Mastering the highest Vibroseis productivity while preserving seismic data quality

Nicolas Tellier[1*], Gilles Ollivrin[1], Stéphane Laroche[1] and Christophe Donval[1] introduce a novel Ultra High-Productivity acquisition technique that enables operators to get close to the maximum theoretical productivity of vibrators while addressing the limitations of the most advanced acquisition methodologies currently in use.

Abstract

Increasing the productivity of seismic acquisition projects has been a key goal for contractors and operators for decades now. It remains topical, mainly in respect of efforts to increase a given project's trace density for a cost in line with the resulting reservoir quality uplift.

The Middle East and North Africa have traditionally pioneered the development and introduction of advanced productivity techniques, given the presence of large hydrocarbon deposits located beneath open terrain with limited anthropogenic activity. After the successful introduction of several high-productivity methods in the region, two of them – DS4 and Unconstrained Vibrators – have won recognition and are now standard on most projects. While the level of productivity these methods enable is unprecedented, they still show some scope for improvement: the productivity of DS4 is not the highest achievable, whereas the aggressive blending associated with unconstrained vibrators acquisitions can affect the overall imaging quality.

In this paper, we introduce a new high-productivity methodology, at the confluence of the two aforementioned methods while addressing their limitations. xDSS makes it possible to reach the ultra-high productivity enabled by unconstrained vibrators, while preserving the blended acquisition golden rules 'randomness in time and space' and 'sparseness in the frequency – wavenumber domain'. The automated observance of these two rules makes it possible to get as close as possible to the maximum achievable source productivity, while delivering to the processors a deblending-friendly dataset.

Introduction: productivity in Vibroseis operations

Increasing the productivity of seismic operations exists in tandem with the industry expectation for higher trace densities (more ray paths illuminating a given area of the subsurface), referred to by various authors as one of the key metrics (together with signal bandwidth and azimuthal/offset distribution) to assess the quality of an acquisition and the subsequent ability to adequately image the subsurface and characterize reservoirs (e.g. Ourabah 2015 and Michou 2017).

Single fleet operation was the norm until the introduction of Flip-Flop in 1991 (two or more fleets operating time sequentially). In an effort to have seismic acquisition systems recording data continuously (with zero dead time), Slip Sweep was then introduced (Rozemond, 1996). With this technique, vibrators are allowed to start to sweep even before others have completed their own vibration. The inter-record harmonic contamination, and thus the minimum slip time constraint associated with Slip Sweep was addressed first with HPVA (Meunier 2002), with other approaches developed in the following years. The productivity of Slip Sweep was pushed further with the V1 shooting strategy (Postel, 2008), where a large number of single vibrators shoot long sweeps with an aggressive slip time. In the HFVS methodology (Krohn 2006), several nearby vibrators repeat simultaneous sweeps with phase encoding, making this high-productivity technique not the most productive, but focused on the preservation of data quality.

While the methods listed above have enjoyed varied degrees of success in the years that followed their introduction, two shooting methodologies, DS4 and unconstrained vibrators, have increasingly won recognition to the point where they are now the

Acquisition Methodology	VP/Day for all fleets (Max observed)	Number of fleets	VP/Day/Fleet (Max observed)
Unconstrained vibrator	45000	35	1300
DS4 (standard D/T rule)	30000	24	1250
DS3	15000	20	750
V1	15000	20	750
Slip-Sweep	6000	10	600

Table 1 Principal high-productivity methodologies: maximum observed production numbers (rounded). The sweeps in use for the different methodologies had a duration around 12 s (except for V1). Note that actual achievable productivity is in reality highly dependent on numerous parameters (sweep length, number of vibrators, shot point spacing, D/T rule, allowed shooting hours per day, etc.)

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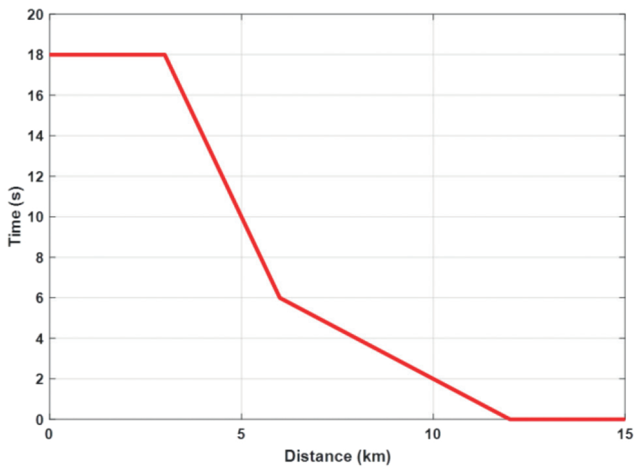


