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High performance Vibroseis for high density wide azimuth land acquisition

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Summary

Conventional 3D seismic surveys have been poorly sampled resulting in noisy images. The advents of high channel technology and acquisition techniques enabling an economical dense sampling have lead to a true 3D design for "super crew" wide azimuth surveys. The improvements in productivity are reflected on tremendous improvements in imaging complex structures.

Introduction

3D land seismic surveys have generally been limited to sparse survey geometries for both technical and economic reasons. As a consequence land data can be poorly-sampled and noisy. Combine this with the other challenges of the onshore environment and it is no surprise that image quality is poor compared to marine seismic. This is despite the fact that land acquisition has generally used wide-azimuth geometries, something which marine seismic has only recently benefited from.

To be more precise we have been forced to use sparse source and receiver grids designed for adequate sampling of signal *only*. This means we are regularly recording aliased coherent noise (such as ground roll) which limits the value of the data for processing. Often the primaries at near offsets are damaged during attempts to attenuate the ground roll. Mid-to-far offsets may also be affected by aliased high-velocity coherent noise such as guided waves, rendering them useless for velocity analysis and imaging.

With the advent of high-channel count recording systems one of the major hurdles for increasing spatial sampling density has been overcome. We are able to deploy either dense receiver spreads with small group intervals and compact arrays or point receivers. This allows to record un-aliased signal *and* noise and therefore do a much better job with noise attenuation during processing. We can then reap the full benefits of long offsets and wide azimuths for processing and imaging.

We need to match this increase in receiver density on the source side. To accomplish this we need a significant increase in source effort whilst decreasing the source array size. With the development of high-performance vibroseis techniques there is an answer, albeit for surveys in terrain appropriate for vibrator trucks. After the introduction of slip-sweep acquisition by PDO (Rozemond, 1996) we saw this as the first real opportunity to improve vibroseis source effort. As a consequence we looked at refining the technique to optimise productivity and developed HPVA High Productivity Vibroseis Acquisition (Meunier et al, 2002).

Slip-sweep acquisition is simply described as starting to sweep at the next VP (vibroseis source point) before the sweep has finished at the current VP. This decreases the cycle-time for recording a shot and increases production rates. However, the shorter the slip-time (waiting time from the start of one sweep to the start of the next), the greater the chance of contamination by harmonic noise.

HPVA is a patented deterministic noise attenuation technique which removes the harmonic noise created by using short slip-times. It therefore allows multiple fleets of vibrators to operate with short slip-times without compromising data quality. As a result, seismic crews could achieve production rates of over 300 VP/hr whilst typical flip-flop production rates were only 150 VP/hr.

High performance vibroseis for high density wide azimuth land acquisition

Slip-sweep and HPVA gave an indication of how vibroseis acquisition could be made more efficient and provided an initial boost to productivity. The next step was to consider the reduction of the source array size.

Vibrator trucks are big. A source array made up of a fleet of 4 or more vibrators is *very* big and will cover something like 25 x 10m. If you are trying to achieve a dense shot grid the physical size of the source array is an obstacle. The obvious answer is to reduce the number of vibrators in the fleet. This gives a larger number of smaller fleets of vibrators which can cover a dense grid of shot-points much more efficiently using slip-sweep techniques.

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In fact the fleet was reduced to a single unit and introduced V1 single vibrator acquisition (Meunier et al, 2007). This provided the next step-change in source productivity, with crews in the Middle East recording up to of 600VP/hr, twice from previous methods.

With production rates of this magnitude V1 opens the way to high-density wide-azimuth acquisition. This brings the benefit of improving image quality via better illumination, better multiple suppression and better azimuthal amplitude and velocity information. The most noticeable improvement is the reduction in the acquisition footprint which is actually proportional to source and receiver line interval (Bianchi et al, 2009) and commonly plagues surveys with sparse geometry.

In implementing V1 acquisition, important technical and operational hurdles were overcome.

Firstly there is the issue of source power and signal amplitude. The reduction in the number of vibrators per fleet can be compensated by increasing the sweep length of the single vibrator, and by increasing the density of the shot points. For a given bin size, the increase in shot density will increase the fold of the recorded dataset giving greater stacking power (and hence signal amplitude) during the processing.

Secondly, with the deployment of a large number of vibrator sources, a robust and efficient operation is the key to success. To ensure this tight schedule can be met, a new concept in vibrator fleet management has been introduced. The vibrators are now automatically allocated slots in a shooting schedule and move independently on their designated shot lines. If a vibrator falls behind and misses its slot, it waits for the next available slot. As the vibrators are all operating independently, this will not slow the progress of the others.
There is also the flexibility with this system to quickly modify the shooting schedule and redeploy the individual units. This could be done to cover for a source failure or add additional effort on source lines with more difficult terrain where transit times from shot point to shot point are longer. This is illustrated by the sequence of production snapshots in Figure 1

