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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) 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).

This paper will first establish the theoretical basis for seismic wavefield interpolation through a new alternative proposed spatial sampling that relaxes Nyquist termed "Fresnel Zone Bin Sampling" theory for alias protected seismic wavefield recording. 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."*

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 “foot-print” 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.

Theory / Method / Workflow

Initiated and motivated by Optiseis Solutions’ 3D design study (Vermeulen 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. 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 and parallel 3D geometries 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 as well as a Kx-Ky footprint measurement. 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 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 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 near to mid-angle range sampling.

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