Figure 1 A typical distance-time rule from the Middle East: vibrators are not allowed to sweep below the red curve, i.e., if they operate too close to the spatiotemporal vicinity. In this example, an 18 s slip time has to be observed below a 3 km source spacing, slip time is progressively reduced until a 12-km source spacing is reached and beyond which simultaneous sweeping is allowed.

standard on most Middle East and North African projects. Table 1 provides a summary of the observed, maximum productivity achieved for the most common high-productivity methodologies.

DS3 (Distance Separated Simultaneous Sweeping) was introduced in 2010 (Bouska 2010). With this technique, two or more fleets shake the same sweep simultaneously, provided that they are separated by a minimum, large distance (about twice the target depth) in order to avoid inter-shot contamination. The survey area is then populated with at least two groups of vibrators that respect the minimum distance selected. Sources within a given group operate either in flip-flop, or slip sweep with a fixed slip time. The DS3 method described by Bouska has, however, rapidly evolved into 'DS4'. Though no clear definition can be found in the literature, it commonly stands for 'Distance Separated Simultaneous Slip Sweep' and refers to the DS3 method enhanced by several features. First, Slip Sweep is allowed even when the minimum distance between groups is not observed. Second, the slip time is dynamic, i.e. it is increased as sources get closer. It led to the definition of Distance/Time rules (D/T rules), a key element of DS4 surveys that set the compromise between productivity and inter-record contamination. Finally, groups of vibrators are no more predefined, but dynamic according to their readiness to operate.

In terms of seismic data, for acquisition systems capable of supporting the methodology one record per fleet is generated, with the corresponding fleet location and associated active channels. DS4 surveys require standard processing, with advanced denoising in particular for the removal of the Slip Sweep cross shot harmonic noise contamination. The achievable productivity is dependent on numerous factors (terrain, D/T rule, number of vibrator fleets, etc.). With the standard Middle East D/T rule (Figure 1) and 24 fleets of vibrators, a maximum of around 30,000 VP a day can be observed.

The unconstrained vibrators acquisition strategy differs from the other methods. Autonomous and independent vibrator fleets operate freely within the survey, starting vibration as soon as they have reached a pre-plot position. No central control is required to monitor the operation, and sweeps being started manually by vibrator drivers remove the dependency on radio communication, which is then only required to monitor the vibration points status. Consequently, this approach removes the waiting time associated with vibrators, an additional benefit is that the process of adding or removing a vibrator from operation has no impact on production. This method can be employed in any terrain, including rugged or complex areas with restricted source manoeuvrability or with poor radio communication. As any number of vibrators can be deployed, the crew productivity is proportional to the quantity of fleets in operation, contrary to DS3/DS4 techniques that tend to reach a plateau owing to the D/T law requirement and their dependency on radio communications. In terms of seismic data, the raw data is highly contaminated by neighbouring shots. An efficient deblending scheme as an initial step in processing is then mandatory (Figure 2), this is no longer a significant issue as processing companies have greatly improved their algorithms in recent years, mainly driven by marine acquisition where blended acquisition is the norm.

This advanced methodology was introduced first by BP (Howe 2008) as Independent Simultaneous Sweeping (ISS). In addition to the above-mentioned considerations, the authors describe two additional key features. First, the use of sweeps of different length for each vibrator fleet. This sweep encoding aims to better facilitate the data deblending. Second, a division of the shooting area into sectors of different size according to accessibility, each sector being shot by a single fleet. This sectorization is intended to avoid sources operating with insufficient

