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MASTER THESIS

High-Productivity Land Seismic Acquisition Techniques: Harmonic Noise Characterization, Attenuation Methods, and Field Performance

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Abstract

High-productivity land seismic acquisition has become essential for reducing survey time and improving operational efficiency in large-scale Vibroseis campaigns. However, techniques such as Slip-Sweep, Distance-Separated Simultaneous Sweeping, and Independent Simultaneous Sweeping introduce complex interference patterns, mainly harmonic noise and blended wavefields, which may affect seismic data quality if not properly controlled. This thesis investigates the evolution of land Vibroseis acquisition from conventional sequential methods to modern high-productivity techniques, with particular focus on harmonic noise generation, behavior, and attenuation. Four attenuation methods are reviewed and compared: HPVA, PSD-Harmonic, CHARM, and ENAGEO-Advance. The comparison is supported by published case studies that illustrate the relationship between acquisition parameters, noise severity, processing stage, and final data quality. Since no proprietary field data were available, the study adopts a literature-based comparative methodology. The main contribution of this work is the development of HNAM-DST, a decision-support tool designed to assist in selecting the most suitable harmonic noise attenuation method according to survey conditions, processing constraints, and quality objectives. The results show that no single attenuation method is optimal for all cases; instead, method selection must consider acquisition mode, slip time, terrain conditions, available software, and required data quality. This work provides a structured framework for linking high-productivity acquisition design with appropriate harmonic noise mitigation strategies.

Keywords: High-productivity acquisition; Vibroseis; Harmonic noise; Slip-Sweep; Deblending; Decision-support tool.

Résumé

L’acquisition sismique terrestre à haute productivité est devenue essentielle pour réduire la durée des campagnes et améliorer l’efficacité opérationnelle des levés Vibroseis à grande échelle. Cependant, des techniques telles que le Slip-Sweep, le Distance-Separated Simultaneous Sweeping et l’Independent Simultaneous Sweeping introduisent des interférences complexes, principalement liées aux bruits harmoniques et aux champs d’ondes superposés, pouvant dégrader la qualité des données sismiques si elles ne sont pas correctement maîtrisées. Ce mémoire étudie l’évolution de l’acquisition Vibroseis terrestre, depuis les méthodes conventionnelles séquentielles jusqu’aux techniques modernes à haute productivité, en mettant l’accent sur la génération, le comportement et l’atténuation des bruits harmoniques. Quatre méthodes d’atténuation sont présentées et comparées : HPVA, PSD-Harmonic, CHARM et ENAGEO-Advance. Cette comparaison s’appuie sur des études de cas publiées, montrant l’influence des paramètres d’acquisition, du niveau de bruit, de l’étape de traitement et des objectifs de qualité. En l’absence de données de terrain propriétaires, l’étude adopte une méthodologie comparative fondée sur la littérature. La contribution principale de ce travail est le développement de HNAM-DST, un outil d’aide à la décision permettant de sélectionner la méthode d’atténuation la plus adaptée aux conditions du levé. Les résultats montrent qu’aucune méthode n’est universellement optimale et que le choix dépend du mode d’acquisition, du slip time, du terrain, des logiciels disponibles et de la qualité recherchée.

Mots-clés : Acquisition haute productivité ; Vibroseis ; Bruit harmonique ; Slip-Sweep ; Déblending ; Aide à la décision.

الملخص

أصبحت تقنيات الاقتناء الزلزالي البري عالية الإنتاجية ضرورية لتقليل مدة الإنجاز وتحسين الكفاءة التشغيلية في المسوحات الزلزالية واسعة النطاق باستخدام مصادر Vibroseis . غير أن تقنيات مثل Slip-Sweep و-Distance Separated Simultaneous Sweeping و Independent Simultaneous Sweeping تؤدي إلى ظهور أنماط معقدة من التداخل، خاصة الضجيج التوافقي وتراكب الحقول الموجية، مما قد يؤثر في جودة المعطيات الزلزالية إذا لم تتم معالجته بطريقة مناسبة. يهدف هذا العمل إلى دراسة تطور الاقتناء الزلزالي البري باستخدام Vibroseis، انطلاقاً من الطرق التقليدية المتسلسلة وصولاً إلى تقنيات الاقتناء الحديثة عالية الإنتاجية، مع التركيز على نشأة الضجيج التوافقي وسلوكه وطرق تخفيفه. تمت دراسة ومقارنة أربع طرق رئيسية لمعالجة هذا الضجيج، وهي HPVA و-PSD Harmonic و CHARM وENAGEO-Advance. وتعتمد المقارنة على دراسات حالة منشورة توضح العلاقة بين معاملات الاقتناء، شدة الضجيج، مرحلة المعالجة، وجودة البيانات النهائية. ونظراً لعدم توفر بيانات ميدانية خاصة، اعتمدت الدراسة على منهجية مقارنة مبنية على المراجع العلمية. تتمثل المساهمة الأساسية لهذا العمل في تطوير أداة HNAM-DST، وهي أداة دعم قرار تساعد على اختيار أنسب طريقة لتخفيف الضجيج التوافقي حسب ظروف المسح وقيود المعالجة وأهداف الجودة. وتبين النتائج أن اختيار الطريقة المناسبة لا يكون ثابتاً، بل يعتمد على نمط الاقتناء، وزمن الانزلاق، وطبيعة الأرض، والبرمجيات المتاحة، ومستوى الجودة المطلوب.

Contents

List of figures

List of tables

Introduction

Context and Industrial Background

Land seismic reflection surveys represent one of the most demanding and resource-intensive operations in subsurface geophysics. They are the primary tool used by the oil and gas industry, and increasingly by geothermal and CO_2 storage projects, to image subsurface geological structures with sufficient resolution for economic decision-making (Yilmaz, 2001; Sheriff & Geldart, 1995). In the Algerian Sahara and across the broader North African and Middle Eastern exploration context, land seismic campaigns cover vast surface areas under challenging logistical and environmental conditions, making acquisition efficiency a central operational and economic concern.

For decades, land seismic acquisition relied on conventional Vibroseis technology: a fleet of vibrators emits a controlled frequency-swept signal at each source location, a listening period follows, and the fleet then moves to the next position. This sequential paradigm delivers reliable, high-quality data but suffers from an intrinsic inefficiency, the vibrators are idle during the listening and movement phases, which can account for more than half of the total acquisition cycle time. At the scale of modern 3D land surveys, this idle time translates directly into weeks of additional field operations and proportionally higher costs (Dean, 2016).

The seismic industry responded to this inefficiency over the past three decades by developing a family of High-Productivity (HP) acquisition techniques that reduce or eliminate idle time by operating multiple vibrator sources with controlled temporal overlap. Flip-Flop acquisition introduced alternating fleets; Slip-Sweep (Rozemond, 1996) reduced the delay between consecutive sweeps below the sweep duration; Distance-Separated Simultaneous Sweeping (DS3, Bouska, 2010) added spatial separation as a means of limiting interference; and Independent Simultaneous Sweeping (ISS, Howe et al., 2008) eliminated synchronization constraints entirely. Each successive technique achieves greater productivity gains, from a factor of 1.5 with Flip-Flop to more than six times conventional output with full ISS.

These gains are not without consequence. When multiple vibrator sources operate simultaneously or with reduced time separation, their seismic wavefields overlap in the recorded data, a condition referred to as blended acquisition. More specifically, the nonlinear mechanical behavior of vibratory sources generates harmonic distortion at integer multiples of the fundamental sweep frequency. In conventional sequential acquisition, these harmonic components are displaced to negative correlation times and fall outside the useful reflection record. In HP acquisition with short slip times, they may contaminate records from neighboring shots, appearing as coherent noise that mimics real reflection events and degrades both the signal-to-noise ratio and the amplitude fidelity of the processed data (Dean, 2016).

Managing this harmonic noise is therefore the central processing challenge introduced by HP acquisition. It cannot be addressed by standard random noise attenuation algorithms, because it is coherent, structured, and directly linked to the acquisition geometry and timing. Dedicated attenuation methods are required, methods that understand the physical origin of the noise and can remove it without damaging the underlying reflection signal.

Problem Statement

Four harmonic noise attenuation methods have been documented in the published literature and are currently deployed in commercial land seismic processing: HPVA (CGG), PSD-Harmonic (BGP), CHARM (Key Seismic), and ENAGEO-Advance. These methods differ fundamentally in their operating principle, the stage of the processing workflow at which they are applied, the type of harmonic contamination they address, and the field conditions under which they are most effective. A practitioner planning the processing workflow for a new HP survey must therefore make a consequential choice: which method is most appropriate for this specific survey, with its specific acquisition parameters, terrain conditions, and quality objectives?

To date, no structured, quantitative framework exists in the published literature to support this choice. Individual papers describe each method and demonstrate its performance in specific contexts, but comparative evaluations remain qualitative and do not address the full range of survey configurations that practitioners encounter. The question of how to translate known survey parameters into a ranked, justified method recommendation has not been systematically answered.

This situation is particularly relevant to ENAGEO, the Algerian national seismic operator, which conducts extensive land Vibroseis surveys in the Saharan basin and operates its own proprietary ENAGEO-Advance processing tool alongside conventional industry methods. For Algerian geophysicists, the ability to position ENAGEO-Advance within a comparative framework, and to identify the conditions under which it is the optimal choice versus alternatives, has both operational and strategic value.

Research Objectives

This thesis addresses the above problem through four articulated research objectives:

- **Objective 1- Theoretical synthesis:** to establish a rigorous theoretical framework covering the full evolution from conventional Vibroseis acquisition to high-productivity techniques, with explicit characterization of the harmonic noise problem as an inherent consequence of HP acquisition.
- **Objective 2- Methodological review:** to document, explain, and compare the four main harmonic noise attenuation methods currently in use, identifying their operating principles, processing stage requirements, and documented performance characteristics.

- **Objective 3 - Empirical validation through published literature:** to evaluate method performance across different survey environments through structured review and comparison of published field case studies, addressing the absence of proprietary field data by leveraging the documented experience of the broader research community.
- **Objective 4 - Applied synthesis:** to develop an original decision-support tool (HNAM-DST) that operationalizes the comparative framework into a parameterized scoring engine, allowing any practitioner to input their survey configuration and receive a ranked, transparent, and literature-grounded method recommendation.

The thesis does not conduct new field acquisition or laboratory experiments. Its methodological contribution is analytical and synthetic, it draws on the existing body of literature to build a comparative framework more structured and actionable than any individual paper provides, and materializes that framework in a practical software tool.

Methodology

The research methodology is structured as a systematic literature-based comparative review, organized in three analytical phases aligned with the three main content chapters.

The first phase, theoretical synthesis, involved a critical reading of foundational texts on Vibroseis acquisition physics and a structured comparison of HP technique specifications across primary sources. The objective was not merely to describe each technique but to construct a coherent causal chain: from the reduction of idle time through the introduction of temporal source overlap, to the generation of blended data, to the emergence of harmonic noise as the central processing challenge. Table 1 in Chapter 1 is the direct product of this analytical phase.

The second phase, methodological review, involved detailed study of the primary documentation for each of the four attenuation methods, including original research papers, SEG extended abstracts, and technical reports. Methods were analyzed along six dimensions that later become the evaluation criteria of the HNAM-DST: processing stage, acquisition technique compatibility, noise severity handling, terrain robustness, software requirements, and the quality-complexity trade-off. Table 2 in Chapter 2 synthesizes this analysis.

The third phase, empirical validation, involved selecting four published case studies representatives of the main HP technique and method combinations, and subjecting them to a structured comparative analysis using a consistent set of performance dimensions (SNR improvement, productivity gain, key limitation). The selection criteria prioritized studies that reported quantitative performance metrics and covered contrasting survey environments. Table 3 in Chapter 3 is the comparative product of this phase.

The fourth phase, applied synthesis, translated the analytical output of the first three phases into the HNAM-DST decision-support tool. The tool implements a weighted multi-criteria scoring matrix derived directly from the method comparison in Chapter 2 and validated against the case study outcomes in Chapter 3. Its design is documented fully in Chapter 4, including all base scores, weight assignments, and dynamic adjustment rules, ensuring complete traceability between the tool's recommendations and the published sources that ground them.

Scope and Limitations

Several important limitations define the scope of this work and should be understood before applying its conclusions.

This thesis covers land Vibroseis acquisition exclusively. Marine seismic, distributed acoustic sensing (DAS), nodal systems, and impulsive sources are outside its scope. The harmonic noise mechanisms described are specific to vibratory sources and do not apply to dynamite or airgun acquisition.

No proprietary field data were available for this study. All empirical evidence in Chapter 3 derives from published open literature. While this limits the ability to test methods on locally specific Algerian survey data, it ensures full reproducibility of the analysis and is a methodologically acceptable approach for a comparative review thesis.

The HNAM-DST scoring matrix was calibrated on the basis of the four case studies reviewed and the comparative literature in Chapter 2. It has not been validated against a large empirical dataset of real survey outcomes with known method performance. The tool should be used as a structured decision aid, not as a substitute for expert judgment.

Thesis Structure

The thesis is organized into four chapters plus a general conclusion, each building on the previous:

- **Chapter 1- Theoretical Framework:** presents the fundamentals of Vibroseis acquisition, traces the evolution from conventional to HP techniques across four generations (Flip-Flop, Slip-Sweep, DS3/DS4, ISS/MSS), provides a comparative summary in Table 1, and establishes the harmonic noise problem as the central challenge motivating Chapters 2 and 3.
- **Chapter 2- Harmonic Noise Attenuation Methods:** reviews and compares the four main attenuation methods (HPVA, PSD-Harmonic, CHARM, ENAGEO-Advance) along with FK and Tau-p domain deblending. Table 2 provides a structured six-column comparison that becomes the direct input to the scoring matrix of Chapter 4.
- **Chapter 3- Comparative Case Studies:** reviews four published field case studies, each pairing a specific HP technique with a specific attenuation method across

contrasting geographic and geological environments. Table 3 synthesizes performance outcomes and identifies cross-case patterns in productivity gains, SNR improvement, and environmental dependencies.

- **Chapter 4 - HNAM-DST Decision-Support Tool:** documents the design, scoring methodology, and recommendation logic of the original decision-support tool developed as the applied contribution of this thesis. Seven input parameters, six evaluation criteria, a full base score matrix, dynamic weight adjustments, and three worked examples are fully described.
- **General Conclusion:** synthesizes findings across all four chapters, answers the central research question, identifies study limitations, and proposes directions for future work including validation on Algerian field data and integration of emerging machine-learning deblending approaches.

Chapter 1: Theoretical Framework

1.1. Fundamentals of Vibroseis Acquisition

1.1.1. Vibroseis Basics: Sweep and Correlation

Seismic reflection acquisition using vibratory sources (Vibroseis) has become the dominant technique for land seismic surveys due to its operational flexibility, repeatability, and reduced environmental impact compared to impulsive sources such as dynamite. In Vibroseis acquisition, seismic energy is generated through a controlled frequency-modulated signal, commonly referred to as a sweep, which is transmitted into the ground through a baseplate in contact with the ground (Sheriff & Geldart, 1995).

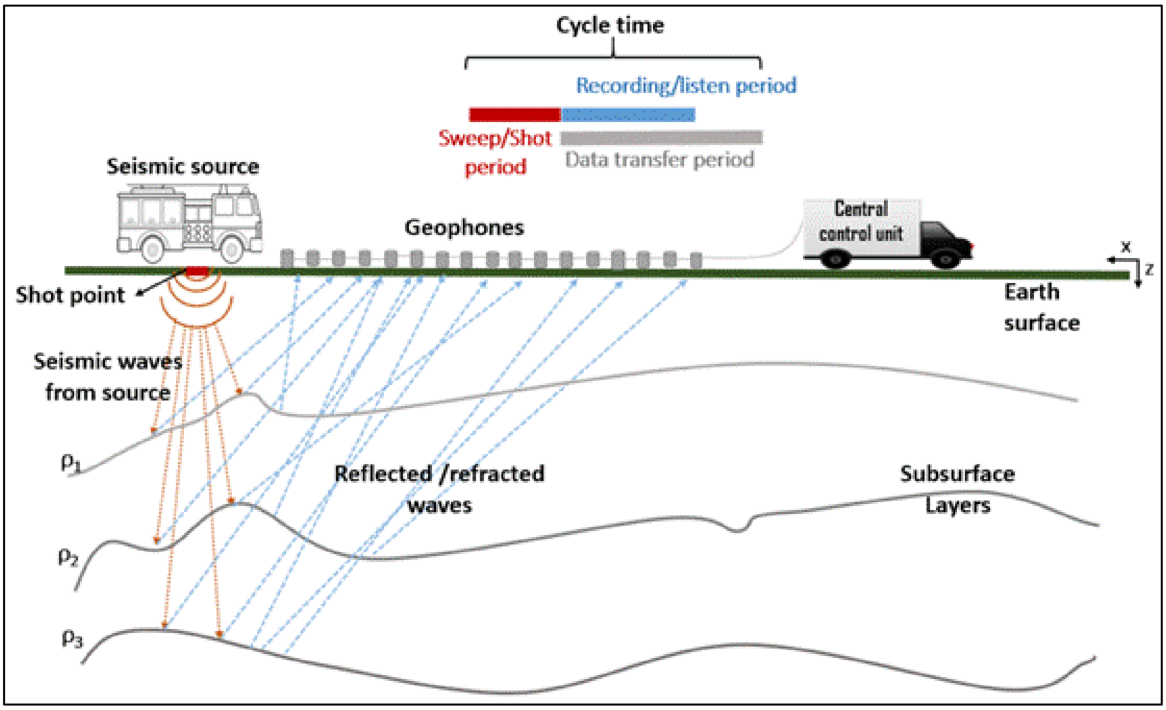

Figure 1: Schematic of a Vibroseis source system showing energy transmission through the baseplate into the subsurface (Makama et al., 2021)

The emitted sweep typically spans a predefined frequency range (e.g., 6–100 Hz) over a fixed duration, allowing for controlled bandwidth and improved signal penetration. Unlike impulsive sources, Vibroseis does not generate a direct reflection response; instead, the recorded signal is a convolution of the Earth's reflectivity with the transmitted sweep. To retrieve the reflectivity series, a correlation process is applied between the recorded data and the pilot sweep, resulting in a compressed wavelet commonly approximated by a Klauder wavelet (Yilmaz, 2001).

