Requirements for Resolution

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Abstract

Every seismic survey has resolution objectives for the final 3D migrated image. Temporal resolution cannot be considered separately from spatial resolution. This would be true even for the case of continuous functions. But in the world of sampled data, the interrelationship is even stronger. A result is that in order to achieve a desired temporal resolution, the most key parameter can sometimes be the spatial sampling interval. If that interval does indeed need to be small, one immediate implication is that very accurate coordinate information is needed for the source and receiver positions. Theoretically this is not a problem in onshore surveys, but it is a little more challenging offshore. Another immediate implication is that a dramatic increase in the number of shots and/or the use of high channel-count systems can be required for the data acquisition. Assessing the resolution obtainable from such candidate survey designs can be accomplished by modeling. Examples are provided.

Introduction

The word "resolution" is often assumed to refer to the specific case of temporal resolution. In that regard, Kallweit & Wood (1982) observed that when two octaves of bandwidth are present, the limit of temporal resolution can be expressed as $1/(1.4 \times FMAX)$. However, equally important is the issue of spatial resolution. One of the methods proposed by Berkhout (1984) for quantifying spatial resolution is via the use of the "spatial wavelet". Two such wavelets are shown in Figure 1.
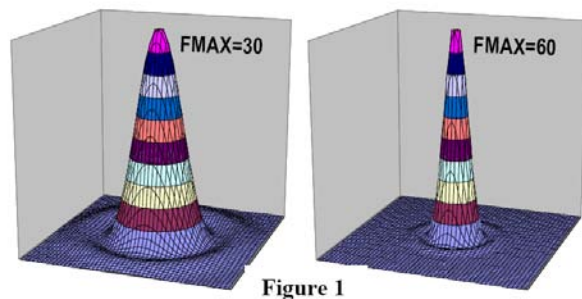

Figure 1; two spatial wavelets with different FMAX values from a survey design study.

The wavelets in Figure 1 are from a survey design analysis in which the temporal FMIN value is the same. The FMAX values are different though – and we see that better temporal resolution leads to better spatial resolution. The key point in this paper, though, is that this relationship works the other way too. That is, better spatial resolution leads to better temporal resolution.

For instance, Figure 2 shows a snapshot of the top boundary of a salt mass. In order for the migration process to be able to produce high temporal frequencies in the images of the reflections beneath the salt, the corrugated nature of the top-salt boundary would need to be portrayed faithfully in the velocity model. However, if a smoothed version of that boundary (denoted by the yellow line in the figure) is used instead, we forfeit the spatial resolution of the top salt. This in turn leads to a forfeiture of the subsalt temporal resolution. This phenomenon is routinely observed both in numerical modeling and in real data sets from the deepwater salt province of the Gulf of Mexico.
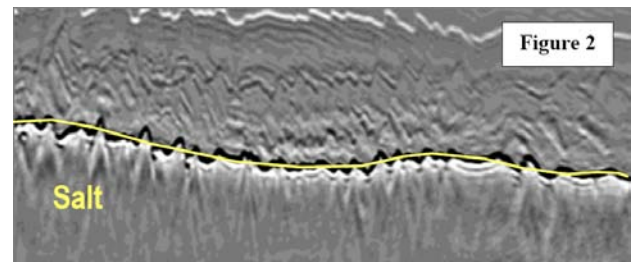

Figure 2; the snap shot of the top boundary of a salt mass, showing a smoothed interpretation in yellow.

Binning requirements

The formulas for simple spatial wavelets are computed analytically from integral equations. However, seismic data are sampled in both time and space, and the imaging calculations use summations of discrete terms. So the spatial resolution in real surveys is more limited than indicated by the spatial wavelets – and the limitation gets worse when the sampling is coarse. To elaborate on this, consider Figure 3.
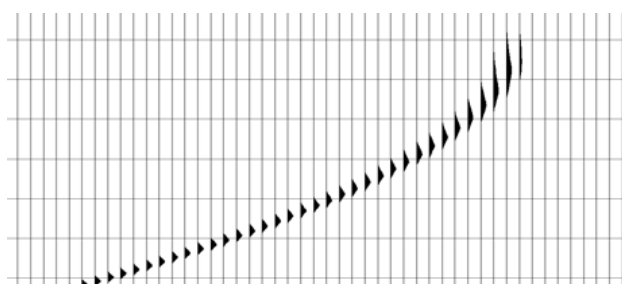
Figure 3; the tail of a migration operator from the zone of interest in a land 3D survey in Texas. The spatial sampling interval is 40 ft (12 m).

