On "Quantitative measures of image resolution for seismic survey design" (Gibson, R.L., and Tzimeas, C., Geophysics, 67, 1844-1852).

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Gibson and Tzimeas (2002) observed that "… the best resolution beneath the salt is obtained with the maximum offset for a trial single-cable marine geometry, not the zero-offset source-receiver pairs" and "… a land circular source/radial receiver line array design shows strong potential for improved resolution over the simple marine geometry". In these comments I will argue that the main reason for these observations is the difference in aperture between the compared data sets.

Quite rightly, Gibson and Tzimeas (2002) point out that for good resolution (imaging, inversion) a whole range of raypaths is needed that meet each other at the subsurface point to be imaged. Hence resolution analysis is considerably more demanding than conventional illumination analysis, which only looks for shot-receiver pairs with reflecting raypaths. Now, before commenting to the analysis and interpretation in Gibson and Tzimeas (2002), it is helpful to consider what to expect *a priori* from resolution analysis in complex geology. I will do so on basis of minimal data sets (MDSs), single-fold data sets suitable for imaging as introduced in Padhi and Holley (1997) and defined precisely in Gesbert (2002). In particular I will use common offset-vector (COV) gathers as a basis for discussion.

Although the ultimate in resolution analysis might be to review the shape of images that can be produced of various scatterers, a more immediate interest is in imaging the complex structure itself and any layering of interest underneath. A first requisite for getting a good image of a point **x** on a reflector is that **x** has been illuminated by a shot-receiver pair in the COV gather. If that point has not been illuminated the image cannot be complete, although it may still be quite reasonable. A second requisite for a good image is that raypaths exist from **x** to a continuous range of shot and receiver positions in the MDS. In other words, it should be possible to compute a diffraction traveltime surface for **x**. This diffraction traveltime surface should exist in a sufficiently large midpoint area [zone of influence (Vermeer, 2002), often called Fresnel zone] around the illuminating midpoint so that the image will be complete.

The flower plot introduced in Lu et al. (2002) provides an instructive way of illustrating the problems encountered in illumination and imaging. Figure 1 is a copy of Figure 2 in Lu et al. (2002). The flower plot shows contours of take-off angle and azimuth angle. These angles are measured with respect to the normal on the reflector in **x**. The flower plot is color-coded for ray amplitude. The flower plot can be used to identify shot-receiver pairs that have illuminated the reflector in **x**, for instance the end points of the white line in Figure 1 lie on the same take-off angle contour and on opposite-angle azimuth contours. Hence these end points define a shot-receiver pair that has illuminated **x**. The white line can be considered as the defining offset vector of a COV gather. Moving it around without rotating it defines other shot-receiver pairs in this gather. The traces corresponding to these shot-receiver pairs *should* contribute to the image in **x** provided they lie inside the zone of influence and they *will* contribute provided rays with sufficient amplitude exist for the endpoints of the offset vector. Note that for the COV gather to be complete there should be complete coverage with the offset vector, i.e., there should be a shot and a receiver in each surface position.

The flower plot of Figure 1 was made for quite a benign area. The (defining) offset vector can be rotated, it can be shortened or enlarged, but there is always a corresponding COV gather that can image **x**. As a consequence, a narrow parallel geometry or a wide orthogonal geometry can equally well be used to image this point (with a slight preference for parallel geometry). Figure 2, also taken from Lu et al. (2002), was made for the more complex situation of a subsurface point below a salt body, close to the salt edge. In the south-west to north-east direction of the flower plot on the left there is a small band without any surface positions that can be connected to **x**. This band

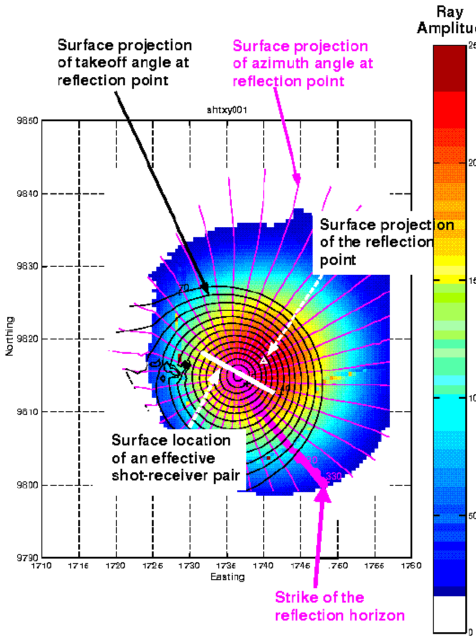

Figure 1. A "Flower Plot" made of amplitude, take-off angles and azimuth angles of seismic rays emanated from a subsurface exploding point, which is the desired reflection point to be illuminated. The horizontal and vertical axes are distances on the surface (from Lu et al., 2002).

