Shifting paradigms in land data acquisition

Malcolm Lansley[*] describes the remarkable technological advances in land seismic that have paved the way for improved ways to design surveys and record data. The result has been a number of paradigm shifts in our understanding of the optimum ways to acquire data.

The first commercial land 3D survey was recorded 40 years ago in Lea County, New Mexico by Geophysical Service (GSI) for a group of interested oil companies. The intention was to demonstrate the feasibility of recording and processing 3D surveys. By today's standards this survey would hardly credit being called 3D, but it was a major step for the industry. Most of the design issues related to 3D survey design (offset and azimuth sampling, etc.) were not well understood and the survey was essentially multiple parallel 2D lines. The geometry did, however, provide a data volume that could be migrated in three dimensions. At the time of this survey, most recording systems available had only 24 recording channels and the first systems capable of 48 channels were being introduced. In order to record 96 receiver groups for each shot on this survey it was necessary to master/slave two 48-channel recording systems.

Figure 1 shows a plot (in blue) of the number of channels that most recording systems could record versus the calendar year. Also shown (in red) is the total number of recording channels that were being used for typical surveys. Note that when this exceeds the number of channels available it indicates that more than one system was being used. Note, also, that the vertical axis is using a logarithmic scale. In 1970, we had not begun to record 3D surveys, but frequently two systems of 24 channels each were used in order to obtain higher fold 2D coverage.

The use of multiple recording systems was quite common until the late 1980s and early 1990s when technology improvements permitted single recording systems to acquire ~1000 channels or more. As more and more 3D surveys were acquired, industry geophysicists began to establish certain 'best practices' that would later become guidelines or paradigms. Some of these paradigms are:

1) Data should be high fold
2) Regular or uniform offset sampling is best
3) In order to obtain uniform offset sampling, narrow azimuth geometries are best
4) Good signal to noise (s/n) ratio is required on the field records
5) In order to achieve a good s/n ratio, source and receiver arrays may be necessary
6) To get good s/n ratio we should minimize noise on the recording spread.

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As time progressed there was a period when the systems were able to record as many channels as survey design geophysicists required, or designs were modified to permit the use of a single system. However, the paradigms still remained without significant change. Today, we have the situation where recording system capability far exceeds normal 3D survey design requirements with systems capable of channel counts in excess of several hundreds of thousands. The technological advances are not only limited to recording systems, but also to many of the other factors that affect seismic recording. Together these changes have permitted a dramatic shift in many of the paradigms that have traditionally been accepted in the industry, but in some regions of the world many old paradigms still remain.

Paradigm shifts

In the early days of land 3D data acquisition, significant effort was applied to striving to record data which had common mid-point (cmp) offset distributions that were uniform. Even with the limited number of recording channels available this was still possible as long as the range of azimuths

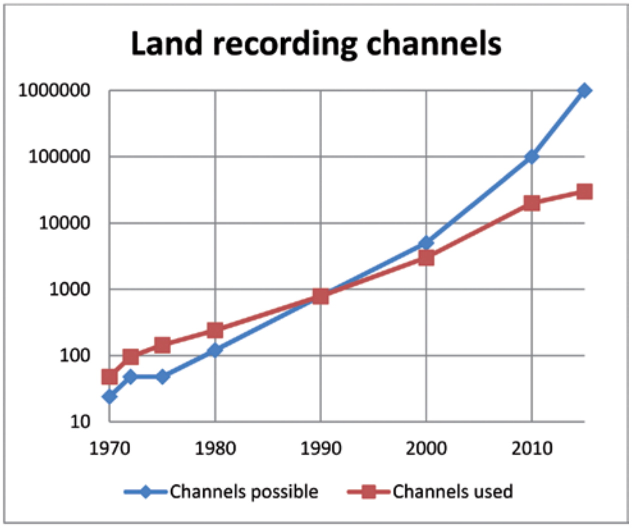


***Figure 1** Plot showing a history of recording system channel counts vs. calendar year. The blue curve shows the number of channels that were typically available on most recording systems. The red curve shows the number of channels that were being used on crews at the time. When this is larger than the number available the crews were using more than one system in a master/slave configuration.*

being recorded was relatively narrow. It was understood by many people, however, that wide azimuth surveys should give better subsurface illumination for both stratigraphy and complex geologic structures. For many years a heated debate existed over which was better, narrow- or wide-azimuth. Unfortunately, these discussions were based on low fold surveys in which there was always a compromise; narrow-azimuth with good offset sampling or wide-azimuth with poor offset sampling. Today, with improved system capabilities we have seen the shift from *narrow-azimuth* to *wide-azimuth* geometries. With a wide-azimuth geometry it is impossible to acquire regularly sampled offset distributions. The offset distribution that results from a wide-azimuth geometry has a greater concentration of long offsets than short offsets. Therefore, what is now recognized as optimum is good offset sampling within each of multiple-azimuth ranges.

