Cost-Effective, High-Density Vibroseis Acquisition
Julien MEUNIER* & Thomas BIANCHI,
Compagnie Générale de Géophysique, 1, rue Léon Migaux 91341 Massy France

Summary
For a wide range of reasons, such as illumination, surface multiple and surface noise reduction, increases in source and receiver density are required in land seismic operations. This increase must be combined with a reduction in the array size. From an operational point of view, an increase in receiver density requires extra investment and extra labor, and may not affect productivity. An increase in source density will affect productivity. From a technical point of view, a significant increase in source density is necessary to balance the associated reduction in array size. The slip sweep technique is an attractive way of optimizing productivity to a level, which can keep the cost of increasing source density within reasonable limits. Refinements in harmonic noise reduction make it possible to take full advantage of its possibilities.

Introduction
In September 2004, at the EAGE research workshop in Rhodes, M. Manin (1) listed the merits of isotropic wavefield sampling in the receiver and shot-point domains which he named 3D² (figure 1): Full target illumination, 3D surface multiple attenuation, wave-equation imaging, 3D surface scattered noise attenuation, optimal recovery of emitted energy to name but a few.

At the same time, typical land seismic acquisition deploys between 1200 and 4000 channels with 50 to 400 source and receiver stations per km² corresponding to station intervals of between 25 and 50m and to line intervals of between 100 and 400m. There is still a long way to go to achieve 3D². Yet the ability of the latest generation of seismic recorders to handle several tens of thousands of channels is a good start. Among the many obstacles in the way, survey cost is certainly not the smallest. To overcome this obstacle we have to design solutions, which must not jeopardize the expected gain in data quality. This paper presents and discusses some possible solutions concerning the Vibroseis source.

Economic issues
The simplest cost model for land seismic acquisition can be expressed in terms of fixed costs and variable cost in the following way:

\[ K_s = (F_s + F_g + F_r + F_m) / \text{Prod} + V_s *d_s + V_r *d_r \]

Where \( K_s \) is the cost per km². Fixed costs are essentially equipment (source, receivers, recorder and miscellaneous) costs; they are expressed per unit of time (in $/month) and their weight is divided by productivity expressed in km²/month. Variable costs are essentially labor costs to deploy a receiver, to prepare and shoot a shot point or to operate a vibrator. They are expressed per sensor \( V_s \) or per SP \( V_r \) and their weight is multiplied by source or receiver density. In this formula, productivity plays a key role: it influences all fixed costs whether linked to sources or receivers.

With everything else unchanged, an increase in either source or receiver density will directly affect variable cost. It will also affect fixed costs: more receivers, more drilling equipment, more vibrators and more recording channels. And finally it will most often hamper productivity. There is a major difference between the effect of source and receiver density: for a very wide range of seismic parameters, it is theoretically possible to adapt the receiver deployment work force to any productivity. But it is more difficult to reduce the time interval between two consecutive SPs, which, in any event, must remain longer than the listening time. If LT is the listening time and WT the monthly working time, the maximum theoretical productivity (corresponding to a zero dead time) is:

\[ \text{Prod}_{\text{max}} = \frac{\text{WT}}{\text{LT} * \text{ds}} \]

With 300 working hours per month, for a 5-s listening time, a 1000 SP/km² density limits the productivity at 216 km²/month. A conventional Vibroseis crew operating 2
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fleets of 3 vibrators in flip-flop mode with a 12 s sweep typically records one VP every 20 to 30 s and can therefore only reach 1/4th to 1/6th of this productivity; we see that the possible improvement is very significant.

The simplest way of reducing costs is to group receivers and sources in arrays. Grouping sensors leads to a reduction in the number of expensive recording channels; grouping shallow holes leads to a reduction in drilling costs relative to a single deep hole; grouping vibrators leads to a reduction in the number of SPs and hence in recording time. Despite their various disadvantages, in particular signal attenuation due to intra array statics and residual NMO\(^2\), arrays have been widely accepted until now. The reason for this acceptance is that dense sampling is needed for noise attenuation rather than for adequate signal sampling. All the array disadvantages are reduced and eventually disappear as their size decreases. Consequently, we must expect SP density to increase while the size of the source array decreases. This will have a major effect on noise reduction.

Ambient noise

The cost structure is not the only dissymmetry between sources and receivers. The square root theory states that in an ideal sum, signal amplitude is proportional to the number of terms and (random) noise amplitude proportional to its square root. Since ambient noise is independent from the source, signal-to-noise ratio is proportional to the number of elements in the source array and to the square root of the number of elements in the receiver array.

Consequently, the reduction in size of the source arrays poses a much greater potential threat to data quality than a reduction in receiver array size. It would take a massive increase in source density to overcome this threat (see figure 2). This would lead to a very significant increase in the survey cost.

