

# High productivity vibroseis techniques: a review



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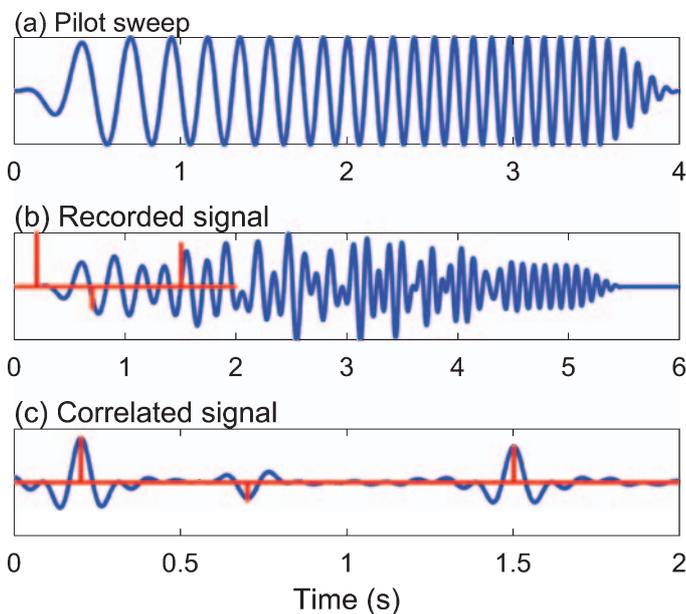
## Overview

Since their introduction in the 1950s hydraulic vibrators have become the source of choice for large land seismic surveys (the vibroseis method), used whenever the terrain will allow. A hydraulic vibrator (Figure 1) transmits energy into the ground via a baseplate held in place by the weight of the vehicle and decoupled from it by airbags. Above the baseplate a reaction-mass, typically between 3500 and 5000 kg, is hydraulically driven up and down, transmitting a signal into the earth.

The transmitted signal (the pilot sweep) typically varies monotonically, between frequencies of about 8 to 100 Hz, over a period of ~18 seconds. Figure 2 is a very simple synthetic example of vibroseis data. Figure 2a shows the pilot sweep, in this case with a limited bandwidth of 2 to 12 Hz over 4 seconds. Figure 2b shows the signal recorded (in blue) resulting from the reflectivity sequence (shown in red), each event is replaced with a copy of the pilot sweep with corresponding magnitude and polarity (i.e. the convolution of the pilot sweep and the reflectivity). Note that the record length is the sum of the pilot sweep length (4 s) and the length of the record we wish to



**Figure 1.** A hydraulic vibrator in action. The baseplate is on the ground between the two axles. The reaction-mass is the large white steel cube directly above the baseplate.



**Figure 2.** A very simple example of extracting reflectivity from a synthetic vibroseis signal using correlation.

obtain after correlation, the listen time (2 s). Figure 2c shows the data after we have correlated the recorded signal with the pilot sweep. Note that each reflectivity event has been replaced by the autocorrelation of the pilot sweep.

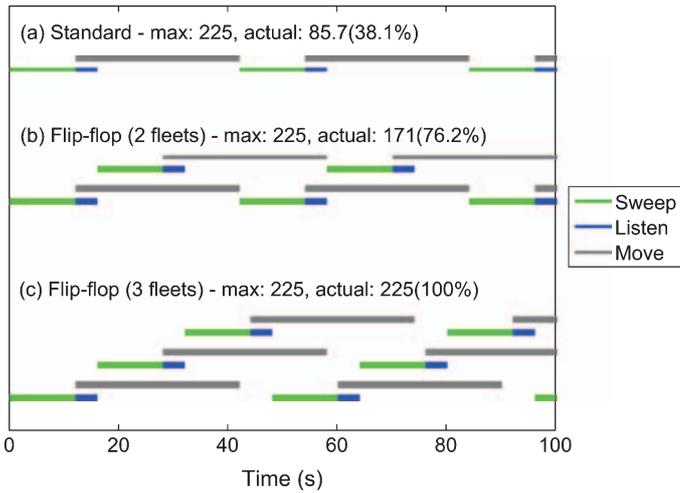
Unfortunately, despite their undoubted value, the cost of land seismic surveys is high. So a number of methods, commonly referred to as *high-productivity techniques*, have been introduced to increase their efficiency and thus reduce their cost. In this article I describe the most commonly used high-productivity techniques. Excluding those that involve phase encoding since they require additional sweeps at each source point, and are therefore not considered to be high-productivity techniques. A description of phase encoding techniques is included in Bagaini (2010).