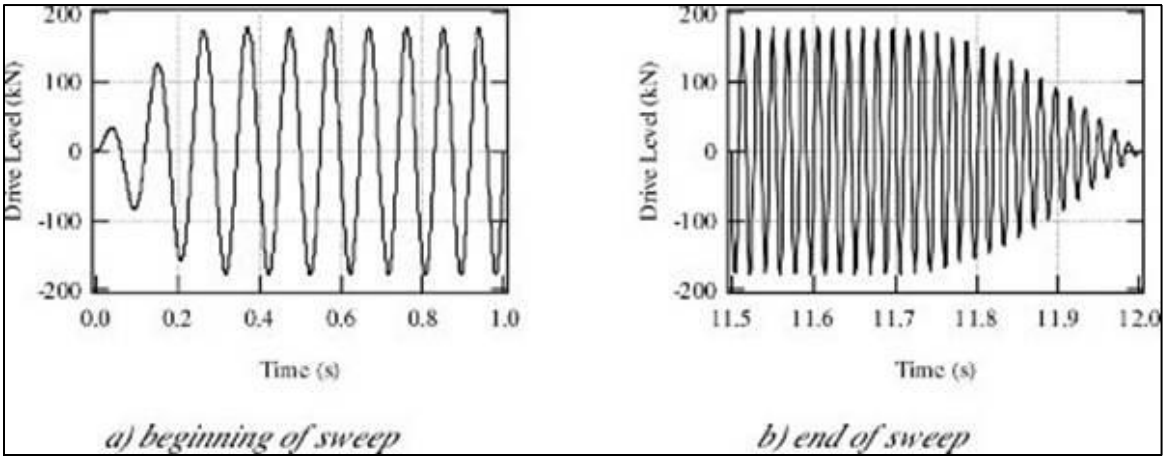

Figure 2: Example of a linear Vibroseis sweep showing frequency variation over time (Kalinski, 2007)

The correlation process is fundamental to Vibroseis data processing. Cross-correlation with the pilot sweep effectively compresses the long-duration signal into a short wavelet, enhancing temporal resolution and improving interpretability. This process redistributes energy, concentrating it at reflection times while spreading noise over a broader time window, thereby improving the signal-to-noise ratio (Yilmaz, 2001). However, the efficiency of this operation strongly depends on the similarity between the pilot sweep and the actual signal transmitted into the subsurface.

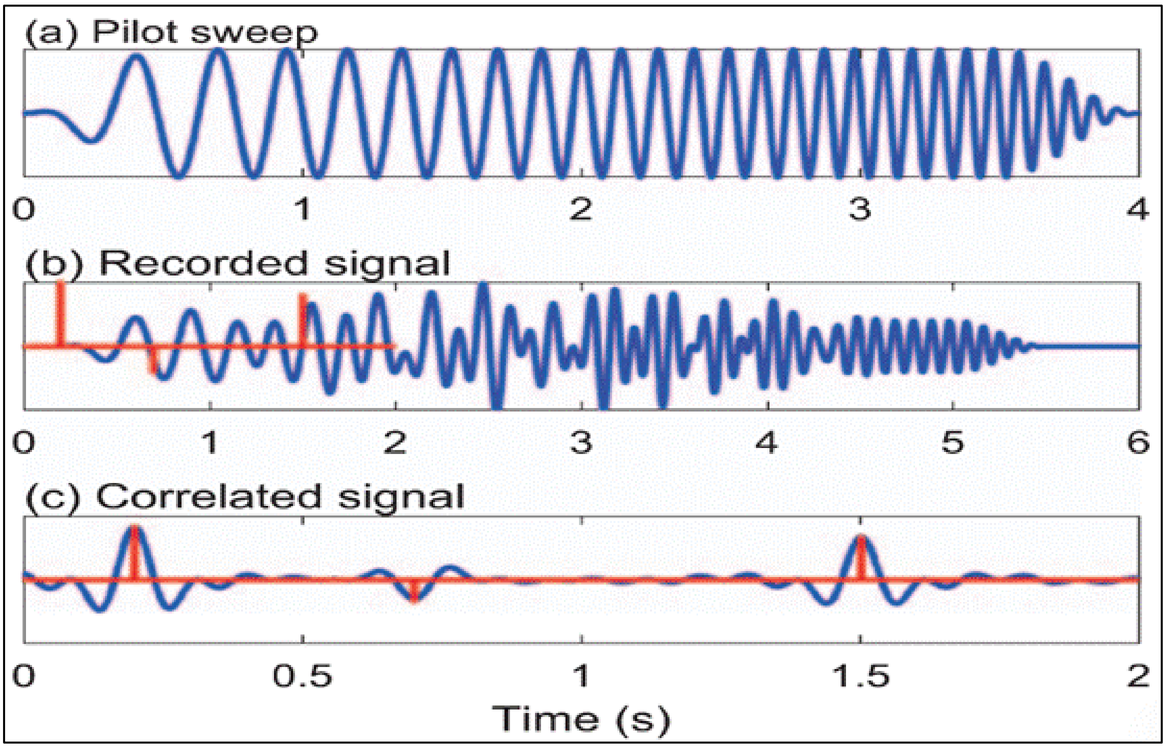

Figure 3:Illustration of the Vibroseis correlation process: sweep compressed into a Klauder wavelet (Dean, 2016)

1.1.2. Signal Fidelity and Ground Force

Signal fidelity is a critical factor in Vibroseis acquisition, governed by baseplate coupling and mechanical response. The baseplate must maintain optimal contact with the ground to ensure that the applied force is effectively transmitted as seismic energy. Poor coupling conditions, such as loose sand, unconsolidated soils, or uneven terrain, can lead to energy loss, phase distortion, and reduced signal repeatability. To monitor and correct these effects, modern systems record the Ground Force, which represents the actual force applied by the vibrator to the ground (Sallas, 1984).

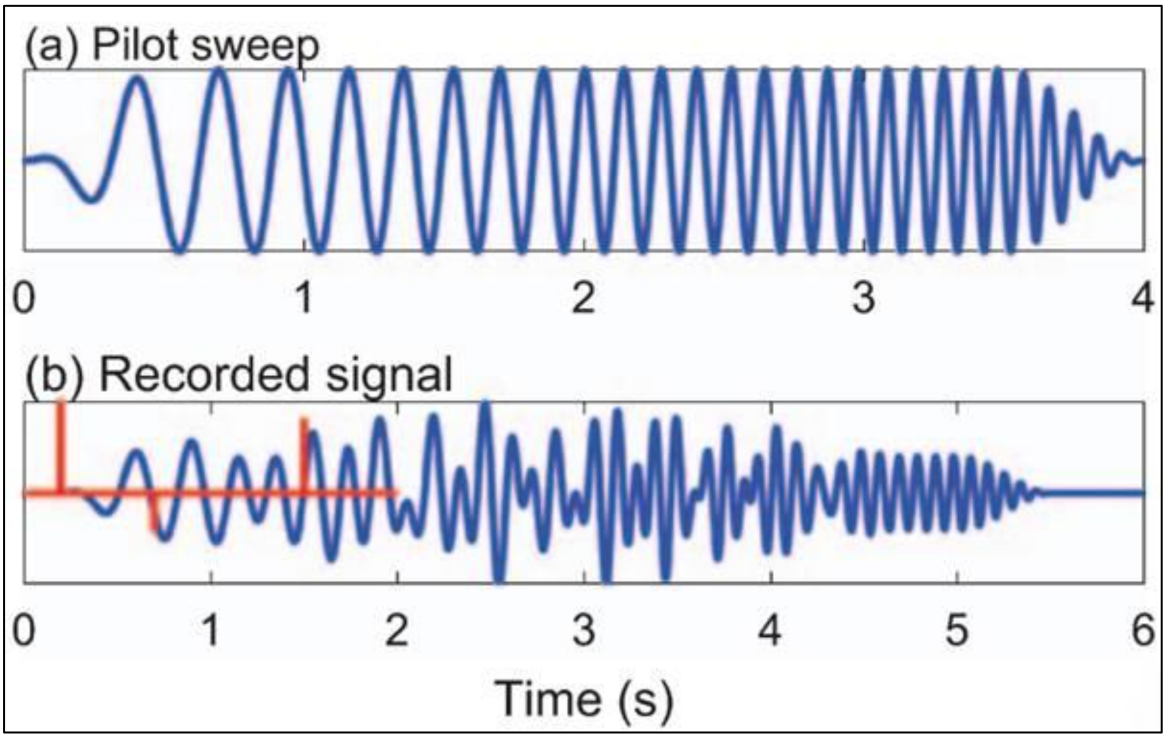

Figure 4:Comparison between pilot sweep and measured Ground Force signal, highlighting distortions from vibrator-ground: interaction (Dean, 2016)

Harmonic distortion is an inherent characteristic of vibratory sources, arising from nonlinearities in the vibrator-ground system. These harmonics correspond to integer multiples of the fundamental sweep frequency and can introduce additional energy into the recorded signal. While some harmonic components may enhance bandwidth, they often act as coherent noise, especially in high-productivity acquisition modes where temporal overlap between sweeps occurs

1.2. Conventional Acquisition Methods

Conventional Vibroseis acquisition is based on a sequential shooting strategy, where a single fleet of vibrators operates point by point along predefined source lines. The acquisition cycle consists of three main phases: sweeping, listening (recording), and moving to the next source location. This sequential workflow ensures high data quality by avoiding interference between successive shots but introduces significant idle time, reducing operational efficiency

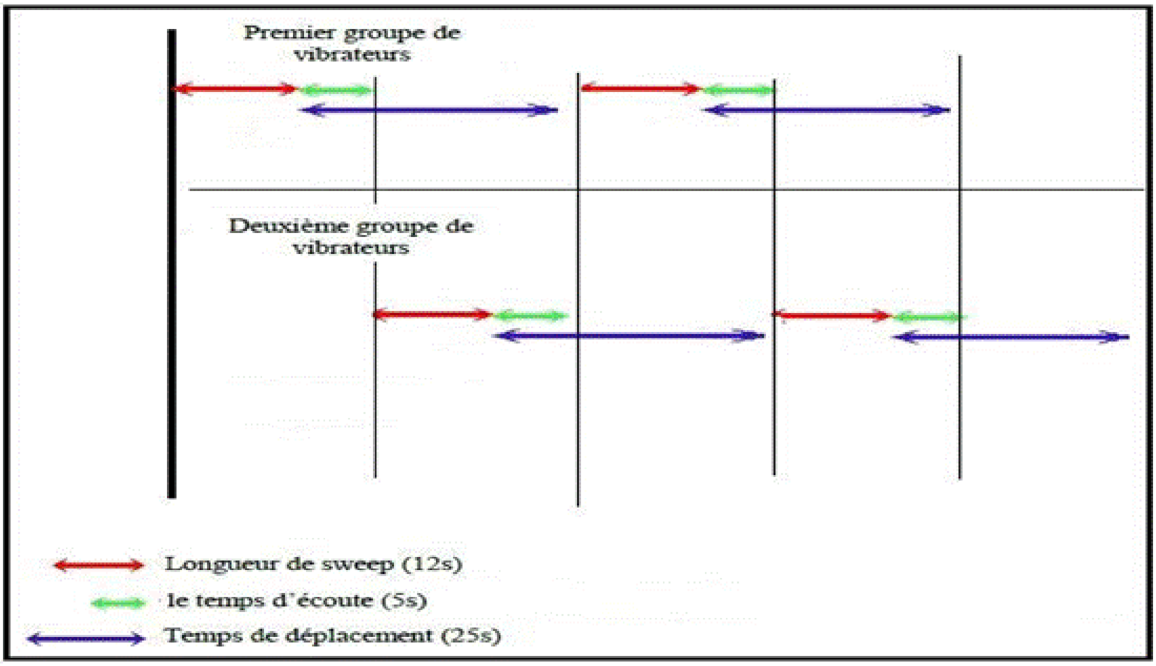

Figure 5: Cycle time of conventional Vibroseis acquisition: sweeping, listening, and movement phases (Taieb & Belbachir, 2020)

To improve productivity while maintaining data quality, the industry introduced the Flip-Flop acquisition technique, which involves two or more vibrator fleets operating alternately. While one fleet is actively sweeping, the other is moving to the next source location, reducing idle time and increasing the number of vibration points acquired per hour.

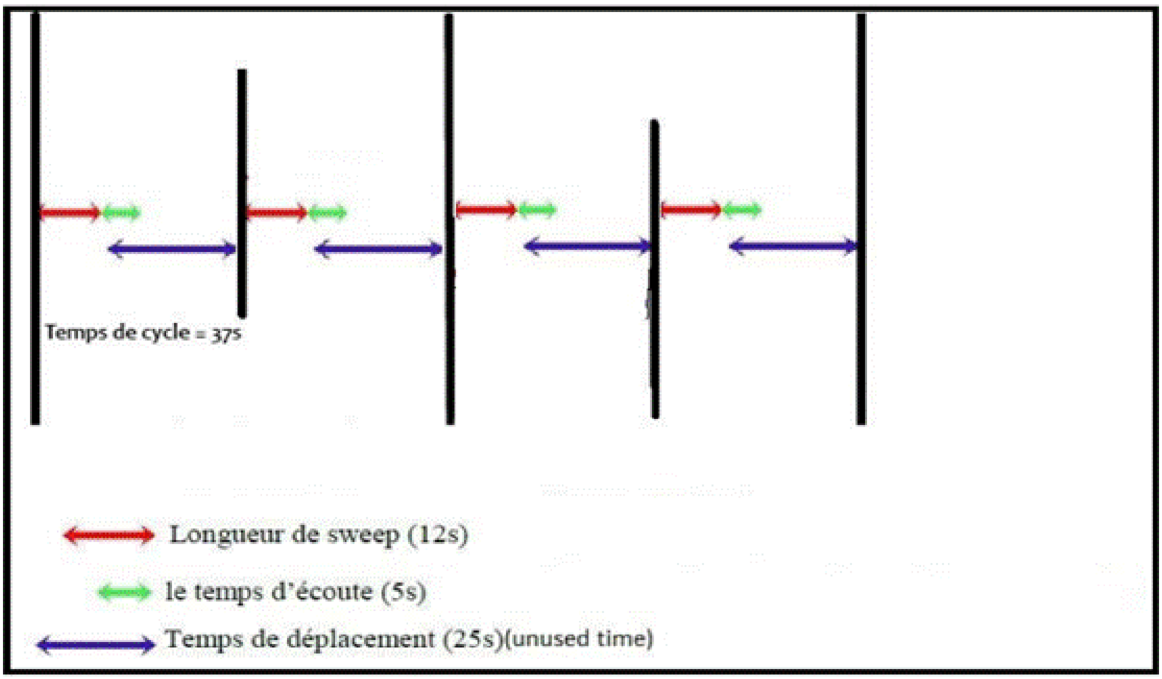

Figure 6: Flip-Flop acquisition: multiple vibrator fleets operating alternately to reduce idle time (Taieb & Belbachir, 2020)

Despite these improvements, conventional and Flip-Flop methods remain fundamentally limited by their sequential nature. Even with optimized coordination, some degree of idle time persists, and productivity gains are bounded by physical constraints. These limitations have motivated the development of high-productivity techniques.

1.3. High-Productivity Acquisition Techniques

The increasing demand for high-resolution seismic imaging, combined with the high cost of land surveys, has led to the development of high-productivity (HP) acquisition techniques. These are commonly referred to as simultaneous source or blended acquisition methods, where multiple sources operate either with reduced time delays or simultaneously Despite these improvements, conventional and Flip-Flop methods remain fundamentally limited by their sequential nature. Even with optimized coordination, some degree of idle time persists, and productivity gains are bounded by physical constraints. These limitations have motivated the development of high-productivity techniques.

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1.3. High-Productivity Acquisition Techniques

1.3.1. Slip-Sweep Technique

The Slip-Sweep method was introduced by Rozemond (1996) as one of the earliest HP Vibroseis techniques. It is based on reducing the delay between consecutive sweeps, the slip-time, so that a new sweep can begin before the previous one has fully completed. This exploits unused time in the frequency-time domain, thereby increasing the number of source points acquired per hour.