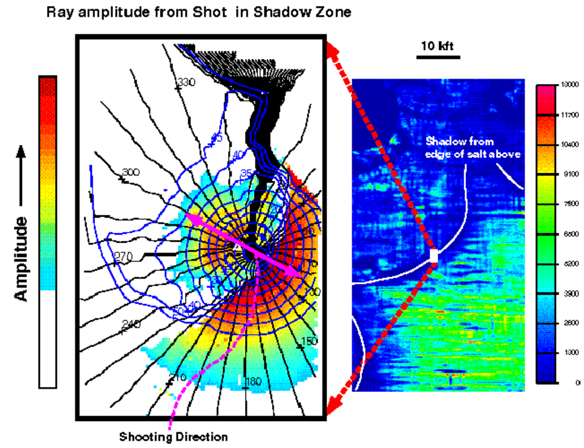

Figure 2. Amplitude map (right) from the speculative 3D survey showing shadow zones at the leading salt edge and the salt-covered area. The Flower Plot on the left indicates that the shadow zone at the leading edge can be illuminated if the data is acquired in a NW-SE direction (from Lu et al., 2002).

separates raypaths outside the salt in the south-east corner from ray paths passing through the salt in the north-west corner. This means that for any COV gather the diffraction traveltime surface cannot be complete due to missing shot-receiver pairs. So, any image made with a COV gather will be more or less distorted, depending on the relative importance of the missing traces. (Interestingly, there are cross-spreads with shot lines and receiver lines entirely inside the colored ray-amplitude area, so that each of those cross-spreads will be able to produce a correct image, provided it possesses a shot-receiver pair that has illuminated **x**.)

In Figure 2 the ray amplitudes inside the central contour for take-off angle of 5° are hidden by black azimuth-contour lines, but would probably have yellow to green colors. One can imagine that other points close to **x** may have zero amplitude inside the central contour, hence will not be illuminated by short offsets. As a consequence, zero-offset or short-offset gathers may locally produce images with more distortion than long-offset gathers. However, it seems unlikely that such differences would persist throughout a survey area. Figure 2 also confirms that illumination quality is dependent on shooting direction, which means that wide-azimuth geometries with their omni-directional shooting stand a better chance of including the more successful shooting directions than narrow-azimuth geometries. The flower plot illustrates as well that it is not straightforward to establish the most successful shooting direction for imaging. Even though a COV gather acquired parallel to the salt edge would not be able to illuminate **x**, it might still produce a better image than a COV gather shot perpendicular to the salt edge (e.g., the gather defined by the pink offset vector in Figure 2) because ray amplitudes are higher outside the salt.

Gibson and Tzimeas (2002) use a source wavelet that is different than the Ricker wavelet used in von Seggern (1991; 1994) and in Vermeer (1999). It is not very different though (apart from a different peak frequency), and one may expect that the horizontal wavelet after imaging has a bell shape as is the case for the Ricker wavelet (von Seggern, 1991). This is confirmed by the cross-section through the zero-offset image of Figure 5 in Gibson and Tzimeas (2002). The horizontal direction shows a bell without any negative lobes, whereas the vertical direction reproduces the source wavelet with two clear negative side lobes. Therefore, it may be inferred that the ideal horizontal response for a 3-D zero-offset geometry in an isotropic medium would be a circular bell for a constant migration radius. The larger this radius the narrower the bell. Vermeer (1999) shows that the width of the bell can be used as a quantitative measure of resolution.

Figure 7 in Vermeer (1999) shows that negative side lobes may develop in case the range of input traces is incomplete. The width of the central lobe may become even narrower than the theoretically best possible width of the bell-shaped response. This means that the width of the positive loop in the center of the response cannot be held representative anymore of the quality of the image, hence of the resolution. The side lobes would have to be included in the measure of resolution (Berkhout, 1984). Many of the images in Figures 9a-c and Figures 12-14 of Gibson and Tzimeas (2002) show negative side lobes, which means that they are distorted. The authors do not state what quantitative measure of resolution they have used in their comparisons of the distorted images.

In keeping with the idea to compare single-fold data sets for resolution analysis, Gibson and Tzimeas (2002) compare short-offset gathers with long-offset gathers acquired with parallel geometry. The comparisons are made in Figure 9a versus 9b and in Figure 12 versus Figure 13. Apart from the difficulty of comparing distorted images, it is not surprising that the long offsets show better resolution than the short offsets because of the large difference in aperture between the two data sets (cf. Figure 10 in Gibson and Tzimeas, 2002). Simple analysis of Beylkin's formula shows that aperture has an overriding effect on resolution (Vermeer, 1997). Hence, when investigating other causes of differences in resolution, it is important to compare data with the same aperture. A fair comparison between short and long offsets would involve the same circular midpoint area around each output point (i.e., the area defined by the migration radius in standard processing). This area should not be affected by lack of data caused by a limited-size survey (unless one wants to study edge effects), which means that the acquisition lines of the marine geometry would have to be extended in both directions. Then the short-offset data would produce better resolution than the long-offset data with exceptions locally where short-offset data have limited flower-plot coverage.

In Figures 9a and 9c and in Figures 12 and 14 Gibson and Tzimeas (2002) compare small offsets of one geometry with small offsets of another geometry. Obviously, in the limit towards zero offset there should be no difference between the results. For small deviations from the limit, i.e., a range of short offsets, the differences should still be minor, because azimuth effects only start playing a significant role for longer offsets. The large differences (mainly in the *y*-direction) shown in the paper can be attributed mostly to the difference in aperture: the land geometry has a circular area of short-offset data all around all output points, whereas the midpoints of the short offsets of the marine geometry do not extend outside the output area in the *y*-direction. Clearly, the land data have larger aperture than the marine data, therefore the land data are expected to have better resolution.

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