## Standard acquisition and flip-flop

Originally, vibroseis crews utilised a single fleet of vibrators, typically comprising of between three and five units. The fleet of vibrators would sweep at a source point then move-up to the next point, sweep, move-up, etc. (Figure 3a). Although easy to manage, this is clearly an inefficient method as the recording system is idle for the majority of the time, in this case more than 60%.

An increase in the number of vibrators on crews enabled the formation of more than one fleet resulting in the introduction of the *flip-flop* method. In flip-flop acquisition fleets move-up between source points while other fleets are sweeping, reducing the dead time between records (Figure 3b). If sufficient fleets are available then we can achieve the theoretical ‘maximum productivity’ (Figure 3c). As shown below, other techniques can increase productivity even further, but flip-flop remains the most popular.

Feature

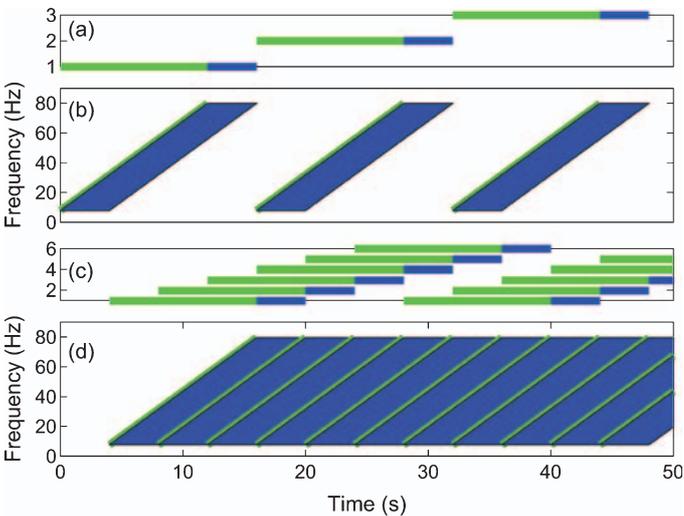


**Figure 3.** Diagrammatic representations of different vibroseis acquisition techniques. The sweep length (green) is 12 s, listen time (blue) 4 s and move-up time (grey) 30 s. The values in the headings are the maximum and actual productivities in source points per hour.

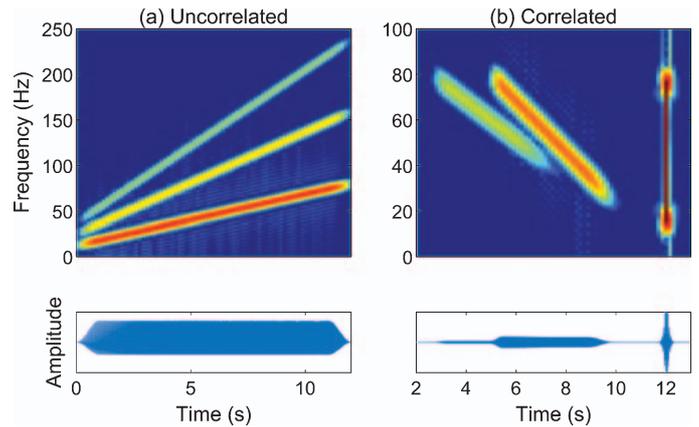
Slip-sweep

Rozemond (1996) was the first to recognise that, although the flip-flop method may appear efficient when viewed as a simple time series (Figure 4a), when viewed in the frequency-time domain there is actually considerable unused time (Figure 4b). The slip-sweep method involves overlapping the sweeps in time (Figure 4c) such that we fill more of the un-used space (Figure 4d). The *slip-time* is defined as the minimum time between the start of subsequent sweeps.

Theoretically, there should be no impact from the use of slip-sweep on data quality but unfortunately, as well as the pilot sweep that is considered signal, the vibrator also emits harmonics (Figure 5a). After correlation the fundamental is compressed to a Klauder wavelet with the harmonics appearing in *negative time* (i.e. before the event with which they are associated, Figure 5b). On real data this results in harmonics associated with the first-breaks (typically one of the strongest events) interfering with the weak events at the bottom of the previous record, if the slip-time is small enough.