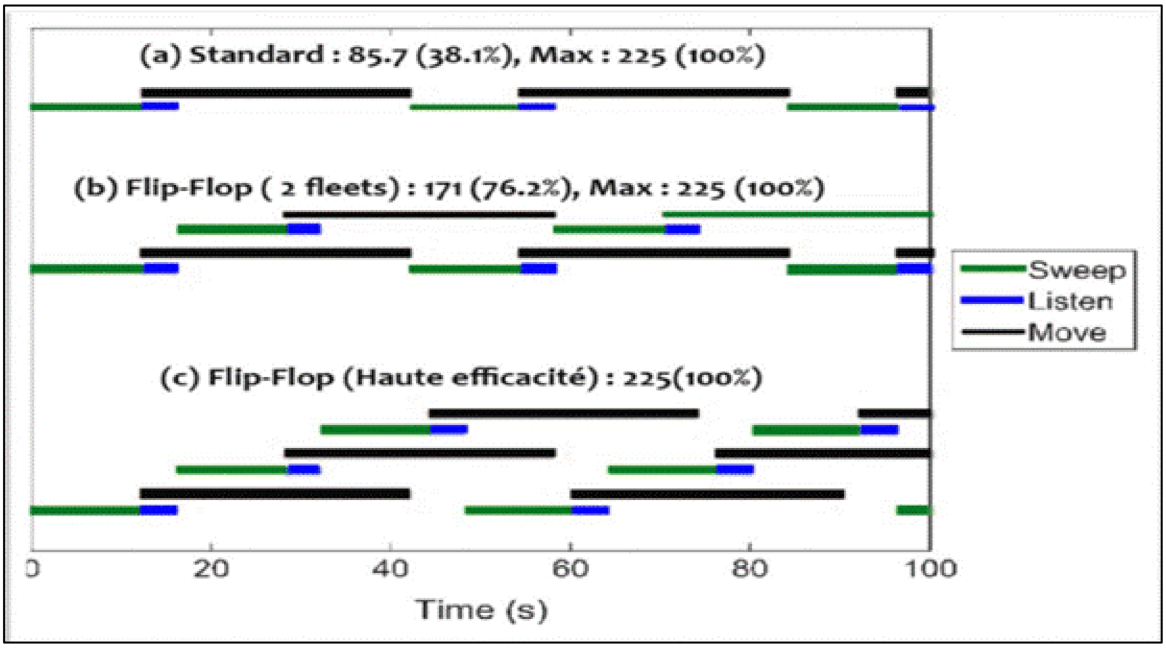

Figure 7: Slip-Sweep technique: temporal overlap between consecutive sweeps (Dean, 2016)

Depending on the chosen slip-time, Slip-Sweep acquisition is classified into three regimes (Dean, 2016):

- Noise-free: slip time is long enough that no harmonic energy overlaps with adjacent records.
- Non-aggressive: limited and manageable harmonic interference.
- Aggressive: strong harmonic interference across records, requiring robust attenuation.

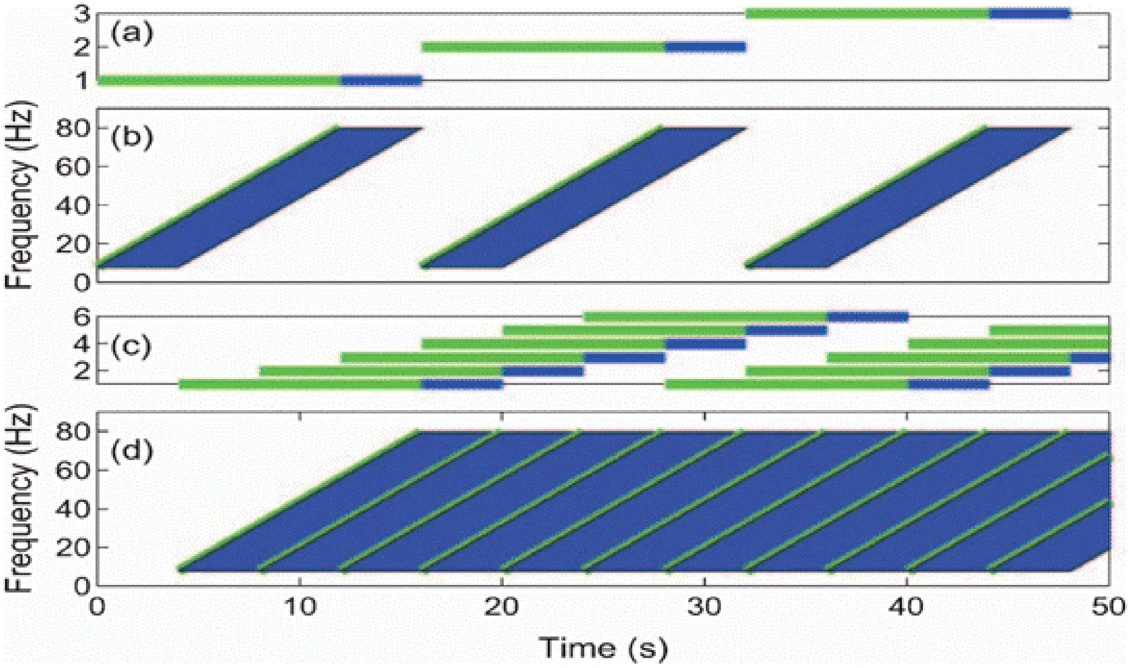

Figure 8: Noise-free, non-aggressive, and aggressive Slip-Sweep regimes based on harmonic interference level (Dean., 2016)

1.3.2. High-Fidelity Vibratory Seismic (HFVS)

High-Fidelity Vibratory Seismic (HFVS), developed by ExxonMobil, focuses on enhancing the fidelity of the emitted signal through improved control of vibrator performance, source signature, and ground coupling. HFVS incorporates precise control of phase, amplitude, and frequency content of the sweep, as well as advanced monitoring of Ground Force, resulting in improved bandwidth, reduced distortion, and better repeatability

From a mathematical perspective, HFVS can be interpreted as an inversion process: when the true emitted signal is known through Ground Force measurements, a more accurate deconvolution is possible, resulting in improved phase stability and amplitude preservation (Krohn & Johnson, 2006). HFVS is best considered as a complementary technique that enhances data quality while working in conjunction with productivity-driven strategies such as Slip-Sweep or ISS.

1.3.3. Distance-Separated Simultaneous Sweeping (DS3/DS4)

Distance-Separated Simultaneous Sweeping (DS3) ensures that simultaneously active sources are separated by a sufficient distance so that their seismic wavefields do not interfere within the recording time window of interest (Bouska, 2010; Dean, 2016). By maintaining a minimum distance between vibrators, the energy generated by one source arrives at the receiver spread outside the useful reflection window of another source.

DS4 combines spatial separation with temporal overlap, increasing acquisition efficiency while maintaining acceptable interference levels (Bouska, 2010). Compared to Slip-Sweep, DS3/DS4 offers improved data quality due to reduced harmonic interference, but requires larger spreads and more complex logistical planning.

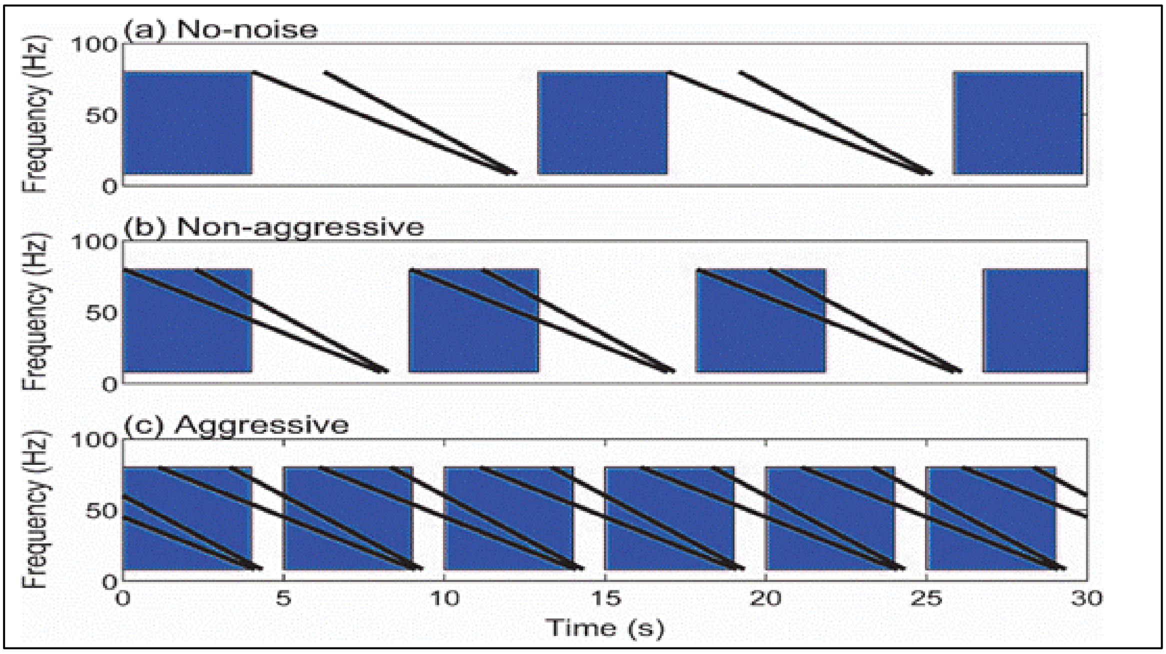

Figure 9: DS3 concept: spatial separation and controlled temporal overlap for improved productivity (Bouska, 2010; Dean, 2016)

1.3.4. Independent Simultaneous Sweeping (ISS) and Managed Spread and Source (MSS)

Independent Simultaneous Sweeping (ISS) represents the most advanced stage of HP Vibroseis acquisition, where multiple vibrators operate completely independently without any synchronization constraints. ISS achieves extremely high productivity levels, with field implementations reporting more than a thousand source points per hour (Howe et al., 2008). The elimination of idle time makes ISS the most efficient acquisition strategy in terms of operational output.

However, ISS relies heavily on deblending techniques to separate individual source contributions during data processing (Abma et al., 2015; Bagaini, 2010). To improve control over this dynamic environment, Managed Spread and Source (MSS) incorporates real-time monitoring and adaptive control of vibrator operations, optimizing source activation based on spatial distribution, receiver coverage, and interference levels (Dean, 2016).

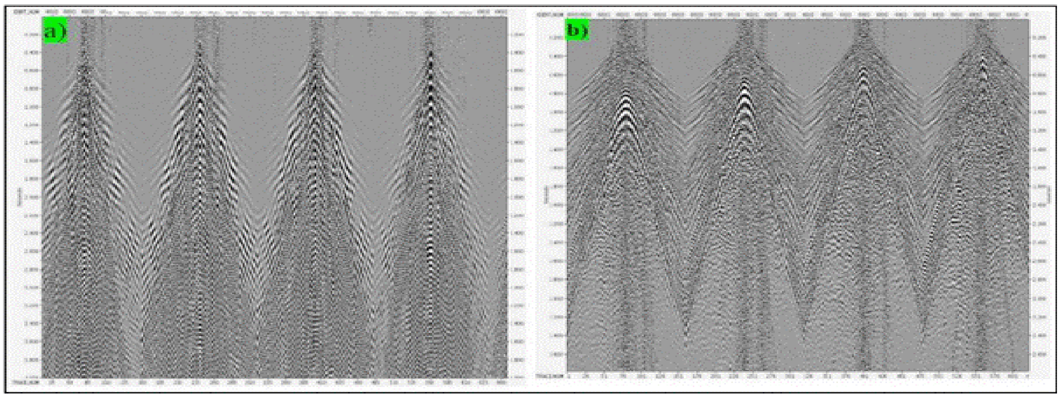

Figure 10: ISS acquisition layout: multiple vibrators operating independently and simultaneously (Sonatrach, 2017)

1.4. Comparative Summary of High-Productivity Techniques

The four main HP acquisition strategies differ significantly in their productivity gains, operational complexity, and the nature of the interference they introduce. Table 1 below summarizes their key characteristics.

Table 1: Comparative summary of high-productivity Vibroseis acquisition techniques

Technique	Productivity Gain	Interference Type	Processing Complexity	Best Environment
Flip-Flop	1.5–2×	Minimal	Low	All terrains
Slip-Sweep	2–4×	Harmonic noise	Moderate	Open desert/flat terrain
DS3/DS4	2–4×	Low (spatial sep.)	Moderate	Large, accessible surveys
ISS/MSS	4–8×	Full blending	High (deblending required)	Large 3D surveys with dense receivers

1.5. The Harmonic Noise Problem

The transition from conventional to high-productivity seismic acquisition introduces a fundamental challenge: signal interference. While techniques such as Slip-Sweep, DS3/DS4, and ISS significantly improve operational efficiency, they also lead to the generation of blended data, where multiple seismic sources contribute simultaneously to the recorded signal (Abma et al., 2015; Bagaini, 2010).

1.5.1. Blended Data: Overlapping Seismic Wavefields

Blended data refers to seismic records in which signals generated by multiple sources are superimposed in time and space. The recorded trace can no longer be interpreted as the response of a single source, it represents the sum of several wavefields, each associated with different source locations and activation times. Specialized deblending algorithms are required to recover individual source responses, relying on differences in timing, spatial distribution, or statistical properties of the signals (Bagaini, 2010).

1.5.2. Harmonic Distortion: Source-Generated Coherent Noise

In high-productivity acquisition, harmonic distortion originates from nonlinear behavior in the vibrator-ground system, generating additional frequency components at integer multiples of the fundamental sweep frequency. After correlation, the fundamental signal is compressed into a short wavelet, while harmonic components appear at different time positions, often at negative times. When overlap occurs, these harmonics may contaminate the useful signal and create artifacts resembling real reflections (Dean, 2016).

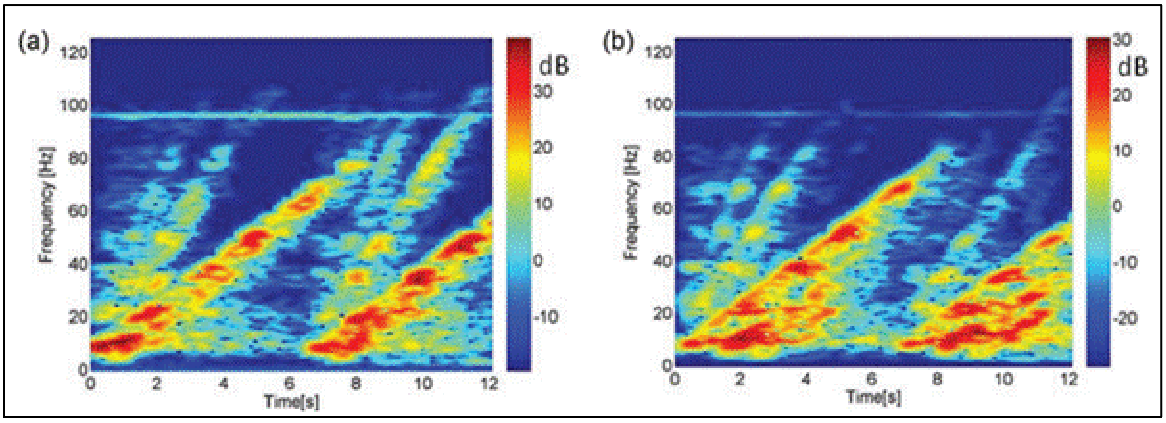

Figure 11: Frequency-time representation of harmonic distortion: fundamental and harmonic components overlapping in HP acquisition (Bagaini, 2010)

1.5.3. Impact on Data Quality

Both blended data and harmonic distortion can reduce the signal-to-noise ratio (SNR), distort amplitudes, and obscure subtle geological features, particularly critical in high-resolution and unconventional reservoir studies. This trade-off between operational efficiency and signal integrity is the central motivation for the noise attenuation methods reviewed in Chapter 2.

This chapter has presented the theoretical foundations of land seismic acquisition, from the fundamentals of Vibroseis sweep generation and correlation to the full spectrum of high-productivity techniques. Each successive technique, from Flip-Flop through Slip-Sweep, DS3/DS4, and finally ISS/MSS, achieves greater productivity at the cost of increasingly complex interference patterns. The harmonic noise problem, introduced in Section 1.5, defines the central processing challenge addressed in Chapter 2.

Chapter 2: Harmonic Noise Attenuation Methods

2.1. Introduction

High-productivity land seismic acquisition using vibratory sources introduces complex noise patterns, mainly related to source interference and harmonic distortion. The mitigation of this noise is carried out through dedicated processing techniques, each targeting a specific type of degradation at a specific stage of the workflow. This chapter presents and compares four established methods: HPVA (CGG), PSD-Harmonic (BGP), CHARM (Key Seismic), and ENAGEO-Advance.

Before examining these methods, it is useful to recall the context established in Chapter 1: in slip-sweep acquisition, the reduction of slip time increases the probability that harmonic energy generated by one vibrator point contaminates neighboring records. This contamination is coherent and cannot be processed as simple random noise, which is why dedicated attenuation algorithms are required.

2.2. Harmonic Noise in Slip-Sweep Acquisition

In vibratory-source acquisition, the interaction between the vibrator baseplate and the near surface is not perfectly linear. The generated signal may therefore contain harmonic components at multiples of the fundamental frequency. In slip-sweep acquisition, the reduction of slip time increases the probability that harmonic energy from one vibrator point contaminates another record, producing coherent interference that cannot be removed by correlation alone (Dean, 2016; Kuhn & Boroumand, 2018).

