NARROW VS. WIDE AZIMUTH LAND 3-D SEISMIC SURVEYS

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It appears that there are two very distinct schools of thought with respect to the patch configuration for land 3-D seismic surveys; often the like or dislike of one over another is based on which part of the business one is involved in rather than on any scientific reason. Oil and gas companies (after all the clients) may prefer a wide recording patch in order to maximize the truly 3-dimensional coverage while acquisition contractors may choose a narrow recording patch for operational reasons (if they were given the choice). There are more reasons than these to consider either recording patch; there are benefits to both that need to be considered when designing a 3-D survey.

The distinction between narrow and wide azimuth surveys is made on the basis of the aspect ratio of the recording patch. The aspect ratio is defined as the cross-line dimension of the patch divided by the in-line dimension. Recording patches with an aspect ratio of less than 0.5 are considered narrow azimuth, while recording patches with an aspect ratio of greater than 0.5 are wide azimuth. Wide azimuth patches often have aspect ratios of 0.8 - 1.0 (Figure 1a), while narrow azimuth patches may very well have aspect ratios as low as 0.2 (Figure 1b).

Comparisons have been compiled to illustrate the major differences between narrow and wide azimuth acquisition using an orthogonal layout. Figures 1, 2 and 3 compare a wide azimuth acquisition consisting of a patch of 12 lines with 60 stations per line in the left column (a, c, e) to a narrow azimuth acquisition comprised of a patch of 6 lines with 120 stations each in the right column (b, d, f). The respective aspect ratios are 0.80 and 0.20 based on station spacing of 60 m and line spacings of 240 m and 360 m. The total number of channels is 720 for both cases.

Many other comparisons are possible on the basis of changing line spacings (in order to alter the aspect ratio), decreasing the number of source points and increasing the number of receiver stations within the patch (in order to reduce the costs if source points are the cost-driving factor). The relative costs of acquiring wide vs. narrow patches is very area dependent and therefore each project is different. Trading of source and receiver points creates an infinite number of variations; we limited ourselves to the utilization of the same number of receivers within the patch, constant station and line spacings.

Fold Distribution. Since neither the source point density nor the number of receivers in the recording patch have been changed, the fold for both acquisition strategies (Figures 1a, b) is the same 30 fold (Figures 1c, 1d). What does change, however, is the configuration of the fold taper; it is very much balanced in the in-line and cross-line directions for the wide patch geometry. The fold taper is much less in the cross-line direction for the narrow azimuth patch (Figure 1d); this can be very beneficial when acquiring a 3-D survey close to an obstacle like a town, no permit zone, river or other shore line - the long axis of the patch should be oriented parallel to the obstacle. The reduction of the fold taper in the cross-line direction occurs at the expense of a longer fold taper in the in-line direction. Careful planning is required to assure sufficient fold coverage. While the full (or nominal) fold is equal for both patches, the fold at 1500 m offsets is significantly lower for the narrow azimuth patch than for the wide azimuth patch (the fold scale is set to be constant in Figures 1e, 1f). This occurs because the chosen offset of 1500 m exceeds the cross-line offset of the narrow azimuth patch. The fold distributions at offsets greater than the cross-line offset for the narrow patch are usually smoother for the narrow than the wide patch.

Offsets. Small-aspect-ratio patches (narrow azimuth) lead to a more linear distribution of offsets quite like the offset distribution of a 2-D line. However, these patches have, as the name indicates, a limited range of azimuths. The comparison of the offset distribution shows that the wide azimuth patch has the traces closer to the source points than the narrow azimuth patch (Figures 2a, 2b), assuming that the same number of receivers, station and line intervals are utilized in the patch. An average trace count of the narrow patch was copied onto the wide patch display (Figure 2a) with the corrected scaling. This display reveals the more linear nature of the offset distribution for the narrow azimuth patch. The peak in the trace count occurs where the maximum cross-line dimension of the patch is reached. Understandably this peak happens at a lesser offset for the narrow azimuth patch compared to the wide patch. The stick diagrams (Figures 2c, 2d and the offset variation within a box (Figures 2e, 2f) indicate that the offset distribution is far better for the wide patch because of the non-linearity in the source–receiver spacing (accomplished through the azimuthal distribution of the receivers).

Azimuths. The azimuth dependent trace count proves the more even distribution of source–receiver pairs for the wide patch (Figures 3a, 3b). The azimuth distribution is far more varied for the wide patch than for the narrow patch (Figures 3c, 3d). The rose diagram (Figures 3e, 3f), where color indicates the multiplicity of the occurrence of a particular source–receiver pair (in offset and azimuth distribution), is extremely focused for the narrow azimuth patch.

