Innovations for geophysical monitoring of 3D and 4D marine surveys

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propose new indicators for assessing the quality of 4D positioning from the repeatability of target illumination and monitoring the source signature variations.

Time-lapse seismic surveys are carried out to reveal production changes in the subsurface reservoir. Ensuring optimal repeatability between the different vintage surveys provides a direct way to minimize 4D noise unrelated to reservoir changes. Positioning repeatability is one of the main issues in 4D towed-streamer acquisition. It is primarily optimized by steering the vessel, source and streamers to match the previous acquisition (or baselines). The remaining mismatches in positions must be assessed to ensure the high quality of the data being acquired. We address the 4D repeatability of positioning through a geophysical target-oriented approach, where repeatability is assessed from the impact on seismic illumination. New and complementary repeatability indicators are derived for onboard quality control at gradual discrimination scales, ranging from shots through navigation lines up to the full acquisition.

Stability of the airgun source is important for both 3D and 4D surveys. Seismic data must be decoupled from the source signal variability in order to correctly resolve the quantitative features related to subsurface properties. During seismic acquisition, it is therefore important to estimate the far-field source signature and monitor its stability to detect out-of-specification shots. The reconstructed far-field source signature can then be used for further shot-to-shot deconvolution of the seismic data.

Repeatability of target illumination

Fold maps indicate the ability of a seismic survey to illuminate the subsurface. In essence, these maps ought to describe where seismic reflections occur in depth and how redundant they are.

Conventionally, fold maps are counted on common-midpoints and 4D quality control of positioning is evaluated in terms of spatial shifts *(DS+DR)* of the associated surface midpoints within a given offset range.

However, in laterally heterogeneous media or for dipping reflectors, the midpoint no longer represents the reflection point. Hit-count and shifts must be restored in common-reflection points to characterize the true illumination on selected depth target horizons. This is particularly achievable for 4D surveys as the subsurface velocity model is known (from the processing of previous vintage surveys).

Several authors have suggested using subsurface coverage maps where the hit-count of illumination of specific depth horizons is computed from ray theory for seismic coverage analysis (Winbow et al, 2004; Pramik et al, 2005; Monk, 2009). In addition, some authors have outlined the role of reflection points in seismic data repeatability for 4D processing (Lacombe et al, 2006; Cantillo, 2012).

We assess the quality of 4D positioning from the repeatability of illumination on the subsurface target at a finer scale, for each shot point and each navigation line. A 4D similarity indicator is introduced to quantify the repeatability between base and monitor illumination imprints on the target horizon. Similarity is evaluated by a matching measurement used in medical image registration (Wood et al., 1993, Hill et al., 2001). Also, on completion of acquisition (or of a swath of acquisition lines), indicators of the smallest *DS+DR* from common reflection-point gathers and the shift in reflection-point *DCRP* are examined.

Reshoot decision support

4D repeatability is first assessed at a fine scale, from individual shot to navigation line, on a quasi-real time basis. The aim is to identify which shots lack sufficient seismic repeatability (with reference to the pre-plot or base survey) and which lines show lowest repeatability as priority candidates for a re-shoot. For this purpose, we introduce a 4D repeatability indicator based on the similarity between the illumination imprints of the current shot versus the reference shot.

For a given target point, illumination fold is defined as the weighted occurrence of reflection impacts, i.e. the number of source-receiver pairs for which reflection takes place at that point.

Seismic sources carry band-limited frequency content and so an asymptotic single reflection point actually gives rise to a range of neighbouring points along the horizon where the rays interfere constructively. Therefore, each source-receiver pair is associated with a trace illumination spread imprint whose area depends on the main central frequency of the source wavelet.

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We define a shot imprint as the target illumination associated with a single acquisition shot, i.e. the summation of the illumination spreads obtained from one source and all the receivers from the towed streamers. A navigation line imprint is defined as the summation of shot imprints from all shots (starboard and portside) belonging to the same navigation line. Hence it represents the depth fold map associated with one navigation line.

