

Multi-Azimuth and Wide-Azimuth lessons for better seismic imaging in complex settings

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SUMMARY

In practice, acquisition and processing solutions to poor seismic illumination begin with an effort to compensate for gross holes in the density of target illumination using conventional Narrow-Azimuth streamer acquisition. As the complexity of the problem increases the case for Multi-Azimuth acquisition builds. Wide-Azimuth acquisition is required in the most challenging scenarios. Correspondingly, the processing and imaging technologies deployed must also improve in sophistication. Recent and ongoing global R&D efforts, complementing several large innovative projects, demonstrate that each of the target illumination concepts and challenges discussed here can be evaluated and contrasted in clear and unambiguous terms.

Key words: Illumination, multi-azimuth, wide-azimuth, imaging, sampling.

INTRODUCTION

In simple terms, every subsurface point at the target should be properly illuminated during a 3D seismic survey, and should have reflected seismic energy with a uniform distribution of source-receiver offsets, azimuths and incidence angles. This definition will be elaborated on later. To use a simple analogy, a 3D seismic survey is similar to a photographic session in a studio. Several light sources are typically required to fully illuminate a subject of the photographic session so that an unblemished and uniformly high resolution image may be possible to capture. Single light sources can be used for special effects and emphasis, but special effects are typically unwanted when producing a high resolution, high quality seismic image of the subsurface. It thus follows that complete target illumination is required in a successful seismic survey. In contrast to a photographic session where there is a void between the camera and the subject, and the topography of the subject is the only influence upon illumination quality, the Earth is a continuously variable medium in all directions.

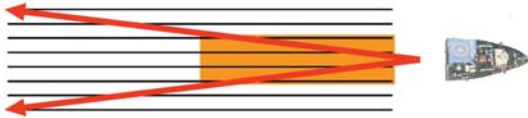
Several factors impact the quality of (seismic) target illumination at some given target reflecting interface:

- The topography of the surface (in a land survey) or the water bottom (in a marine survey),
- The complex three-dimensional velocity media between the surface/water bottom and the target. In geological terms, vertical and lateral velocity variations occur because of structural, stratigraphic and lithological complexities. High velocity contrasts have the most impact upon ray path geometry - notably basalt/intrusions, salt, chalk and carbonate layers, and
- The topography of the target interface.

In the most extreme cases, the overburden effects upon wave propagation are so severe that no coherent target events can be imaged because of the lack of illumination. Data processing cannot generate data that have not been recorded - even with the most sophisticated processing and imaging technologies. The most typical example is sub-salt challenges in the Gulf of Mexico. So-called Wide-Azimuth acquisition is increasingly used in an attempt to overcome such problems (Figure 1). Wide Azimuth seismic follows a very simple strategy - for each receiver layout a large range of short to long offset source positions are used over a large range of source-receiver azimuths. In a land or seafloor 3D survey this is accomplished by using a long cross-spread shooting template or a source grid that is much larger than the receiver patch. In a marine 3D survey this is accomplished by using one or more source vessels additional to the main source and streamer vessel - the additional source vessel(s) acquire shot lines parallel to the streamer vessel pre-plot, but typically at a range of short to long offsets in the cross-line direction. Wide Azimuth provides no guarantee of a solution to the most severe target illumination problems - the very wide aperture/azimuth wave propagation may be so complex that even the most sophisticated processing and imaging solutions still fail. In the least case, the source-receiver geometries inherent in typical Wide-Azimuth surveys are unsuitable for the "regular geometry" assumptions of standard migration algorithms - even Kirchhoff migration may fail. Shot domain Wave Equation Pre-Stack Depth Migration (WEPSDM) is typically required. WEPSDM is computationally expensive, benefits from 3D data regularization schemes during the pre-processing, and a suitably accurate 3D velocity model must be

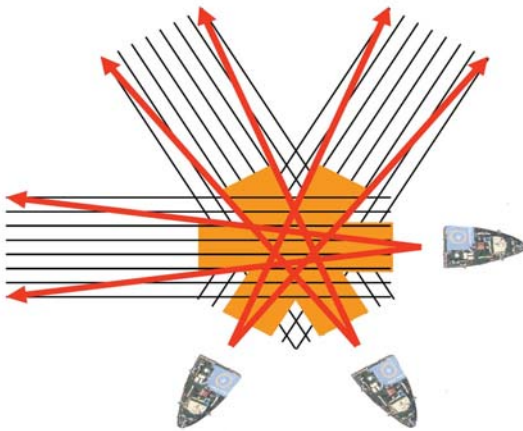
first established - collectively, Wide-Azimuth acquisition and the associated processing and imaging is not a trivial enterprise. Proper pre-survey planning must be pursued before contemplating Wide-Azimuth seismic.

