Cost efficient acquisition to reduce coarse land 3D line spacings through beyond Nyquist interpolation and wavefield reconstruction for signal and noise

by Bill Goodway, Apache Corporation.

Summary

To ensure comparable land cross-spread 3D to 2D data quality, many authors advocate dense in-line receiver and in-line shot station sampling but ignore the receiver and shot line dimensions that are generally 10 to 20 times larger than station spacings. Consequently land 3Ds are routinely acquired with coarse cross-lines with a severe asymmetry between line and station dimensions resulting in extremely erratic offset and azimuth sampling within and between bins. This asymmetry causes severe statistical and aliasing limitations for key processing and inversion steps such as surface consistent statics, pre-stack migration (PSTM) and even AVO due to a lack of near offsets, as all of these applications have strict requirements for dense regularly sampled shot, receiver and common reflection point domains. By contrast, 2D linear spatial sampling is regular and dense with fold that is higher by the same line to station spacing ratio of cross-spread 3D's i.e. by factors of 10 to 20 times. The reason for this is that 2D fold is a function of shot spacing that is routinely acquired to be equal to the receiver spacing, while 3D fold is a function of line spacing (shot and receiver) that is considerably coarser than station spacings. This irregularly sampled lower fold aliases high wavenumber surface noise and leaks interbed multiple interference that contaminates signal in the standard gather domains of common shot, receiver, offset, azimuth and mid-point, thereby distorting the final 3D stack in subtle ways resulting directly in drilling failure for stratigraphic targets. However reducing line spacings to station dimensions incurs significant additional cost and may be environmentally prohibitive.

Introduction

One solution or compromise to the dilemma of acquisition cost versus PSTM sampling is to acquire a wide azimuth parallel geometry with coincident shots and receivers that naturally reduces the line dimension to the station spacing in the in-line direction and efficiently allows for a finer cross-line spacing that may be regular or staggered/dithered (see following discussion on random sampling). However the compromise is that the cross-line spacing creates an asymmetric coarse cross-line bin that needs to be reduced by factors of 2 to 6 times in order to create the desired symmetric bin of the cross-spread 3D design. A design variously termed MegaBin or SlimBin that achieves this goal was tested through an oversampled decimation experiment and introduced in the 90's by Goodway and Ragan while at PanCanadian (1996). Ever since its introduction the MegaBin technique has been vociferously denounced, with good reason as this regular coarse cross-line bin spacing leads to aliasing that violates the Nyquist wavenumber limit. However in the last few years coarse cross-line interpolation has gained wide acceptance through the research and implementation of pre-stack 5D Minimum Weighted Norm Interpolation (MWNI) by Liu and Sacchi (2004) and Trad (2009) that has allowed previously Nyquist-challenged processes such as PSTM to succeed. This brings the discussion back to the origins of the MegaBin design regarding the method and ability of spatial interpolation to actually recover signal and even the more challenging noise wavefield. At the time of its introduction in the 90's the MegaBin design purposefully incorporated and aimed to recover the coarse cross-line bin size through interpolation both pre- and post-stack. At that time many authors rejected the ability of interpolation to successfully de-alias coarse sampling as the commonly quoted statement "you can't recover what you did not pay for" clearly indicates. However notable exceptions to this thinking included Spitz (1991) and Claerbout (1998) who showed that the spatial Nyquist limit when viewed as a

wavenumber bandwidth can be overcome, i.e. de-aliased, by assuming that the un-aliased, low temporal frequencies share the same linear velocity or plane as the aliased, higher temporal frequencies. In addition this spatial bandwidth need not be contiguous, i.e. the wavefield may be comprised of a few planes with wavenumbers both below and well above the Nyquist limit as long as the sum of these wavenumbers did not exceed Nyquist. Both authors concluded that the assumption of a smoothly varying linear model for the wavefield (or a plane wave decomposition in a limiting sense), permits a reasonable reconstruction of the pre-migrated wavefield at finer spatial sampling, by using F-X spatial prediction. The MegaBin patent awarded to PanCanadian required recovery beyond Nyquist of the coarse cross-line dimension through processes such as F-X interpolation that primarily de-aliases signal as pre-conditioning for PSTM, but in some cases for linear noise attenuation that is more challenging due to its spatially sporadic high wavenumbers.

Theory and Method

Seismic trace interpolation seeks to accurately recover the signal wavefield beyond the wavenumber Nyquist limit. This enables PSTM to achieve the design criterion resolution (i.e. bin size) by removing anti-aliasing restrictions (operator and data) and reduces migration artifacts such as frequency dependent aliased dispersion. There are two generic types of trace interpolation; explicit and implicit. An example of explicit methods include model based F-X (or F-K) prediction or projection (Spitz 1991, Soubaras 1997 and Claerbout 1998) while MWNI is an example of the implicit approach.