Shot imprints are processed as images, which means, pixels (reflection points) with different intensities (illumination amplitude). Current and reference shot imprints are compared with an adapted partitioned intensity uniformity metric (PIU), originally introduced by Wood et al (1993) in medical image registration. The PIU metric is adapted to provide a scalar percentage measurement of similarity between reference and monitor imprints (Figure 1). In the same way, it can be used to evaluate similarity of illumination between individual or several adjacent navigation lines from different vintages (Figure 2). A ranking of lines can then be provided on a regular basis, where the lines showing the lowest repeatability of illumination are flagged with the highest re-shoot priority (Figure 3). Such information complements conventional geometrical criteria, providing additional support for identifying the most relevant re-shoot options.

These 4D-repeatability indicators jointly assess source and receiver positioning during towed-streamers surveys and under-shoots, or only source positioning over node surveys.

Quality control for processing

On completion of the acquisition (or swath of lines), the monitor positions are assessed with respect to base positions from a processing viewpoint. Additional 4D quality indicators are derived from the 4D binning process.

In conventional 4D binning, base and monitor common-midpoint gathers are formed at each depth bin within a given offset class. Within each common-midpoint gather, one pair of base and monitor traces is selected which satisfies a given criterion, for example, traces providing the minimum surface spatial shift $(DS+DR)_{CMP}$. In a similar manner, common reflection point gathers can be formed at each depth bin for each offset class. Within each common reflection point gather (*a priori* different from the common midpoint gather at the same depth bin), selection of base and monitor trace pairs can be achieved using various criteria, for example, traces providing the minimum surface spatial shift $(DS+DR)_{CRP}$, or the minimum depth spatial shift in reflection point *DCRP*. For each common-reflection bin, the depth spatial shift *DCRP* is defined as the minimum value of all reflection hit shifts from all traces within the offset class. Depending on local dip and lateral heterogeneities in the overburden, a mismatch in source and receiver surface positions does not necessarily induce a shift in the subsurface reflection point in the same locations and proportions (Figure 4). As a quality indicator, we can check that the illumination shift *DCRP* remains below processing resolution (smaller than the processing bin's size or within Fresnel resolution).

Common-offset class might ideally be replaced with common reflection-angle class at the subsurface bin (defined by aperture and azimuth ranges).

Source signature monitoring

Source signature stability is critical for both 3D and 4D surveys, to ensure that there are no artificial variations that could be interpreted as variations in the subsurface geology or reservoir state.

A conventional source array is typically composed of 20 to 40 airguns of different volumes. For a broader bandwidth signal, synchronized airguns are placed at several depths (BroadSource technology). These composite and flexible configurations are towed by the seismic vessel in a changing sea

