Introduction

Source generated noise is one of the major limitation of land seismic data quality. Despite improvements in 3D noise attenuation routines, and efforts made to record un-aliased seismic data, residual noise always manages to leak through the filter because it shows low velocity discrimination with primaries (intra bed multiples) or because its nature is too chaotic (diffracted ground-roll). The presence of acquisition footprints in the final section proves our poor ability in source noise attenuation. The relationship between attenuation of this residual noise and spatial sampling will be analysed in the first section. The second section will propose a way to reduce the level of this residual noise through dense surface sampling while keeping acquisition time and cost under control in Vibroseis operations. The third section will show experimental results.

Source Noise attenuation

One of the major issues in land processing is the attenuation of source-generated noise. Because the discrimination between signal and noise is based on differential move-out, it must be carried out in a domain where the source-receiver distance is well sampled. For orthogonal geometries the most suitable domain is the cross-spread domain where the sampling intervals are equal to source and receiver intervals. There are two limitations that affect the efficiency of the attenuation. The first is aliasing of the lowest velocity noises; it can be overcome by using group interval and arrays adapted to the smallest noise wavelength. The second limitation is insufficient differential move-out between noise and signal: internal multiples, refracted waves, and apexes of diffracted surface waves. (Vermeer 2008) can hardly be attenuated without affecting the signal. The stack can be seen as a 2-D noise attenuation filter. The distances between array elements are twice the source and receiver line intervals. The response of such a filter is seen on figure 1(a) where 1 is represented in red and 0 in blue. Signal is concentrated around the peak at the \{Kx Ky\} origin. The other peaks will let noise leak at their Kx, Ky wave number. To reduce noise leakage through the stack operator, due to aliasing, the spacing between the peaks must be increased. This corresponds to a reduction in source and receiver line intervals.

Pre and post stack migrations are also efficient filters for source noise attenuation, especially for long wavelength noises that were not attenuated in the cross-spread domain, as stated above. Such an effect is shown in figure 1(b) and(c). Signal is focused around K=0 whereas noise leakage decreases when wave numbers increase. From a noise point of view, migration is close to a space and time variant F-K filter which mutes K > F/C*sin(θ) where C is the migration velocity and θ is the maximum dip. The above stack filter response is only valid for radial noise propagating directly from source to receiver and thus cannot be extended to backscattered ground roll. The apex location of the diffraction hyperbolas generated by a point scatter depends on the positions of the cross spread center relative to
the scatter point. Consequently the apex amplitude will be reduced by the stack, which is the sum of overlapping cross-spreads. To illustrate this point, 3 geometries with different line spacing were used to generate synthetics cubes of one surface scatter (see figure 2). The GR velocity is 1000 m/s with a dominant frequency of 10Hz. These synthetics show that the apexes of the diffracted Ground Roll faint when line intervals decrease and that the combination of stack with 3D FK efficiently attenuates back scattered ground roll. In addition, shorter distances between lines lead to less geometry discontinuities in the common offset vector tiles, better image gathers and better velocity determination.

![Figure 2: Stack of a ground roll surface scatter with different line intervals](image)

**Single vibrator acquisition**

Unlike the receiver array, the source array geometry is more determined by operational constraints (essentially the minimum distance between vibrators for safe operations), than by geophysical constraints. We propose to use single vibrators operating in slip sweep mode combined with areal receiver arrays for adequate anti alias protection. This solution has numerous advantages, among them, isotropic source, full signal preservation, improved maneuverability and access in rough terrain compared to multi-vibrator fleets.

