High Resolution of Streamer Seismic Data

Introduction

High resolution of seismic data results when high frequency geological features in close proximity can be precisely focused without any contamination from artefacts or noise (i.e. high signal-to-noise ratio). In general, recoverable frequency bandwidth is an important factor for vertical resolution, and dense 3D spatial sampling is an important factor for spatial resolution. Vertical and horizontal resolution is linked by the success of high frequency focusing and imaging. Without pursuing a theoretical treatise, the following section discusses the geophysical principles that are relevant for high-resolution seismic imaging.

High Resolution Acquisition and Processing

High resolution imaging depends upon the following:

• Every subsurface point at the target should be properly illuminated during acquisition, and should have reflected seismic energy with a uniform distribution of source-receiver offsets and azimuths. If achieved, pre-stack migration can focus the seismic energy without loss of resolution and without artefacts caused by asymmetric sampling. Overall, the correct technical criterion for high resolution imaging is that “A large specular reflection aperture at every subsurface image point is complemented by complete spatial sampling of the recorded wavefield” (see also below). In reality, subsurface illumination is always irregular, and may even be characterized by large "holes" when complex geology exists between the surface and the target.

Figure 1 presents results for two orthogonal shooting directions from a 3D modelling study of the illumination of a rugose target surface below a complex overburden. The colours represent the illumination density at the target for each shooting direction. The upper two results are different, and neither is ideal. The summation of the results in the lower figure yields a far more uniform illumination result. This is the foundation of Multi-Azimuth 3D seismic, which is featured in TechLink Vol. 5, No. 3 (July 2005).

Summary

High resolution of 3D seismic data is achieved by the application of rigorous geophysical principles. In particular, the systematic pursuit of: 1. Uniform target illumination, 2. Dense spatial sampling of the reflected wavefield, and 3. Careful processing and imaging, will collectively deliver an optimum result. Note that the final step can never be successfully completed without the platform of proper target illumination and wavefield sampling. Several 3D data examples are used to demonstrate how flexible survey design and implementation can robustly achieve very high resolution target imaging for all target depths and challenges.

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**High Resolution Acquisition and Processing**

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- Source-receiver reciprocity will be achieved if equal length source and receiver arrays are used, as well as equal shot and receiver intervals are used (Vermeer’s “2D symmetric sampling”). This objective is almost never achieved in practice because shot interval and shot array length are typically too large. Symmetric sampling can avoid loss of frequency bandwidth and resolution related to shooting direction.

- The frequency bandwidth of primary reflections recorded on to tape during an acquisition survey must be as large as possible. Recorded frequency bandwidth is a function of source array design, and most notably, the source and streamer towing depths. Decreasing source and/or streamer depth corresponds to increasing frequency bandwidth, increasing operational noise, and decreasing signal-to-noise ratio. Attenuation effects in the Earth increase with increasing target depth, reducing both the dominant frequency and the frequency bandwidth of seismic data. Every effort should be made at all target depths to maximize both the low and high frequency content of the data during acquisition.

- The recorded frequency bandwidth will ideally be preserved throughout the entire processing flow. In practice, multi-channel filtering operations and pre-stack migration are all explicitly dependent upon dense 3D spatial sampling to avoid aliasing effects of events with steep apparent dips or strong curvature. Aliasing will result in the loss of higher frequency content and the introduction of artefacts. Therefore, both inline and cross-line bin size must be as physically small as possible. Crossline bin size is typically coarse, and thus places the strongest constraint upon highest recoverable frequency in processing.

- The acquisition platforms of uniform target illumination and dense 3D spatial sampling will optimize all algorithms used to remove complex noise and multiples present in the field data. Noise and multiple-free data is necessary for optimal velocity model building.

- Accurate 3D velocities are required during data processing and migration to avoid smearing and loss of resolution. Dense trace sampling allows high-fidelity pre-stack migration to optimize the accuracy of velocity semblances during picking and model building.

Three case examples below illustrate different strategies for optimizing high resolution imaging via a combination of proper target illumination and dense wavefield sampling. These principles are the foundation for HD3D (High Density 3D) acquisition and processing.