Towards the end of the 1990s and in the early 2000s we began to acquire a better understanding of the imaging processes and a greater use of pre-stack migration algorithms ensued. It became clear that it was not the cmp fold by itself that was important, but how well we sampled the actual wavefield in both offsets and azimuths. Lansley (2004) discussed this paradigm shift from *fold* to *trace density* in some detail. The improved capabilities of the recording systems enabled a rapid adoption of this philosophy in some parts of the world, such as deserts and other areas with open surface access. In these types of areas, acquisition of surveys with high trace density quite quickly became standard. Unfortunately, in some other regions the problems of surface access and permitting have limited the extent to which trace density has been increased.

Figure 2 (Wombell et al., 2011) shows a comparison of two data sets from the South Oman Salt Basin. The section on the left is a narrow azimuth legacy (2008) data set with a trace density of approximately 160,000 traces/km^2 and on the right a wide-azimuth high density survey acquired in 2009. This comparison demonstrates the benefits that can be achieved with the combination of wide-azimuth and high density. The benefits of either wider azimuth or higher trace density are difficult to separate since processing of wide-azimuth data is much more difficult if the sampling of offset ranges within different azimuth ranges is compromised. The new survey was acquired with a 'super-crew' with 25,000 channels of Sercel 428XL recording equipment with an equivalent number of strings of 12 geophones. The receiver spacing was 25m with a 200 m receiver line interval. The crew had 16 vibrators that were used with distance separated simultaneous sweeping (Bouska, 2009) on a grid of 50 m by 50 m. With 8000 live recording channels this resulted in a trace density of 6.4 million traces/km^2, a factor of 40 times that of typical legacy surveys in the same area.

When 2D data was the primary seismic that was used for interpretation, the signal to noise of the individual records was extremely important. The actual interpretation may have been made on single fold data, and even after the invention of common depth point (CDP) or common mid-point (CMP) stacking (Harry Mayne, 1962) individual reflections were frequently hand-picked on shot records for static computations or for other data processing analysis. Therefore, large arrays of geophones were a standard method of attenuating both random noise and also source-generated noises such as ground roll. Unfortunately, these arrays also attenuated the signals that we wished to record. As the effort to increase trace density continued, inline sampling intervals for both sources and receivers began to diminish. For receivers, this was relatively easy because of the improved system capabilities.

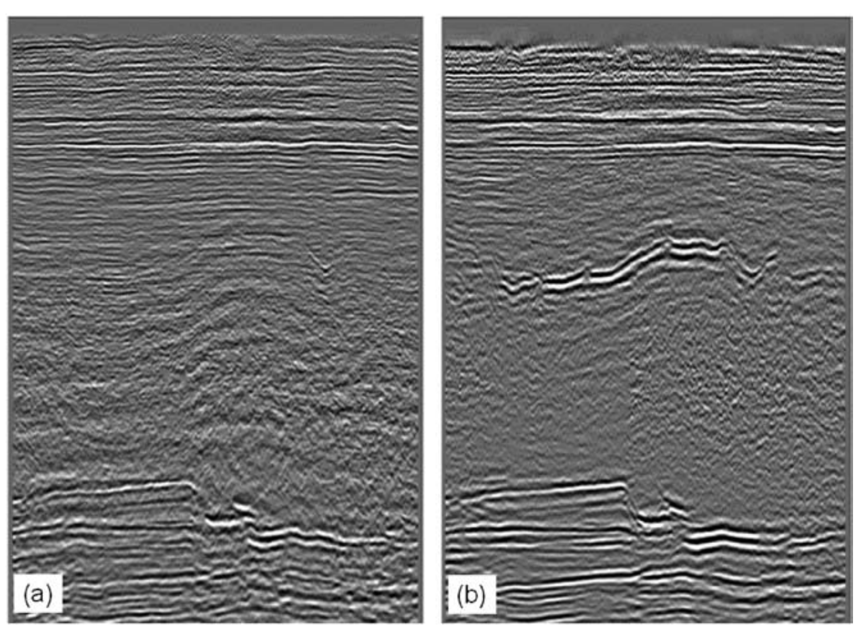


***Figure 2** Datasets from the Southern Oman Salt Basin: (a) Legacy narrow-azimuth data with 2008 data processing and including pre-stack depth migration (PSDM), (b) Wide-azimuth data acquisition with wide-azimuth data processing sequence with PSDM (Data courtesy of Petroleum Development Oman).*