Source-generated noise

It was shown \(^3\) that simple linear field arrays made radial noise de-aliased in the cross-spread domain. When ground roll is purely radial, 3D velocity filtering in this domain is an efficient way to separate signal from noise. However, if this is not the case, i.e. when ground roll is backscattered by surface heterogeneities, velocity filtering needs to be applied in the 3D SP domain or in the 3D receiver domain \(^4\). This property may very well be the most convincing advantage of an increase in source density. This advantage can be seen in figure 3: filtering in the 3D receiver domain (using a dense SP grid) has significantly weakened the apexes of the diffraction hyperbolae.

Slip Sweep: a possible solution for the Vibroseis source

In Vibroseis operations, an increase in source density can be obtained economically through high order simultaneous recording techniques such as the slip sweep technique\(^5\) or phase encoding techniques\(^6\). Yet these techniques suffer from distortion, which contaminates the data in proportion to the productivity increase generated. The slip sweep technique consists in a vibrator starting a new sweep before...
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the previous one has ended. The time interval between two consecutive sweeps controls productivity. It is called the slip time. The shortest allowable slip time is the listening time. From a purely operational point of view, the optimal slip time is obtained when each vibrator either vibrates or moves. For a 25-m station interval, it may take each vibrator an average of 15 s. to move from one VP to the next. If we consider a 32-s sweep, the optimal slip time is given by the graph in figure 4. With these parameters, it would take 10 fleets to achieve the maximum productivity allowed by a 5-s listening time. This corresponds to the recording of roughly three times more SPs than our conventional crew with 2 fleets of 3 vibrators. Combined with a 3-fold increase in sweep length (from 12 to 32), it would allow the reduction of the source array from 3 to 1 vibrator without the risk of a lower signal to ambient noise ratio. However, seismic solutions cannot be considered from a purely operational point of view. We cannot ignore distortion, which, in Vibroseis operations, is most often larger than 10 to 20%. A method to reduce this contamination was introduced at the 72nd SEG convention in 2002.

Problem of harmonic distortion

When a vibrating truck generates frequency f, it also generates harmonic energy at frequency 2f, 3f, ... nf due to harmonic distortion in the vibrator mechanism and at the vibrator-earth contact point. In conventional Vibroseis operations, signals of increasing frequency ("up-sweeps") are used and the correlation process rejects harmonic energy at negative times where it cannot affect the data.

In slip-sweep operations, however, the interval between two consecutive sweeps (slip time) is too short to prevent interference between the harmonic noise and the previous record. This harmonic contamination becomes more critical when the slip time is shortened relative to the sweep length. Figure 5 shows a time-frequency map of a correlated slip-sweep record. Such a record includes several overlapping SPs. It is called a mother record. The area of harmonic noise is divided into two parts, the part that does not interfere (it lies in between shots) and the part that interferes with fundamental energy. This area of interfering energy increases, either when the sweep length increases, or the slip time decreases. An interesting feature is that when the slip time is equal to the listening time, total harmonic contamination no longer depends on the sweep length.

![Figure 4: Optimal slip time function of the number of vibrator fleets. Moving time: 15 s. Sweep time: 32 s. Listening time: 5 s.](image)

Comparative tests

We conducted comparative tests on a 3D survey recorded in slip-sweep mode with the following parameters: 32 s sweep 8-90 Hz, log 6dB, six single vibrators, six-second slip time. In this geographical area the harmonic noise is mainly due to first breaks at short offsets. Because of the very high ratio between the sweep length (32 s.) and the slip time (6 s.), the harmonic noise is spread over the four previous shot points of the mother record (Figure 6). The right-hand part of this figure represents a frequency-time map of a short offset trace after correlation. It shows the interference between harmonic noise and signal. Fundamental energy is horizontal, whereas harmonic distortion dips and bends due to the logarithmic sweep.
A method of harmonic noise reduction known as HPVA (High-Productivity Vibroseis Acquisition) has been developed based on estimation of the Vibroseis signature in order to predict the harmonic noise generated by each individual VP in order to subtract it. Results show that the level of harmonic noise has been reduced to the level of ambient noise (see figure 7).

**Conclusion**

An increase in SP density combined with a reduction in the array size will bring many advantages. In land seismic operations, scattered noise attenuation is not the least of these advantages. However, seismic costs will prevent such an increase from being accepted unless it comes with a corresponding productivity gain. In Vibroseis operations, multi-source acquisition techniques can provide this gain. We have shown that refinements in harmonic noise reduction make it possible to take full benefit of the possibilities of the slip sweep technique. Ultimately this technique can make a dense grid of single vibrator SPs compare economically with conventional vibrator arrays.

**References**