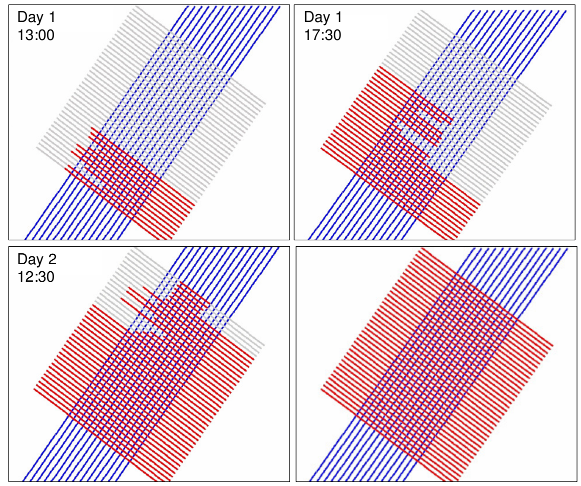

Figure 1: sequence of production snapshot

The final challenge is recording the dataset. With long sweeps, short slip-times and multiple sources firing on an intensive schedule, a continuous stream of data flows from the receivers which forms the raw "mother records" illustrated in Figure 2. The data is therefore recorded continuously along with accurately synchronised source information and shooting "time-stamps". Due to the short slip times used in V1 acquisition the data is highly affected by harmonic noise. Figure 2 also illustrates how HPVA processing is applied to the data to attenuate this noise.

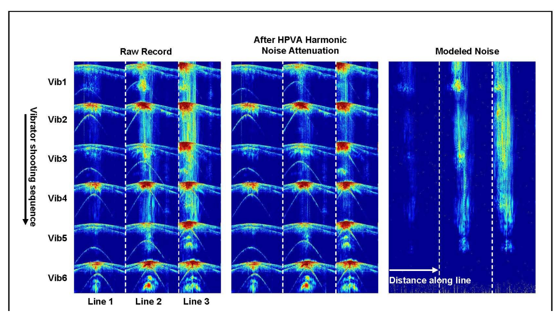

Figure 2: continuous recording mother record after correlation

In geophysical terms the point-source single vibrator eliminates undesirable source array side-effects such as intra-array statics and residual normal-moveout across the array, both of which can attenuate the signal. This makes V1 ideal for high-resolution imaging, with high-fold or smaller CMP bin size.

Single-vibrator operations decrease the footprint of the source array, reducing environmental impact. This is particularly important in sensitive areas such as Arctic tundra. Depending on the local environmental regime, a strategy that uses dense shot lines or sparse shot lines can be adopted, both of which benefit from V1 operations. The dense shot-line strategy would use a single vibrator on each line, reducing tire damage per line and effectively diluting the environmental impact more evenly over the survey area. For sparse shot lines, fleets of single vibrators can roll along acquiring sets of dense shot points. The result is more data acquired more quickly and with the same impact as conventional operations.

Figure 3 provides an example of the reduced acquisition footprint achievable through denser spatial sampling (Bianchi et al, 2009).

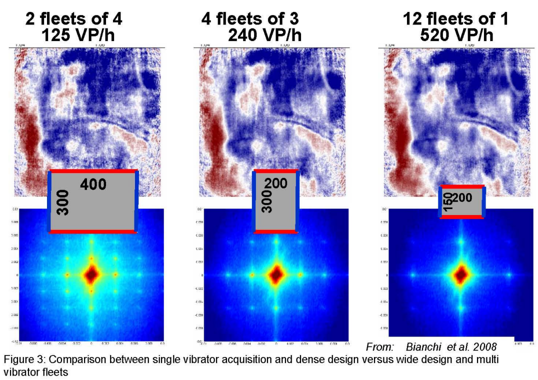

Figure 3: Comparison of acquisition footprint versus spatial sampling density

CGGVeritas is at the forefront of high-density land acquisition, combining high-channel counts and high-performance vibroseis techniques on two "Super-crews" currently in operation in the Middle East. These crews are setting new production records and new standards in many aspects of operations.

Land	**Reference 3D**	**WAZ 1**	**WAZ 2 Single sensor**
Receiver interval	50 m	25 m	7.5 m
VP interval	50 m	50 m	7.5 m
Bin size (m2)	**25*25**	**12.5*12.5**	**3.75*3.75**
Receiver line interval	250 m	200 m	120 m
VP line interval	200 m	50 m	90 m
# lines	16	20	36
Aspect Ratio	**0.3**	**0.8**	**0.83**
# of channels / VP	**4000**	**8000**	**24192**
Fold	**250**	**1000**	**504**
Million traces per km2	**0.4**	**6.4**	**35.8 / 2.2**

Figure 4: Comparison of some figures for a conventional 3D crew and two "super crews"

The crews use dense source grids with compact receiver arrays (crew 1 operating with 25,000 channels), or dense spreads of point receivers (crew 2 operating with 40,000 channels) to achieve dense wavefield sampling. The density of these new generation land datasets can be up to 100 times that of conventional surveys, and for reference, about 10 times that of current marine wide-azimuth surveys.

