TECH LINK
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Optimal 3D Seismic Acquisition with High-Density 3D (HD3D)

HD3D Fundamentals

The ultimate goal in a seismic acquisition experiment is to perform dense and even sampling in both time and space, so that any aliasing is avoided. Unfortunately, 3D streamer acquisition has historically been forced to compromise spatial sampling in the name of efficiency and cost. Modern seismic vessels such as the Ramforms, with their massive towing capacities, have changed the way in which seismic data is acquired. Dual-source shooting has dominated exploration, by comparison to single-source shooting, because the streamer separation with single-source shooting must be halved to preserve cross-line processing fidelity. In the old days of limited streamer capacity, small streamer spreads were prohibitively expensive to deploy. Now, the ability to tow 12 - 16 long streamers at 25.0 to 50.0 m separation, with no loss of efficiency (i.e. no increase in downtime), has reduced costs so that single-source acquisition is cost effective. Such surveys have benefits of increased fold, improved 3D spatial resolution, and improved imaging quality. At the same time, certain survey locations are more amenable to dual-source shooting in high-density (close streamer separation) 3D mode, where the gains in cross-line spatial sampling more than offset the compromise in fold.

Issues Related to Seismic Resolution and Imaging Quality

In simple terms, resolution is a function of spatial sampling, frequency bandwidth, migration aperture size, and subsurface illumination.

Summary

Overall, the HD3D acquisition approach simply provides what we have always wanted in terms of data sampling. Then, more advanced applications such as time-lapse (4D) reservoir monitoring will allow greater repeatability and reservoir definition between successive surveys. Furthermore, certain production scale applications will benefit from a combination of HD3D spatial sampling benefits and innovative shooting templates (e.g. sail line overlap). As always, subtle acquisition parameterization must vary on case-by-case, target specific basis, but the HD3D acquisition method is universally optimal in all locations.

Let us begin with the merits of the (inline) shot density. In comparison to dual-source shooting, single-source