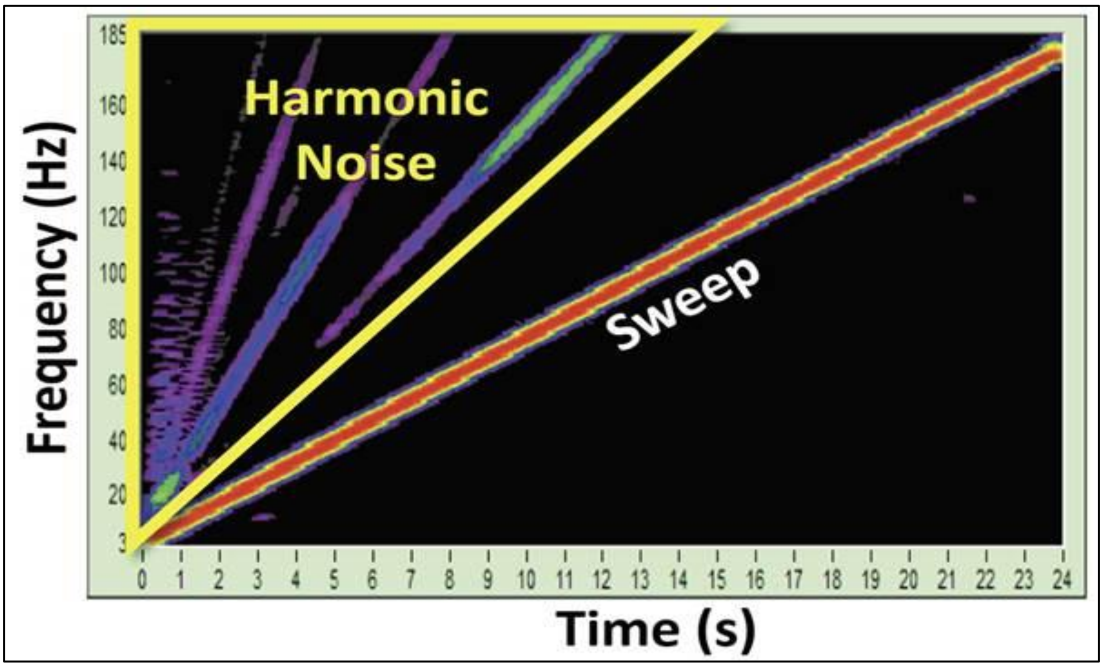

Figure 12: Fundamental and harmonic components on a frequency-time plot

The degree of harmonic contamination is mainly controlled by the slip time. When the slip time is sufficiently long, harmonic components do not interfere significantly with adjacent records. When it is reduced, harmonic noise may affect neighboring records, depending on how aggressive the acquisition parameters are.

2.3. Harmonic Noise Behavior Before and After Correlation

Before correlation, the fundamental component and its harmonics are distributed along the sweep duration in the time-frequency domain. After correlation, the fundamental signal is concentrated into a compact wavelet, whereas the harmonic components are displaced toward negative times. This explains why harmonic noise can contaminate adjacent records in slip-sweep acquisition: when slip time is short, the negative-time harmonic response may overlap with seismic events from previous shots.

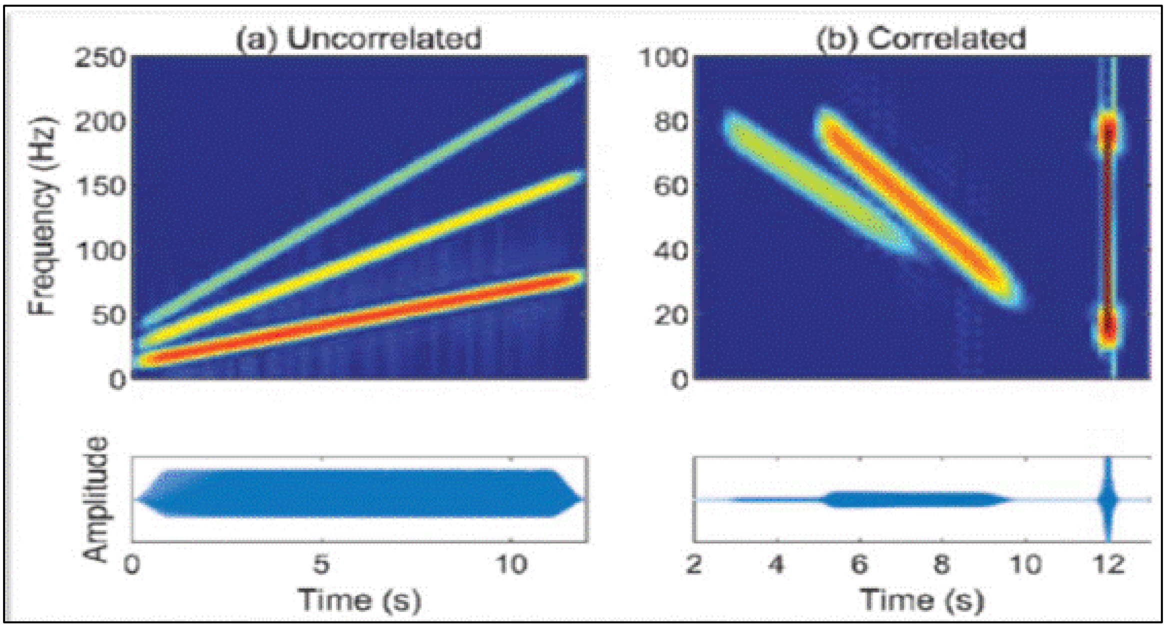

Figure 13: Fundamental and harmonic components before and after correlation, showing negative-time harmonic response (Dean, 2016)

This behavior also shows why harmonic noise cannot be removed by correlation alone. Dedicated harmonic attenuation methods are required after acquisition and correlation, particularly when high-productivity techniques are used.

2.4. Method 1: HPVA (CGG)

HPVA (High-Productivity Vibroseis Acquisition) is a processing approach developed to manage the harmonic noise problem while maintaining acquisition efficiency. The principle is based on the fact that harmonic noise has a specific, predictable behavior in both the time and frequency domains. Harmonic components appear at higher-order frequencies and may be shifted into time intervals where they interfere with neighboring records, making their attenuation possible through a processing approach that identifies and reduces harmonic energy without damaging the fundamental seismic signal.

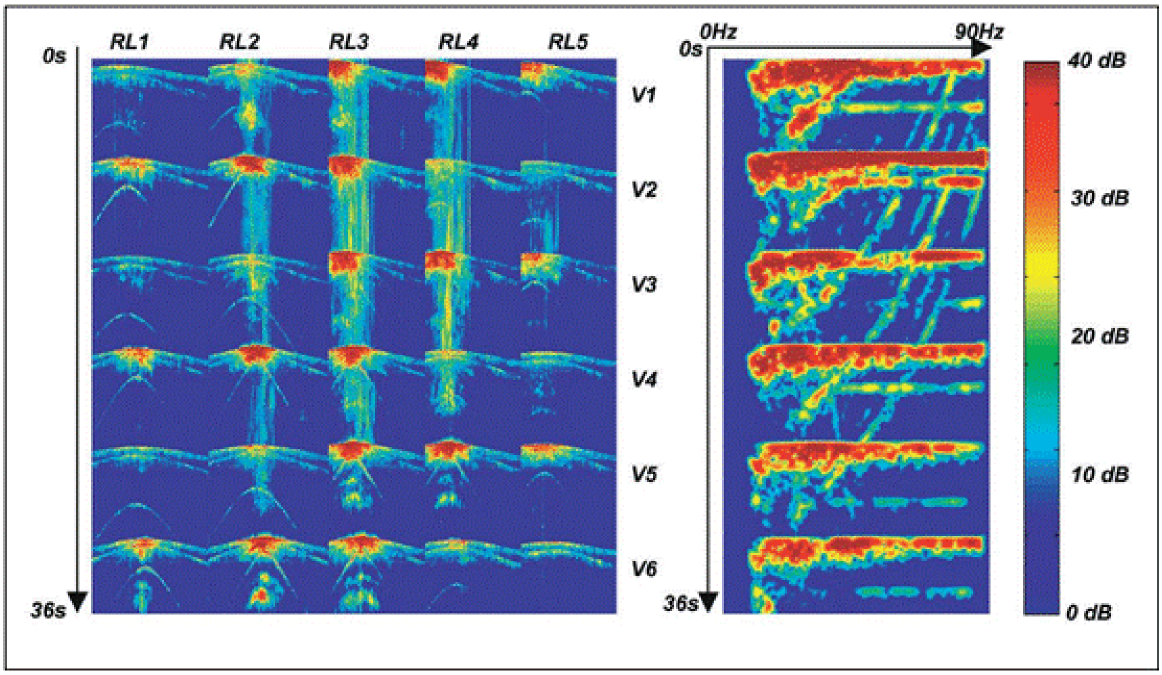

Figure 14: Correlated seismic data before HPVA processing with corresponding time-frequency representation (Taieb & Belbachir, 2020)

After HPVA processing, harmonic components are strongly reduced and the seismic record becomes cleaner. The comparison before and after processing shows that attenuation mainly affects the unwanted harmonic energy while preserving the continuity of useful seismic events. A further comparison between conventional records and HPVA-processed slip-sweep records allows evaluation of both data quality and operational efficiency.

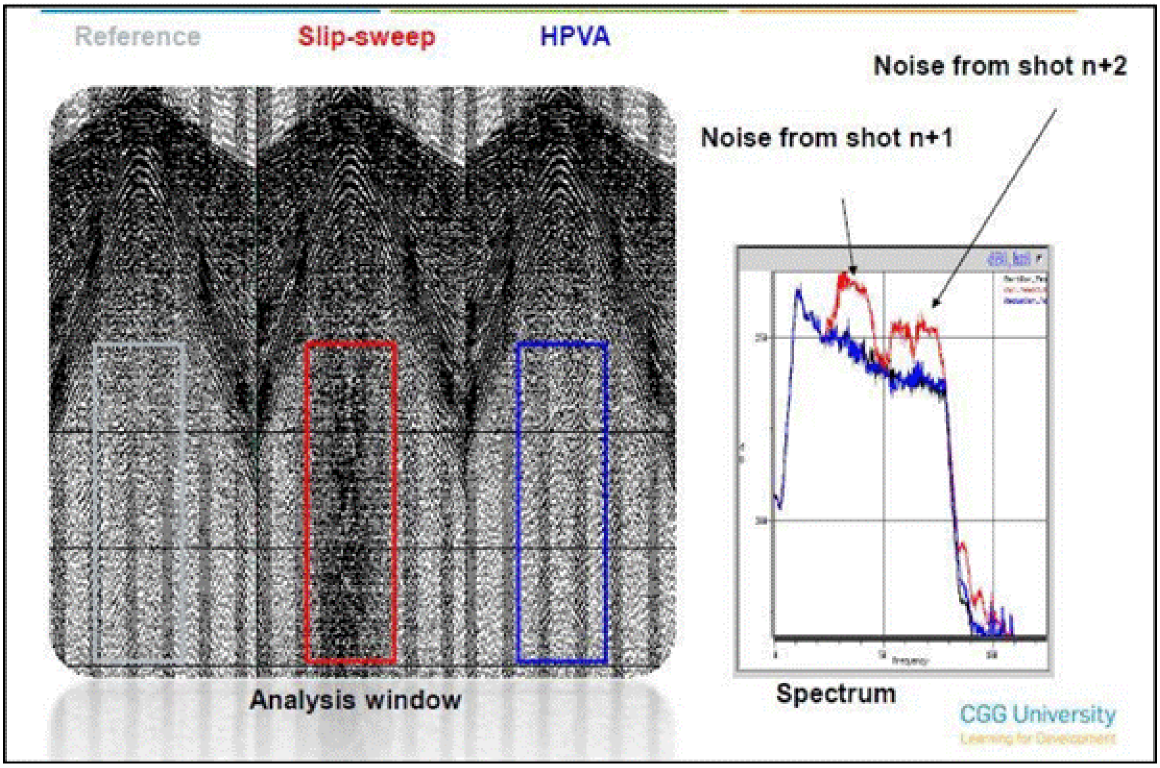

Figure 15: Comparison between conventional acquisition and slip-sweep data processed by HPVA (Taieb & Belbachir, 2020)

HPVA is particularly relevant when reduced slip time is required to improve field productivity, but where the final seismic image must remain reliable for interpretation. Its main value lies in combining acquisition efficiency with signal preservation.

2.5. Method 2: PSD-Harmonic (BGP)

The PSD-Harmonic approach is a software-based method developed to reduce harmonic noise in HP acquisition. Its key distinction is that it can be applied before correlation, where harmonic contamination is still directly linked to the original sweep signal. Since harmonic noise is generated at multiples of the fundamental sweep frequency, the software analyzes the frequency content of recorded data, detects harmonic energy, and applies a filtering process to attenuate this component before it becomes more difficult to manage in later processing stages.

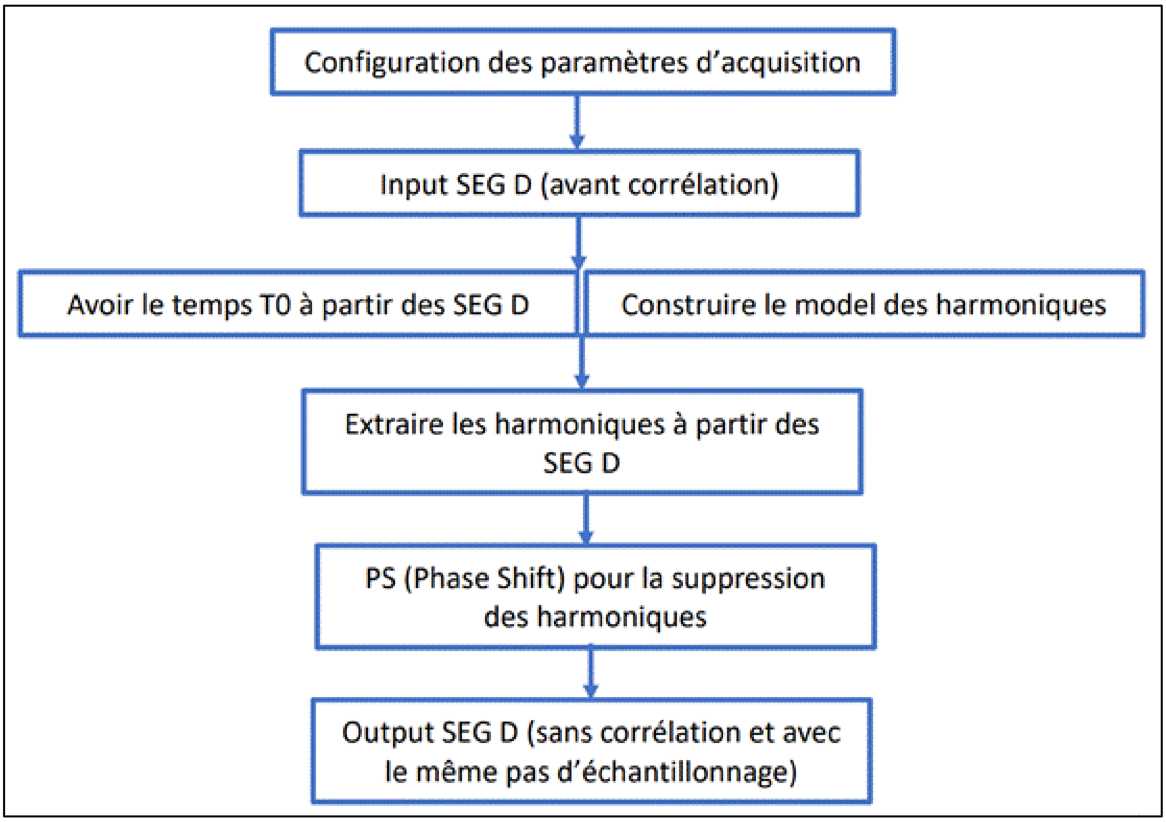

Figure 16: Workflow of PSD-Harmonic software for harmonic noise attenuation

A major advantage of this approach is that it processes harmonic noise before correlation. After correlation, harmonic components may be displaced into negative time and may overlap with useful events from neighboring records. By attenuating part of the harmonic content early in the workflow, PSD-Harmonic reduces the risk of spreading harmonic contamination into the final correlated data. This method is therefore particularly useful as a pre-conditioning step before further processing.

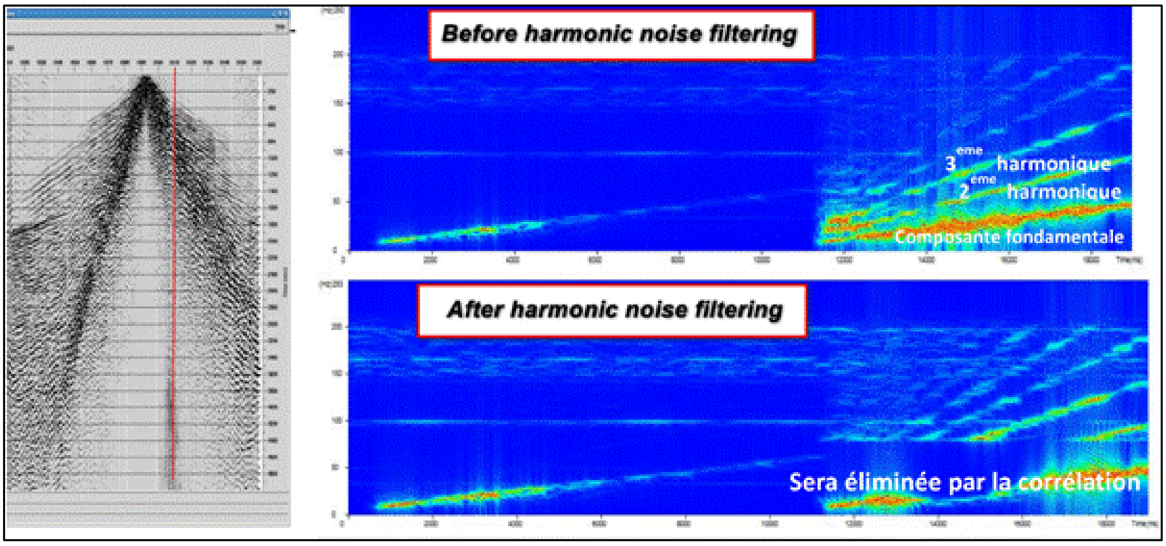

Figure 17: Partial filtering of harmonic noise using PSD-Harmonic before correlation (Taieb & Belbachir, 2020)

2.6. Method 3: CHARM (Key Seismic)

The CHARM method (Cleaning Harmonic noise) is based on identifying coherent harmonic contamination affecting a record, estimating its contribution, and removing it from the contaminated record by subtraction. In slip-sweep acquisition, the harmonic energy generated by one vibrator point may enter the recording window of another vibrator point, producing coherent events not related to the geological response of the subsurface.