The volume of data acquired can be in excess of 2 TB per day and is a challenge in itself. It tests the limits of current recording systems and require substantial in-field computing infrastructure to perform QC and in-field processing.

All this effort is worthwhile. With a properly sampled seismic wavefield (including signal and coherent noise) the full benefits of wide-azimuth acquisition can be realized through the latest WAZ land processing:

> Improved noise & multiple attenuation with true 3D WAZ algorithms
> High-resolution velocities and statics for improved imaging
> Azimuthal velocity analysis for improved imaging
> Wide-azimuth illumination of targets for improved imaging
> High quality pre-stack information for reservoir and fracture characterisation

Case study of one high density wide azimuth "super crew"

Conventional seismic surveys in the Middle East have typically been unable to accurately and reliably delineate carbonates in salt formation. The density of the sampling in these surveys has been insufficient to adequately sample the noise and signal, so that aggressive noise attenuation approaches have been required. These surveys have also been relatively narrow azimuth, resulting in poor cross-line noise attenuation and illumination problems.

A 'New Generation Seismic' initiative was designed to make a step change in the density of seismic acquisition by recording well sampled wide-azimuth data in a cost effective manner with the objective of dramatically improving the quality of seismic imaging (Sambell *et al.*, 2009). The application of true WAZ algorithms to data with much better sampling should significantly improve the noise and multiples attenuation. The more uniform illumination from the WAZ acquisition geometry should result in a more accurate velocity model and improved imaging.

This high-density crew in Middle East enabled a true land WAZ survey to be acquired with an inline offset of 5km, a cross-line offset of 4km and a fold above 2000 assuming a bin size of 25m by 25m. This can be compared to conventional narrow azimuth surveys in the region that typically employed narrow geometries with four receiver lines and a 50m inline receiver station, giving a fold of around 100.

The processing of such a high-density, wide-azimuth survey presented a range of challenges and opportunities. The wide-azimuth nature of the acquisition meant that all domains, including common-shot, common-receiver, cross-spread and CMP, were all truly 3D and the sheer size of the data volume, which was more than 140Tb, presented a major challenge.

Key elements of the WAZ processing sequence included WAZ ground roll attenuation (Le Meur *et al.*, 2008) and 3D Radon demultiple (Hugonnet *et al.*, 2008). Usually salt structure presents dips which results in azimuthal variation in the velocity (i.e., dip-moveout related) even if there is no anisotropy present. Because of this, an azimuthally varying velocity field was required during the pre-processing for applications such as residual statics and 3D Radon, as well as to generate QC stacks.

The processing sequence is illustrated in Figure 5 which shows a CMP gather at various stages of the pre-processing. Although the raw input data is significantly contaminated by ground-roll, guided-waves and multiples, it can be seen that the coherent noise is well sampled by the high-density acquisition and can be very effectively attenuated. After the noise has been attenuated, some of the primary reflections show an obvious 'jitter' which is a result of the (pre-imaging) azimuthal velocity variations mixed together in a CMP ordered by absolute offset. Applying an azimuthally varying moveout correction effectively removes this distortion on the primary data prior to residual statics and Radon demultiple.

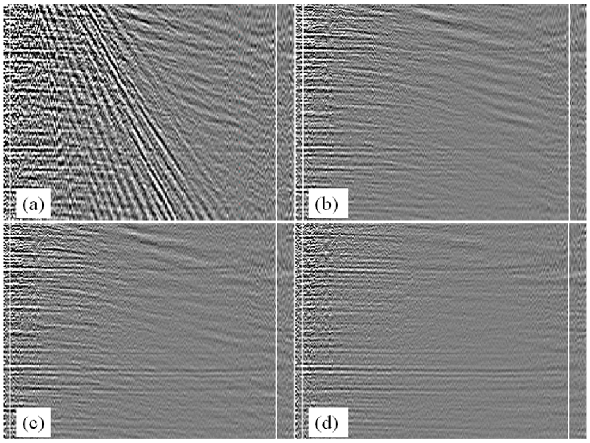

Figure 5: 3D CMP gather (sorted by absolute offset) illustrating the processing sequence. (a) Raw,
(b) ground-roll attenuation, (c) azimuthal velocity correction and (d) 3D Radon de-multiple. (Wombell et al, 2009)

The combination of the new high-density wide-azimuth data and the use of true wide-azimuth processing algorithms that fully honour and exploit this data, results in substantially improved imaging.

Conclusions

Wide azimuth combined with high density of receivers and sources have been successfully implemented on Middle East "super crews". These high-density wide-azimuth land seismic surveys have been a combined effort of both acquisition and processing. Land 'super-crews' have yielded substantial improvements in productivity that enabled such surveys to be acquired in a cost effective manner. A range of true wide-azimuth processing algorithms that are able to exploit such well sampled data have produced significantly improved seismic imaging. It is likely that there will be continuing improvement in both acquisition and processing during the coming years.

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