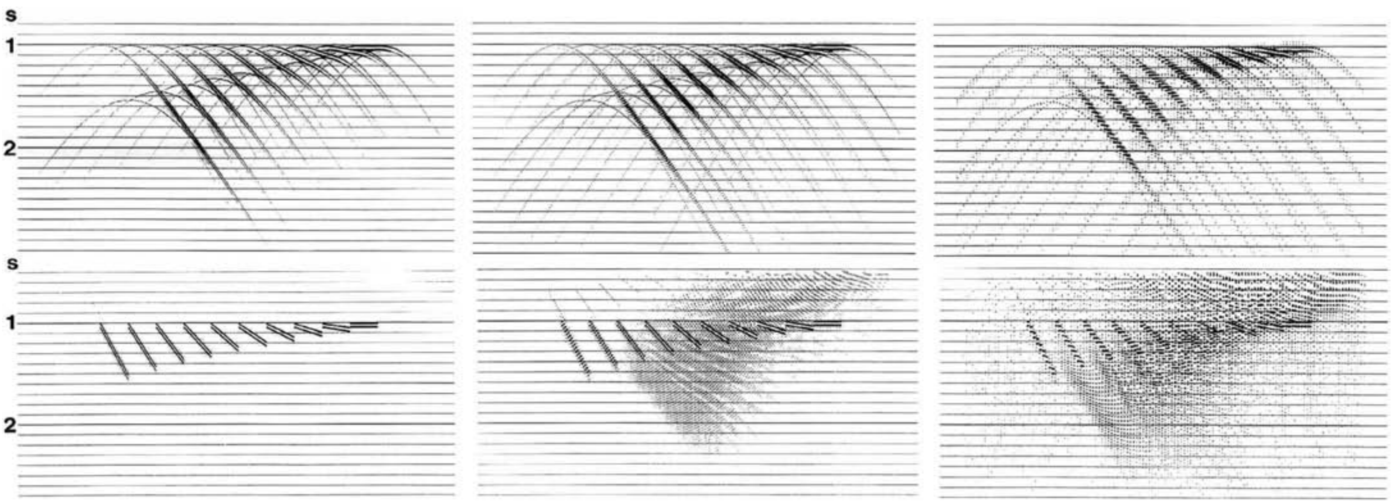

Figure 1: A series of zero-offset synthetic stacks of dipping interfaces are plotted along the top row, with trace spacings (bin sizes) of 25.0, 50.0, and 100.0 m respectively. Note the aliasing at large trace spacing, typical of conventional dual-source CMP gather trace spacing. Migration results are shown along the lower row. Note the extreme contamination by migration noise when trace spacing exceeds 25.0 m. Migration resolution is clearly a function of tight spatial sampling. From Yilmaz (1987).

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Issues Related to Seismic Resolution and Imaging Quality

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shooting doubles CMP fold (increasing the S/N ratio by 40%) and halves the trace spacing in the common-offset, -receiver, and -midpoint domains, thereby optimizing all multi-channel pre-stack processing operations. However, the associated doubling of the cross-line bin size for a given streamer separation will compromise cross-line (and full volume) resolution, unless the streamer separation is correspondingly halved. Ramform vessels can simultaneously deploy up to 16 streamers, at separations as small as 25 m. Therefore, it is technically possible to use single-source shooting in a cost-effective manner, allowing optimum inline spatial sampling, fold recovery, and the preservation of high frequencies during processing. Overall, dense streamer acquisition provides tight receiver sampling in both the inline and cross-line directions, and tight shot sampling in the shooting (inline) direction. Remedies to problems associated with coarse cross-line shot sampling are discussed below.

It is not commonly recognised how single-source acquisition will significantly benefit the seismic processing of the data. Pre-stack spatial sampling (in the common midpoint and offset domains) must be very tight for any type of multi-channel filtering algorithm to be successful. Alternatively, we must apply severe hi-cut frequency filtering during processing, thereby destroying bandwidth. Figure 1 demonstrates the effects of migration aliasing upon data degradation. Successful Radon demultiple requires a small trace spacing in the CMP domain so that a sufficiently large range of p-values can be modelled, thereby preserving AVO (amplitude versus offset) and steep dips after demultiple. Pre-stack sampling is particularly important for surface related multiple elimination (SRME), where the shot and receiver spacing should ideally be the same. Less requirement for pre- and post-stack interpolation will also improve the temporal and horizontal resolution of the data. Pre-stack analyses like AVO and AVA (amplitude versus azimuth) are improved by the enhanced spatial and azimuth sampling, and the greater trace densities. In addition, data are very well conditioned for applications within reservoir characterization and 4D.

