Marine acquisition: Moving beyond the signal-to-noise ratio?

Andrew Long, PGS Technology (Perth), offers a challenge to conventional thinking on signal-to-noise ratio in the context of 3D multi-streamer acquisition surveys arguing for more attention to all the factors contributing to 'noise' in seismic images

The definition of exactly what comprises 'signal' and 'noise' on seismic data is ill-defined, but it can be said that noise is the unwanted component of the target frequency spectra, which is not directly related to, or correlated with, the primary reflection energy. If signal and noise could be separated into two distinct amplitude spectra, then the maxima of the spectra may be closely aligned (less easily separable), or more distinct (more easily separable). Irrespective of the comparative spectra, the signal-to-noise ratio (S/N ratio) is typically defined as being simply the logarithmic ratio of the maximum amplitudes from each of the signal and noise spectra. This is obviously too vague to be usefully descriptive of data quality, however, the S/N ratio is a universally ascribed term in seismic data analysis. Quite commonly, the term is used as a more qualitative or colloquial description of general data coherency and resolution.

Improvements in S/N quality are generally attributed to the fold of stack. By the well-known square root relationship, increasing the stack fold suppresses random (not coherent) noise. However, many other factors contribute to the 'noise' contaminating seismic images, as discussed below.

Historical efforts have been made to quantify the nature of the S/N ratio, and its relationship to data quality. Junger (1964) observed that 'For a signal-to-noise ratio greater than two, the signal predominates visually, and only a slight improvement in quality can be obtained with additional improvements in the signal-to-noise ratio'. Hence, it is observed that once the random noise component is suppressed below a certain threshold, other factors than mere fold are clearly contributing to the quality of the seismic image. It is quite poorly established how more complicated acquisition parameters, such as multi-streamer spread dimensions and shooting templates, influence the 'S/N ratio' of seismic data, particularly after the application of multi-channel pre-stack processing algorithms, notably pre-stack migration.

In the sections below, I describe how 'noise' is manifested both during acquisition and processing, in the context of 3D marine multi-streamer acquisition parameters. I demonstrate how misleading and inappropriate it is to only consider data quality in terms of fold and simple S/N ratio measurements.

Seismic noise

Our goal with the reflection seismic experiment is to obtain the most clearly defined, high resolution image of the subsurface geology, free of contaminating noise.

Imaging and Resolution consists of two components:

1. Reconstructing the reflection wavelet with maximum dynamic range, and separability from adjacent events
2. Minimizing artifacts that contaminate the event

A significant component of the seismic 'noise' contaminating 3D images actually arises during processing, as an unfortunate, and inescapable, artifact from poor 3D spatial sampling (refer also to Regone, 1998). Aliased data creates noise during the application of any multi-channel processing operation, notably migration. Low-pass filtering is consequently applied in an attempt to avoid such problems, thereby destroying bandwidth. When the cross-line acquisition dimension is sampled at an equally small interval as the inline dimension, a much larger frequency bandwidth than typical of standard 3D acquisition can preserved throughout all stages of processing, free of aliasing, and free of artifacts. Tight spatial sampling must also be complemented by uniform subsurface illumination coverage. Imaging artifacts are created if discontinuities in the surface (CMP) fold, offset, and azimuth coverage exist, and if discontinuities in the common reflection point (subsurface) fold, offset, and azimuth illumination coverage exist.

Such discontinuities (notably, any large holes), and their manifested imaging artifacts, may be obvious via significant phenomena such as the cross-line footprint (which is related to shooting direction), or subtle and less obvious data degradation. In practice, various changes in the acquisition template can be used to complement tight spatial sampling with improved target illumination. Examples are shooting strike and/or anti-parallel (Long *et al.*, 2003), sail line overlap acquisition (e.g. Hoffmann *et al.*, 2002), or multi-azimuth shooting (e.g. Hegna & Gaus, 2003).

Overall, noise is an insidious beast, manifested in many forms throughout acquisition and processing, each noise type often related to other noise suffered earlier in the exploration sequence. The principle argued here is that acquisition should be pursued to embrace a more sophisticated strategy than has historically been the case – such that pre-stack imaging can exploit the full 3D wavefield, without being contaminated by artifacts. These artifacts have historically been misinterpreted as simple noise related to field acquisition, and quite often, simply not recognized as being deeply embedded within the data at all. With the benefit of new case examples (below), one can appreciate the significance of the underlying signal, quite unrelated to any noise envelope that can be suppressed by mere fold, or expressed by a trivial statistical estimate such as the S/N ratio.

A generic example

Figure 1 takes the famous Mona Lisa example, and demonstrates that the S/N ratio is of marginal consequence to interpretability. In the upper row of Figure 1, image quality is optimal, representing the perfect case of optimal acquisition + optimal imaging. In the lower rows, image quality has been degraded, representing the typical case of compromises in acquisition and/or processing yielding inferior resolution. We see that despite the underlying 'signal' quality, the images are quite comparable when S/N ratio is poor. However, when S/N ratio improves, the difference in image quality becomes very distinct. The key message here is that improvements in S/N ratio have only limited benefit – we must improve the underlying signal quality, if the ultimate interpretable image is to be achieved. Such improvements arise by careful acquisition parameterization, as demonstrated below.