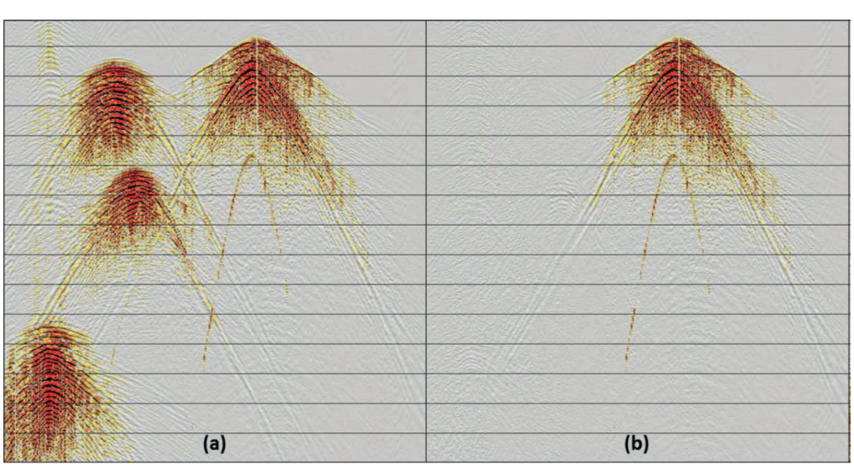


Figure 2 An example of blended shots: a) before deblending, b) after deblending. From Guillouet, 2016.

spatiotemporal separation. However, these two key features are not applied in practice on commercial surveys. As they have clear implications with regard to adherence to the deblending golden rules (described in the following section) and consequently on the overall data quality, it is the choice of the authors to make a distinction between the ISS methodology, as described by Howe, and its real-world field application, herein referred to as unconstrained vibrators. Note, however, that the term ISS is commonly used to denote both methodologies, without concern for their subtleties.

Despite record productivity achieved in a test environment (Pecholcs 2010) more than ten years ago, and the demonstration of the efficiency of the method in areas affected by short shooting windows (Kommedal 2016), the take-up of the unconstrained vibrators methodology has remained relatively slow. While the DS4 approach is still favoured in the Middle East and North Africa, a renewed interest in unconstrained vibrators methodology has been noted by the authors. As an example, up to 45,000 VP/day productivity was achieved recently in the region, using 35 single vibrators for production, this ten years after achieving similar productivities in a test environment. It is also of note that unlike DS4 methodology that inherently requires large spreads and open terrains, some applications of unconstrained vibrators in urban and agricultural areas are starting to emerge.

Limitations of existing HP techniques

The implementation of the DS4 methodology requires large spreads, in order to maintain the minimum distance for simultaneous sweeping and to achieve the associated productivity benefit. Relatively ‘easy’ terrain (i.e., with limited obstacles or vibrator detours) is also to be favoured to ease source deployment and reach the maximum productivity achievable with the method. Bouska provides clear guidance for the setting of the minimum distance for simultaneous sweeping (Bouska 2010), but despite efforts to reduce this minimum distance at the early stage of the method, the industry tends to observe a cautious approach and favour an optimum productivity/quality compromise. In terms of productivity, the DS4 thus exhibits a limitation related to the distance/time rule setting, except as has happened in cases where the number of fleets deployed is underestimated with regard to the rule selected. The second productivity limitation is related to the centralized nature of DS4 acquisitions and dependency on radio communications, with firing orders sent by radio to vibrators. While this radio delay can represent up to two seconds per sweep, the centralization of the acquisition also prevents any VP to fall outside of the selected distance/time rule.

Unconstrained vibrators acquisitions are tightly associated with their subsequent deblending. Indeed, to recover the blended seismic signal and avoid leaving unwanted blending noise in records, two ‘golden rules’ have to be observed at the acquisition stage:

- **Deblending Golden Rule No.1:** Randomness in time and space (i.e., no generation of artificial coherent events) (Figure 3).
- **Deblending Golden Rule No.2:** Sparseness in the frequency – wavenumber domain (i.e., signal focalization in the FK domain not perturbed by interferences exhibiting equivalent energy levels) (Figure 4).