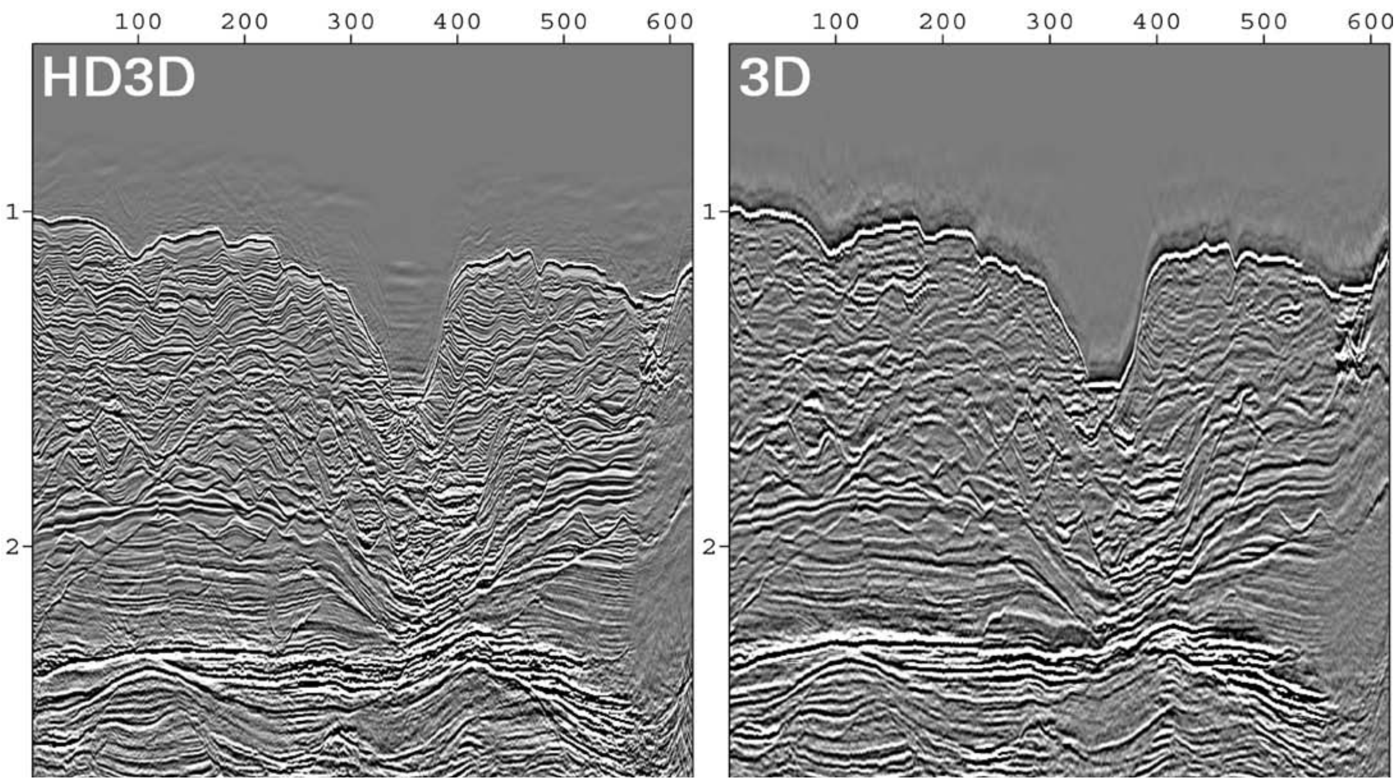

Figure 2: Comparison of 2002 high-density 3D (HD3D) data (left) vs. 1991 3D data (right) in offshore Philippines. The 2002 data was acquired with 6.25 x 12.5 m bin size, 54 fold, 691,000 traces per square kilometer, and is processed with a preliminary Kirchhoff PSTM flow. The 1991 data was acquired with 13.33 x 26.66 m bin size, 34 fold, 95,000 traces per square kilometer, and is processed with a full PSDM flow (converted to TWT for display). Significant resolution improvements (up to 15 dB increase at 70 Hz) have been achieved in the 2002 HD3D dataset by a combination of tight 3D spatial sampling, higher fold, better navigation, and better target illumination during acquisition. In particular, better spatial sampling has allowed the preservation of much larger frequency bandwidth throughout each processing step (without aliasing). The 2002 HD3D results are expected to improve even further after PSDM processing and spectral whitening. 1991 data courtesy of Shell.

