitude fidelity. Part 2: Present 3D design tests for environmentally sustainable sparse perturbed parallel geometries. EAGE Frist Break January 2025.

Linden, D. A., 1959. A discussion of sampling theorems: Proceeds of the IRE, 47, 1219-1226.

Liu, B. and Sacchi, M. D., 2004, Minimum weighted norm interpolation of seismic records: Geophysics, Vol 69, 1560-1568.

Monk, D. J., 2009, Fresnel zone binning: Application to 3D seismic fold and coverage assessment; TLE, 28, no. 3, 288–295.

Monk, D. J., 2010, Fresnel zone binning: Fresnel-zone shape with offset and velocity function; Geophysics, 75, no. 1, T9–T14.

Monk, D. J., 2020, Survey design and seismic acquisition for land, marine, and in-between in light of new technology and techniques: SEG, Distinguished Instructor Series, **23**, https://doi. org/10.1190/1.9781560803713.

Naghizadeh M. and M. Sacchi, (2007), Multistep autoregressive reconstruction of seismic records, Geophysics, 72, V111-V118.

Naghizadeh, M., 2015, Double-weave 3D seismic acquisition — Part 1: Sampling and sparse Fourier reconstruction; Geophysics, 80, WD143-WD162.

Naghizadeh, M., A. Crook, and S. Bossaer, 2022, Optimal infilling of seismic stations using Fresnel zone binning analysis; SEG Technical Program Expanded Abstracts: 75-79.

Naghizadeh, M., R. Pearcy, and A. Crook; A Derivative-Guided Seismic Data Reconstruction Method: Geoconvention 2026 abstracts.

Nyquist, H., 1928, Certain topics in telegraph transmission theory: Trans.Am.Inst.Elec.Eng.47,617- 644.

Poole, A., J. Quigley, E. Muyzert, N. Allouche, P. Edme, N. Goujon; Gradient recording in practice: a comparative field trial of a 5C land seismic gradient sensor
2019 SEG International Exposition and 89th Annual Meeting, 10.1190/segam2019-3215616.1

Rigdon K., 1995, “Designing Full Azimuth 3D Seismic Surveys”; CSEG. Convention Abstracts, 94-95.

Shannon, C. E., 1949, Communication in the presence of noise: Proc., Inst. Radio Eng., 37, 10 - 21.

Trad D., 2009, “Five-dimensional interpolation: Recovering from acquisition constraints”; Geophysics, 74, V123--V132.

Vassallo, M., Ozbek, A., Ozdemir, K., and Eggenberger, K., Crossline wavefield reconstruction from multi-component streamer data: multichannel interpolation by matching pursuit 2010 Geophysics, Vol 75, No 6, and SEG annual meeting abstract.

Vermeer G., “ 3D Symmetric sampling”; 1994 SEG Ann. Mtg. Expnd. Abstracts, 906-909.

Vermeer G., 3D Symmetric sampling in Land Data Acquisition; 1995 CSEG Annual Convention Abstracts,169-170.

Vermeer G., 3D Seismic survey design; 2002 SEG Geophysical Reference Series No. 12.

Vermeer G., Comments on Fresnel zone binning — Can it be used to determine maximum allowable holes in coverage of long offsets? TLE June 2022, 418-420.

Vermeulen P., A. Crook, M. Naghizadeh, and S. Ross, “Turn your seismic program into a lean, green, resolution machine”; GeoConvention conference abstracts; Calgary 2022.