Lansley (1993) identified a number of issues associated with wide and narrow patches. It is interesting to review some of these issues in the light of some recent advances in processing techniques and other considerations.

AVO (Conventional and Full Waveform (or multi-component)). The Shuey approximation to the full Zoeppritz equations is widely used in AVO studies. It is interesting to note that there is a $\sin^2 \theta$ (t,x) term in this equation, where θ (t,x) is the incident angle corresponding to the sample at position (t,x). Thus, at each time “t”, there is an x^2 dependence in the computation of the amplitude variation. This would imply that for isotropic AVO (same AVO effect at every azimuth), a wide patch (offset varies as x^2) would sample the offsets better than a narrow patch (offset varies as x), leading to a more accurate determination of the AVO gradient.

For azimuthally anisotropic AVO a wide patch allows investigation at different azimuths. This may require higher fold such that there is sufficient fold in each azimuth slice for reliable AVO estimation. A narrow patch measures consistent AVO response in one direction only; it cannot allow for AVO analysis in all azimuths. If azimuthal anisotropy is present in the AVO response, a narrow patch would merely give consistent AVO measurements in one direction of the survey and not measure the anisotropy in other azimuths. Therefore anisotropy might go undetected with a narrow azimuth patch. Thus if anisotropic behavior e.g., fracture orientation, is sought, a wide azimuth survey is preferred.

Anisotropy. In the case of transverse isotropy (TI) either wide or narrow patches suffice. If the TI layer (e.g. a thick shale) is dipping in various directions a wide patch survey allows for better treatment and recognition of the TI effects. A horizontal TI layer creates a problem with conversion to depth, the seismic velocities cannot be simply used for depth conversion as they are generally too fast (assuming the layer to be faster in the horizontal plane than the vertical plane, as is the case for a thick Shale). If this TI layer is dipping or terminates within the survey area there is also a problem with lateral position in space (Ferguson and Margrave, 1998). In order to analyze and correct for this effect it is necessary to estimate velocity in two orthogonal directions. This is not possible with a narrow azimuth survey. If the axis of symmetry of the dipping TI layer rotates throughout the survey area only a wide azimuth survey could enable its analysis and correction.

Azimuthal anisotropy can only be recognized by analyzing all azimuths. To avoid ambiguity the fold needs to be sufficiently high to allow analysis of at least three azimuthal slices. In theory it is only necessary to analyze two orthogonal directions but if the axis of symmetry is unknown this could be ambiguous. For instance the survey could be oriented at 45 degrees with respect to the axis of symmetry of the azimuthal anisotropy and would appear to be the same in both axes and thus not to have azimuthal anisotropy.

Incorporating full waveform measurements, i.e. the shear component, can increase the ability to detect azimuthal anisotropy.

DMO. Recent advances in DMO processing have removed the necessity of regular offset sampling, which is a strength of the narrow patch design. Cooper, Williams, et al, (1997) showed it is possible to apply conventional DMO to irregularly sampled 3-D data using interpolation techniques. Wang (1999) has demonstrated the use of the Radon Transform to solve the problem of applying DMO in cases where the offset-azimuth distribution is irregular. Thus there is no advantage to be gained by either narrow or wide patches as far as DMO is concerned. There is still a problem of DMO “shadow” caused by loss of dipping reflections at long offsets when a narrow patch (e.g. multi-streamer marine) is used in the dip direction. There is also a problem of periodic offset distribution with this same geometry (multi-streamer) that gives rise to “amplitude striping” after DMO. Note that any DMO algorithm which depends on consistency of common offset gathers will be subject to artifacts, given that almost all commonly used geometries have some inconsistency in offset distribution. Cross-line amplitude striping is more evident in narrow patches than in wide patches. DMO equalization techniques recently introduced by several contractors can overcome some of these problems but they cannot overcome the problem of no illumination (Vermeer, 1997). This issue has been addressed by various attempts at interpolation, which can alleviate the appearance of artifacts. Interpolation is no substitute for illumination as interpolation must make some assumption of uniformity, which may or may not exist. There are indications that DMO is tending to become obsolete, and in some areas it already is, but the issue of illumination is still present.

Imaging. There have been many papers published in recent years on new methods of DMO and migration (both time and depth, pre- and post-stack). Many methods handle irregular offset/azimuth distributions well. The questions remaining are mostly concerned with adequate spatial sampling and spatial continuity of the geometry. Vermeer (1999) points out that the resolution for single fold 3-D data sets with limited extent (e.g. a cross-spread or a shot gather) depends on the position of the output point with respect to the center of the data set. Thus limiting the extent in one direction (cross-line) leads to different resolutions in the in-line and cross-line directions. Combining such data sets does not change these resolution properties. The final combined result therefore shows variations in resolution that depend on the period of overlap of the data sets and the in-line and cross-line offsets of the basic data set (e.g. shot). Clearly the best results are obtained from a square patch (equal in-line and cross-line offsets). For the case of parallel geometries (marine), the single source, single streamer creates common offset data sets with no variation from one midpoint line to the next. This gives rise to perfectly imaged results across the entire survey with no variation in resolution. Multi-source multi-streamer acquisition shows periodic changes in achievable resolution because of the discontinuous common-offset gathers (Vermeer, 1997).