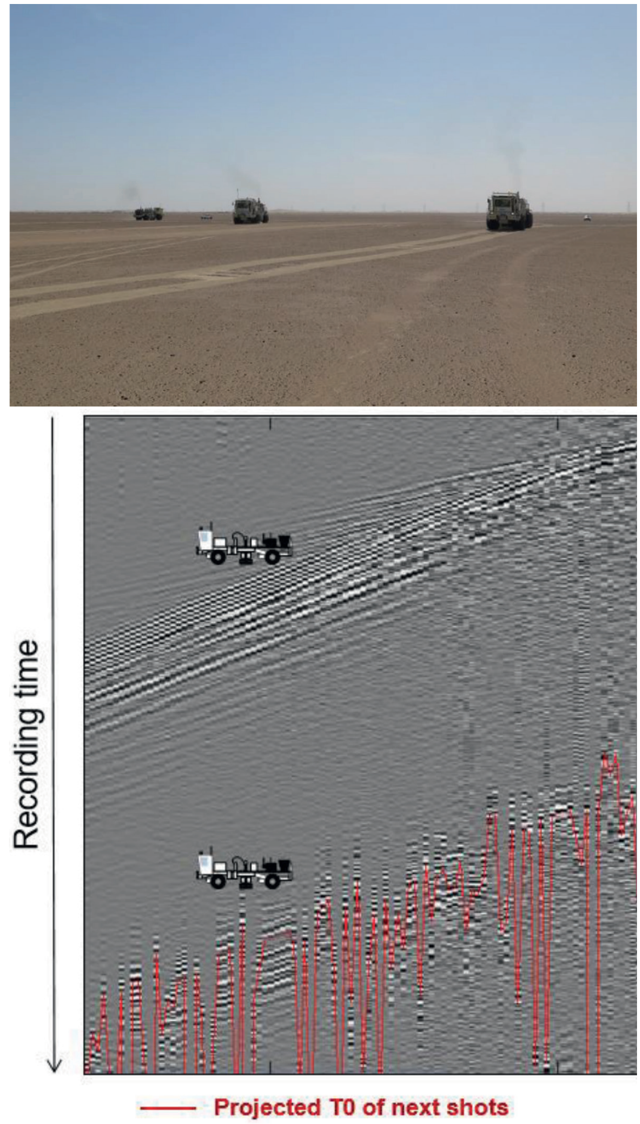


Figure 3 Illustration of the deblending golden rule No.1: (Top) Drivers in line of sight tend to synchronize their driving and sweeping pace. (Bottom) An example of synchronization outcome in the CRG domain, largely used in most deblending methods. On this example, time randomness is not respected (two vibrators releasing their sweeps with the same slip time): the cross-talk contamination appears as organized, which is very likely to prevent its subsequent removal. (From A. Berthaud, personal communication).

These two golden rules become more difficult to observe on high-density surveys using numerous fleets: with up to 50 active single vibrators deployed on the most advanced surveys, the likelihood of infringing the randomness and sparseness requirements is much higher.

However, the means exist to make unconstrained vibrators acquisitions as compliant as possible with an efficient deblending. They mainly consist of properly scheduling shooting operations, with the purpose to adhere to the deblending golden rules mentioned above. However, such a scheduling is reportedly laborious and complex, and needs moreover to be dynamic to cope with unforeseen events. In practice, and as for the sectorization and sweep encoding foreseen by Howe in the ISS method, operation scheduling is rarely implemented or quickly dismissed. In addition, adequately dithering the vibrations when sources