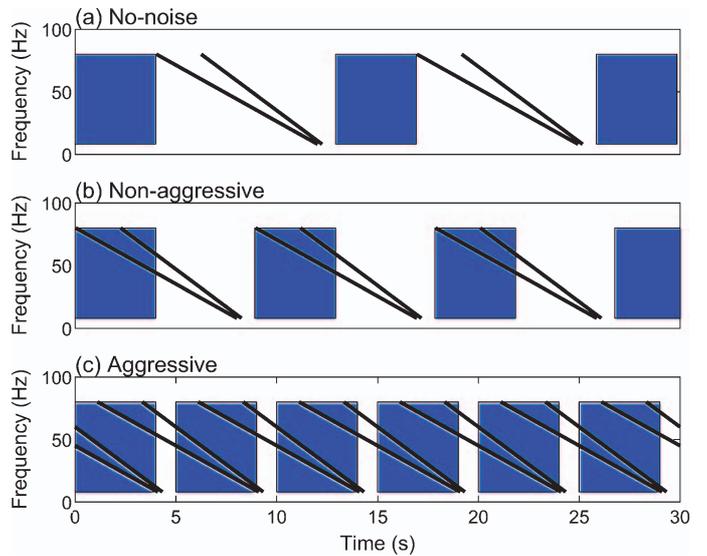


**Figure 4.** Diagrammatic representation of the slip-sweep method.



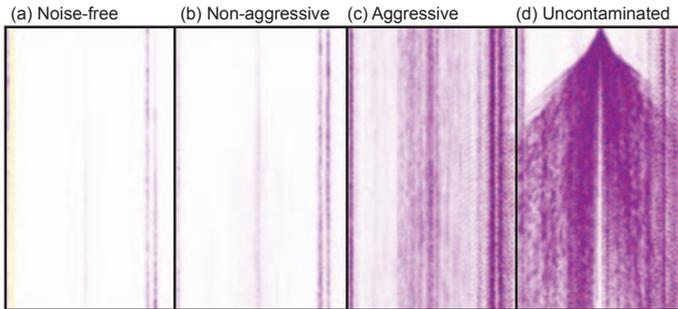
**Figure 5.** Synthetic vibroseis traces showing the fundamental (the strongest component) and two harmonics with decreasing strength before (a) and after (b) correlation. The noise train shown before the fundamental in (b) would appear at the bottom of the previous record if the slip-time allowed.

Obviously the interference can be controlled by limiting the slip-time. In practice slip-sweep acquisition can be divided into three categories depending on the slip-time chosen and the resulting level of interference (Dean et al., 2010). *Noise-free* acquisition occurs when the slip-time is such that the harmonics do not appear in the preceding record (Figure 6a), *non-aggressive* (Figure 6b), and *aggressive* (Figure 6c) slip-sweep is where the previous record is contaminated by the harmonics from a single and multiple shots respectively.



**Figure 6.** Diagrammatic representation of the three different types of slip-sweep acquisition. The blue box indicates the region of the frequency-time domain occupied by a single record (after correlation). The black lines indicate the extent of the first two harmonics. The number of black lines overlapping the blue boxes is an indication of the level of interference noise.

Figure 7 shows examples of the cross-harmonic noise resulting from the choice of slip-time along with an uncontaminated record. The noise-free record (Figure 7a) shows no sign of harmonic noise contamination (the noise seen is vehicle noise), while for the non-aggressive data (Figure 7b) the noise is noticeable but decreases up the record. The noise on the aggressive data (Figure 7c) is significant across the whole record. For limited amounts of cross-harmonic noise it often simply stacks out, if not, then various methodologies exist for removing noise, but clearly it is better not to record it in the first place.

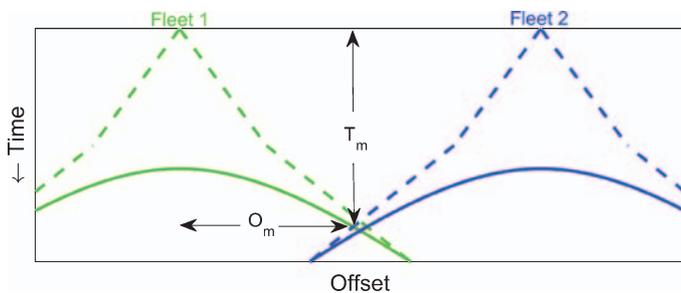


**Figure 7.** Examples of observed cross-harmonic interference noise for the different types of slip-sweep acquisition. The record length is 4 s. Adapted from Dean et al., (2010).