Spatial continuity can be enhanced by maximizing the extent of the basic data set in all directions. Discontinuities exist at the edges of basic data sets. The process of migration causes spatial wavelet stretch (Vermeer, 1999), partly as a function of NMO stretch and partly as a function of vertical stretch due to dip. This stretch decreases with increasing aperture and increases with source to receiver offset. For a given aperture, which is generally the case, the amount of stretch will vary with source to receiver offset. For areal (e.g. orthogonal) geometries with a wide patch, this stretch occurs at the same rate in the in-line and cross-line directions, as the maximum offset is equivalent in both directions. In the narrow patch, there are more discontinuities in the narrow direction than in the wide directionin-line, as there is more stretch in the long offset direction than in the short offset direction. The implications are less migration artifacts with a wide azimuth survey than with a narrow azimuth survey.

One final consideration is that a 3-D shot recorded by a wide patch receives more widespread signal (specular reflections) than a narrow patch. Thus for areal geometries, a wide patch forms more consistent (artifact free) images than a narrow patch geometry. The degree of consistency still needs to be determined at this time and more research is required.

Migration Sampling. The seismic wavefield propagates in a manner proportional to the square of offset. It thus seems likely that sampling the wavefield in a similar fashion yields better imaging (with wide azimuth patches). There appears to be evidence for this, e.g. in Bouska (1998). If the periodicity in offset distribution (change of offset samples from one CMP to the next) is larger than a Fresnel zone, then artifacts may occur due to differing amounts of migration noise. It is possible to create this condition in both wide and narrow patches (cf. section on Imaging above).

Coherent Noise Attenuation. It is normally prohibitively expensive to correctly sample the noise wavefield, due to the very low apparent velocities. Land surveys, and to some extent ocean bottom cable surveys, are generally close to undersampling the signal wavefield also, because of cost. Coherent noise has a tendency to be oriented in preferential azimuthal directions. Both the severity of the noise, its apparent velocity, and its orientation can change within the survey area. This can cause artifacts that can be more complex than a simple match to the acquisition geometry might reveal.

Noise attenuation (especially linear shot noise or ground roll) depends on the offset distribution within each CMP – given conventional processing. The “stack response” is the usual determining factor. Curiously, the linear offset distribution of a narrow patch is often better suited to attenuating linear noise. A narrow survey has a fairly regular offset distribution and thus 2-D techniques such as simple FK filters and receiver and/or shot arrays are effective. In particular many designers have observed that a narrow double zig-zag provides a nearly perfect stack response (similar to 2-D). Thus FK and Tau-p techniques work well if the noise is in-line with the shooting direction but if there is a large component of backscatter, (e.g. recording parallel to a cliff), there can be many artifacts due to varying suppression of the noise. In such cases, wide azimuth surveys are found to cancel such backscattered energy better than narrow. Many wide azimuth land surveys have now been acquired, and processing techniques have been developed to handle the noise present in these (e.g., Wang, 1997, Gaiser, 1997). In the case of a slow velocity noise trend, the bias towards longer offsets in a wide patch may be beneficial. Migration tends to alleviate the artifacts by combining trace energy from many neighboring CMP bins. If line spacings are larger than a Fresnel zone, migration may not entirely remove these noise remnant artifacts.

Finally, can shot and geophone arrays help? The short answer is yes and no. In theory, linear source arrays in one direction and linear geophone arrays in an orthogonal direction create an areal response to cancel noise in all directions. However, backscatter noise will not be handled correctly by such an arrangement. Thus, for severe backscatter, it is better to use a point source and an areal distribution (e.g. square) for the geophones. The question of inter-array statics and apparent primary velocities at large offsets often dictates how large these arrays can be before they start to attenuate too much high frequency.

Multiple Attenuation. The process of CMP stack is still one of the most powerful ways to attenuate strong multiples. The higher ratio of far to near offsets in a wide patch is better suited to multiple attenuation than the more linear offset mix seen in a narrow patch, particularly when the differential moveout is small. It is possible for the multiple energy to have strong azimuthal variations. In such instances a wide patch survey must have sufficient fold to allow multiple removal techniques to work by splitting the data into azimuthal segments, processing each segment and finally recombining. Multiple remnants are more severe when the ratio of far to near traces is lower. Thus around the edges of surveys, where only near traces exist, it is possible that such remnants can cause migration artifacts that reach into the survey by a distance comparable to several Fresnel zones (Galbraith & Hall, 1996). Synthetic modeling can reveal the amount of multiple attenuation for different geometries.