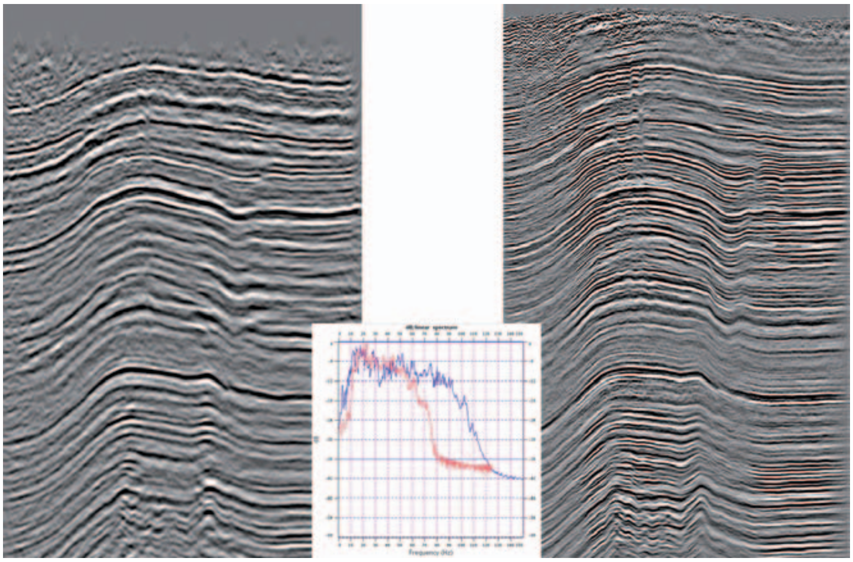


Figure 3 *A comparison of seismic lines across the Dukhan field extracted from a legacy survey (L) and from the new high density, wide-azimuth survey (R) The spectral plot in red shows that of the legacy data and in blue the new survey. The improvements in bandwidth can clearly be seen (Figure originally from Seeni et al., 2011. Data courtesy of Qatar Petroleum).*

In order to reduce the amount of equipment that had to be deployed, as the inline sampling interval was reduced, the receiver array size (i.e., the number of geophones per trace) was also reduced. This reduction in array size has continued to the point where, on many of the recent surveys with very high trace density, we can observe the shift from *receiver arrays* to *point receivers*.

Surface sources such as vibrators have always been considered 'weak' sources when compared with explosives. Because of this, as the performance of both the mechanical systems and the control electronics improved to permit very accurate synchronization of multiple vibrators, arrays of vibrators were generally used. In addition, in many cases multiple sweeps were also being recorded at the same location or in a short array and were vertically (or diversity) stacked in order to create a single source record. This was done in order to improve the signal to random noise ratio. What was frequently misunderstood was that much of the noise that is typically believed to be 'random' was, in fact, scattered source-generated noise that was not adequately sampled during recording. Because the scattered noise is coherent from sweep to sweep, it was quite often seen that the stacking of multiple sweeps at a single location did not significantly improve the quality of the shot record (Quigley, 2000 and Cooper, 2002.) If the vibrator effort can be more widely distributed (less effort per location but with a much greater number of locations), the sampling of the scattered noises will be more diverse and these noises will be attenuated in the imaging processes. Thus for sources, there has also been a desire for smaller source intervals and a higher density of source points. From a cost perspective, this is difficult to achieve with explosives because of the cost of drilling and loading, etc. With vibrators it has led to a move from *vibrator arrays with several vibrators and several sweeps* to a *single vibrator and single sweep or point source*. Needless to say, improvements in data storage and computer processing power are also essential.