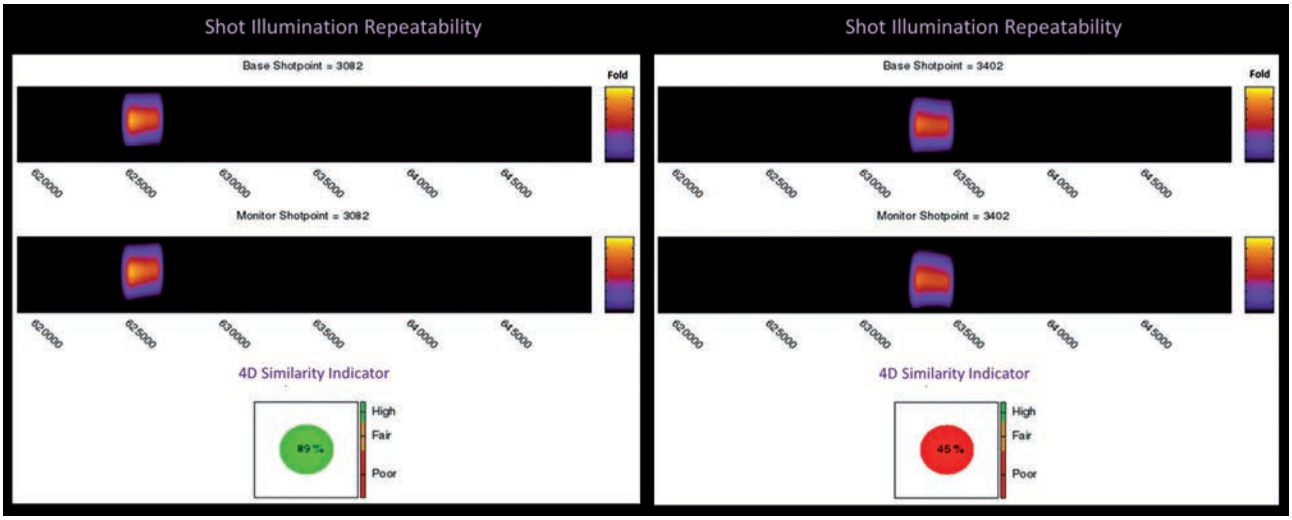


***Figure 1** Shot Repeatability Indicator based on similarity of illumination imprints.*

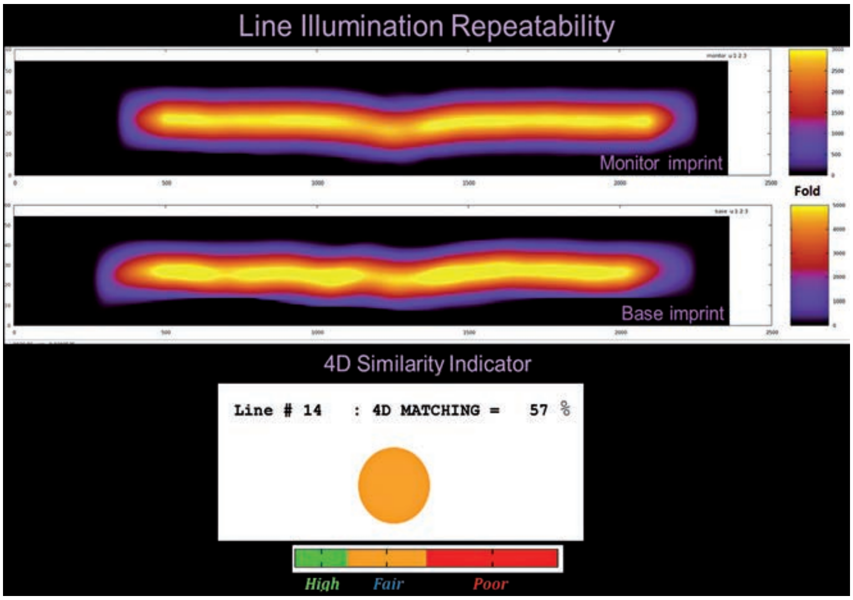
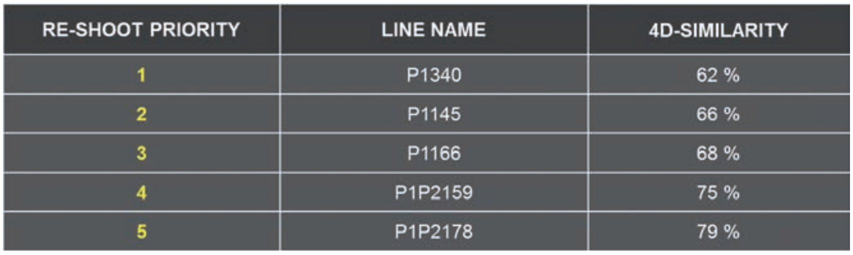


Figure 2 *Line Repeatability Indicator based on similarity of illumination imprints.*



RE-SHOOT PRIORITY	LINE NAME	4D-SIMILARITY
1	P1340	62 %
2	P1145	66 %
3	P1166	68 %
4	P1P2159	75 %
5	P1P2178	79 %

Figure 3 *Ranking of lines for re-shoot priority based on repeatability of illumination.*