Line Orientation. It is noteworthy that the offset distribution of a narrow azimuth patch can be improved significantly by using an angle less than 90E between the source and receiver lines (e.g. Figure 4a). Generally it is desirable to have the relative geometry repeat with every swath. The angle is set as follows:

$\not\subset = \tan^{-1}$ SLI / (swath width x RLI)

where SLI and RLI are the source and receiver line intervals respectively, and swath width refers to the number of receiver line intervals over which source points are taken. In the above example the angle of the source lines with the orthogonal to the receiver lines is 26.565E. The offset distribution is improved significantly over the orthogonal layout (compare Figures 4b and 2d). The aspect ratio of the patch merely increased from 0.20 to 0.27 by extending the swath width to three receiver line intervals. The offset distribution within a box shows no patterning at all anymore (compare Figures 4c and 2f). Similar to the double zig-zag mentioned above, such a non-orthogonal layout improves the stack response for narrow patch surveys.

Statics Coupling. – or the lack of it – is the problem. One simple way to solve this is to use geometries like Flexi-bin (Cordsen, 1993a, 1993b, 1995) or staggered line recording (GRI, 1994). These geometries lead to statics coupling throughout the survey with the interleaving of midpoints. As well one could consider using larger bin sizes for static purposes only. Processing tricks such as smoothing the CMP average during a Gauss-Seidel iteration still leave the long wavelength component unresolved (Wisecup, 1994). The only way to determine such components is through the use of 3-D refraction statics programs. Most refraction statics algorithms involve matrix solutions where shot and receiver delays and velocities (slowness) at CMPs are related to observed first break times for each refracting layer. Lack of coupling caused by regular geometries once again leads to a smoothing requirement and the possibility of bulk shifts from one group of CMPs to another. Thus for each refractor, it is still essential to have coupling in the in-line and cross-line directions. This implies that the cross-line offset should be comparable to the in-line offset, so that deeper refractors are sampled equally in all directions.

True 3-D Sampling. Is true 3-D sampling necessary? Specular reflections occur at every vertical angle and azimuth. We do not sample the 5-D wavefield completely. Thus our 3-D subsets should sample each wavefield as well as possible – implying equal extent in all directions. The combination of the 3-D subsets should be as smooth as possible (minimal discontinuities) in all directions. If any 3-D effects exist (e.g. azimuthal anisotropy), they can only be detected by measurements (shot–receiver pairs) in all directions. The short answer is, in general, yes!

However, the desire to attenuate different types of noise can lead to different requirements – as can the desire for effective AVO processing (high enough fold at each azimuth).

Cost and Ease of Acquisition. "Cheapest is best" – Lansley, 1999. Unfortunately this oft repeated statement reigns supreme in today's climate. However, "The most expensive 3-D is one that does not meet its objectives." A 3-D survey will add much new information. It is only useful if the value of this information is greater than its cost. There is always pressure on saving cost but this must be balanced against the need to solve the problem. It is always worth remembering that acquisition costs a lot more than processing; technical advances in processing can get more out of the data, however any 3-D must be acquired to image the sub-surface properly and hence meet its technical objectives. In considering a 3-D, its whole life cycle should be considered; for example, this may mean using the initial survey as a baseline for time-lapse 3-D surveys.

Whether or not a narrow patch is cheaper to acquire than a wide patch depends on numerous factors; i.e. number of channels in the patch, source and receiver line and station spacings, shot-hole drilling costs, cost to lay and move the equipment, crew productivity, etc. A wide patch is often better for the appearance, and therefore the interpretability, of the final processed result (AVO, anisotropy, DMO, imaging, multiple attenuation, statics).

Wams and Rozemond, 1998, discussed wide patch orthogonal acquisition in Oman and suggested that not only could data quality of a narrow azimuth single zig-zag design be equaled or improved upon, but that the double zig-zag design resulted in much higher productivity, keeping the cost per square kilometer constant compared to the single zig-zag method employed previously. Employing the slip-sweep technique as well resulted in a further productivity increase (this issue).

There is no fixed answer. Each survey must be planned carefully with a compromising attitude to acquiring the best, well-sampled image of the subsurface, reducing noise the most, and perhaps most importantly – solving the most relevant issues at the lowest possible cost.

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In all figures showing lines, the receiver lines are laid out east-west and are shown in blue.
The source lines are shown in red.