When introduced by Petroleum Development Oman in 1998, the slip-sweep method resulted in a doubling of productivity over the flip-flop method (Matheny et al., 2009). Nevertheless it has seen only limited adoption elsewhere. Within Oman it has since been replaced by a new, even more productive, technique described next.

### Distance separated simultaneous sweeping

Beasley (2008) recognised that, if the receiver line was long enough, shots fired at either end of the line would interfere below the reflections of interest. This idea is the foundation of the *Distance Separated Simultaneous Sweeping* (DS<sup>3</sup>) technique (Bouska 2010). The method (Figure 8) relies on the recording spread being large enough to allow the required separation between fleets, which depends on the location but is typically of the order of 10 km.



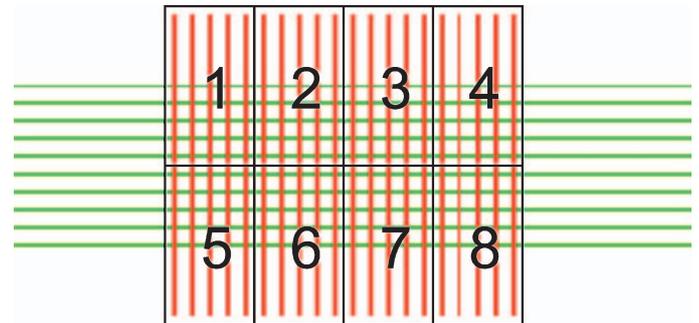
**Figure 8.** Diagram of the DS<sup>3</sup> method. The two fleets 1 (green) and 2 (blue) sweep simultaneously, producing reflections of from the horizon of interest (solid lines) that intersect with the other's noise (dashed lines) only at times and offsets greater than  $T_m$  and  $O_m$  respectively. Adapted from Bouska (2010).

Bouska (2010) reported a peak productivity of 1,024 records/hour using 15 vibrators within an  $18.5 \times 11$  km receiver patch, compared to about 1000 records/day for previous flip-flop surveys and 1700 records/day for slip-sweep. Stone and Bouska (2013) combined the DS<sup>3</sup> and slip-sweep methods, achieving productivities of up to 1060 records/hour using 24 vibrators within a  $12.6 \times 28$  km receiver patch.

### Independent simultaneous sweeping

*Independent Simultaneous Sweeping* (ISS also known as *blended acquisition*) was first introduced by Howe et al. (2008). The source points are divided into separate areas each with a fleet (usually containing a single vibrator) as shown in Figure 9. The fleets then acquire the source points independently, i.e. they

sweep whenever they are ready irrespective of what the other fleets are doing, with the acquisition system continuously recording data.



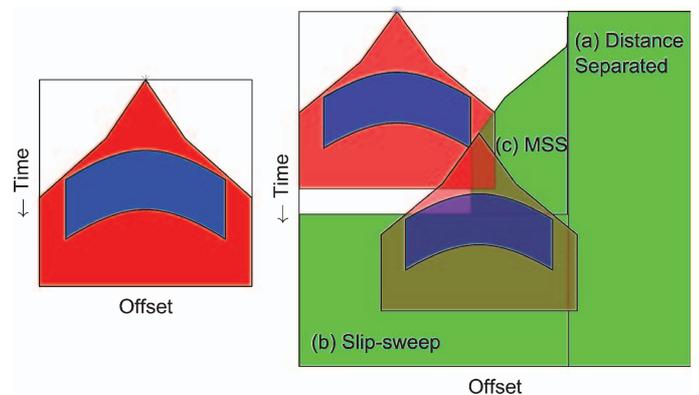
**Figure 9.** Diagram showing the configuration for an ISS survey. The source lines (in red, receiver lines in green) have been divided between eight fleets which acquire their respective source points autonomously.

Originally the fleets used sweeps with different lengths, or pseudorandom sweeps (Dean 2014), but later this approach was discarded in favour of every fleet using the same sweep, which simplified acquisition with no discernible effect on data quality (Abma et al., 2015). This technique requires the system to be recording data continuously, from which each record is then extracted. The effect of any interference between records that remains after extraction/deblending and noise removal is considered to be more than offset by improvements due to the increase in spatial sampling made possible by the efficiency (Abma et al., 2015).