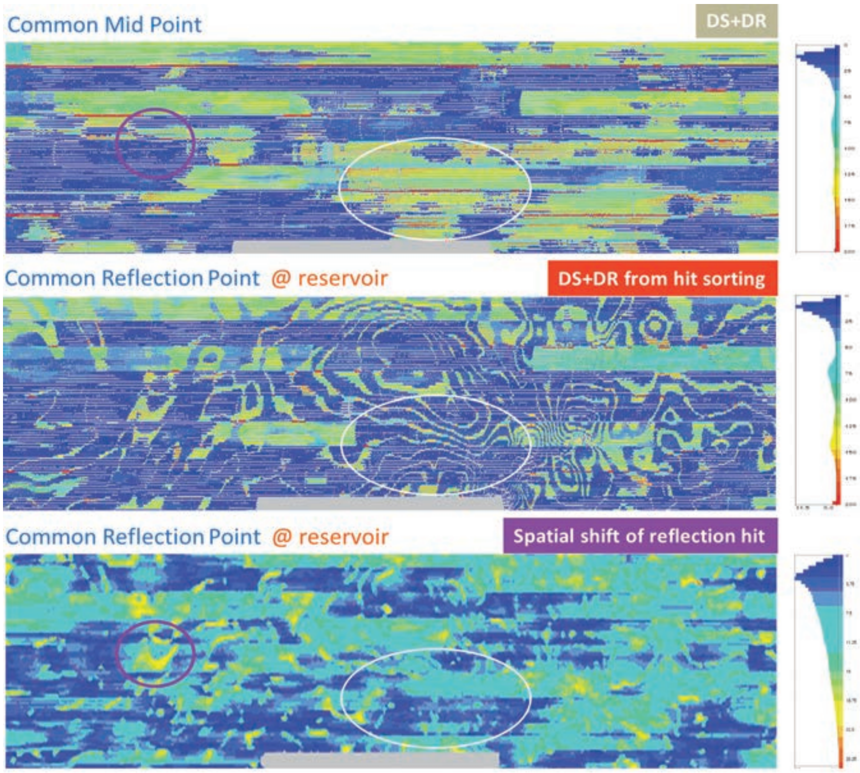


Figure 4 *4D Binning in CMP versus CRP.*

environment, making the array itself a complex and dynamic system. The source signal resulting from this coupled system is likely to vary both in the time (shot-to-shot) and observation directions.

Several authors (Dragoset, 2000; Laws and Kragh, 2002) have studied the causes of signal instability, among which are gun failure (dropouts and delays), variations in the flexible array pattern and scattering from the changing rough sea surface. Monitoring the vertical signature can be naturally derived from the signal attributes. Monitoring the directivity is a more complex issue. Measurements of array geometry from GPS antennae lack accuracy and directivity is defined in three dimensions (the frequency and two parameters for the observation direction). We propose various indicators for onboard monitoring of the source far-field signal from shot to shot. Vertical signature is monitored in both the time and frequency domains. An inversion method is used to recover the individual airgun positions with better resolution and derive accurate estimations of array geometry and directivity. Stability indicators are then introduced to monitor the three-dimensional directivity (or useful focus parts), that are based on image registration metrics.

Monitoring at vertical incidence

The far-field signature of the airgun array is difficult to measure, and one practical technique is to estimate it from near-field recordings (hydrophones placed 1 m above each airgun). The near-fields carry interaction between all of the simultaneously fired airguns as well as the sea surface. Ziolkowski et al. (1982) introduced an inversion method in which the far-field is expressed as a sum of so-called notionals, which are responses of virtual point sources disentangled from mutual interaction.

Here, the far-fields are reconstructed by further taking into account the non-spherical propagation within the array (Ni et al., 2012). Monitoring is carried out with respect to a fixed reference signal, or sliding window of successive shots, to derive trends. For 4D applications, the reference far-field may be the corresponding base shot far-field signature, if available. Figure 5 shows the monitoring of the far-field signature from shot to shot, in terms of time (top) and vertical stability indicator (bottom) defined by NRMS measurements on zero-phased time signatures. Several other indicators can be used, based for example on amplitude-related variations.