Case examples

Malampaya Field, Philippines

In 2002, PGS Exploration acquired the 1100 km^2 Malampaya MC3D survey in the NW Palawan Basin, offshore Philippines. A deep carbonate reservoir is located in a deep water setting. Imaging at the target is complicated by discontinuous reflectivity and the effects of significant noise phenomena associated with complex stratigraphic patterns in the overburden, and the rugose, deep, water bottom. Pre-survey planning by both PGS and the multi-client survey participants concluded that 'strike' shooting would be used, with anti-parallel sail line shooting used to improve the uniformity of subsurface target illumination coverage.

The *Ramform Challenger* was used to tow 12 x 4050 m streamers at 50 m separation, shooting in dual-source mode at 18.75 m shot interval. Thus, the natural CMP bin size (inline x cross-line) was 6.25 x 12.5 m, at 54 fold. In terms of trace densities, the new high-density 3D survey yielded 691,000 traces/km^2, in comparison to 95 000 traces/km^2 corresponding to existing 3D data in the area.

Several significant changes in acquisition parameters must be explicitly noted. The tight cross-line spatial sampling allowed steeply dipping events from the rugose sea floor to be preserved throughout processing, free of aliasing. Therefore, higher frequencies could be exploited (without aliasing noise) by the (Kirchhoff PSTM) migration operator, resulting in greater overall stack bandwidth and resolution, than was the case achieved with the 26.66 m bin widths used for previous 3D acquisition and PSDM processing. Prior to any spectral whitening processing, the data amplitudes at 70 Hz are between 6 dB (3.2 s TWT) and 15 dB (1.6 s TWT) stronger on the new high-density 3D data (Figure 2). In addition to much better resolution, the 2002 PSTM data has better coherency, following Krey (1987), who analytically relates 3D bin sampling to Kirchhoff

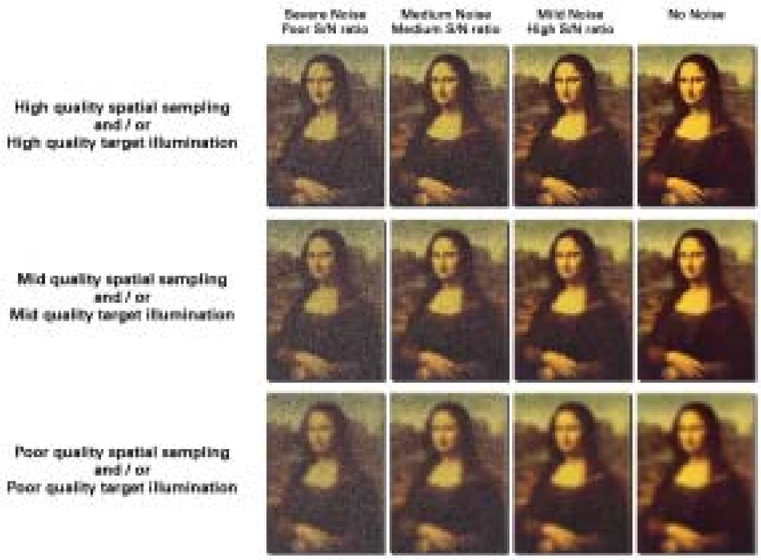

Figure 1 *A demonstration of the irrelevance of S/N ratio, when pursuing the ultimate imaging quality. When S/N ratio is poor, an inherently high quality signal is quite indistinguishable from a low quality signal. However, as S/N ratio improves, we begin to recognize that other underlying factors than the uncorrelated noise envelope affect the degree to which signal resolution and quality can be achieved.*

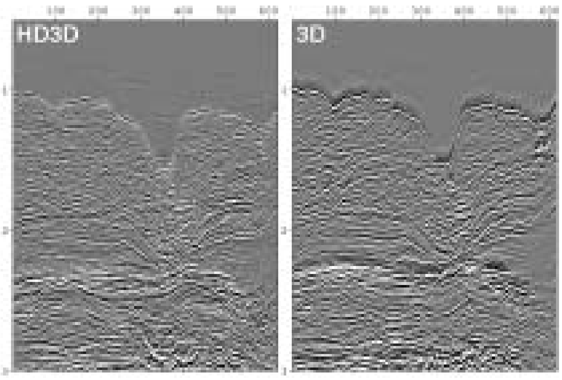

Figure 2 *Comparison of 1991 3D data (left) vs. 2002 high-density Malampaya HDMC3D data (right). The 2002 HDMC3D data was processed with a Kirchhoff PSTM flow. The 1991 data was processed with a PSDM flow (converted to TWT for display). Significant resolution improvements have been achieved in the 2002 HD3D dataset by a combination of tight 3D spatial sampling and better target illumination during acquisition. The 2002 HD3D results are expected to improve even further after PSDM processing and spectral whitening. (1991 data courtesy of Shell).*