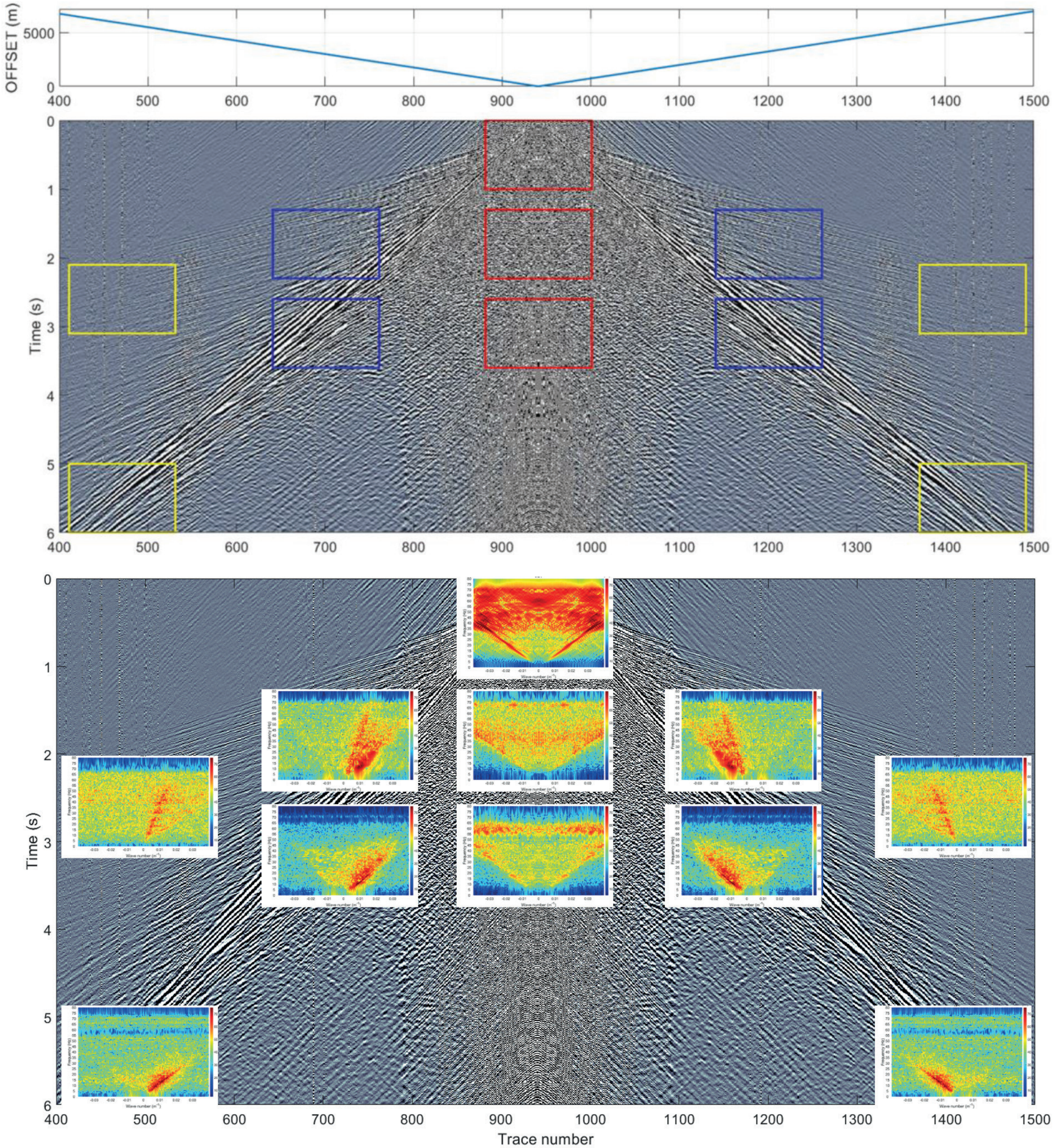


Figure 4 Illustration of the deblending Golden Rule No.2: (Top) This non-blended record (source gather) already exhibits strong amplitude contamination at short offsets. (Bottom) The corresponding FK analyses shows that linear events can't be discriminated at short offsets, unlike mid and long offsets. This ability to discriminate linear events (for further deblending in the curvelet domain) would be even more compromised when acquiring data in an uncontrolled blended acquisition context (additional contamination from nearby sources), thus making the overall deblending outcome speculative.

resume operation after a stand-by proves highly speculative when voice radio is the only link between the observer and vibrators.

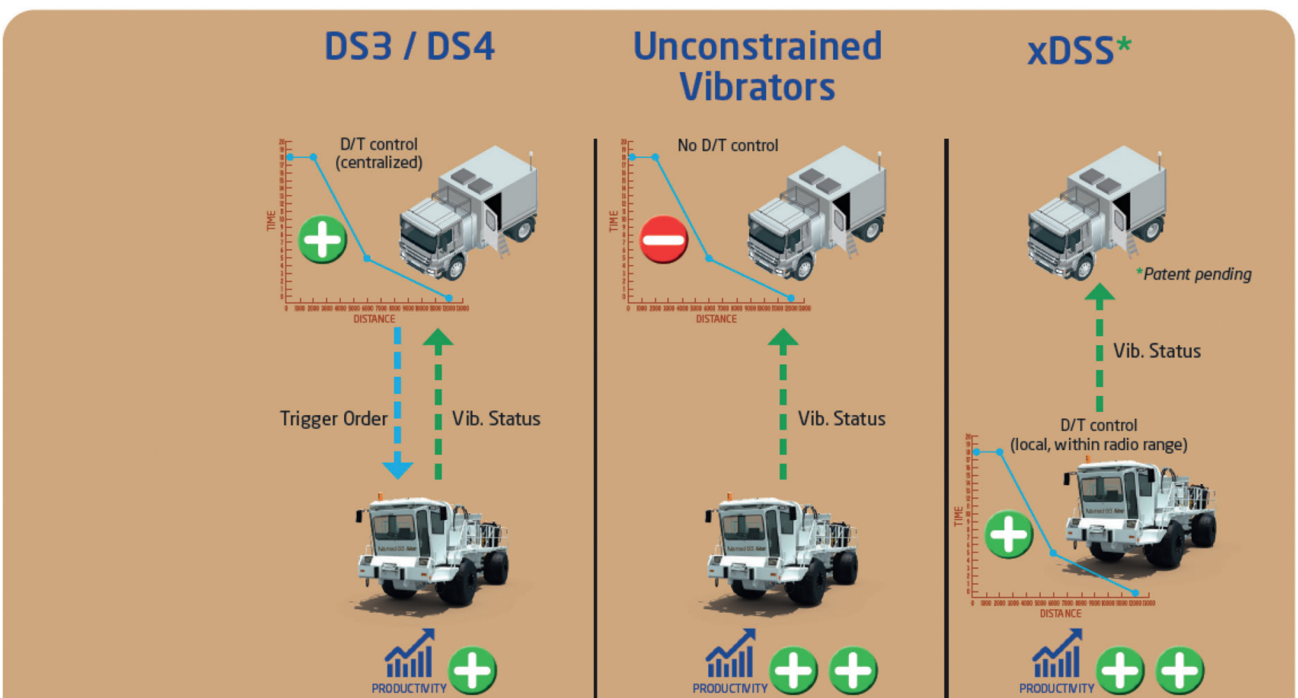
Overcoming current limitations in autonomous HP methods