Monitoring of directivity

Source directivity is induced by the non-isotropic array pattern and conditioned by the separation of source sub-arrays and airgun depth, the volumes of the guns and the differences in firing time.

We developed a method for inverting the source array geometry based on near-field recordings from alternate starboard and portside sources. When one source is firing, the near-field recordings from the other source array are analyzed to locate the positions of both arrays by an optimization

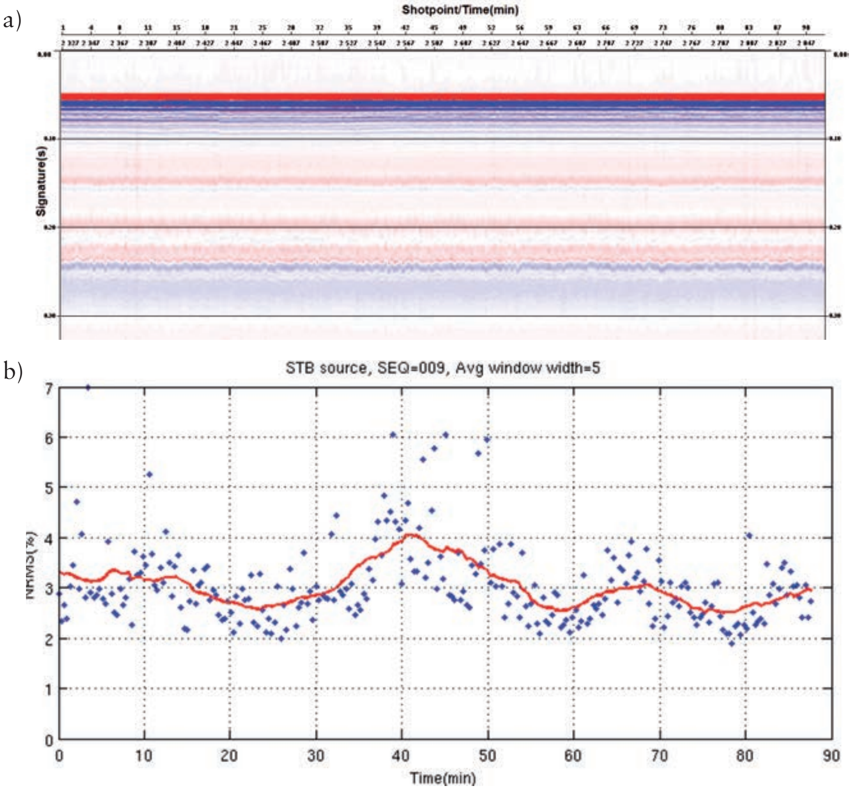


***Figure 5** Far-field signature from shot to shot.*

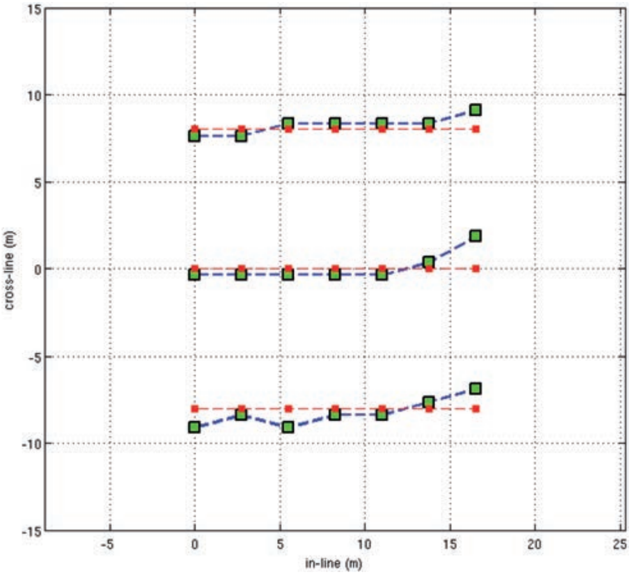


***Figure 6** Joint inversion of airgun positions from source array near-fields.*

algorithm, where GPS positions are used as an initial guess. The method allows the reconstruction of the actual airgun positions with higher accuracy (up to 0.2 m) than GPS measurements. Figure 6 displays an example of inverted source array geometry formed by three sub-arrays (bottom), showing that airgun positions estimated from seismic recordings may differ by up to 2 to 3 m from theoretical positions (top).