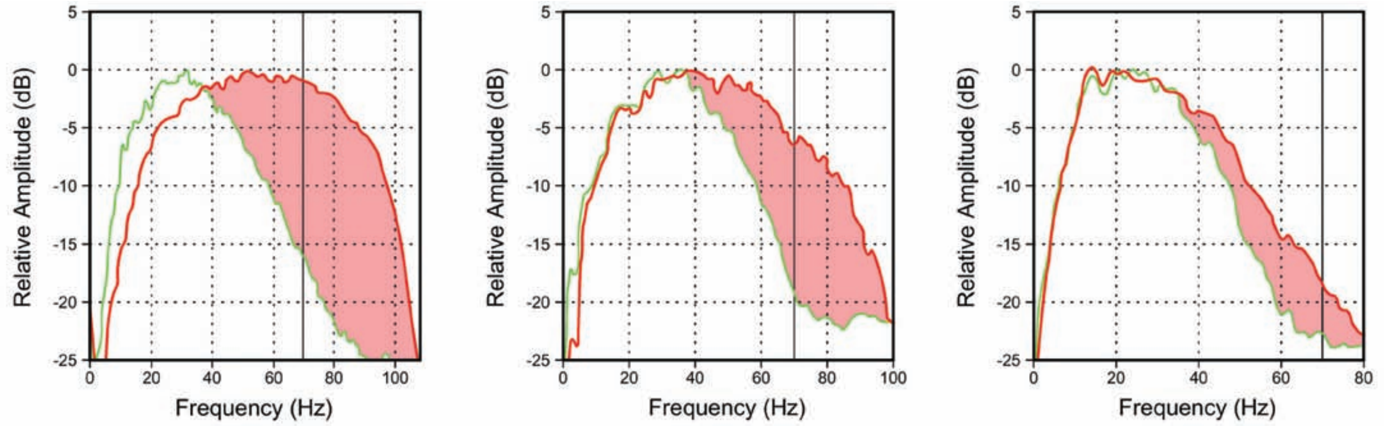

Figure 3: Superimposed amplitude spectra from the 2002 HD3D and 1991 3D Malampaya data, at shallow, mid, and deep target depths. The HD3D data is between 6 and 15 dB stronger than the traditional 3D at 70 Hz.

Conversely, in areas of stronger primary reflectivity and higher S/N, it may be preferable to exploit the cross-line sampling advantage of dual-source high-density shooting - particularly with respect to pre-stack imaging and resolution. PGS Exploration acquired the 1100 km2 Malampaya MC3D survey during 2002 in the NW Palawan basin, offshore Philippines. 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. Strict vertical resolution requirements sought 70 - 80 Hz frequencies at the 3.0 - 3.2 s TWT target level. Consequently, source/streamer depths of 5.0/6.0 m were used. Modelling of the horizontal resolution requirements indicated that in the ideal case of steepest dip imaging, the pre-migration bin size must be no larger than 12.8 m. In the pursuit of optimal resolution, it was decided that 12.5 m cross-line spatial sampling would be acquired. The Ramform Challenger was used to tow 12 x 4050 streamers at 50.0 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 HD3D survey yielded 691,000 traces/km2, in comparison to 95,000 traces/km2 corresponding to existing 3D data in the area.

Following the completion of acquisition, full Kirchhoff PSTM processing was used in production. Data interrogation and comparison to existing 1991 and 1993 3D data indicated significant improvements in the structural imaging and resolution of the target events (Figure 2). After PSTM, and 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 3). Furthermore, the 2002 PSTM data has better fault resolution than PSDM versions of the earlier 3D data sets (Figure 4). Such statistics are testament to the power of HD3D acquisition, even in an area containing rugose water bottom and chaotic stratigraphic trends such as the Malampaya MC3D area.

Ultimately, we would like to acquire 12.5 m cross-line spatial sampling and very high fold. This will be achieved in the next generation of high-density 3D surveys, using 25.0 m streamer separation with