In the first full ISS survey productivities of up to 1,200 source points per hour were achieved using 14 single-vibrator fleets (Howe et al., 2009). Using ISS Pecholcs et al. (2010) achieved productivities of over 45 000 source points per day using 18 single-vibrator fleets.

### Managed spread and source

*Managed Spread and Source* (MSS) effectively encompasses all the previously detailed methods via a set of acquisition 'rules'. An example of such rules is shown in Figure 10. The left panel shows a shot record where the regions of signal (shown in blue)



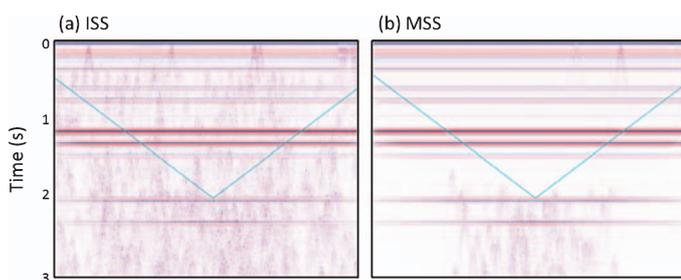
**Figure 10.** Example of some simple MSS rules. The left panels shows a single record with areas of signal and noise shown in blue and red respectively. The right panel shows the areas of the offset/time domain within which a second fleet can start sweeping in green. A second record, on the boundary of the green zone, is also shown.



## Feature

and noise (shown in red) have been defined. The right hand panel shows the resulting rules that are applied during acquisition. The signal and noise regions in the offset/time domain for a shot are shown in blue and red as before. The green regions indicate areas of the domain within which another fleet can begin sweeping without its noise zone overlapping the signal zone of the previous shot and vice versa. The area labelled as 'a' indicates a region where interference is avoided by distance separation, the area labelled as 'b' indicates an area where interference is avoided by time separation, i.e. slip-sweep. The irregularly shaped region labelled 'c' is one that can only be defined using MSS rules, the impact of a second sweep starting on the boundary of this region is included to show how the noise region from the second shot does not impact the signal region of the first.

Figure 11 shows the resulting CMP stack for synthetic data generating using ISS and MSS simulations. The MSS result is significantly less noisy than the ISS result. Some noise does leak through around 2 s but this is due to the lack of offset limits (all offsets were included in the stack rather than just those within 2,000 m). Overall the MSS data would have taken 5% longer to acquire (productivity was enhanced by queue management as detailed in Dean (2012)).



**Figure 11.** Stacks of synthetic (a) ISS and (b) MSS data. The blue line indicates the fold. Image courtesy of WesternGeco.

## Discussion

Although this article is primarily concerned with vibroseis acquisition techniques, these techniques cannot be addressed in isolation, being both enabled by, and enabling, other technologies. Techniques involving large receiver spreads (ISS/DS<sup>3</sup>/MSS) require large channel count systems, often incorporating point-receivers rather than arrays to reduce the total number of sensors that need to be deployed. Techniques where the sources act independently (ISS) require GPS timing plus an acquisition system capable of recording data continuously rather than creating discrete records. Even simpler techniques, such as slip-sweep, require the acquisition system to be able to record files with durations long enough to encompass multiple records. In-turn, high-productivity techniques have resulted in order-of-magnitude increases in productivity, enabling the acquisition of wide-azimuth surveys with dense source points and folds of more than 9,000 (Pecholcs et al., 2012).

To take full advantage of the adoption of these techniques, a change in mind-set with regards to survey planning is required. Most importantly, the additional source energy possible is better spent increasing the fold of the survey by increasing the number of source points, rather than increasing the amount of energy emitted at each source point (Bianchi et al., 2009; Matheny et al., 2009). So when comparing different acquisition plans, we

may need to balance the loss in source energy at each point due to a reduction in the number of vibrators in each fleet (the SNR is proportional to the number of vibrators and the square root of the sweep length (Dean and Tulett 2014)) against the number of extra source points made possible. Even the productivity of more traditional surveys can be improved through the use of slip-sweep, often without any detrimental effect on data quality.

The acquisition method chosen is always a trade-off between productivity and interference. The less restrictions applied to when the vibrators can sweep results in the highest productivity, but unfortunately, also results in the most interference. Nevertheless, the resulting increase in source density may more than compensate for the individually noisy shot records. Perhaps the key point is that the choice of acquisition method needs to be part of the survey design process, and not merely an afterthought, so that such trade-offs can be properly evaluated.

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