The radiation pattern of the far-field signal describes its amplitude directivity, A, as a function of frequency ω and observation direction, defined from the source position by two Euler angles (θ,φ). Therefore the directivity, $A\ (\omega,\theta,\varphi)$, is a three-dimensional dataset. It is commonly represented in polar coordinates. Figure 7 shows typical examples of radiation cross-sections at azimuth $\varphi = 90°$, for conventional (left) and broadband sources (right). The influence of the source array geometry on radiation pattern is illustrated in Figure 8 from the previous example of array geometries for a conventional source. Close-ups on the two cross-line patterns calculated respectively from the theoretical (left) and inverted (right) array geometries are presented, showing detectable changes in amplitude and shape.

Monitoring the source signal directivity requires a careful but easy comparison method of two three-dimensional datasets. We process the directivity spheres as images, which means, pixels (at observation coordinates $\mathbf{x}(\omega,\theta,\varphi)$) with different intensities (amplitude A). Current and reference spheres are compared with an adaptation of medical image registration metrics, such as Mutual Information (MI) and Partitioned Intensity Uniformity (PIU).

Figure 9 shows the monitoring of a broadband source cross-line radiation in a 5–150 Hz frequency range, over 110 shots from a navigation line. MI and PIU measures are reasonably well-correlated through a linear adaption, showing as convenient metrics with good stability. Such metrics provide easy scalar indicators to monitor the trends and variations occurring within three-dimensional directivity sets.

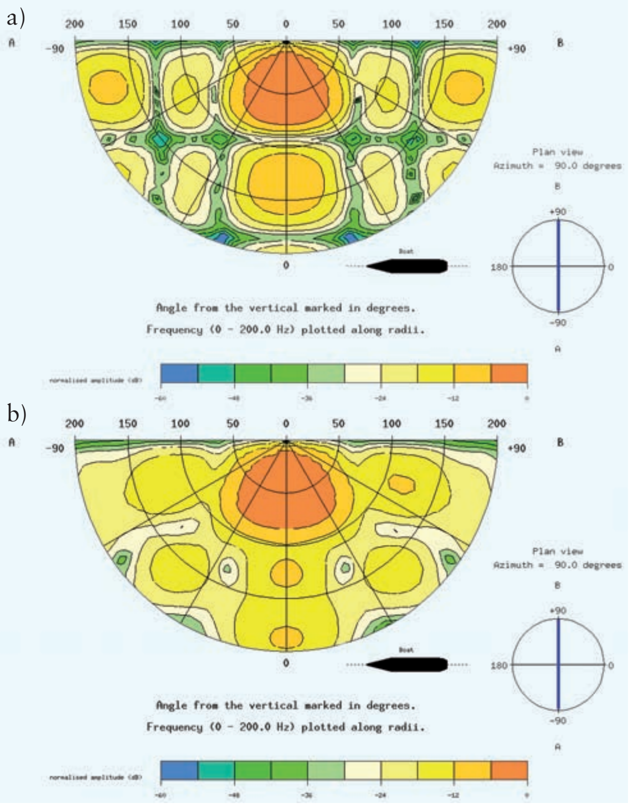


***Figure 7** Cross-line sections in the directivity sphere of (a) conventional and (b) broadband sources.*

Finally, stability indicators for each shot can be displayed as shot attributes on the acquisition geometry to localize critical shots and identify sequences sharing common signal features for further deconvolution.

Conclusion

We assess the quality of positioning during 4D marine acquisition from the repeatability of the illumination induced on the reservoir horizon. The approach converts a surface geometrical mismatch into a subsurface target illumination mismatch, accounting for overburden heterogeneity and reservoir horizon dip. Repeatability indicators are designed at various scales to provide on-board quality control of data and real-time support for re-shoot decisions.