Narrow-Azimuth (conventional)



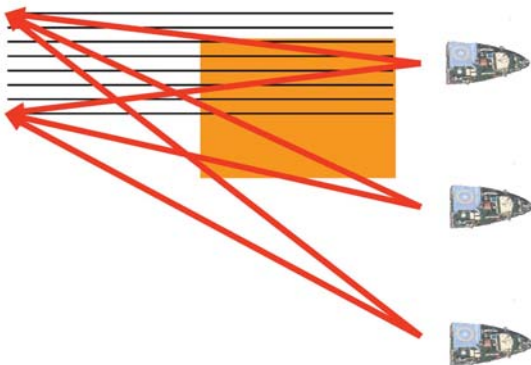
Narrow range of azimuths

Multi-Azimuth Acquisition



Multiple range of azimuths

Wide-Azimuth Acquisition



Wider range of azimuths

Figure 1. Schematic comparison of Narrow-Azimuth ("conventional") vs. Multi-Azimuth vs. Wide-Azimuth streamer 3D acquisition.

A MORE RIGOROUS DEFINITION OF "ILLUMINATION"

A key component of any successful high resolution imaging exercise is the absence of any artifacts. In gross terms, systematic variations in target illumination create the well-known shallow "cross-line acquisition footprint". On a smaller scale, any asymmetry in target illumination will create some kind of smearing or imaging artifact. Note that all these discussions assume each of the primary, multiple and noise wavefields is not aliased. Any type of data aliasing will create severe processing or imaging problems - which are not discussed here. A convenient starting point in a more rigorous discussion is the concept of minimal data sets (Padhi and Holley, 1997). This is not as complex as it may first seem.

The concept of minimal data sets is as follows. In principle, if a target interface is uniformly and completely illuminated in the common midpoint (CMP) domain, then it should be possible to extract several single fold subsets - such that each trace in a given subset (a "minimal data set") has identical source-receiver offset and azimuth. In the absence of any noise or multiples, it should be possible to migrate each subset such that the result has no artifacts. The sum of all such migrated subsets will correspondingly also yield no artifacts. Conversely, if the illumination within some subsets is not uniform (there are holes - missing offsets or azimuths), then the migrated subset will contain severe artifacts. The summation of all subsets will likewise contain artifacts, smearing and degraded quality and resolution.

The key aspect is of course what comprises "uniformly and completely illuminated". Reference to Figure 2 illustrates that the "ideal" 3D survey geometry includes a dense 3D grid of source and receiver positions. No source or receiver location is identical so that redundant source-receiver combinations are avoided. For each source position a dense areal receiver array is used - such that a complete and continuous range of source-receiver offsets and azimuths is recorded for each shot. This scenario would satisfy the minimal data set criteria.

In both the land and the seafloor 3D acquisition cases the source and the receivers are completely decoupled. Therefore, they can be located independently of each other. Provided that there are no obstructions to the deployment of the sources and receivers, it is possible in principle to deploy the sources and receivers over a large area (as in our example), thereby providing a complete illumination of the subsurface target, whilst simultaneously spatially sampling the reflected wavefield very densely. In the streamer case, the source and the receivers are coupled, and there is consequently far more restriction upon the flexibility of 3D data acquisition. It is typically the case that at short source-receiver offsets, a relatively large range of source-receiver azimuths is recorded - restricted to a hemisphere (the streamers are coupled behind the source position). At larger source-receiver offsets a much narrower arc of source-receiver azimuths is typically acquired. These restrictions are a factor in the pursuit of Multi-Azimuth (discussed later, and refer to Figure 1) and Wide-Azimuth (already discussed) seismic.

Another concept relevant to the minimal data set criteria is the symmetric sampling criteria of Vermeer. 3D symmetric sampling (Vermeer, 1998) is achieved if the 3D source and receiver geometry with equal source and receiver intervals in

the first figure is complemented by equal size (ideally point-sized) source and receiver arrays (or "patterns"). Equal-sized source and receiver arrays are required to avoid shooting direction-dependent variations in source-receiver directivity. As indicated by yellow crosses in Figure 2, 3D symmetric sampling is typically impossible in modern multi-streamer 3D surveys because the cross-line shot interval is typically very coarse. This issue is particularly challenging to 3D SRME (surface related multiple elimination) processing, which is discussed later. The only streamer 3D scenarios that might come relatively satisfy 3D symmetric sampling are single-streamer 3D acquisition or multi-streamer acquisition with very dense sail line separation and the source placed in the middle of the streamer spread. As described in Ramsden *et al.* (2005), the pursuit of 2D symmetric sampling (addressing only inline source and receiver intervals and arrays) complemented by dense streamer spacing may nevertheless produce excellent high resolution imaging without artifacts (given that target illumination is quite uniform).