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In this figure, it is seen that the temporal frequency content of the operator is less on the traces where the dip is steep. This is because the method of Abma et al. (1999) was used to de-alias the operator. If such anti-alias protection were not provided, the imaging process would yield artifacts. Most onshore 3D surveys in North America do not use such a small binning dimension. Dimensions ranging from 80 ft (24 m) to 110 ft (34 m) are more common. That means that the anti-alias conditioning of the migration operator, and the corresponding loss of resolution in the final image, is more severe than just depicted. This is demonstrated in Figure 4. A depth-varying velocity function from the Texas survey was used to model diffractions from two closely spaced points in the zone of interest. Those diffractions were then migrated and stacked. The results from two candidate survey designs are shown. The macro designs were identical. However, the specific source and receiver intervals were different to yield the 40-ft and 80-ft CMP bin dimensions. We can see that the 40-ft CMP bin design clearly resolves the two points that are 200 ft (61 m) apart, but the 80-ft design does not. Also, analyses of spectra (not shown) reveal that the temporal bandwidth for the 40-ft case is better than that from the 80-ft scenario – again confirming the inter-relationship of temporal and lateral resolution.
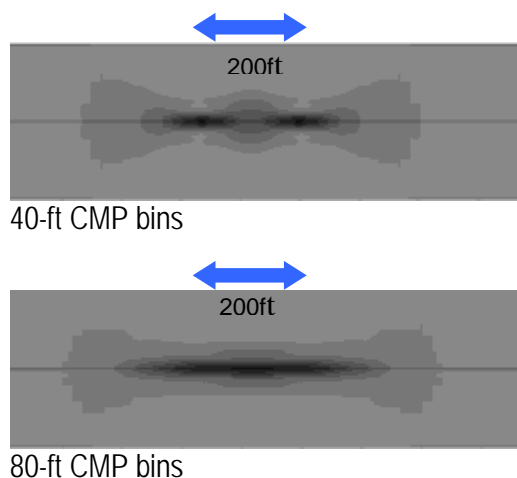

40-ft CMP bins

80-ft CMP bins

Figure 4; Modeled diffractions from two closely spaced points for two separate bin designs.

Stacks of time-migrated real data from the Texas field are shown in Figure 5. The panel on the left is from a fairly recent acquisition effort that used the 40-ft CMP geometry while the panel on the right is from a legacy effort at the same location. The legacy acquisition used a 110-ft CMP design. The zone of interest (~3 seconds) is captured in the panels. The resolution benefit from the smaller bins is evident. In fact the full benefit on the left is not fully exposed because the traces there were decimated for the purpose of display comparison. The benefit of the denser sampling is even more evident in shallower sections. For instance, karsted zones are very clear in the shallow time slice shown in Figure 6. The situation is similar in marine surveys. Figure 7 shows an example from the Mexican sector of the Gulf of Mexico. In this case we show the result from an inversion of the final data. As discussed by Salter et al. (2005), the increased resolution obtained from this denser survey geometry reveals high-porosity sweet spots (identified in purple) that were never seen in previous 3D data sets.
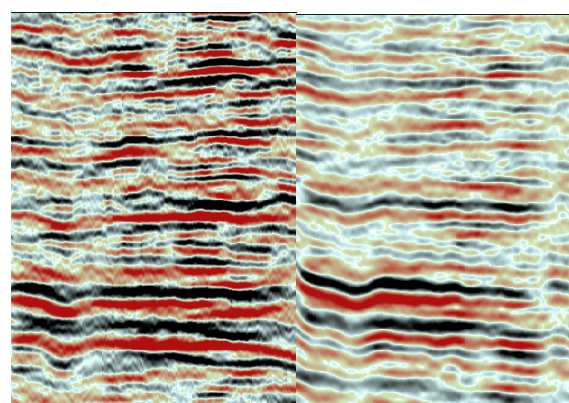

Figure 5; Stacks of time migrated real data, with new acquisition with tighter bin spacing on the left, compared to legacy data on the right with wider bin spacing.