Seeni et al., 2011 describe some of the initial data processing of an extremely high density survey which was acquired in Qatar for Qatar Petroleum over the Dukhan field. The survey was acquired in 2009 and 2010 and demonstrates the benefits that can be attributed to many of the issues discussed in this article: point source, point receiver, high density, wide azimuth, fine spatial sampling along both source and receiver lines, and close source and receiver line spacing. The survey was recorded using a Sercel 428XL system with single geophones at 7.5 m on receiver lines spaced 120 m apart. The crew was equipped with 40,000 recording channels of which 24,192 active receiver stations were recorded for every source location. The vibrators were used in fleets, but using HFVS so the data could be separated into point sources. The source points were also spaced at 7.5 m along receiver lines spaced only 90 m apart. This results in a natural bin size of 3.75 m by 3.75 m with a fold of 504, which gives a trace density of 35.84 million traces/km^2. Figure 3 shows two cross-sections from this area, the one on the left being a legacy survey and on the right from the new survey. At the time these displays were made, the processing of the new survey had not been completed. The displays shown were extracted from the pilot test processing in which some array forming had been performed after statics and velocity analysis. Nevertheless, the improvements in the data quality are remarkable. Also, the frequency spectra clearly show the considerable increase in bandwidth that has been obtained. Figure 4 shows a comparison of time slices extracted from the same two data sets in which the new survey (R) exhibits significantly finer structural detail.

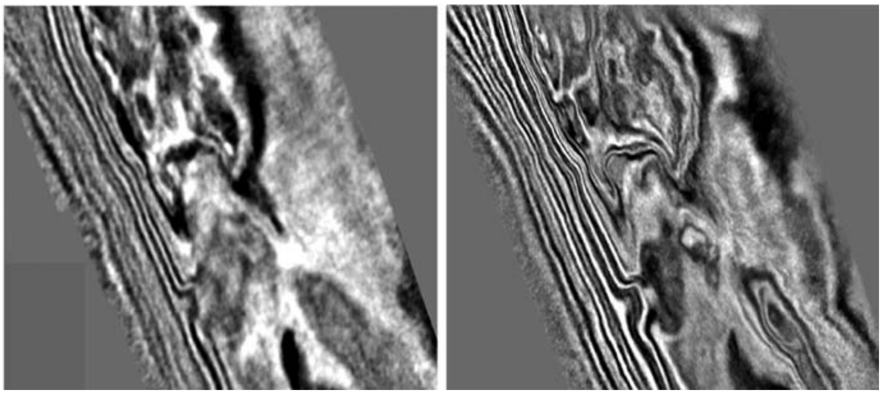
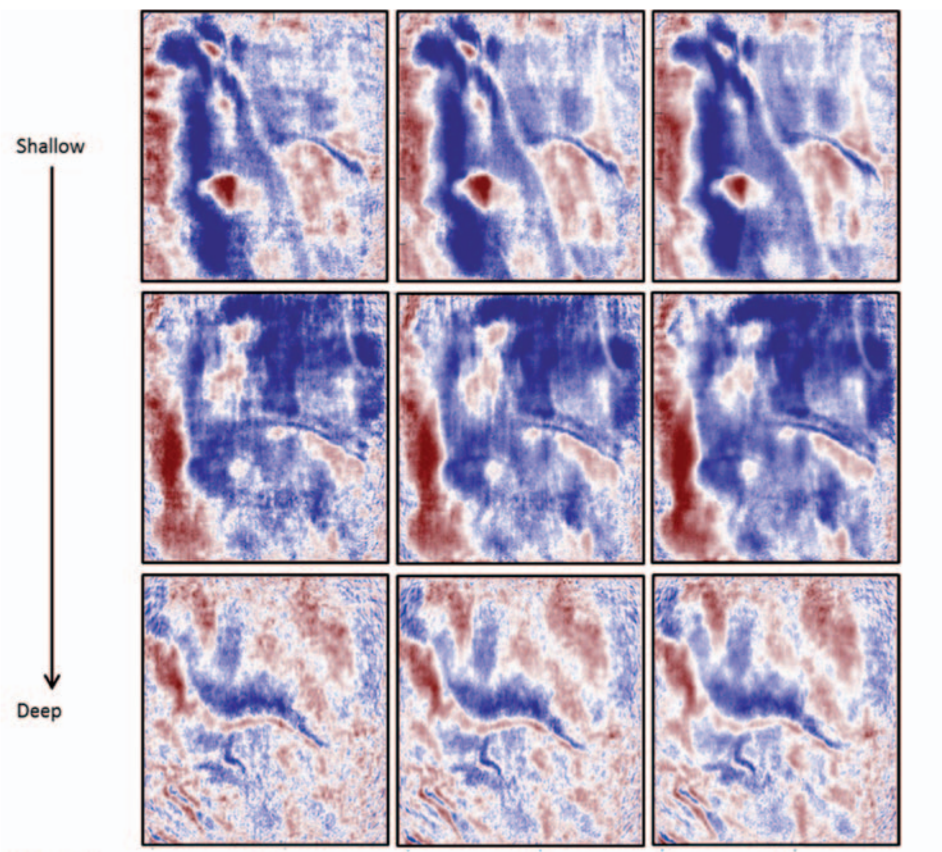