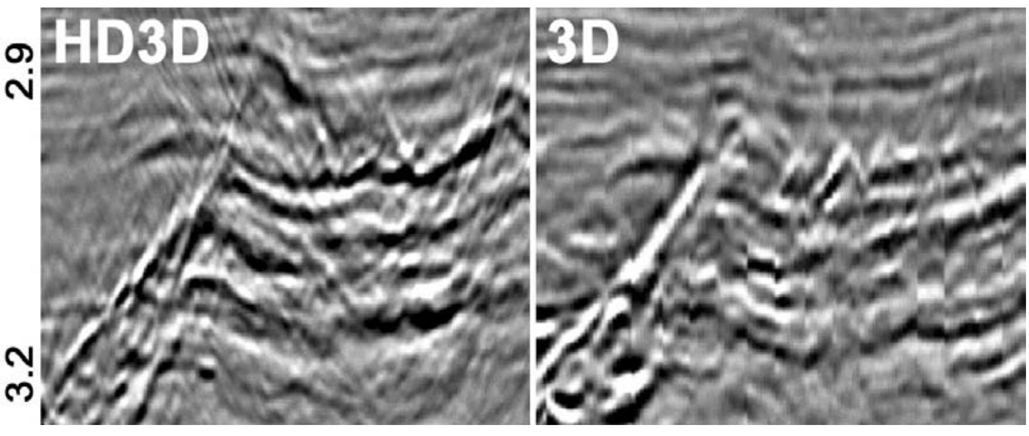

Figure 4: Comparison of 2002 high-density 3D (HD3D) data (left: preliminary PSTM) vs. 1991 3D Malampaya data (right: final PSDM converted to TWT). Note the significantly improved structural integrity and resolution in the HD3D data (left). The 2002 HD3D results are expected to improve even further after PSDM processing and spectral whitening. 1991 data courtesy of Shell.

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single-source shooting. Currently, it is easier to use 50.0 m streamer separation with dual-source shooting and short shot interval, e.g. 12.5 m dual-source shot interval. The obvious limitation is a reduction in record length to 4 seconds. The choice of single- vs. dual-source shooting obviously must be based upon considerations of primary reflectivity, noise type and strength, and resolution and imaging objectives.

A final acquisition consideration is that of shooting direction. Although the topic has historically been hotly debated, and must include several theoretical, practical, and logistical issues, one issue is unambiguously clear - any geology dipping in the cross-line direction must not be aliased by coarse spatial sampling. Few geological structures are 2.5D in nature (i.e. dimensionally constant in one direction), and the terms "dip" and "strike" only have regional significance. Although several "3D" pre-stack multi-channel filtering processing routines have a pseudo-2D bias in the shooting direction, it is an irrevocable fact that 3D sampling and target illumination must be uniformly tight and consistent in all directions. Hence, the simple premise of HD3D acquisition: Optimal sampling, without compromising operational cost.

Survey cost is primarily a function of line length and streamer spread width, i.e. the number of sail lines required to complete the survey. HD3D streamer acquisition is proven to incur no additional downtime compared to traditional 3D, and the unique Ramform vessel design provides equipment management with unmatched efficiency.

4D Advantages of HD3D

HD3D offers the tight sampling/high resolution and high fold/high S/N required for detailed reservoir studies. One of the major challenges in 4D processing is to apply techniques that suppress non-geological differences between the initial (baseline) and the subsequent (monitor) surveys. Data regularization during processing has proven to be a successful method in maximizing survey repeatability. However, as regularization techniques require anti-alias protection, higher frequencies can easily be lost in the process. With denser sampling, in particular with the cross-line direction, regularization is significantly more effective, and with less associated processing artefacts.

Ideally, both the baseline and monitor surveys are acquired in (compatible) HD3D mode - a rapidly growing trend worldwide. However, we frequently face the problem that the monitor and baseline surveys do not have the same survey configurations, and we consequently have to compare two surveys with contrasting source-receiver azimuths and different sampling. For streamer surveys, the flexibility of HD3D makes it feasible to acquire swaths that are overlapping, thereby providing a larger range of azimuths for all source-receiver configurations, and improving the cross-line shot sampling. If we are acquiring a monitor survey, HD3D acquisition will normally give more hits per bin than the base line survey. The surplus of data makes it possible to achieve a better match between the data that are used in each bin from the monitor and base line surveys respectively - a monitor survey acquired in HD3D mode allows us to pick out the traces that have the optimum match to the base survey offsets and azimuths. In addition, the level of non-repeatable noise will be reduced through use of directional noise suppression, and because imaging algorithms create less processing artifacts when a redundancy of offsets and azimuths are available within each CMP bin. Many noise suppression processes suffer because the data are well sampled in only one direction. HD3D data allows superior directional noise suppression because of the wider range of azimuths available.

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