Coordinate accuracy requirements

Of course hand-in-hand with the drive for greater spatial resolution should be the drive for greater accuracy in source and receiver location information. That is understandably more challenging in the offshore case. To investigate this issue, modeling and subsequent migration tests similar to those described in Figure 4 were executed again. However, this time marine acquisition geometries were used as well as the velocity function for a target that was 6130 m deep in the Gulf of Mexico. After the modeling of the diffraction surfaces was performed using predetermined acquisition geometries, the source and receiver coordinates were perturbed. This caused the migration to be conducted with inaccurate coordinate information.

Three scenarios are featured in Figure 8. The panel on the left is used for reference. In that case, the correct coordinates were used for the migration. As discussed before, the diffraction surfaces do not migrate back to

perfect spikes in time or space because of several reasons including the bandwidth limitation caused by sampling. The panel in the middle shows the results obtained when the receiver coordinates were perturbed using a Gaussian distribution characterized by a 3-m standard deviation. That is the type of accuracy that was available from the acoustic positioning system used in the recording of the data featured in Figure 7. The panel on the right shows the result when the perturbation standard deviation was 20 m. That is the type of accuracy that was available in early surveys that relied on compasses only for streamer location data. We can see that the loss of resolution induced by the 3-m inaccuracy is no greater than the loss already induced by sampling the wavefield into bins. The two point diffractors that are separated by 30 m are easily resolved. However, those diffractors are not resolved when the standard deviation is 20 m.

Note that in this exercise the bin dimensions are 5 m. So, small bins by themselves are not sufficient for good resolution. Accuracy in coordinates is required to support the small-bin effort.

Enabling technologies

Improved (temporal and spatial) resolution requires denser spatial sampling. This naturally implies that massively more shots (via continuous recording techniques) and/or higher channel counts are required in acquisition. Indeed the combination of the two can be exceptionally powerful – as witnessed in some onshore programs in the Middle East and North Africa where the desert environments place minimal restriction on access. However, in North and South America topography, vegetation, infrastructure, habitats, and many other things often severely restrict where shot points can be placed. In those cases, the burden of denser spatial sampling is placed more on the channel count.

Whatever the case, the quest for better sampling also implies that each shot should ideally be a point (as in the case of a single vibrator) and each receiver should be recorded by a separate channel – otherwise there will be smearing of the signal. But this is not to say that it would be sufficient simply to use more channels and more computers. An order of magnitude increase in the number of live channels requires paradigm shifts in data QC, data transfer, and processing. It also requires improvements in things like positioning accuracy – as mentioned above.

So assuming all of those hurdles are overcome, how many live channels would we like to have in each shot? Well frankly, at the risk of sounding greedy, 1 million sounds like a satisfying, round number. To place this desire in context, large "conventional" acquisition systems used today in land and marine surveys might have 4,000 to 5,000 channels. The unconventional systems used to acquire the land and marine examples featured in Figures 5 through 7 used approximately 20,000 live channels. (Those surveys made use of the single-sensor approach – thereby allowing some of the uplifts in resolution to arise not just from the binning issue, but also from other factors related to the ability to address noise and statics issues better.)
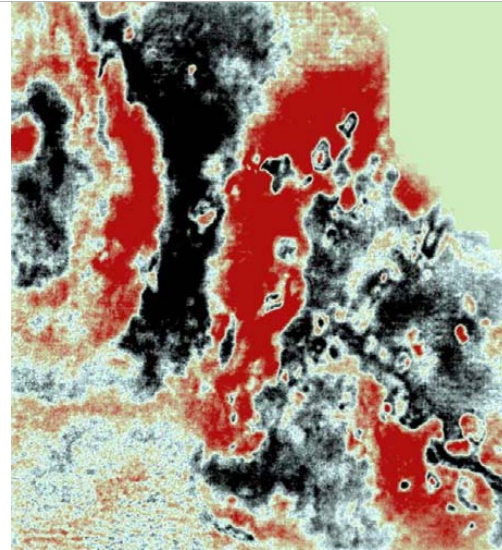