Figure 4 *Time slices from the same two surveys shown in Figure 3. The new, wide-azimuth, high density survey (R) shows dramatically improved imaging in comparison with the legacy survey (L) (Figure originally from Seeni et al., 2011. Data courtesy of Qatar Petroleum).*



Data set	A	B	C
# of vibrators / SP	3	3	1
Receiver line int. (m)	400	200	200
Source line int. (m)	300	300	100
Fold	82	163	327

Figure 5 *Shows time slices at different times (from shallow to deep) for three different survey geometries. The table on the left shows the variations between the different geometries.*

The continued efforts to increase trace densities and improve the sampling for attenuation of direct-arriving and scattered source-generated noises has led to smaller intervals between the receiver lines and the source lines or the shift from *coarse line sampling* to *finer line sampling* for both sources and receivers. Bianchi et al. (2011) show a nice example from Egypt (Figure 5) which compares data recorded with arrays of three vibrators with that from a single vibrator. In the analysis, there is also a comparison of different source and receiver line intervals. In order to maintain a comparable S/ambient noise ratio (<= -3 dB) the sweep lengths were adjusted. From the data it can be clearly seen that the data (C) with the individual vibrator sweeps and the finer line sampling have a significantly reduced 'footprint' and superior imaging, particularly on the time slice at the intermediate time. It is interesting to note that in many recent surveys in areas of clear or open access for vibrators there is no longer a distinction between source line interval and source interval along the lines. The source spacing is the same in both X and Y and we have what is now commonly termed 'carpet shooting'.

It should be noted that the last example was recorded using slip-sweep, which was introduced to the industry by Rozemund in 1996. Since the requirement to increase the source density has been a dominant factor in many of these changes, slip sweep was one of the first methods that addressed the increased time and cost of acquiring such high density surveys. In slip sweep acquisition, successive sweeps from different vibrators or groups of vibrators are allowed to overlap to improve productivity. In independent simultaneous sweeping or ISS (Howe, 2008), multiple vibrators are sweeping at different locations simultaneously and with random sweep start times. These and other high productivity methods have required the implementation of additional capabilities in the recording systems. Continuous recording is essential, together with the ability to record a very large 'superspread' of active receivers. The 'superspread' ensures that, no matter where the vibrators are located, the expected receiver stations are always live and being recorded. In some of these high productivity vibroseis techniques, the direct noise interference of these multiple sources on the individual shot record from another location results in dramatically lower s/n. The result is the paradigm shift from *good s/n on individual shots* to *poorer s/n, but with excellent offset and azimuth sampling*.

In addition to continuous recording, there are a number of other equipment advances which are necessary. The use of RTK GPS permits accurate positioning of the vibrator locations when sweeping and also navigation of the vibrator from one source position to the next, allowing for stakeless (i.e., no survey stakes) recording. The use of GPS timing on both the recording systems and the vibrator control electronics permit accurate time synchronization to allow the data to be recovered correctly. In modern vibrator control electronics (e.g., Sercel VE464) adaptation of technology originally used for telecommunications has now provided the capability of using up to 32 fleets of vibrators on a single radio channel, again improving the speed of the seismic recording operations.

The combination of many of these changes when recording high productivity vibroseis surveys has led to the data acquisition paradigm shift from *good quality field records recorded with line discipline* to *lots of poorer quality records*. This is a major change for observers in the field. Many observers learned their jobs when good quality records were expected and crews were frequently shut down for excessive noise on the recording spread. Today, with many of these acquisition methodologies the data are recorded without any vibroseis correlation or processing and the traditional field record may not be available in the recording truck. Alternatively, just a limited sample of correlated records may be available for quality control. With tens or even hundreds of thousands of live recording channels, it is impossible for an observer to verify that every trace is within specifications. Therefore, the system itself has to be capable of checking specifications and notifying the observer if anything is not functioning correctly.

Finally, if normal shot records are not available for every shot, the quality control paradigm shifts from *QC every trace of every shot* to *do we need any QC at all*?

Conclusions

During the early days of 3D recording a number of best practices were developed and later became established as 'fundamentals' of survey design or acquisition paradigms. In recent years, the industry has been able to take advantage of major improvements in seismic recording instruments and other related equipment. These improvements have enabled geophysicists to discover many innovative ways to utilize modern recording systems. As a result, our paradigms have shifted in ways that most people would not have envisaged a few years ago. Technology will continue to improve and geophysicists will continue to innovate. We can therefore expect to see similar paradigm shifts in the future.

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