Vermeer (1998) acknowledges that minimal data sets are almost never achieved in practice (notably for streamer acquisition), and describes various processing solutions that attempt to approximate minimal data sets by complex trace sorting and interpolation. This is beyond the discussion here.

Overall, it is evident that "illumination" can address many complementary but distinct issues:

- The density of seismic energy reflected from a target interface, and/or
- The uniformity of the source-receiver offsets and azimuths corresponding to each CMP trace.

In practice the CMP assumption is invalid, so the most "correct" description of "ideal" illumination is "a large specular reflection aperture at every subsurface image point (not CMP location) is complemented by complete spatial sampling of the recorded wavefield". If a suitably accurate 3D velocity model can be built, such an appropriately illuminated seismic volume should yield the optimum combination of high resolution, artifact-free imaging.

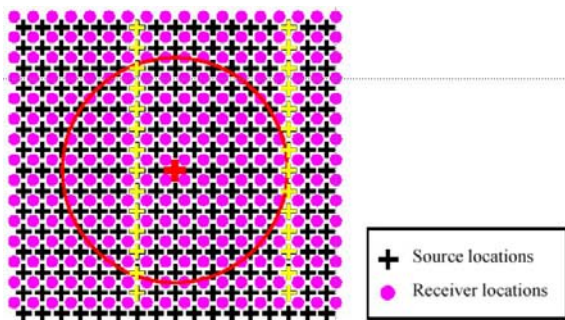


Figure 2. The "ideal" 3D survey geometry. Each shot location is recorded by a dense grid of receivers. As indicated by the two lines of yellow crosses, standard multi-streamer 3D acquisition involves reasonably dense inline shot intervals but very coarse cross-line shot intervals.

IMPROVING ILLUMINATION IN PRACTICE

Figure 3 presents a 3D ray tracing modelling study based on the Varg field in the North Sea (from Gaus and Hegna, 2003). Each of these results is different. This observation relates to the first description of "illumination" in the previous section - "the fundamental density of seismic energy reflected from a target interface". It is relevant to observe that illumination is never perfect. The colour scale in Figure 4 represents the distribution of source-receiver offsets being reflected from each subsurface point at the target (using the same ray tracing results). It is clear when moving from left to right that the uniformity of illumination quickly builds up from any one shooting direction to a combination of three shooting directions. This second observation relates to the first description of "illumination" in the previous section - "the uniformity of the source-receiver offsets and azimuths corresponding to each CMP trace". A clear demonstration is made that a combination of surveys that are acquired in different directions provides a better quality target illumination. The optimum combination of shooting directions will be location-specific. This demonstration is the foundation of Multi-Azimuth seismic.

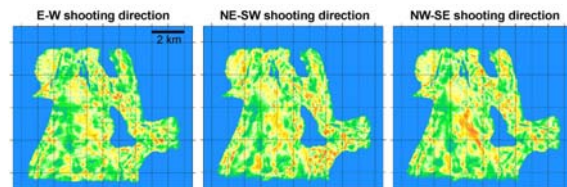


Figure 3. Modelled subsurface illumination maps showing the subsurface "hit density" for the Varg survey area in the North Sea. Each result is different, and none is ideal.

Multi-Azimuth seismic is typically discussed only in the context of the first definition of illumination ("the fundamental density of seismic energy reflected from a target interface"). This under-acknowledges the power of the Multi-Azimuth strategy, which is in fact bringing the final 3D seismic volume closer to the minimum data set ideals - as illustrated in Figure 4. As associated with minimal data sets, Multi-Azimuth seismic inevitably corresponds to artifact-free, high-quality seismic imaging. Figure 5 demonstrates a profound improvement in data clarity and resolution at the Base Cretaceous target horizon of the Varg field was achieved when all three available azimuths were combined in processing to output the final Multi-Azimuth dataset.