The resulting loss in source power is compensated by the increased fold and by a longer sweep. In order to keep survey cost reasonable, simultaneous vibroseis technique must be used. The slip sweep method because of its high flexibility, with all vibrator groups being fully independent, and its simplicity is preferred to other simultaneous techniques. With single vibrator slip sweep, harmonic noise and penetration are serious problems to be taken into account. Harmonic noise reduction was indeed proposed by Meunier & Bianchi (2002). Concerning penetration, the same authors (2005) showed that the desired signal to ambient noise ratio could be achieved in slip sweep operations by adjusting the number of source groups to combine adequate sweep length and optimum productivity. Single vibrator slip-sweep operations with minimum slip time typically lead to a 4-fold increase in SP productivity relative to conventional flip-flop operations. This gain can be used to increase SP density

**Single vibrator experiment**

An experiment was conducted on a seismic crew operating in Egypt. The crew recorded 14 lines of 140 stations, with a 50-m group interval, and a 200-m receiver line interval. Orthogonal shooting was used with 5.6-km source lines. The SP interval was 25-m and the source-line interval 300-m. The resulting fold was 163. The crew operated with 4 fleets of 3 vibrators in Slip Sweep mode with a 16 s sweep length and a 10 s slip time, achieving a productivity of 327 VPs or 1.23 km² per hour. The
A single vibrator test consisted in re-shooting part of the survey with 12 fleets of single vibrators using the same 25-m SP interval, a shorter, 150-m source-line interval and a longer sweep of 42 seconds. This led to a division by 3 of the source force, a multiplication by 2 of the source density, and a multiplication by 2.6 of the sweep length. According to the square root law, the signal to ambient noise ratio was degraded by 2.3 dB but we felt that in this area ambient noise is dominated by source-generated noise.

The duration of the test was 23.5 hours over 3 days. The productivity was 678 VP/h (1.27 km²) during the first 2 days. The third day productivity was lower due to external (line) problems.

Data processing was fairly straightforward with no other specific process than CGGVeritas HPVA (High-Productivity Vibroseis Acquisition) proprietary harmonic noise reduction. This process consists in harmonic noise estimation using the recorded force and in its subsequent subtraction from the data. The other processing parameters were borrowed from the standards production processing for this area.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>N vibrator / SP</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>RL interval</td>
<td>400</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>SL interval</td>
<td>300</td>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>Fold</td>
<td>82</td>
<td>163</td>
<td>327</td>
</tr>
<tr>
<td>S/Ambient Noise</td>
<td>-3 db</td>
<td>0 dB</td>
<td>-2.3 dB</td>
</tr>
</tbody>
</table>

Table 1

3 datasets (A, B and C) could be compared. B is the production dataset, C is the single vibrator dataset and A is the production dataset where every other receiver line is kept. Table 1 summarizes the main differences between these 3 acquisitions design. Dataset A could be acquired in flip-flop mode in the same amount of time as datasets B and C. Previous experience suggests that dataset A would be very similar to a flip-flop acquisition, whereas it was acquired in slip-sweep mode.

As a result of better noise cancellation during stack and migration processes, vertical sections show better spatial continuity (figure 3) and time-slices less footprints (figure 4), when SP and RP densities increase. To better illustrate the correlation between geometry and the noise cancellation, Kx-Ky transform of the migrated time slices were computed and averaged. Because the geology is mainly flat, almost all the signal is concentrated around K=0, in the Kx, Ky plane and looks similar for the 3 datasets. The noise energy is precisely located at the points where the theoretical stack response exhibits no attenuation. The presence of this residual noise is reduced from A to C as the stack response leakage is pushed towards higher wave numbers where the attenuation provided by migration is higher.
Conclusions

It is commonly accepted that to improve seismic image quality, the acquisition requirements are to reduce the sampling interval, to acquire wide azimuth data and to reduce source and receiver line intervals. The third requirement has been relatively neglected, probably because of excessive confidence in our ability to attenuate organized noise and also because of its great influence on survey cost. As shown by the above example, residual noise is often found on real data at wave numbers precisely predicted by the acquisition geometry template. Until our processing techniques can perfectly separate primary reflections from multiple and from ground roll, we know only one way of reducing this residual noise: reduce source and/or receiver line intervals. Single vibrator acquisition associated to the slip sweep technique and harmonic noise attenuation can be an efficient tool to acquire dense source grids under cost and time constraints.

References