Figure 1. Wide vs. narrow patch – template and fold

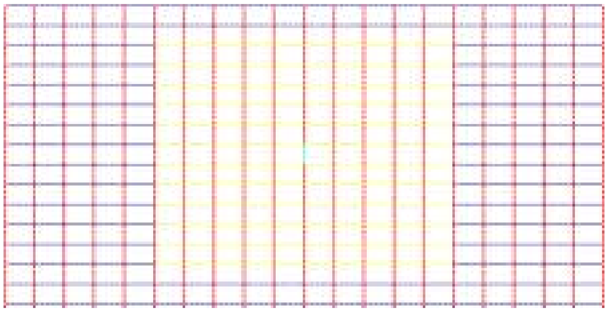


Figure 1a. Wide azimuth template

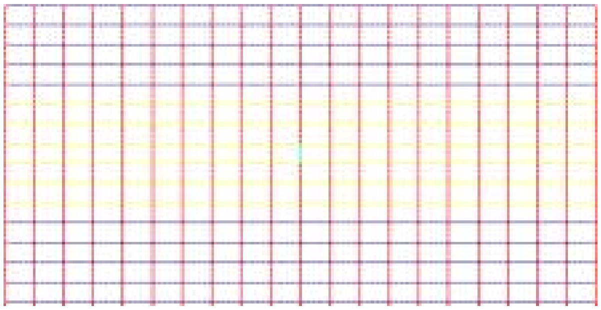


Figure1b. Narrow azimuth template

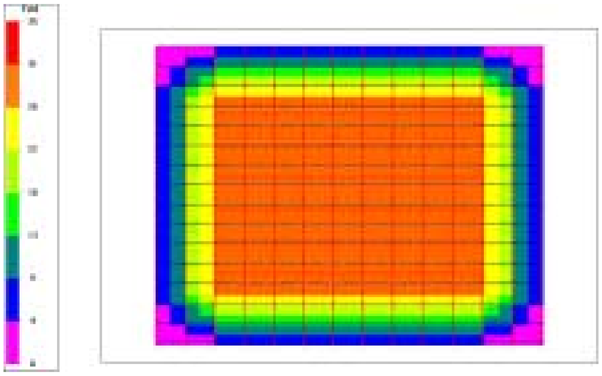


Figure 1c. Wide azimuth fold distribution at full offsets

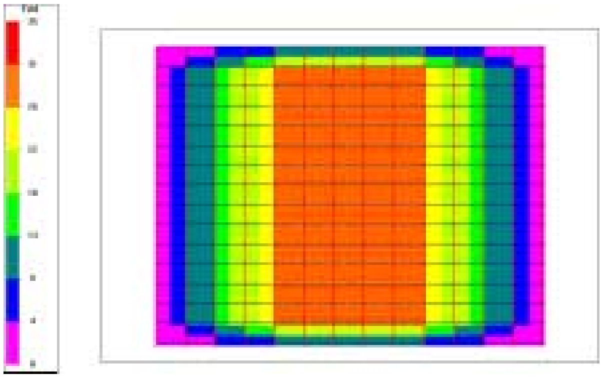


Figure 1d. Narrow azimuth gold distribution at full offsets

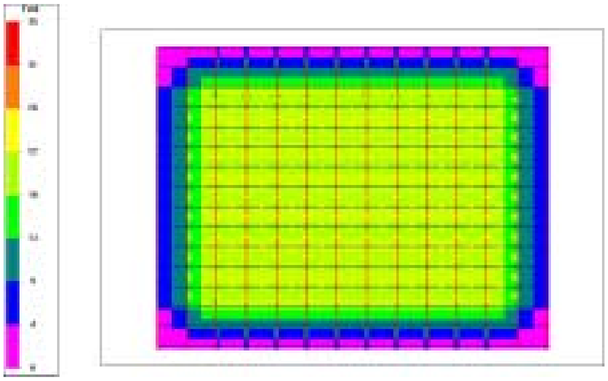


Figure 1e. Wide azimuth fold distribution at 1500m offsets

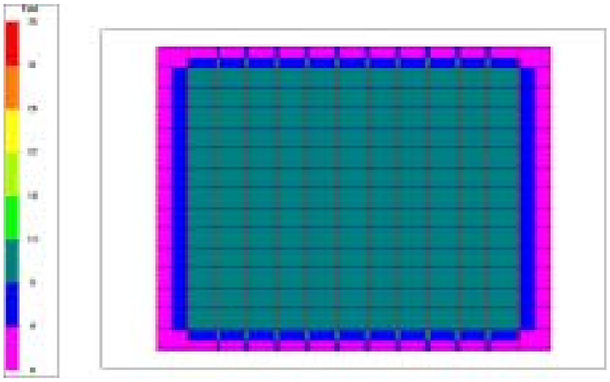