Figure 6; the benefit of denser sampling in shallower sections, shown here in the karsted zones are very clear in the shallow time slice shown

Today the capabilities of the marine single-sensor system can record up to 80,000 live channels. The main limitation is how many streamers can be towed by the vessel. And the land single-sensor system can record up to 150,000 live channels. These channel counts are not yet at 1million, but they clearly do provide the wherewithal to achieve resolution results much better than in the case of legacy systems – especially when those high-channel systems are married with increased shot point densities.
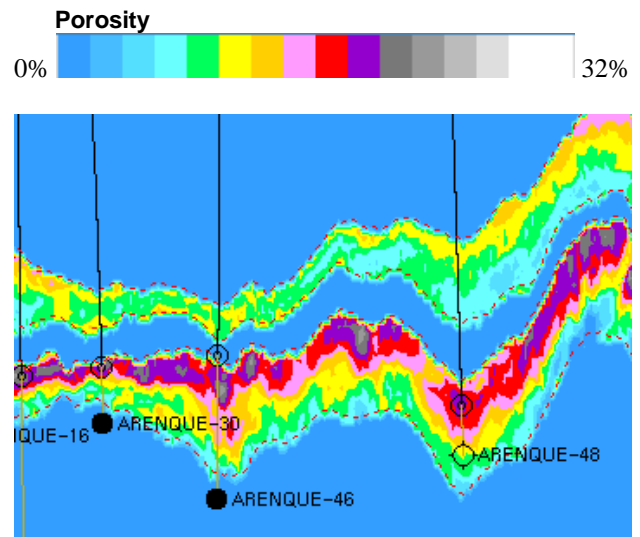

Figure 7; Porosity variations shown in an example of seismic acquired with a high channel count.

Challenges

As mentioned above, the strategy to improve resolution by using more closely-spaced shots and channels for better calculation of Kirchhoff-style integrals can unfortunately be sabotaged when access in the survey area is limited. This is a key issue that is examined in survey design studies. But even when access is not a problem, the challenges do not rest solely within the acquisition and processing umbrella. For instance, extending the frequency range and thereby improving the resolution of valid signal can reveal complex fault patterns that hamper the use of auto-tracking in interpretation. This is certainly compounded if the increased bandwidth also passes higher-frequency noise. Again, this is an issue examined in proper survey design analyses
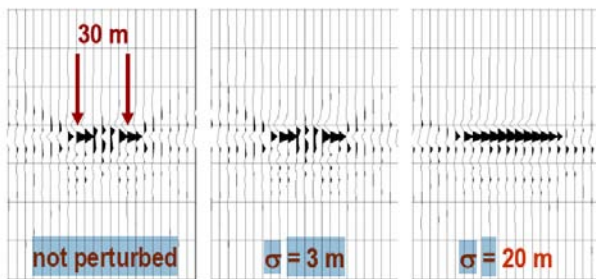

Figure 8; Comparison of migrated results when perturbations are introduced into the coordinate information.

Conclusions

What we have said here is that resolution is multifaceted. Good temporal resolution does not depend simply on how much high frequency energy our seismic sources can pump into the ground. Good temporal resolution in the 3D migrated image also requires good spatial sampling. Good spatial sampling requires high channel counts. High channel counts require a paradigm shift in everything from QC procedures to final interpretation.

Also, the very definition of "sampling" implies discrete sampling - not mixing. This means that the information recorded in each channel should come from a single point receiver – not from an array. Noise suppression and data reduction can be performed in far more intelligent ways than by simply smearing measurements in the field.

And finally, the big questions of course are just how small do the bins have to be, and how many channels are needed? In other words, what are the requirements in the field design that are needed to meet the requirements in resolution?

Projects with which the authors have been involved employed bins as small as 3 m or so. Such density is certainly not yet required in most areas, but as a matter of practice, proper survey evaluation and design studies need be conducted to answer these field-specific questions.

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