The xDSS methodology is at the crossroad between DS4 and unconstrained vibrator methodologies (Figure 5). Developed specifically to preserve the unrivalled production level afforded by the unconstrained vibrator methodology, it provides optimal quality in terms of deblending by avoiding the possible non-observance of strict randomness in shooting operations, or a poor sparseness in the frequency – wavenumber domain related to sources operating in an uncontrolled spatial and temporal vicinity. To achieve such, a distance/time rule is set, but contrary to DS4 operation its control is no longer centralized at the recorder, but transferred to autonomous vibrators that act as a decentralized network taking optimal shooting decisions, within their radio range (5 km typical, distance beyond which operations revert back to the standard unconstrained vibrators methodology).

This decentralized source control management thus eliminates the radio delay (up to 2 s per sweep) associated with the transmission of firing orders in DS4 operation. The distance/time law can then be relaxed, making closer shots possible, especially when used in combination with an efficient solution for inter-record harmonic removal (Ollivrin 2019) that contributes to the success of the deblending process. The randomness in shooting is further favoured by the absence of radio time slots (e.g., Figure 6a for a DS4 example) and by the application of an automated time dithering in shooting when resuming operation after a stand-by and restart by several vibrators.

In terms of operation and contrary to the case with unconstrained vibrators, autonomous vibrators can be remotely and instantaneously activated or deactivated from the recorder, instead of acting by means of radio calls to vibrator drivers. The shooting management is automatic once the distance/time rule is set, thus releasing the observer to focus on other duties. The implementation of xDSS is in practice straightforward, with a set up centralized at the recorder: it does not require hardware add-ons, additional radios or prior expertise. The xDSS integrated solution is supported by the VE464 vibrator electronics when used in combination with the 508XT acquisition system. As an alternative for projects acquired with wireless acquisition systems, the xDSS methodology is supported by the SMA (Source MAnager). This recently introduced standalone/portable solution has been developed to host the source management technologies of 508XT with a direct interface to the VE464. SMA supports all VE464 high-productivity and signal quality features, and aims to facilitate the management of sources deployed in combination with wireless acquisition systems, in particular the WiNG system that benefits from a high level of integration.

The productivity of xDSS surveys is expected to be equivalent to those acquired with the unconstrained vibrators methodology. Indeed, while a minimum of supervision remains necessary to avoid sources falling within the D/T exclusion zone, the xDSS methodology relieves the crew of the numerous reshoots commonly associated with the unconstrained vibrators methodologies (owing to infringement of the deblending golden rules, detected by field geophysicists and only once the daily production is completed). Figure 6 displays examples of Distance/time VP spreading for the three high-productivity methodologies.