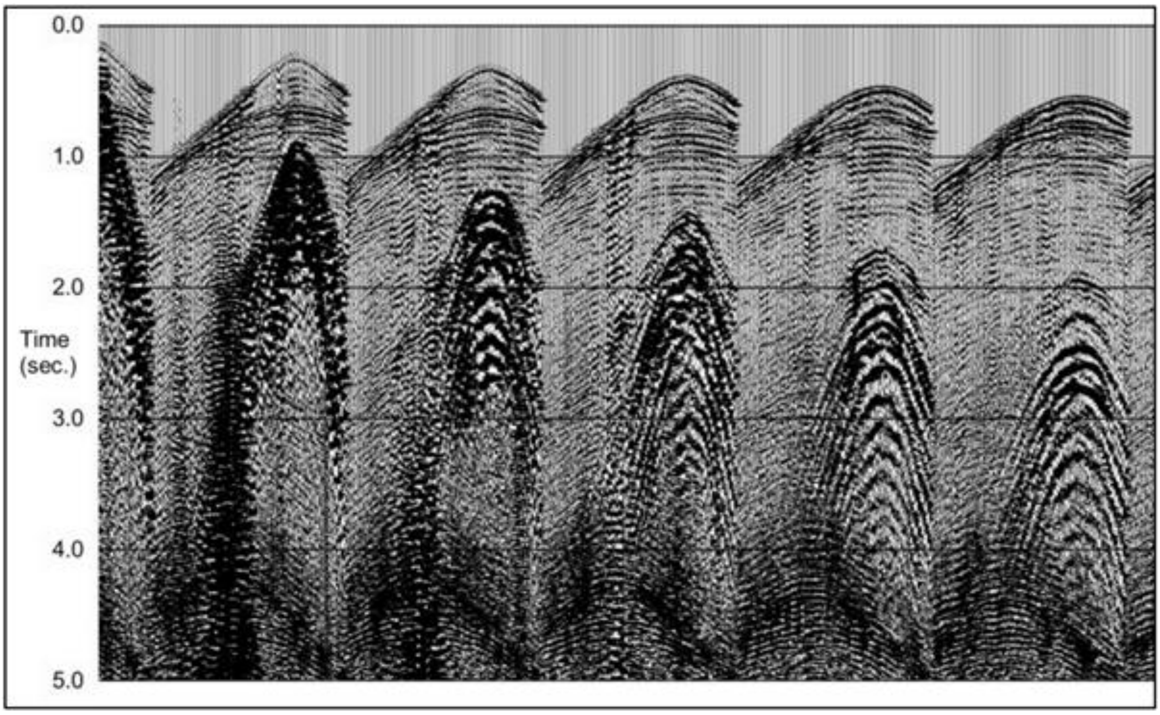

Figure 18: Record contaminated by harmonic noise from the previous shot (Taieb & Belbachir, 2020)

An important advantage of CHARM is that it provides the removed noise component separately as a residual. If the residual mainly contains harmonic patterns and does not contain significant useful seismic reflections, the attenuation process can be considered well controlled. This three-output approach, contaminated input, cleaned record, and residual, makes CHARM practical not only for attenuation but also for quality control.

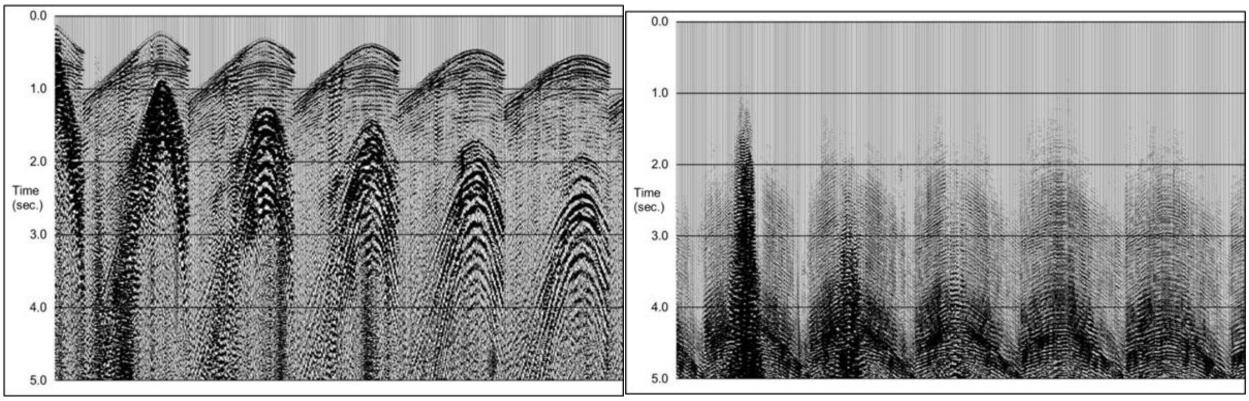

Figure 19: Left- Same record after CHARM processing; right – Residual (removed harmonic noise) (Taieb & Belbachir, 2020)

2.7. Method 4: ENAGEO-Advance

ENAGEO-Advance is a harmonic noise attenuation approach designed specifically for slip-sweep data. Its principle is based on constructing an attenuation operator, the ADVANCE operator, that accounts for the relationship between the fundamental component of the sweep and the harmonic components generated during vibration. This operator is more selective than a simple frequency filter because it targets harmonic distortion specifically rather than removing broad frequency content.

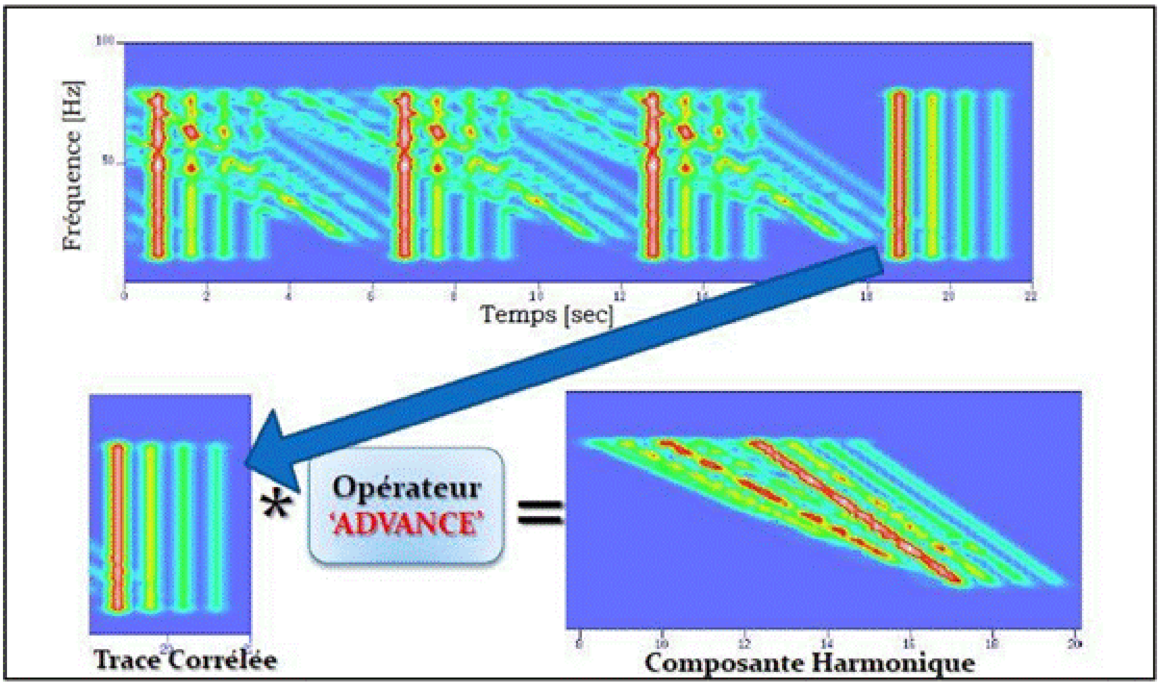

Figure 20: Calculation of the ADVANCE operator for harmonic distortion attenuation (ENAGEO, 2011)

A key feature of ENAGEO-Advance is that it considers harmonic contamination as part of the VP acquisition sequence: harmonics generated by one VP may contaminate another VP, and the method must account for the temporal relationship between successive VPs. The general cleaning sequence processes each contaminated record while considering its relationship with neighboring records. This sequential logic ensures that all affected VPs are processed coherently, without introducing artificial discontinuities.

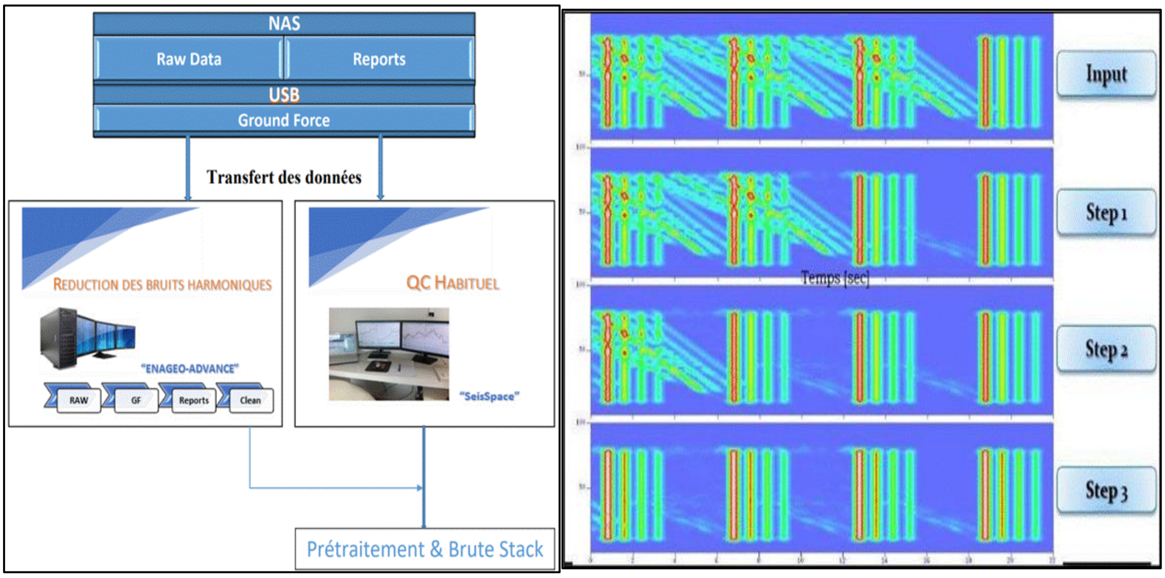

Figure 21:Data circulation in slip-sweep mode and VP cleaning sequence (ENAGEO, 2011)

The effectiveness of ENAGEO-Advance is evaluated by comparing raw data, cleaned data, and the residual component. Ideally the residual should contain mainly harmonic noise, with little or no useful reflection energy. This three-component comparison provides a practical quality-control framework.

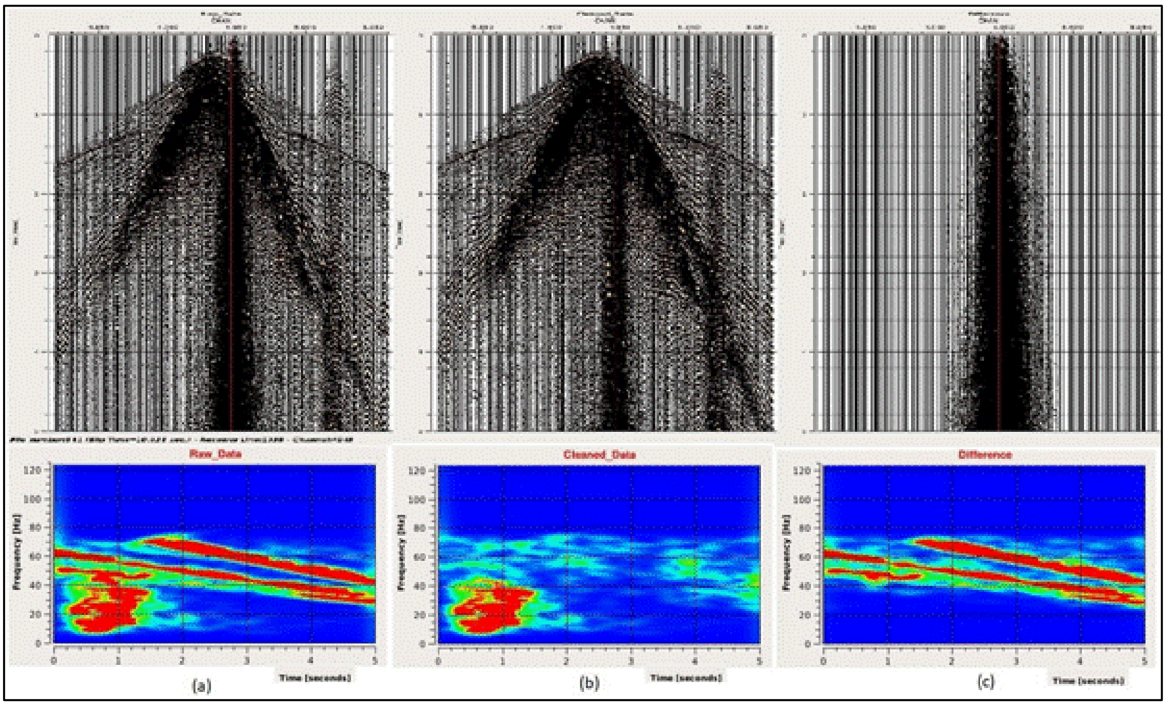

Figure 22:Shot and spectral analysis: (a) Raw data, (b) Cleaned data, (c) Residual component (VibroSeisLab/ENAGEO-Advance)

2.8. Deblending in the FK and Tau-p Domains

Beyond harmonic noise specifically, blended acquisition data can also be separated using transform-domain filtering. In the frequency-wavenumber (FK) domain, seismic events are organized according to their dip and direction of propagation. Overlapping signals from different sources generate coherent energy with different dips compared to primary reflections, making them distinguishable in the FK spectrum (Ikelle & Amundsen, 2005).

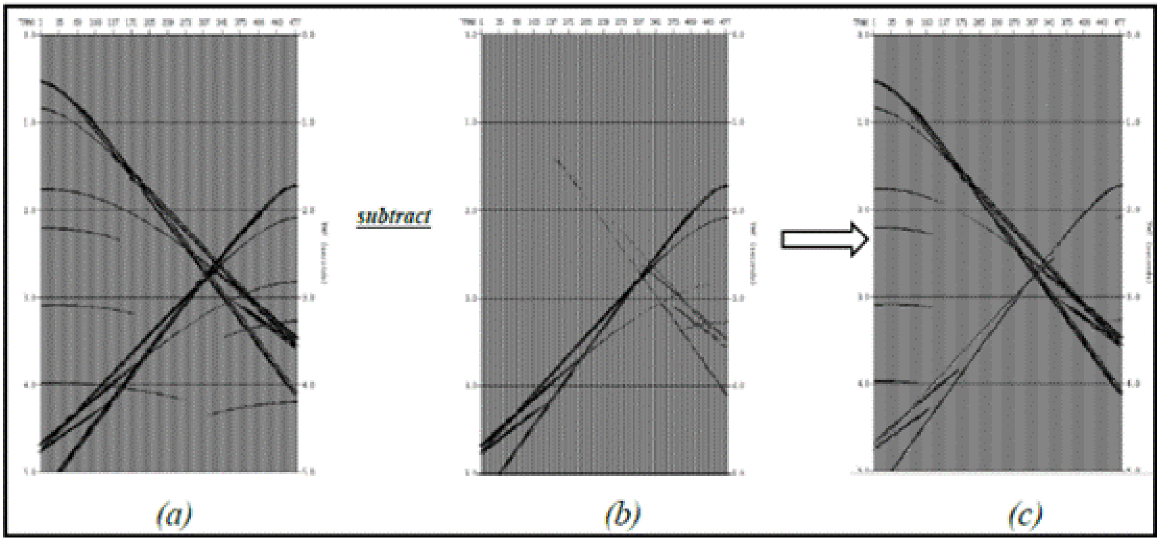

Figure 23:FK filtering process: (a) Blended input, (b) FK domain, (c) Deblended output (Uzma Mahmood, 2012)

The Tau-p transform reorganizes data according to apparent velocity. Events with different velocities map into different locations, allowing separation between primary reflections and interfering signals. The Tau-p method is particularly useful when signal and interference have similar dips but different velocities, and is often used in combination with FK filtering (Donati & Martin, 1996).