Similarity between base and monitor illumination imprints is evaluated shot by shot (or navigation line by line) from an adapted image registration metric. This affords straightforward location of critical shots, providing an easy tool to identify and rank re-shoot options. Shot indicators can be extended to integrate various other geophysical parameters simultaneously (for example, source signal stability and a measurement of noise level).

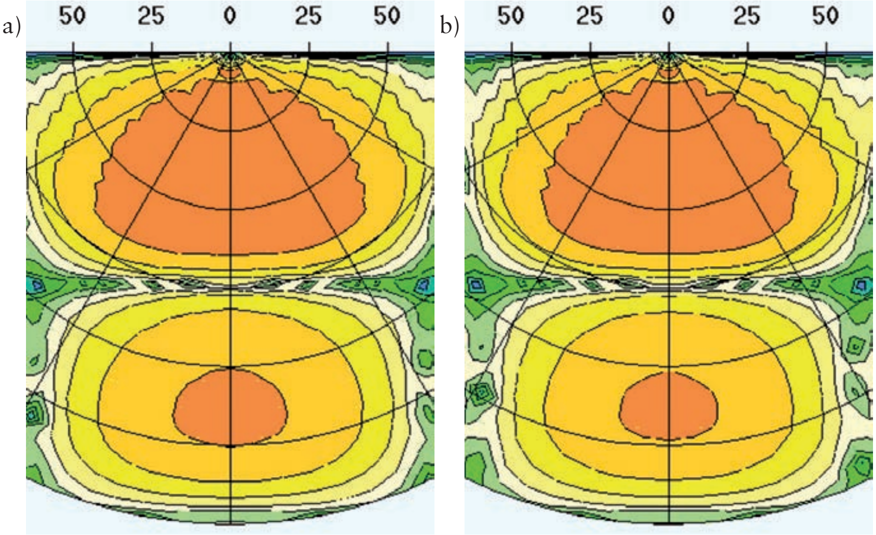


Figure 8 *Variations in directivity patterns associated with (a) theoretical and (b) reconstructed source array geometries.*

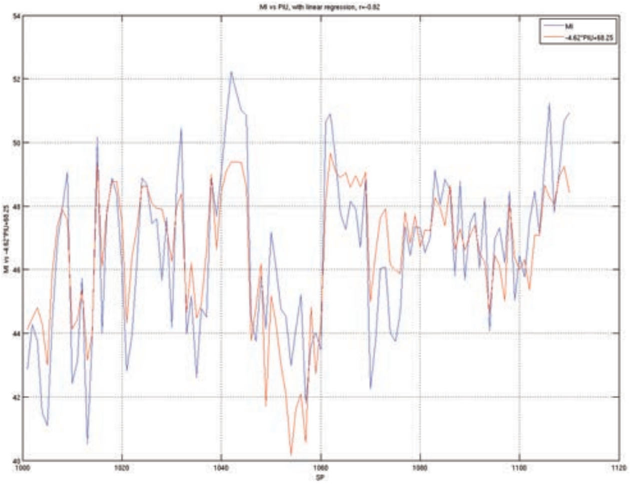


Figure 9 *Shot-to-shot MI and PIU of cross-line directivity: the two metrics show high correlation (r = –0.83).*

Matched seismic data subsets (base and monitor) are delivered for processing, that have been selected from 4D binning in common reflection point gathers to preserve, at best, the specular reflective events from the reservoir.

Also, the far-field source signature is reconstructed and monitored with several stability indicators in the three dimensions of radiation. The lateral directivity is calculated from an accurate estimation of the source array geometry, retrieved from the joint inversion of near-field recordings of starboard and portside source arrays. Adapted image registration metrics allow easy assessment of amplitude variations within the full directivity set, or within limited portions of interest (such as useful incidence range, or a specific frequency bandwidth). Such monitoring enables us to detect out-of-specification shots and identify seismic sections sharing common features, for shot-to-shot deconvolution or any appropriate correction at a subsequent processing stage.

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