Figure 1f. Narrow azimuth fold distribution at 1500m offsets

Figure 2. Wide vs. narrow patch – offset distribution

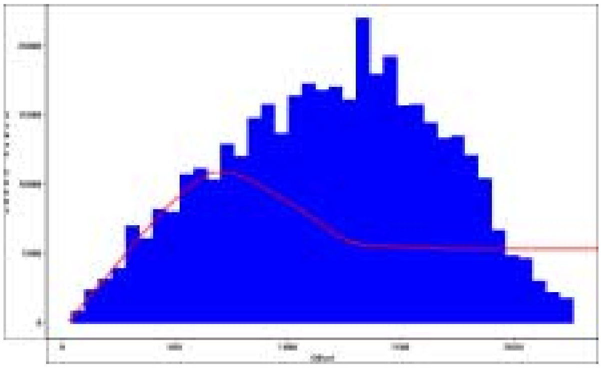


Figure 2a. Wide azimuth offset distribution – trace count

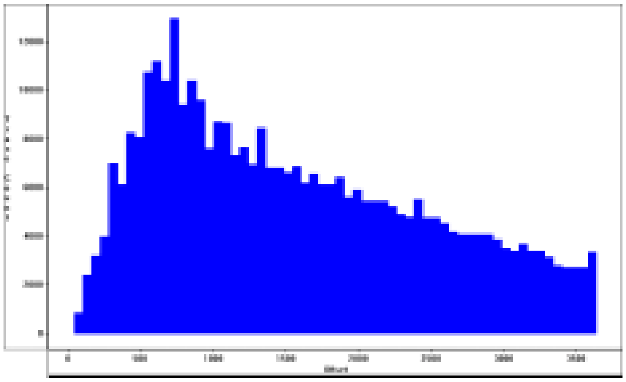


Figure 2b. Narrow azimuth offset distribution – trace count

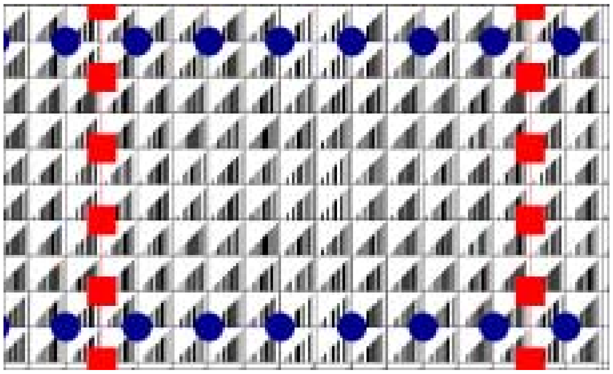
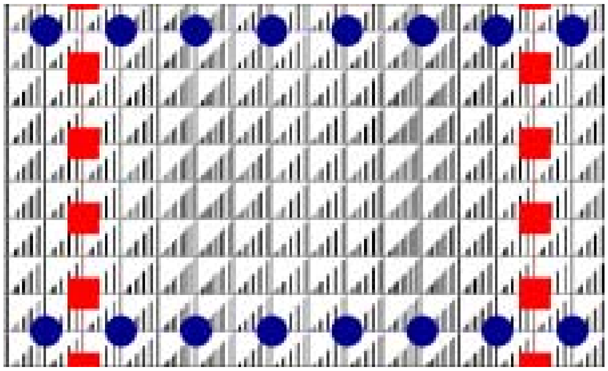


Figure 2c. Wide azimuth offset distribution – Stick diagram



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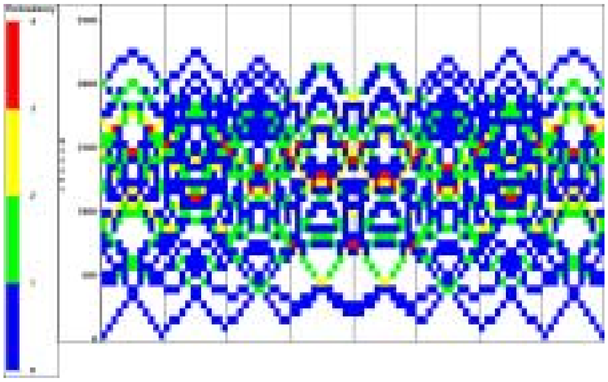