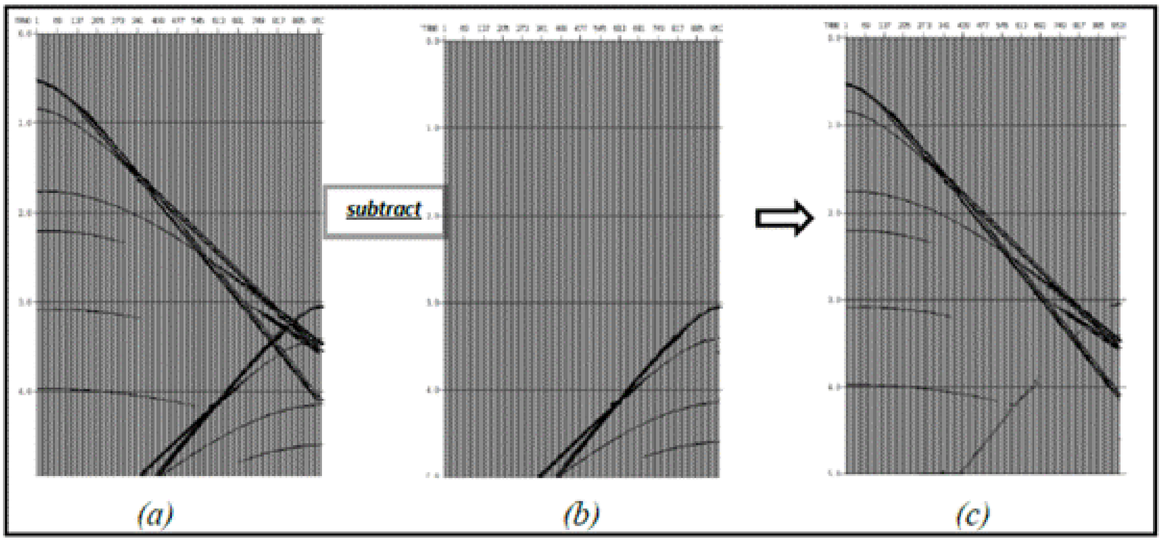

Figure 24:Tau-p filtering process: (a) Blended input, (b) Tau-p domain, (c) Deblended output (Mahmood, 2012)

2.9. Comparative Analysis of the Four Methods

The four methods described above address harmonic noise attenuation from different angles, applied at different stages of the processing workflow. Table 2 summarizes their key characteristics to facilitate practical method selection.

Table 2: Comparison of harmonic noise attenuation methods

Method	Principle	Processing Stage	Effectiveness	Limitations	Best Use Case
HPVA (CGG)	Correlates Ground Force to estimate and suppress harmonic energy in correlated gathers	Post-correlation	Moderate to strong; effective for standard slip-sweep regimes	Less effective when noise is very aggressive; requires stable Ground Force	Evaluating HP acquisition quality vs. conventional baseline
PSD-Harmonic (BGP)	Identifies harmonic frequency bands in pre-correlation data and attenuates them spectrally	Pre-correlation	Good for early-stage noise; reduces propagation into correlated domain	May miss harmonic energy that is frequency-interleaved with signal	Pre-conditioning slip-sweep data before correlation
CHARM (Key Seismic)	Isolates coherent harmonic events by subtraction; provides residual for QC	Post-correlation	High, especially for isolated contamination from adjacent VPs	Risk of over-subtraction if signal and noise overlap in dip/freq	Cleaning individual contaminated shot records; QC verification
ENAGEO-Advance	Builds ADVANCE operator from VP sequence relationships; cleans all VPs coherently	Pre- and post-correlation	High; adapts to acquisition sequence; handles VP-to-VP contamination	Requires accurate VP timing and sequence metadata	Systematic full-dataset cleaning in slip-sweep surveys

The choice of method depends on the processing objective. For evaluating HP acquisition performance relative to conventional data, HPVA provides a useful comparison framework. For reducing harmonic noise before correlation, PSD-Harmonic is most appropriate. When contamination is clearly visible and can be isolated, CHARM offers a controlled subtraction approach. For slip-sweep datasets requiring systematic VP-to-VP processing, ENAGEO-Advance is the most relevant because it directly addresses harmonic interference between vibrator points.

It is also important to note that these methods are not mutually exclusive. In practice, they can be combined: PSD-Harmonic may be applied first as a pre-conditioning step, followed by CHARM or ENAGEO-Advance for residual correction. The goal in all cases is to reduce harmonic contamination without compromising the integrity of primary seismic reflections.

This chapter has reviewed four established harmonic noise attenuation methods used in high-productivity Vibroseis acquisition: HPVA, PSD-Harmonic, CHARM, and ENAGEO-Advance. Each method operates according to a different logic and is suited to different stages of the processing workflow and different levels of contamination. The comparative analysis in Table 2 provides a practical decision framework.

Two complementary transform-domain deblending approaches, FK filtering and Tau-p filtering, were also presented for cases where blending interference extends beyond harmonic noise alone. Chapter 3 now draws on published field case studies to evaluate how these methods perform in real survey environments, providing an empirical perspective that complements the theoretical comparison made here.

Chapter 3: Comparative Case Studies from Published Literature

3.1. Introduction

Since no proprietary field data were available for this study, this chapter adopts a structured literature-based approach: it reviews and compares published real-world case studies where both conventional and high-productivity acquisition were applied and where harmonic noise attenuation results were documented. This methodology is well-established in geophysical research and allows the performance of different acquisition-processing combinations to be evaluated across a range of survey environments and geological contexts.

Four case studies are examined, each corresponding to a different HP technique and noise attenuation method. The chapter concludes with a cross-case comparative analysis and practical recommendations for survey designers.

3.2. Case Study 1: Slip-Sweep with Harmonic Filtering in a Desert Environment

3.2.1. Survey Context

The foundational case for Slip-Sweep acquisition is presented by Rozemond (1996), describing early field trials in a Middle Eastern desert environment. The survey objective was to demonstrate that reducing the slip time between consecutive sweeps could substantially increase production rates without unacceptably degrading seismic data quality.

3.2.2. Acquisition Parameters

The trial used a linear sweep over a frequency range of approximately 10–100 Hz, with sweep lengths of 12–18 seconds. Slip times were varied systematically across tests to evaluate the transition between noise-free, non-aggressive, and aggressive regimes (as later formalized by Dean, 2016). Multiple vibrator fleets were used to maximize productivity.

3.2.3. Noise Attenuation Approach

Post-correlation harmonic filtering was applied based on the frequency-time behavior of harmonic components. The approach is conceptually similar to what is later formalized in HPVA, targeting energy that appears at predictable harmonic offsets in the correlated record.

3.2.4. Results

Rozemond (1996) demonstrated that for moderate slip times (non-aggressive regime), harmonic noise could be sufficiently attenuated to yield data quality comparable to conventional sequential acquisition. Productivity gains of approximately 2–3 times conventional VP/hour rates were reported. More aggressive slip times introduced residual noise that required additional processing, confirming the direct relationship between slip time and data quality described in Chapter 1.

3.3. Case Study 2: ISS with Deblending in a Large 3D Survey

3.3.1. Survey Context

Howe et al. (2008) describe the application of Independent Simultaneous Sweeping (ISS) in a large-scale 3D land survey in North Africa. The objective was to demonstrate that ISS could achieve ultra-high productivity rates while delivering seismic data of sufficient quality for interpretation after deblending.

3.3.2. Acquisition Parameters

The ISS configuration involved multiple vibrators operating completely independently, each initiating sweeps without synchronization constraints. Production rates exceeded 1,000 VP/hour, representing a factor of 4–6 increase over conventional acquisition. Linear sweeps of 10–84 Hz and approximately 12 seconds length were used. Receiver spreads were dense to support deblending.

3.3.3. Noise Attenuation Approach

The fully blended nature of ISS data required a complete deblending workflow: FK-domain separation was applied first to exploit dip differences between overlapping wavefields, followed by iterative subtraction to remove residual interference. The deblending approach is closely related to what Bagaini (2010) describes for ISS processing.

3.3.4. Results

After deblending, the ISS data showed near-conventional reflection quality in terms of continuity, amplitude, and signal-to-noise ratio. The study confirmed that ISS is viable for large surveys where receiver infrastructure is dense enough to support the deblending process. The trade-off is a significantly more complex processing workflow compared to slip-sweep, requiring careful QC at each stage.

3.4. Case Study 3: ISS with CHARM in Complex Terrain

3.4.1. Survey Context

Bagaini (2010) presents an evaluation of ISS in an environment with irregular terrain, where the controlled randomness of source activation leads to more complex interference patterns than in flat desert environments. The study specifically evaluates CHARM as a harmonic noise cleaning tool within the broader ISS deblending workflow.

3.4.2. Acquisition Parameters

Sources were activated with controlled randomness to ensure appropriate subsurface illumination. The survey used both linear and non-linear sweeps, with sweep lengths of approximately 14 seconds over a frequency range of 8–100 Hz. VP density was higher than in conventional surveys to compensate for the blended nature of the data.

3.4.3. Noise Attenuation Approach

CHARM was applied to identify and subtract coherent harmonic contamination from individual shot records. The method's residual analysis was used as a quality-control indicator to verify that useful signal was preserved. CHARM was applied before the main deblending stage to reduce harmonic interference that would otherwise complicate the separation of overlapping wavefields.

3.4.4. Results

CHARM successfully attenuated harmonic events in the majority of contaminated records. The residual analysis confirmed that the removed energy was predominantly harmonic rather than useful reflection energy. Post-CHARM deblending then achieved good separation of individual source contributions, yielding a clean stacked section. However, the study noted that in areas of steep terrain, vibrator ground coupling was less stable, which reduced the consistency of CHARM's subtraction operator.

3.5. Case Study 4: Slip-Sweep with ENAGEO-Advance in an Algerian Context

3.5.1. Survey Context

Taieb & Belbachir (2020) and associated ENAGEO technical documentation describe the application of slip-sweep acquisition in the Algerian Saharan basin, a survey context closely related to ENAGEO's operational environment. The study evaluates ENAGEO-Advance as the primary harmonic noise attenuation tool, applied systematically across a full VP dataset.

3.5.2. Acquisition Parameters

The survey used a frequency range of 6–80 Hz with sweep lengths of approximately 14 seconds. Slip times were chosen in the non-aggressive to moderately aggressive range to balance productivity and data quality. Source geometry followed standard 3D land acquisition patterns adapted to Saharan terrain (flat, open access, limited vegetation). VP spacing was reduced relative to conventional to partially compensate for productivity-driven noise.

3.5.3. Noise Attenuation Approach

ENAGEO-Advance was applied by first constructing the ADVANCE operator from the VP acquisition sequence, then cleaning each VP record in sequence order, accounting for harmonic contamination from neighboring sweeps. Single-VP tests were performed first to validate the operator before full-dataset processing.

3.5.4. Results

The ENAGEO-Advance approach effectively removed VP-to-VP harmonic contamination across the full dataset. The cleaned data showed improved continuity of reflection events and a measurable increase in signal-to-noise ratio relative to the raw slip-sweep records. Comparison between conventional records and ENAGEO-Advance-processed slip-sweep data showed that the harmonic attenuation brought the slip-sweep data quality close to the conventional baseline, while achieving approximately 2–3 times the conventional productivity rate. The residual panels confirmed that the removed energy was predominantly harmonic rather than useful signal.

3.6. Cross-Case Comparative Analysis

Table 3 below synthesizes the four case studies across the key performance dimensions.

Table 3: Summary comparison of published case studies

Case	Region	HP Technique	Noise Method	SNR Improvement	Productivity Gain	Key Limitation
Case 1 (Rozemond 1996)	Middle East (desert)	Slip-Sweep (slip time 4–8 s)	HPVA / post-corr. harmonic filtering	Significant; harmonics suppressed below noise floor	~2–3× conventional VP/hour rate	Aggressive slip times can leave residual noise
Case 2 (Howe et al. 2008)	North Africa / Sahara	ISS – Independent Simultaneous Sweeping	Deblending + FK/Tau-p separation	High; near-conventional quality achieved after deblending	~4–6× conventional; >1000 VP/hour	Complex processing; requires robust receiver spread
Case 3 (Bagaini 2010)	Transition zone / complex terrain	ISS with controlled randomness	CHARM – subtraction of coherent harmonic events	Good; residual analysis confirms signal preservation	3–4× conventional	Terrain variability affects operator stability
Case 4 (Taieb & Belbachir 2020)	Algeria / Saharan basin	Slip-Sweep (ENAGEO survey context)	ENAGEO-Advance VP sequence operator	High; VP-to-VP contamination effectively removed	2–3× conventional; full dataset cleaned consistently	Requires precise VP timing and sequence metadata

Several patterns emerge from this cross-case comparison:

First, productivity and processing complexity are strongly correlated. Slip-Sweep (Cases 1 and 4) achieves moderate productivity gains (2–4×) with manageable processing workflows, while ISS (Cases 2 and 3) achieves much higher gains (4–8×) but requires substantially more complex deblending. Survey designers must therefore weigh the operational benefit against the processing cost.

Second, all four methods succeed in bringing HP data quality close to conventional baselines when appropriately applied. The key variable is not the method itself but the match between the method and the acquisition regime: HPVA and ENAGEO-Advance are most effective for slip-sweep regimes; FK/Tau-p deblending and CHARM are more appropriate for ISS and fully blended data.

Third, the terrain and ground coupling conditions affect all methods. Desert environments (Cases 1 and 4) provide the most stable conditions for harmonic attenuation, while complex terrain (Case 3) introduces variability that reduces operator consistency. This environmental factor should be considered at the survey design stage, not only during processing.

3.7. Discussion and Recommendations

Based on the cross-case analysis, the following practical recommendations can be offered for survey designers and processing engineers working with HP Vibroseis acquisition:

- Match the slip time to the noise regime. For surveys where data quality is critical, use slip times in the noise-free or non-aggressive regime (as defined in Chapter 1) even if this moderately reduces productivity. The processing burden of aggressive harmonic noise often outweighs the productivity gain.
- Apply pre-correlation filtering (PSD-Harmonic) as a standard pre-conditioning step for slip-sweep data. Attenuating part of the harmonic energy before correlation limits its propagation into later processing stages.
- Use CHARM or ENAGEO-Advance for VP-to-VP contamination. Both methods are specifically designed to handle the coherent harmonic interference pattern that is characteristic of slip-sweep. The choice between them depends on data volume, software availability, and QC requirements.
- Reserve ISS for surveys with dense receiver infrastructure. ISS achieves the highest productivity gains but requires robust deblending. Without sufficient receiver density, deblending quality degrades and the productivity advantage may be partially offset by data quality loss.
- Always include residual analysis as a QC step. The residual between raw and cleaned data provides a direct indicator of whether the attenuation targeted harmonic noise or inadvertently removed useful reflection energy.

This chapter has reviewed four published case studies spanning the main high-productivity acquisition techniques, Slip-Sweep (Rozemond, 1996; Taieb & Belbachir, 2020), ISS (Howe et al., 2008; Bagaini, 2010), and the corresponding noise attenuation methods evaluated in Chapter 2. The cross-case analysis confirms that HP acquisition can achieve near-conventional data quality when appropriately matched with the right attenuation workflow. Productivity gains range from 2× for moderate slip-sweep to 6× or more for full ISS, with processing complexity scaling accordingly. The environmental context, particularly terrain stability and ground coupling, is a significant modulator of method effectiveness across all cases.

Chapter 4: HNAM-DST- A Decision-Support Tool for Harmonic Noise Attenuation Method Selection

4.1. Introduction and Motivation

The three preceding chapters have established that harmonic noise attenuation in high-productivity Vibroseis acquisition is not a single-method problem. The choice between HPVA, PSD-Harmonic, CHARM, and ENAGEO-Advance depends on a combination of acquisition parameters, field conditions, processing constraints, and quality objectives, none of which is fixed across surveys. Chapter 2 provided a comparative analysis of these methods, and Chapter 3 demonstrated through published case studies that method performance varies substantially across survey environments.

However, the existing literature does not provide a structured, quantitative framework that translates survey-specific parameters directly into a method recommendation. Practitioners must currently rely on experience and case-by-case judgment. This gap motivated the development of the Harmonic Noise Attenuation Method Decision-Support Tool (HNAM-DST), which constitutes the original applied contribution of this thesis.

HNAM-DST is an interactive, browser-based tool that implements a weighted multi-criterion scoring framework. Given seven input parameters describing the survey configuration, the tool computes a suitability score for each of the four attenuation methods, identifies the optimal recommendation with a written justification, and generates a corresponding five-step processing workflow. The tool runs entirely offline in any standard web browser, requires no installation, and is designed to be used both as a practical decision aid in professional contexts and as a reproducible, auditable academic instrument.

This chapter documents the full design rationale, input parameter definitions, scoring methodology, and recommendation logic.

4.2. Tool Architecture and Interface

4.2.1. Technical Implementation

HNAM-DST is implemented as a single self-contained HTML file incorporating HTML5 markup, CSS3 styling, and vanilla JavaScript. The entire tool, including the scoring engine, display logic, and all reference data, is contained within this single file. No external server, database, library, or network connection is required at runtime. The tool is therefore fully portable and suitable for use in offline field and office environments, and can be opened directly in any modern web browser by double-clicking the file.

The scoring computation is performed client-side in the browser. All seven input parameters are read at evaluation time, the scoring matrix is queried, dynamic weight adjustments are applied, weighted scores are computed, and results are rendered, all within a fraction of a second. Because no data leaves the browser, the tool is also fully privacy-compliant for surveys with confidential acquisition parameters.

4.2.2. Interface Layout

The interface is structured in two panels. The left panel contains the seven input parameter controls: five drop-down selectors for categorical parameters and two range sliders for continuous parameters. The right panel, activated when the user clicks the "Evaluate & Recommend" button, displays the following four output components in sequence:

- **The primary recommendation block**: displays the winning method name and a context-specific justification paragraph generated from the input configuration.
- **The scored method ranking**: shows all four methods with numerical scores out of 100, proportional score bars, and color-coded suitability tags specific to the current parameters.
- **The scoring matrix breakdown table**: shows the raw score (0–10) for each method on each criterion and the applied criterion weight, with row highlighting for the winning method's strongest criteria.
- **The recommended processing workflow**: presents a five-step sequential procedure specific to the recommended method, with a step title and a descriptive action note for each step.
- **The active criteria weights display**: shows the final normalized percentage weight assigned to each criterion for the current input configuration, making the weighting logic fully transparent.