	DS3 / DS4	Unconstrained Vibrators	xDSS
Distance/Time control	Yes	None	Yes
Distance/ Time management	Centralized	N/A	Local
Source productivity	Affected by radio delay	Unconstrained	Unconstrained
Quality (randomness in time and space)	Randomness not mandatory, but affected by radio communication when necessary for processing	Poor when vibrators are in line of sight	Fully managed within radio range

Figure 5 xDSS principle compared to DS3/DS4 and unconstrained vibrators (top), with the benefits and drawbacks associated to each methodology (bottom).

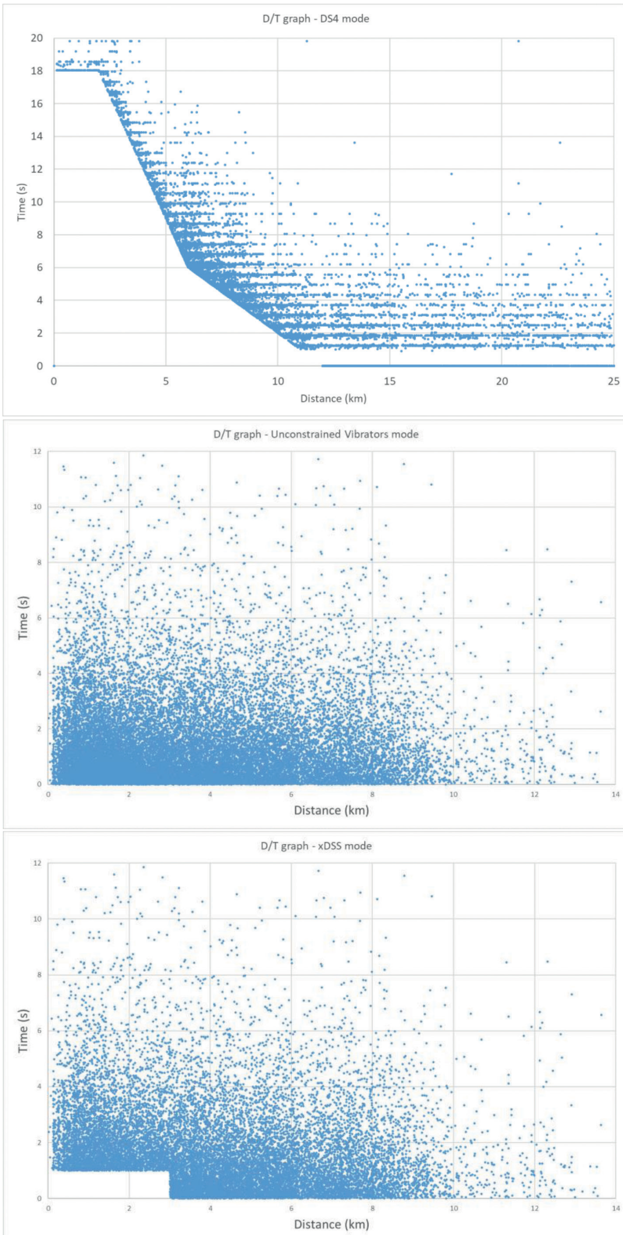


Figure 6 D/T (distance/time) shot repartition for the three high-productivity methodologies. (a) DS4 with standard D/T rule, commercial production example. The D/T rule is respected, but radio communication prevents reaching the vibrators max productivity. (b) Unconstrained vibrators, commercial production example: numerous VPs are shot in a close spatiotemporal vicinity, while some organization in shooting appears at short source distance, which infringes on the deblending golden rules. (c) xDSS expected results, roughly derived from (b) with the associated D/T exclusion zone. This exclusion zone is customizable (3 km, 1s in our example).

Conclusion

Seismic equipment has been the key enabler for the introduction of the high-productivity methodologies that currently make it possible to reach unprecedented productivity and thus support the industry expectation for higher trace densities for a cost in-line with the resulting reservoir quality uplift. A new method, xDSS, has been developed to address the limitations associated with these standard and widespread methodologies. By removing the radio delay associated with centralized control in DS4, valuable seconds are saved for each VP shot, thus opening the way for less stringent distance/time rules. Closer to unconstrained vibrators acquisition than DS4 in terms of operating principle and achievable productivities, xDSS enhances the dataset quality by respecting the deblending golden rules: randomness in time and space, and sparseness in the frequency – wavenumber domain. Fully automated and designed to be straightforward in use, the first implementation of xDSS on commercial surveys is expected in the near future. A future next step to improve the quality of surveys acquired with aggressive blending methodologies will likely lie in source encoding, a strong trend currently observed for marine acquisition.

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