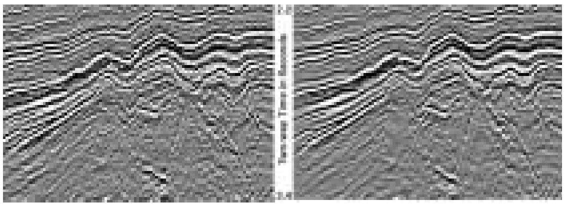

Figure 3 *Comparison of 3D seismic data acquired in one direction (left: 270/90° acquisition) with 3D seismic data composed of three directions (right: 270/90°, 150/330°, and 30/210°). Image clarity, continuity, and resolution, benefits by a combination of improved cross-line spatial sampling in both the receiver and shot domains, improved target illumination, and increased azimuthal sampling at all offsets.*

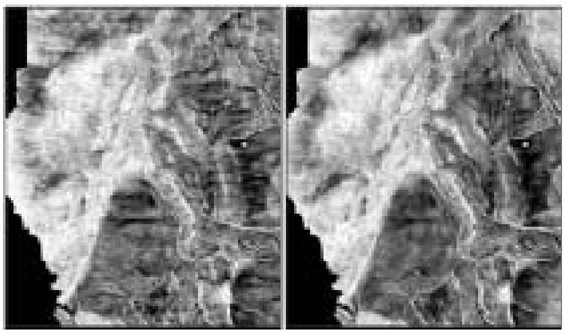

Figure 4 *Comparison of base Cretaceous (target) amplitude maps for 3D seismic data acquired in one direction (left: 270/90° acquisition) vs. 3D seismic data composed of three directions (right: 270/90°, 150/330°, and 30/210°). Both the acquisition footprint and other processing artifacts are greatly decreased on the right (multi-azimuth HD3D acquisition), demonstrating how pre-stack imaging benefits from improved azimuthal sampling and illumination.*

migration coherency. The combination of (regional) strike shooting direction and alternating sail line shooting has yielded better target illumination density, minimizing acquisition footprint artifacts in the manner of Gesbert (2003), and minimizing imaging artifacts in the manner of Long *et al.* (2003).

Despite the rugose water bottom and chaotic stratigraphic trends dominating this location, the application of PGS proprietary High Density 3D (HD3D) acquisition to a shooting template which improves the uniformity of target illumination, has yielded significant improvements in data resolution, coherency, and interpretability.

Varg Field, North Sea

In 2002, PGS Exploration acquired the 200 km^2 Varg 3D survey in Production License 038, on the Norwegian side of the Southern North Sea. The Varg reservoir consists of interbedded sandstones and shales, beneath thin shales and high velocity chalk layers. The combination of relatively thin sands and complex faulting due to salt related tectonics makes the reservoir challenging both to interpret and to produce. Comprehensive pre-survey planning by PGS recommended that new 3D acquisition decrease cross-line sampling relative to existing 3D data, and that two shooting directions at azimuths of 150/330° and 30/210° be simultaneously acquired, thereby optimising the complementary target illumination from each shooting direction. The *Ramform Viking* was used to tow 8 x 4050 m streamers at 100 m separation, shooting in dual-source mode at 18.75 m shot interval, for each shooting direction. A detailed pre-stack depth migration (PSDM) approach was used to combine the two new datasets with an existing 270/90° dataset to yield a single output cube (Hegna & Gaus, 2003).

Comparison of the existing 270/90° PSDM result with the combined three surveys processed to PSDM (Figure 3) demonstrates a significant improvement in data continuity, the absence of noise, and increased resolution. The absence of acquisition and processing artifacts on Figure 4 (amplitude maps at the target horizon) demonstrates how pre-stack imaging benefits from 3D data with well-sampled azimuths across all offsets. The increased cross-line spatial sampling in both the receiver and shot domains must be particularly noted, when pursuing such a multi-azimuthal approach.

In a location of highly challenging reflectivity and resolution, a successful step-out well has already been drilled, doubling daily production, and an additional appraisal well intersected a gross hydrocarbon column of 90 m.

Conclusions

3D seismic acquisition should be pursued to embrace a more sophisticated strategy than has historically been the case so that pre-stack imaging can exploit the full 3D wavefield, without being contaminated by artifacts. These artifacts have historically been misinterpreted as simple noise related to field acquisition, and quite often, simply not recognized as being embedded within the data at all. With the benefit of new case examples, it is easy to appreciate the many acquisition factors that contribute to the quality of the underlying signal, quite unrelated to any noise envelope that can be suppressed by mere fold, or expressed by a trivial statistical estimate such as the S/N ratio. Image quality is still restricted by the quality of the acquisition experiment, even if we have a 'high S/N ratio'.

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