All output components update dynamically each time the user re-evaluates with new parameters, without any page reload.

4.3. Input Parameter Definitions

The seven input parameters were selected to represent the primary variables that the literature identifies as determinants of harmonic noise behavior and attenuation method effectiveness (Meunier & Bianchi, 2005; Abd El-Aal, 2011; Bagaini et al., 2012). Each parameter is defined below with its available values and its grounding in published sources.

4.3.1. Parameter 1: Acquisition Technique

This parameter identifies the high-productivity method used in the survey. It is the most fundamental structural determinant of both the type and the severity of harmonic interference, because each technique produces a distinct temporal overlap pattern between source activations (Dean, 2016; Bagaini et al., 2012; Huo et al., 2012). Four options are provided:

- **Slip-Sweep:** consecutive sweeps overlap by a controlled slip time; harmonic contamination is coherent and VP-to-VP sequential in nature (Rozemond, 1996).
- **Independent Simultaneous Sweeping (ISS):** multiple vibrators operate fully independently; produces fully blended data requiring deblending before harmonic attenuation (Howe et al., 2008).

- **Distance-Separated Simultaneous Sweeping (DS3):** spatial separation limits interference; harmonic noise is present but less severe than Slip-Sweep (Bouska, 2010).
- **Flip-Flop:** alternating fleets with minimal overlap; nearest to conventional acquisition; harmonic noise is typically low to moderate

4.3.2. Parameter 2: Slip Time

Slip time is the interval in seconds between the start of one sweep and the start of the next consecutive sweep. It is entered via a range slider from 1 second (highly aggressive) to 14 seconds (approaching the noise-free regime), with a step of 0.5 seconds. This is the primary quantitative indicator of harmonic contamination severity in Slip-Sweep acquisition (Meunier & Bianchi, 2005; Zhang et al., 2012).

The theoretical basis for this parameter is established by Dean (2016), who define three interference regimes as a function of slip time relative to sweep length and the harmonic offset in the correlated domain. HNAM-DST uses the slip time value to dynamically adjust the effective severity parameter when the technique is Slip-Sweep, applying the following override rules derived from Dean (2016) and Rozemond (1996):

Slip time range	Effective severity override	Regime (Dean, 2016)
≤ 3 seconds	Forced to High regardless of manual selection	Aggressive: strong harmonic overlap across records
3 – 7 seconds	Manual selection preserved; Low upgraded to Moderate	Non-aggressive: limited, manageable interference
> 7 seconds	High downgraded to Moderate; other levels preserved	Noise-free to near-noise-free: minimal overlap

4.3.3. Parameter 3: Harmonic Noise Severity

This parameter captures the observed level of harmonic contamination on the raw records, as assessed by visual inspection of shot gathers and time-frequency analysis (Abd El-Aal, 2011; Liu et al., 2022). Three levels are defined, consistent with the qualitative severity descriptions used in Taieb & Belbachir (2020) and Bagaini (2010):

Level	Observable characteristics on shot records	Typical acquisition context
Low	Harmonic bands barely visible; traces essentially clean; no significant overlap with primary reflections	Long slip times; stable vibrators; noise-free regime (Dean, 2016)
Moderate	Clear harmonic bands in time-frequency representation; limited overlap with useful signal; attenuation recommended but not urgent	Non-aggressive slip-sweep; standard DS3/DS4 operations
High	Strong coherent contamination across multiple consecutive records; harmonics mask or distort reflections;	Aggressive slip times (< 3 s); fully blended ISS; high vibrator density

Level	Observable characteristics on shot records	Typical acquisition context
	attenuation is essential before any further processing	

4.3.4. Parameter 4: Terrain and Ground Coupling

This parameter represents the expected stability of vibrator-ground coupling and near-surface conditions (Sallas, 1984; Castor et al., 2015), which directly governs how accurately any operator-based attenuation method can estimate and remove harmonic components. Ground coupling conditions determine the repeatability of the emitted signal and therefore the reliability of Ground Force measurements used by HPVA and ENAGEO-Advance (Sallas, 1984). Three levels are defined:

- **Stable**: flat desert, hardpan, compacted soil. Vibrator coupling is consistent and repeatable across VPs; all operator-based methods perform reliably.
- **Moderate**: mixed sand/gravel, gentle topographic relief. Some variability in coupling; operator-based methods remain effective with per-VP QC monitoring.
- **Complex**: dunes, rocky outcrops, soft or highly variable near-surface. Coupling instability reduces the performance of operator-based methods (HPVA and ENAGEO-Advance); favors methods that do not require a stable physics-based operator (CHARM, PSD-Harmonic), as documented in Bagaini (2010).

4.3.5. Parameter 5: Processing Stage Available

This parameter defines at which stage of the processing sequence harmonic attenuation will be applied (Abd El-Aal, 2011; Zhang et al., 2012; Castor et al., 2015). It is assigned the highest base weight of any criterion (20%), reflecting the fact that applying a method in the wrong processing domain is a fundamental workflow error that no other parameter can compensate for. Three options are provided:

- **Pre-correlation only**: attenuation applied to raw, uncorrelated records. Only PSD-Harmonic is designed to operate effectively in this domain, where harmonic energy is still frequency-ordered according to the sweep law and has not yet been displaced to negative correlation times (Taieb & Belbachir, 2020).
- **Post-correlation only**: attenuation applied after correlation, where harmonic components appear at predictable negative time offsets. HPVA, CHARM, and ENAGEO-Advance all operate in this domain.
- **Both stages available**: full workflow flexibility. This configuration slightly favors ENAGEO-Advance (which can combine pre- and post-correlation steps) and enables PSD-Harmonic as a complementary pre-conditioning stage before any post-correlation method.

4.3.6. Parameter 6: Data Quality Priority

This parameter is a five-point integer scale expressing the relative priority placed on data quality versus processing speed and simplicity. It is entered via a range slider from 1 (speed priority) to 5 (quality priority). The underlying rationale is that survey objectives differ substantially: a regional reconnaissance survey tolerates more residual noise than a detailed reservoir characterization study requiring amplitude-preserving processing (Bagaini et al., 2012; Huo et al., 2012; Liu et al., 2022).

At lower priority levels (1–2), simpler methods with lower computational burden are favored, HPVA and PSD-Harmonic receive higher quality/complexity scores. At higher priority levels (4–5), methods offering more thorough attenuation and built-in quality control, CHARM (through residual analysis) and ENAGEO-Advance (through VP-sequence operator calibration), are favored despite greater complexity.

4.3.7. Parameter 7: Software and Processing Tools Available

This parameter identifies which specialist harmonic attenuation software is available to the processing team. Five options are provided: ENAGEO-Advance, CHARM / Key Seismic, PSD-Harmonic (BGP), HPVA / CGG tools, and generic processing only (FK/Tau-p filtering, no specialist tool). This criterion is weighted at 15% base and receives a +5 point bonus when any specialist tool is selected (see Section 4.5), reflecting that software availability is a near-binding practical constraint: recommending a method that requires tools the team does not possess is not actionable.

When a specialist tool is explicitly available, the software criterion score for that tool's method is 10/10 (maximum), while all other methods receive reduced scores (4–6/10). When only generic tools are available, all methods receive a moderate score of 6/10 on this criterion, meaning other criteria become more decisive.

4.4. The Scoring Matrix

4.4.1. Structure and Scoring Formula

The scoring matrix is the analytical core of HNAM-DST. It assigns a raw suitability score from 0 to 10 to each of the four methods for each of the six evaluation criteria, for every possible combination of input values. These scores are multiplied by the corresponding normalized criterion weights and summed to produce the final recommendation score for each method.

The scoring formula applied to method m is:

$$\text{Score}(\boldsymbol{m}) = \frac{\sum_i [\boldsymbol{w_i} \times \boldsymbol{s}(\boldsymbol{i}, \boldsymbol{m})]}{\mathbf{10}}$$

$$\boldsymbol{for\ i\ in\ 1 \ldots 7 criteria}$$

where w_i is the normalized weight of criterion i (percentage, summing to 100 across all criteria) and s_{im} is the raw score of method m on criterion i (integer from 0 to 10). Dividing by 10 rescales the weighted sum so that a method scoring 10/10 on all criteria at equal weights would achieve 100.

4.4.2. Full Base Score Matrix

The base scores were assigned by synthesizing the comparative analysis in Chapter 2 and the case study evidence from Chapter 3. Each score reflects the expected suitability of a method under a specific criterion value, grounded in documented performance in the reviewed literature. Table 4 presents the complete matrix.

Table 4: Full base score matrix: raw suitability scores (0–10) per method per criterion value. Scores in bold indicate the highest value in each row.

Criterion	Value	HPVA	PSD	CHARM	ENAGEO
Processing stage	Pre-correlation	4	10	4	6
	Post-correlation	9	4	9	8
	Both stages	8	8	8	9
Technique	Slip-Sweep	7	7	8	10
	ISS	5	5	8	5
	DS3/DS4	7	6	6	6
	Flip-Flop	8	5	5	5
Noise severity	Low	8	6	6	7
	Moderate	8	7	8	9
	High	6	6	9	9
Terrain	Stable	8	8	8	9
	Moderate	7	7	7	8
	Complex	5	6	7	6
Software	ENAGEO-Advance	4	5	6	10
	CHARM / Key Seismic	4	5	10	5
	PSD-Harmonic (BGP)	4	10	5	5
	HPVA / CGG tools	10	4	5	5
	Generic only (FK/Tau-p)	6	6	6	6
Quality priority	1 - speed priority	9	8	7	6
	2	8	8	7	7
	3 - balanced	7	7	8	8
	4	6	6	8	9
	5 - quality priority	5	5	8	9

4.4.3. Rationale for Key Score Assignments

Each score reflects the expected suitability of a method under a specific criterion value, grounded in documented performance in the reviewed literature (Abd El-Aal, 2011; Zhang et al., 2012).

Processing stage - Pre-correlation domain: PSD-Harmonic receives the maximum score of 10/10 for the pre-correlation stage because it is the only method specifically designed to operate in the uncorrelated domain, where harmonic components are still frequency-ordered according to the sweep rate law. HPVA and CHARM both receive 4/10 for pre-correlation because neither method was designed for or documented in that domain (Meunier & Bianchi, 2005; Taieb & Belbachir, 2020). ENAGEO-Advance receives 6/10 because while primarily a post-correlation method, elements of its operator construction involve pre-correlation signal analysis.

Technique - Slip-Sweep: ENAGEO-Advance receives 10/10 because it was specifically developed to address VP-to-VP harmonic contamination, which is the defining noise pattern of slip-sweep acquisition. No other method directly models the sequential contamination logic between consecutive VPs in the acquisition order (Taieb & Belbachir, 2020). CHARM receives 8/10 because its record-by-record subtraction approach is applicable to any acquisition mode. HPVA and PSD-Harmonic both receive 7/10 because they are documented for slip-sweep contexts but do not specifically address VP-sequence contamination.

Noise severity – High: CHARM and ENAGEO-Advance both receive 9/10 at high severity because they provide the most thorough and verifiable attenuation under severe conditions: CHARM through residual panel QC, ENAGEO-Advance through full VP-sequence operator calibration. HPVA receives 6/10 at high severity because its Ground Force estimation is less effective when multiple overlapping harmonic orders produce complex interference patterns

Terrain - Complex conditions: CHARM receives the highest score of 7/10 for complex terrain because its subtraction approach identifies coherent harmonic events visually without requiring a stable physics-based operator. ENAGEO-Advance and HPVA both receive 6/10 and 5/10 respectively for complex terrain, because both depend on stable Ground Force measurements and consistent vibrator-ground coupling for accurate operator construction, conditions that complex terrain undermines (Sallas, 1984; Bagaini, 2010).

4.5. Dynamic Weight Adjustment Mechanism

4.5.1. Principle

A fixed weight scheme applied uniformly across all configurations would fail to capture the context-dependence of criterion importance (Pecholcs et al., 2010; Bagaini et al., 2012; Huo et al., 2012). For example, when a specific specialist tool is available, software availability functions as a near-binding constraint and should exert proportionally higher influence on the final score. Conversely, when both processing stages are available, the stage criterion becomes less discriminating. HNAM-DST therefore uses a dynamic adjustment mechanism: base criterion weights are increased by a fixed number of points when specific conditions are met, before normalization to 100%.

4.5.2. Adjustment Rules

Five adjustment rules are defined, as shown in Table 5. These rules were designed to reflect the practical observation that certain survey configurations make some criteria more decisive than others, based on the operational logic described in the case studies of Chapter 3.

Table 5: Dynamic weight adjustment rules applied before normalization to 100%

Criterion	Trigger condition	Points added	Rationale
Processing stage fit	Both stages available	+5 pts	Greater flexibility means stage matching is more important as all methods become viable and the choice is genuinely discriminating
Acquisition technique match	Technique = Slip-Sweep	+4 pts	Slip-Sweep is the most method-sensitive regime; technique-method alignment is highly discriminating for this specific acquisition mode
Noise severity handling	Severity = High	+4 pts	At high severity the method's noise-handling capability becomes the dominant performance concern, outweighing other considerations
Software availability	Any specialist tool selected (not "generic only")	+5 pts	When a specific tool is available, recommending a method that requires different software is not operationally feasible regardless of score on other criteria
Quality / complexity balance	Quality priority ≥ 4	+3 pts	At high quality priority the method's thoroughness becomes more important than processing simplicity or speed

4.5.3. Normalization Procedure

After applying all applicable adjustment rules, the six adjusted criterion weights are summed and each is divided by the total and multiplied by 100, producing normalized percentage weights that sum exactly to 100. This ensures that the final score remains on a 0–100 scale regardless of how many adjustments rules fire simultaneously for a given configuration.

The normalization formula is:

$$\boldsymbol{w_i^{(\text{norm})}} = \frac{\boldsymbol{w_i^{(\text{base})}} + \boldsymbol{\Delta w_i}}{\sum_j \left(\boldsymbol{w_j^{(\text{base})}} + \boldsymbol{\Delta w_j}\right)} \times \mathbf{100}$$

Table 6 shows the base weights and the approximate maximum adjusted weight for each criterion, reflecting a scenario in which all applicable adjustment rules fire simultaneously.

Table 6:Criterion base weights and maximum adjusted weights

Criterion	Base weight	Max. adjusted weight (approx.)	Conditions for maximum
Processing stage fit	20%	~23%	Both stages available
Acquisition technique match	20%	~23%	Technique = Slip-Sweep
Noise severity handling	18%	~21%	Severity = High
Terrain and ground coupling	14%	14%	No adjustment rule applies
Software availability	15%	~18%	Specialist tool selected
Quality / complexity balance	13%	~15%	Quality priority ≥ 4

4.6. Recommendation Generation Logic

4.6.1. Scoring and Ranking

After computing the weighted score for each of the four methods using the formula in Section 4.4.1, the tool ranks the methods in descending order of their total score. The method with the highest score is identified as the primary recommendation and displayed in the recommendation block. All four ranked scores are shown in the score cards panel to provide full transparency over the comparative assessment.

The scores displayed in the interface are integer-rounded. In the rare case of a tie in rounded scores, the method appearing first in the canonical ordering (HPVA → PSD-Harmonic → CHARM → ENAGEO-Advance, reflecting historical order of introduction in the literature) is selected as the primary recommendation.

4.6.2. Recommendation Justification Text

For each possible winning method, a fixed justification paragraph is displayed in the recommendation block. Each text explains, in context-neutral but method-specific terms, why the method is the appropriate choice. The texts are grounded in the method characteristics identified in Chapter 2:

- **HPVA:** justified by its Ground Force-based post-correlation operator and its established role as a quality benchmark tool for comparing conventional and HP data quality (Meunier & Bianchi, 2005).
- **PSD-Harmonic:** justified by its early-stage pre-correlation intervention, which limits harmonic energy propagation into the correlated domain before it becomes more complex to attenuate (Taieb & Belbachir, 2020).

- **CHARM:** justified by its residual QC output providing verifiable control over what was removed, and its robustness under high-severity and variable-terrain conditions (Bagaini, 2010).
- **ENAGEO-Advance:** justified by its VP-sequence operator logic that directly matches the slip-sweep acquisition paradigm, providing systematic full-dataset cleaning with traceable VP-to-VP contamination modeling (Taieb & Belbachir, 2020).

4.6.3. Suitability Tags

Each method card in the ranked output displays three color-coded suitability tags generated dynamically from the current input parameters. Tags use a three-color scheme: green (well suited), amber (partially suited or attention needed), red (poor fit or constraint violated). The tag logic is as follows:

Method	Tag 1	Tag 2	Tag 3
HPVA	Processing stage (green=post/both, amber=pre)	Ground Force based (neutral info)	Technique fit (green=Slip-Sweep or Flip-Flop, amber=other)
PSD-Harmonic	Processing stage (green=pre/both, red=post only)	Spectral filtering (neutral info)	Stage available (green=pre or both, red=post only)
CHARM	Processing stage (green=post/both)	Subtraction + QC residual (neutral info)	Severity match (green=High, neutral=other)
ENAGEO-Advance	VP sequence operator (neutral info)	Technique fit (green=Slip-Sweep, amber=other)	Software (green=ENAGEO selected, amber=other)

4.6.4. Processing Workflow Generation

Each of the four methods is associated with a fixed five-step processing workflow that appears when that method wins the evaluation. These workflows were written based on the procedural descriptions in the primary literature for each method and represent the standard recommended implementation sequence (Meunier & Bianchi, 2005; Abd El-Aal, 2011; Zhang et al., 2012; Taieb & Belbachir, 2020). The five steps cover raw data QC, operator construction or software setup, the core attenuation operation, residual or output QC, and final comparison with a reference dataset.