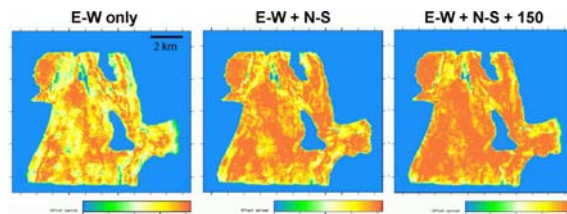


Figure 4. Modelled subsurface illumination maps showing the offset distribution (i.e. number of unique offsets) for the Varg survey area in the North Sea. The density and uniformity of offset coverage improves as more shooting directions are combined (Single-Azimuth vs. Dual-Azimuth).

vs. Triple-Azimuth).

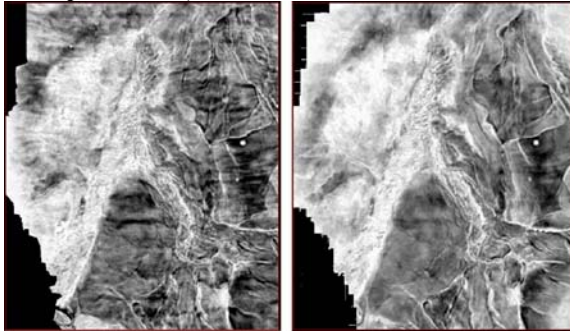


Figure 5. Amplitude maps for the Varg target horizon in the North Sea, derived from a Single-Azimuth dip 3D survey (left) and Multi-Azimuth shooting (right). Improved illumination and subsurface sampling has resulted in significantly greater data quality, clarity, and resolution.

THE MISSING ELEMENT: CROSS-LINE SHOT SAMPLING

Coarse cross-line shot intervals are used in streamer 3D surveys to allow an “acceptable” survey efficiency. Increased cross-line shot frequency can be achieved by several strategies:

- Closer shot lines (i.e. more sail lines required to complete the total survey),
- If the same streamer configuration is used then an “overlap” of CMP coverage will be recorded along the seam between each sail line. This will be beneficial for improved source-receiver azimuth repeatability in any 4D (time-lapse) project, will typically reduce infill requirements, and will be beneficial to 3D SRME processing,
- If less streamers are used in order to avoid any overlap then the survey will simply record a narrower range of source-receiver azimuths for all offsets,
- Interleave shooting - every second sail line is staggered laterally by half a cross-line bin dimension to record a 3D seismic volume with half the nominal cross-line bin dimensions. Aside from some potential logistical challenges, this is a strategy used to acquire high-density 3D data with coarse streamer separation,
- Additional source vessels used in a Wide-Azimuth survey configuration.

van Borselen *et al.* (2005) has demonstrated that improved cross-line shot density complemented by high-density 3D streamer configurations is the optimum platform for high-quality 3D SRME processing. Most 3D surveys compromise cross-line shot density in the pursuit of higher efficiency, so the data regularisation and pre-processing used in successful 3D SRME algorithms must be suitably customised. Better acquisition will always yield better processing and imaging.

This final discussion relates to the second description of “illumination” in the previous section – “The uniformity of the source-receiver offsets and azimuths corresponding to each CMP trace”.

CONCLUSIONS

The most “correct” description of ideal illumination is “a large specular reflection aperture at every subsurface image point (not CMP location) is complemented by complete spatial sampling of the recorded wavefield”. If a suitably accurate 3D velocity model can be built, such an appropriately illuminated seismic volume should yield the optimum combination of high resolution, artifact-free imaging.

In practice, acquisition and processing solutions to “poor illumination” begin with the simplest definition of illumination - an effort is made to compensate for gross “holes” in the density of target illumination. As the complexity of the problem increases, the focus must shift towards more sophisticated definitions of illumination - and the case for Multi-Azimuth acquisition builds, or Wide-Azimuth acquisition in the most challenging scenarios. Correspondingly, the processing and imaging technologies deployed must also improve in sophistication and effort. Initially, time domain processing may suffice (notably pre-stack time migration or PSTM), but once the CMP assumption fails it becomes necessary to address the most sophisticated definition of subsurface image point illumination (above). Pre-stack depth migration (PSDM) will be necessary - but will be successful only if suitably accurate velocity models can be built. In the case of Wide-Azimuth seismic it will typically be necessary to pursue Wave Equation PSDM (WEPSDM).

Fortunately, pre-survey planning is quite sophisticated and reliable (Long, 2004). Each of the target illumination concepts and challenges discussed here can be evaluated and contrasted in reasonable time frames.

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