Figure 2e. Wide azimuth offset distribution – offset variation within a box

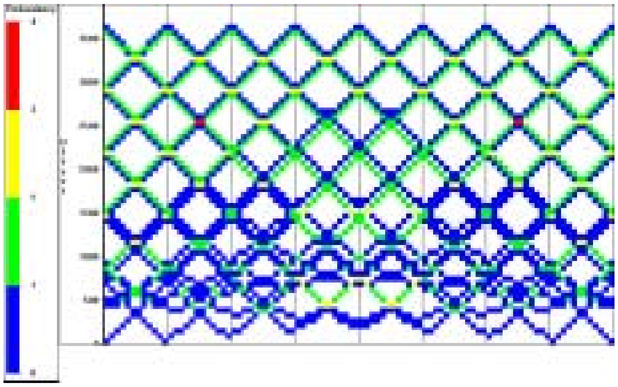

Figure 2f. Narrow azimuth offset distribution – offset variation within a box

Figure 3. Wide vs. narrow patch – azimuth distribution

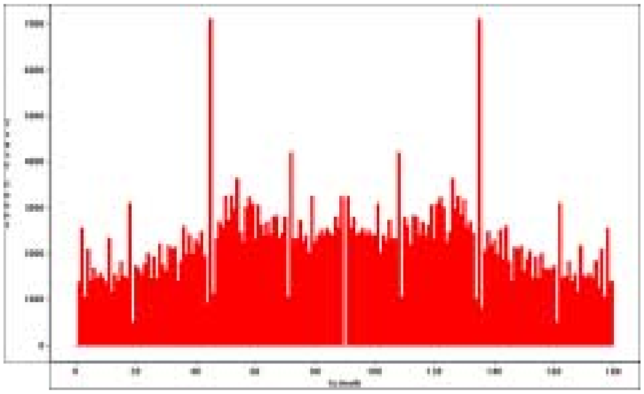

Figure 3a. Wide azimuth azimuth distribution – trace count

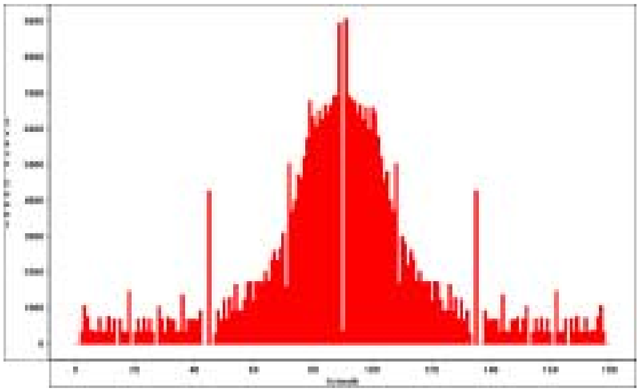

Figure 3b. Narrow azimuth azimuth distribution – trace count

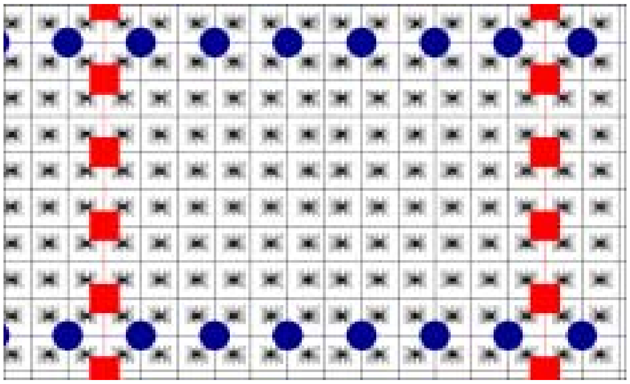

Figure 3c. Wide azimuth azimuth distribution – spider diagram

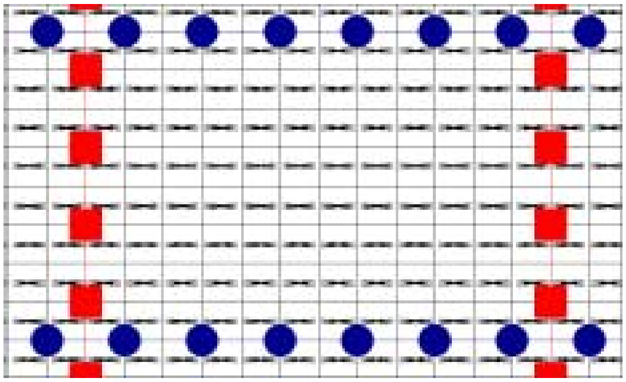

Figure 3d. Narrow azimuth azimuth distribution – spider diagram