Explicit model based interpolation is possible because the recorded signal can be decomposed into small discrete stationary phase plane waves (Fresnel zones) representing a piece of the un-migrated wavefield and structure. As large aperture scattering angles illuminate the subsurface structure, so many bins contain information about that structure. Model based interpolation exploits this recorded information to reconstruct a version of the finely sampled continuous wavefield that would have been recorded at the surface. Neither rays nor the convolutional model predict these discrete Fresnel planes, as neither deals with the issue of spatial resolution. In practice the offset Fresnel zone is 5 to 20 times the bin size, allowing for sufficient Fresnel zone energy to be captured by relatively sparse bins that are far coarser than the output bin size from migration.

Unlike model driven de-aliasing methods, MWNI does not actually de-alias data beyond the Nyquist limit. The reason for this is that MWNI as its name implies, relies on iteratively reinforcing the correct un-aliased wavenumbers in the presence of aliased wavenumbers. In order to achieve this, the un-aliased data must have a stronger statistical representation in F-K space than the contaminating aliased wavenumbers. This misunderstanding of MWNI's ability to de-alias was recently expounded at a lunchbox talk by Cary (April 2011) where the suggestion was to resort to random sampling, as this statistically reduces the strength of aliased wavenumbers by smearing the strong regularly sampled aliases across the full range of low signal to high noise wavenumbers. However the reliance on statistics for these implicit methods might pose a risk given there are three kinds of lies: lies, damned lies, and statistics! Furthermore, this randomness is difficult to achieve and not acquired in practice by cross-spread 3D's due to logistical field limitations. An easier alternative mentioned above, is to simulate randomness or introduce irregularity by staggering or dithering the cross-line spacings in parallel geometries such as MegaBin.

So far the discussion for land 3D has focused exclusively on the Nyquist limit as formulated by Shannon's (1949) sinc interpolation that forms the basis for MWNI. What has not appeared in the land 3D debate 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 sampling theorem of Linden (1959). In theory the method accurately recovers aliased wavenumbers by simultaneously exploiting point sampling and various orders of derivatives or gradients using sinc interpolation combined with a Taylor series expansion. At a minimum this multichannel sinc interpolator of Linden increases the bandwidth up to a factor of two using first order gradients. However, contrary to data-independent interpolators, it is possible to dealias the spectrum to a much higher order using (data-dependent) multichannel matching pursuit methods. This new technology for wavefield recovery

and imaging introduced by WesternGeco for marine applications termed "IsoMetrix", overcomes coarse line sampling compromises by enabling the accurate reconstruction of the seismic wavefield at bin 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 (e.g. 12.5-m x 12.5-m) point-receiver surface grid (Vassallo et.al 2010).The resulting fine sampling in both crossline and inline directions makes the data suitable for use in a wide variety of interpretation and modeling applications, such as high-resolution near-surface imaging, deep reservoir characterization, and 4D reservoir monitoring. The IsoMetrix point-receiver full bandwidth data fulfils the sampling requirements for accurate PSTM imaging of deep targets while preserving high-resolution shallow data. This step change in image quality and 4D repeatability provides new opportunities to mitigate exploration and production risk and reduce overall finding and development costs through cost efficient fit for purpose acquisition.

Conclusions

Inspired by the IsoMetrix technology in marine seismics, the presentation will demonstrate the potential of this experimental technology in recording the full waveform to produce higher quality seismic images for 3D land data within the context of both the past and future solutions described above. The goal is to accurately recover an inherent and severe acquisition sampling limitation that arises from coarse land 3D line spacings whether they are cross-spread or linear in design.

The author wishes to acknowledge WesternGeco for adapting and advancing its established marine "IsoMetrix" applications to specific land 3D signal and noise wavefield recovery using the related concept of Seismic Wavefield Gradiometry.

References

Cary, P., An Investigation into 5D Interpolation with the MWNI Algorithm: April 2011 CSEG Lunchbox

Claerbout, J. F., 2004, Earth Soundings Analysis: Processing versus Inversion: Chapter 8, Missing-data restoration p 181-211.

Goodway, W., and Ragan, B., 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.

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.

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

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

Soubaras, R., 1997, Spatial interpolation of aliased seismic data: 67th Ann. Intemat. Mtg. Soc. Expl. Geophys., Expanded Abstracts, paper SP4.11.

Spitz, S., 1991, Seismic trace interpolation in the FX domain: Geophysics 56, 785-794

Trad, D., 2009.Five-dimensional interpolation. Recovering from acquisition constraints Geophysics. Vol 74 No. 6.

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. J. 0., 1990, Seismic wavefield sampling: Soc.Expl. Geophys.