**Shallow to Moderate Target Depth Examples**

**Example 1: Gulf of Thailand**

Pre-survey objectives for targets at 0.3 – 1.3 s TWT included very high resolution imaging, with useful frequency content up to 150 Hz. These objectives were achieved using the following acquisition parameters:
- 50 m streamer separation, 4 m source and 4 m streamer depth.
- A spatially compact source array designed to minimize source directivity, delivering high frequency output for large source emission angles. Furthermore, 12.5 m dual-source shot interval complemented by shot interpolation in processing was designed to deliver equal shot and receiver intervals. This pursuit honoured Vermeer’s 2D symmetric sampling.
- The availability of unaliased diffraction hyperbolae enabled the successful application of high resolution linear and parabolic noise and multiple removal algorithms in processing. High-resolution Kirchhoff pre-stack time migration (PSTM) was complemented by tight 3D spatial sampling and high trace density, yielding the desired high resolution and high signal-to-noise ratio (Figure 2).
- Several successful exploration wells were drilled in 2005, intersecting large oil and gas columns.

**Example 2: East Java Sea**

Outstanding resolution and data clarity was achieved in the target range of 0.7 – 1.5 s TWT in an area plagued by complex carbonates and high historical seismic noise content:
- 62.5 m streamer separation, 5 m source and 6 m streamer depth, 12.5 m dual-source shot interval. 12 streamers being towed enabled daily production rates in excess of 50 km²/day for the 3963 km² HD3D survey.
- The high signal-to-noise quality and excellent resolution of the East Java Sea HD3D data have revealed the presence of numerous, often complex prospects on both the upper and lower
Kujung (carbonate) levels, as well as at the deeper basement levels. Migration pathways can thus be interpreted, making detailed prospectivity analysis possible. The availability of unaliased diffraction hyperbolae enabled the successful application of high resolution linear and parabolic noise and multiple removal algorithms in processing. High-resolution Kirchhoff PSTM delivered outstanding high resolution and data quality at all target depths (Figure 3).

**Deep Target Depth Example: Deepwater Philippines**

HD3D acquisition and processing overcame an historical inability to image a structurally complex carbonate reservoir at ~3.2 s TWT below a very rugose, deep water bottom, and undercompacted, stratigraphically complex overburden:

- 50 m streamer separation, 5 m source, 6 m streamer depth, 12 streamers.
- Anti-parallel shooting was used to improve target illumination below the rugose water bottom and complex overburden.
- At 70 Hz, the new HD3D data above the target is 15 dB stronger than the existing 3D data – without any spectral whitening or Q compensation being applied during processing (Figure 4). Furthermore, the PSTM processing of the HD3D data has better fault resolution than pre-stack depth migration (PSDM) versions of the earlier 3D datasets.

Figure 2: A section from the Gulf of Thailand HD3D survey across a deviated well (left), demonstrating a good match between the seismic and the synthetic. The gamma ray and sonic logs illustrate the ability of the seismic to resolve the top and base of individual sand bodies. Time slices at 949 ms TWT (upper left) and 958 ms TWT (lower left) of a Similarity cube generated from the 2004 3D seismic data also demonstrate outstanding resolution of complex channel patterns and en echelon faults. The right figure demonstrates that the HD3D data have matched the frequency content of a 2D site survey, which towed a 160 in source array at 1.5 m depth, and used 2.5 m streamer depth. Figures courtesy of Pearl Energy Ltd

Figure 3: (Left) Time slice from the East Java Sea HD3D survey at 0.15 s TWT. Resolution of the complex meandering channel system is excellent. Horizontal scale = 15 km. (Right) 3D perspective display from the holoSeis™ immersive visualization and interpretation system. The Top Kujung I (carbonate) surface interpreted here (~ 1.0 s TWT) reveals the density and complex distribution of carbonates throughout the HD3D survey area.
High resolution of 3D seismic data is achieved by the application of rigorous geophysical principles. In particular, the systematic pursuit of: 1. Uniform target illumination, 2. Dense spatial sampling of the reflected wavefield, and 3. Careful processing and imaging, will collectively deliver an optimum result. Note that the final step can never be successfully completed without the platform of proper target illumination and wavefield sampling.

This discussion has presented three examples of HD3D acquisition and processing, demonstrating how HD3D acquisition can be adapted very easily to different challenges, providing the best platform for subsequent processing success. Proper pre-survey planning will always address the following collective issues:

- A source array design which maximizes frequency bandwidth for all target depths, whilst delivering a stable source wavelet.
- Source and streamer depths customized for the target frequency bandwidth, whilst being appropriate for the geological, environmental, and geophysical factors expected to impact the survey.
- Close adherence to 2D symmetric sampling criteria where possible, thereby allowing processing to minimize noise and artefacts, and to increase signal-to-noise content.
- The use of dense 3D spatial sampling, appropriate to the target frequency bandwidth, including the alias-free acquisition of all diffraction and noise events for later removal in processing.
- A customized 3D processing flow, including regularization, noise attenuation, multiple removal, and pre-stack migration should exploit all the benefits of a properly sampled 3D dataset.