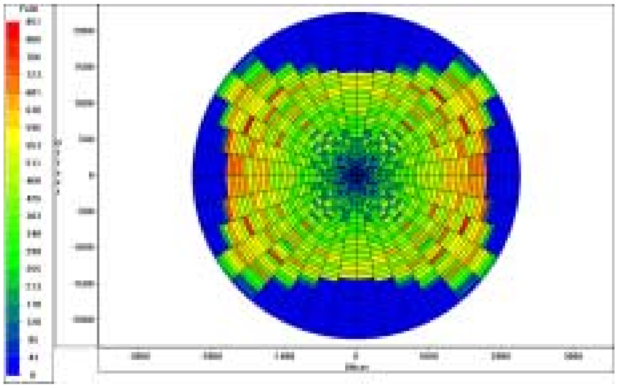

Figure 3e. Wide azimuth azimuth distribution – rose diagram

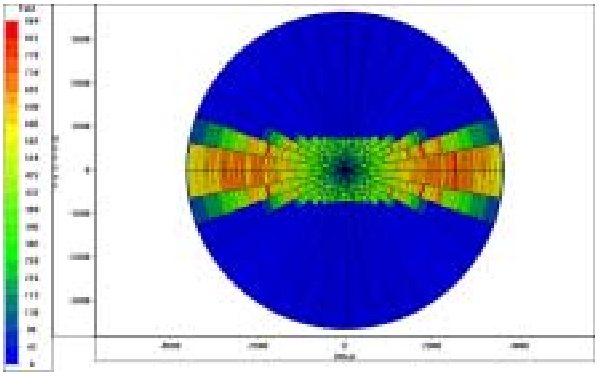

Figure 3f. Narrow azimuth azimuth distribution – rose diagram

Figure 4. Narrow patch with non-orthogonal geometry

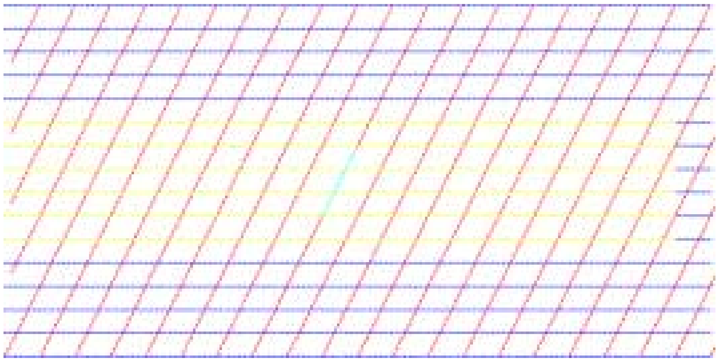

Figure 4a. Example of a non-orthogonal layout (6 line patch with a swath width of 3 lines, RLI = 240 m, SLI = 360 m)

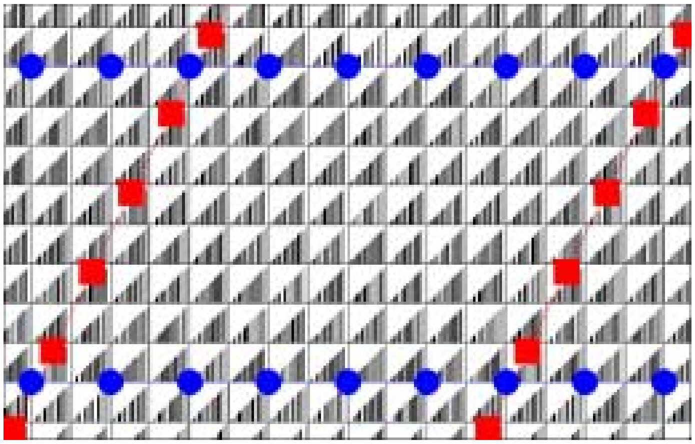

Figure 4b. Narrow azimuth patch, non-orthogonal layout – stick diagram (cf. Figure 2d)

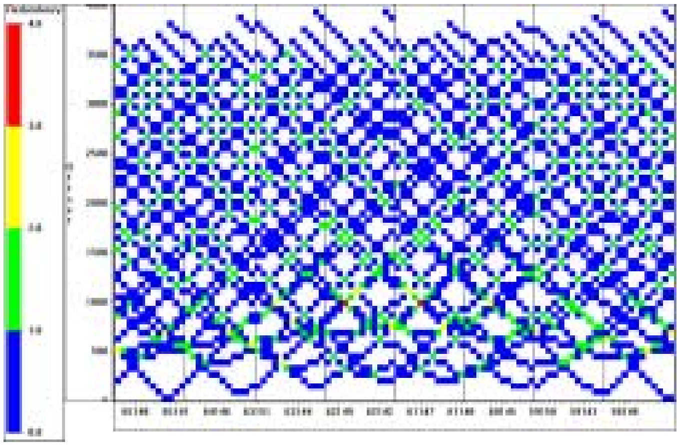

Figure 4c. Narrow azimuth patch, non-orthogonal layout – offset variation within a box (cf. Figure 2f)