The workflow is not dynamically generated from parameters, it is a method-specific reference procedure that provides an immediately actionable guide for the processing team. The rationale for five steps (rather than more or fewer) is that this level of granularity matches the procedural descriptions found in the reviewed literature (Meunier & Bianchi, 2005; Taieb & Belbachir, 2020; Bagaini, 2010) and provides sufficient detail for practical planning without attempting to replace a full processing specification document

4.7. Worked Examples

Three worked examples illustrate the tool's behavior across contrasting survey configurations. For each example the input parameters are defined, the scoring outcome is summarized, and the recommendation is interpreted against the published literature.

4.7.1. Example 1: Non-Aggressive Slip-Sweep Survey in a Stable Desert Environment

Table 7:Input parameters for Example 1

Parameter	Selected value
Acquisition technique	Slip-Sweep
Slip time	6.0 s (non-aggressive regime (Dean, 2016))
Harmonic noise severity	Moderate
Terrain / ground coupling	Stable (flat desert, compacted sand)
Processing stage available	Post-correlation only
Data quality priority	3 / 5 (balanced)
Software available	ENAGEO-Advance

Scoring outcome: The technique match criterion scores ENAGEO-Advance at 10/10; the software criterion at 10/10; post-correlation stage at 8/10; stable terrain at 9/10; moderate severity at 9/10; balanced quality priority at 8/10. With the technique-match weight boosted by the Slip-Sweep adjustment rule (+4 pts) and the software weight boosted by the specialist tool rule (+5 pts), ENAGEO-Advance accumulates a total score well above all alternatives. CHARM is the second-ranked method (recommended as a complementary approach for individual contaminated records where VP-sequence cleaning is insufficient).

Interpretation: This result is consistent with Case Study 4 in Chapter 3 (Taieb & Belbachir, 2020), where a Slip-Sweep survey in the Algerian Sahara using ENAGEO-Advance achieved successful full-dataset VP-sequence harmonic cleaning with near-conventional data quality on the final stacked section.

4.7.2. Example 2: Aggressive ISS Survey in Complex Terrain, High Quality Priority

Table 8: Input parameters for Example 2

Parameter	Selected value
Acquisition technique	ISS (Independent Simultaneous Sweeping)
Slip time	3.0 s (Aggressive (equivalent to full ISS blending))
Harmonic noise severity	High
Terrain / ground coupling	Complex (rocky outcrops, variable near-surface)
Processing stage available	Post-correlation only
Data quality priority	5 / 5 (quality priority)

Parameter	Selected value
Software available	CHARM / Key Seismic

Scoring outcome: High severity triggers the severity weight adjustment (+4 pts). The quality priority adjustment also fires (+3 pts). CHARM scores 9/10 on severity, 7/10 on terrain (its strongest terrain score in the complex row), 10/10 on software, 9/10 on post-correlation stage, and 8/10 on quality priority. ENAGEO-Advance scores lower because the technique is ISS rather than Slip-Sweep (score 5/10 on technique) and terrain is complex (6/10). HPVA scores lower due to complex terrain (5/10) and high severity (6/10). PSD-Harmonic scores low due to the post-correlation stage constraint (4/10).

Interpretation: CHARM is recommended. This is consistent with Case Study 3 in Chapter 3 (Bagaini, 2010), where CHARM was documented as effective for ISS data in complex terrain, with its residual analysis providing the critical QC verification needed under high-severity conditions.

4.7.3. Example 3: Pre-Correlation Intervention Required, Speed Priority

Table 9: Input parameters for Example 3

Parameter	Selected value
Acquisition technique	Slip-Sweep
Slip time	8.0 s (approaching noise-free regime)
Harmonic noise severity	Moderate
Terrain / ground coupling	Moderate (mixed sand and gravel)
Processing stage available	Pre-correlation only
Data quality priority	2 / 5 (speed priority)
Software available	PSD-Harmonic (BGP)

Scoring outcome: When the processing stage is pre-correlation only, PSD-Harmonic scores 10/10 on the stage criterion, the only method that can operate meaningfully in the uncorrelated domain. All other methods score 4/10 on stage. Combined with a software match score of 10/10, PSD-Harmonic dominates the ranking regardless of other criterion scores. At a quality priority of 2, the quality/complexity criterion also slightly favors PSD-Harmonic (8/10 versus 7/10 for CHARM and ENAGEO-Advance).

Interpretation: PSD-Harmonic is recommended. The recommendation text emphasizes the importance of early-stage intervention in limiting harmonic propagation into the correlated domain, which is the primary processing logic documented in Taieb & Belbachir (2020) for this configuration.

4.8. Limitations and Scope of Applicability

HNAM-DST provides structured, reproducible guidance but operates under several constraints that define its appropriate scope of application.

The base scores in Table 4 derive from a qualitative synthesis of the published case studies reviewed in Chapters 2 and 3. They represent informed judgment grounded in the literature, but have not been formally calibrated against a large empirical dataset of real survey outcomes with known method performance results. Score refinement through systematic field benchmarking would strengthen the framework and is identified as a priority direction for future work.

The tool evaluates four specific methods only, corresponding to those documented in the reviewed literature. Other harmonic attenuation approaches, including proprietary algorithms from service companies not covered in this study, are not represented (Zhang et al., 2012; Castor et al., 2015; Liu et al., 2022). The tool should not be interpreted as providing an exhaustive evaluation of all available options.

The recommendation logic produces a single primary method and does not generate combined or sequential workflow recommendations. In practice, PSD-Harmonic is often applied as a pre-conditioning step before a post-correlation method; the tool's second-ranked method should be considered as a potential complementary stage rather than a discarded alternative.

The tool is scoped to land Vibroseis acquisition only. Marine seismic, node-based acquisition without conventional Vibroseis sources, and DAS-based systems produce different noise characteristics that are outside the parameter space of the current framework.

The five-step processing workflows are generic reference procedures. Real surveys may require additional QC loops, parameter iterations, or sub-steps not captured in the five-step template. The workflow should be understood as a structured starting point, not a complete processing specification.

This chapter has documented the complete design and implementation of HNAM-DST, a browser-based decision-support tool for harmonic noise attenuation method selection in high-productivity land Vibroseis acquisition. The tool operationalizes the comparative analysis of Chapters 2 and 3 into a quantitative, parameterized scoring framework applicable to any survey configuration defined by seven input parameters.

The core academic contribution is the scoring matrix in Table 4.1, which assigns literature-grounded suitability scores to each of the four methods across six evaluation criteria, combined with a dynamic weight adjustment mechanism that ensures context-dominant criteria exert proportionally higher influence when specific survey conditions apply. Every score, weight, and adjustment rule in the framework is explicitly traceable to a published source reviewed in this thesis, making the tool fully auditable and extensible.

Three worked examples demonstrated that the tool produces recommendations consistent with the case study outcomes reviewed in Chapter 3: ENAGEO-Advance for stable Slip-

Sweep surveys with matching software; CHARM for high-severity, complex-terrain ISS surveys; and PSD-Harmonic when only pre-correlation intervention is available. This internal consistency validates the scoring logic, though formal empirical calibration against a larger set of real survey outcomes remains an important direction for future development.

HNAM-DST represents the applied synthesis of this thesis: a practical, self-contained, and reproducible tool that transforms a literature-based comparative analysis into actionable engineering guidance. It provides a direct answer to the question of original contribution, the students did not merely review existing work, but synthesized it into a new instrument that did not previously exist in the published literature.

General Conclusion

Main Results

This thesis set out to answer a single central question: can high-productivity land Vibroseis acquisition techniques be deployed at full productivity without incurring unacceptable seismic data quality loss, and if so, under what conditions and with which attenuation methods? The answer, derived across four chapters of systematic analysis, is affirmative, but conditional.

Chapter 1 established the theoretical foundation. The evolution from conventional sequential Vibroseis acquisition through Flip-Flop, Slip-Sweep, DS3/DS4, and ISS/MSS represents a progressive exchange: each generation achieves higher productivity by introducing greater temporal overlap between source activations, and each thereby introduces a more complex interference problem. The harmonic noise problem, coherent contamination arising from nonlinear vibrator behavior, displaced to negative correlation times and potentially overlapping adjacent records at short slip times, is not an implementation defect. It is an inherent physical consequence of the productivity strategy, confirmed across all HP techniques in the reviewed literature. The comparative summary in Table 1 made this trade-off explicit: no HP technique achieves productivity gain without some form of interference challenge.

Chapter 2 demonstrated that four dedicated attenuation methods, HPVA, PSD-Harmonic, CHARM, and ENAGEO-Advance, address this challenge from complementary angles. PSD-Harmonic intervenes pre-correlation, targeting harmonic energy in the sweep domain before it propagates into correlated records. HPVA and CHARM operate post-correlation, the former using Ground Force-based estimation and the latter using record-by-record coherent subtraction with residual QC. ENAGEO-Advance takes the most systematic approach, treating harmonic contamination as a sequential VP-to-VP problem and constructing a full dataset operator calibrated to the acquisition sequence. These methods are not competing alternatives, they are functionally distinct tools suited to different survey contexts, processing stages, and noise regimes. The comparative analysis in Table 2 formalized these distinctions across six evaluation dimensions.

Chapter 3 confirmed, through four published field case studies, that the productivity-quality trade-off is consistently manageable when the right method is applied to the right configuration. Rozemond (1996) demonstrated that Slip-Sweep in the non-aggressive regime yields near-conventional quality after post-correlation filtering, with 2-3× productivity gains. Howe et al. (2008) showed that ISS can exceed 1,000 VP/hour while achieving near-conventional stacked section quality after deblending, at the cost of substantially more complex processing. Bagaini (2010) confirmed that CHARM handles complex-terrain ISS data effectively, provided residual analysis is used to verify that signal is not inadvertently removed. Taieb & Belbachir (2020) documented that ENAGEO-

Advance systematically cleans full VP-sequence slip-sweep datasets, recovering near-conventional reflection continuity and SNR with 2-3× productivity gains in the Algerian Saharan context. The cross-case analysis in Table 3 revealed three structural patterns: productivity scales with processing complexity; all methods succeed when correctly matched to their regime; and terrain stability is a significant and often underestimated modulator of method effectiveness.

Chapter 4 translated this comparative analysis into a practical, original contribution: HNAM-DST, a browser-based decision-support tool that accepts seven survey-specific input parameters and produces a scored, ranked recommendation across all four methods with full transparency over the weighting logic. The tool's scoring matrix is entirely grounded in the literature reviewed in Chapters 2 and 3, every base score and weight adjustment is traceable to a published source. Three worked examples demonstrated that the tool produces recommendations consistent with the published case study outcomes, validating the internal consistency of the scoring framework.

Answer to the Central Research Question

High-productivity land Vibroseis acquisition can be deployed without unacceptable data quality loss under three conditions:

(1) the acquisition parameters, particularly slip time, are matched to an appropriate noise regime;

(2) a suitable attenuation method is selected based on the specific survey configuration; and

(3) that method is applied systematically with residual analysis as a quality control step. The productivity–quality trade-off is manageable, not inherent.

This answer has important practical implications. It means that the choice of attenuation method is not a processing afterthought, it is a survey design decision that should be made concurrently with the selection of the HP acquisition technique. A Slip-Sweep survey planned without an appropriate harmonic attenuation workflow is not just an open processing question; it is an incomplete acquisition design. The HNAM-DST tool provides a structured mechanism for making this design decision at the planning stage, before the field campaign begins.

This thesis makes three contributions to the geophysical literature on high-productivity acquisition:

First, it provides the first structured, multi-dimensional comparison of four harmonic noise attenuation methods within a unified analytical framework (Table 2, Chapter 2). While individual methods have been described and demonstrated in isolation, no prior publication has systematically compared HPVA, PSD-Harmonic, CHARM, and ENAGEO-Advance across the same six dimensions, processing stage, technique compatibility, noise severity handling, terrain robustness, software requirements, and quality-complexity balance, in a single document.

Second, it provides a structured cross-case comparison of four published field implementations using a consistent performance template (Table 3, Chapter 3). The analysis identifies three empirical patterns, productivity-complexity scaling, method-regime matching, and terrain modulation, that are implicit in individual case studies but have not previously been drawn together into explicit cross-case conclusions.

Third, it introduces the HNAM-DST decision-support tool (Chapter 4), the first parameterized, weighted scoring framework for harmonic noise attenuation method selection documented in the geophysical literature. The tool is self-contained, offline-capable, and fully traceable to published sources, making it both a practical aid for survey designers and an extensible research instrument for future calibration and development.

Limitations

Three limitations of this work should be clearly acknowledged.

The absence of proprietary field data means that all empirical evidence is derived from published literature. Published case studies may reflect a positive publication bias, surveys where methods performed well are more likely to be written up and submitted than surveys where methods failed or produced ambiguous results. The cross-case conclusions in Chapter 3, while internally consistent, should therefore be interpreted as representative of best-practice implementations rather than as exhaustive performance characterizations.

The HNAM-DST scoring matrix is calibrated on a small evidence base of four case studies and a qualitative synthesis of method descriptions. The base scores and weight assignments represent informed, literature-grounded judgment, but they have not been validated through a formal statistical calibration against a large dataset of real survey outcomes. Scores may require revision as additional empirical evidence becomes available, particularly for edge cases not covered by the reviewed literature.

The tool covers four methods only, corresponding to those documented in the reviewed literature. Proprietary methods from other service companies, hybrid approaches, and emerging machine-learning-based deblending techniques, which are increasingly documented in recent SEG and EAGE publications, are not represented in the current framework. The tool should not be used to draw conclusions about methods outside its scope.

Directions for Future Work

Several directions for future development are suggested by the findings of this thesis:

- **Validation on Algerian field data:** The most direct extension of this work would apply the HNAM-DST framework to real Vibroseis survey data from the Algerian Saharan basin. ENAGEO's operational datasets would provide an ideal testbed for validating the tool's recommendation logic in the specific geological and logistical context most relevant to Algerian geophysicists.

- **Scoring matrix calibration:** As additional published case studies accumulate, particularly for ISS with ENAGEO-Advance, and for DS3/DS4 with CHARM, the base scores in Table 4 could be refined through systematic quantitative calibration, potentially using Bayesian updating or multi-criteria decision analysis methods.
- **Integration of machine learning deblending:** Deep-learning-based source separation approaches (e.g., CNN-based deblending, U-Net architectures applied to blended seismic) are emerging as a fifth category of HP data processing tool. Extending HNAM-DST to cover these methods would require documenting their performance characteristics with sufficient consistency to populate the scoring matrix.
- **Quantitative SNR benchmarking:** A controlled synthetic experiment applying all four methods to the same blended dataset under identical conditions would allow a direct, quantitative SNR comparison that the current literature-based analysis cannot provide. Such a benchmark study would both validate the relative effectiveness scores in Table 4 and produce a publishable contribution in its own right.
- **Extension to 4D and time-lapse surveys:** Repeatability requirements in 4D seismic monitoring introduce additional constraints on HP acquisition, not just SNR but wavefield consistency between baseline and monitor surveys. The implications of harmonic noise for 4D repeatability metrics (NRMS, PRM) represent an unexplored application domain for the methods reviewed here.

High-productivity land seismic acquisition is not a future technology, it is the current operational standard for large-scale 3D land surveys worldwide, including in Algeria. The harmonic noise problem it introduces is equally current, and the attenuation methods reviewed in this thesis are actively used in commercial processing today. The gap that motivated this work, the absence of a structured, transparent decision framework for method selection, is therefore a practical gap, not merely an academic one.

This thesis has attempted to close that gap, within the constraints of a literature-based study, by providing the structured comparison and applied synthesis that the literature does not yet offer in consolidated form. The HNAM-DST tool, while modest in scope, represents a first step toward making that synthesis operational. Its value lies not in the sophistication of its algorithms but in the clarity of its logic: every recommendation it produces is traceable, every weight is justified, and every score reflects a deliberate analytical judgment grounded in the published record.

It is hoped that this work will serve both as a reference for practitioners planning HP Vibroseis surveys in the Algerian Sahara and as a foundation for future research that extends, calibrates, and ultimately supersedes the framework presented here.

References

Abd El-Aal, A. K. (2011). Harmonic by harmonic removal technique for improving vibroseis data quality. *Geophysical Prospecting*, *59*(2), 279–294. https://doi.org/10.1111/j.1365-2478.2010.00918.

Abma, R., Howe, D., Foster, M., Ahmed, I., Tanis, M., Zhang, Q., & Alexander, G. (2015). Independent simultaneous source acquisition and processing. *Geophysics*, *80*(6), WD37–WD44. https://doi.org/10.1190/geo2015-0078.1

Bagaini, C. (2010). Acquisition and processing of simultaneous vibroseis data. *Geophysical Prospecting*, *58*(1), 81–99. https://doi.org/10.1111/j.1365-2478.2009.00842.x

Bagaini, C., Daly, M., & Moore, I. (2012). The acquisition and processing of dithered slip-sweep vibroseis data. *Geophysical Prospecting*, *60*(4), 618–639. https://doi.org/10.1111/j.1365-2478.2012.01085.x

Bouska, J. (2010). Distance separated simultaneous sweeping, for fast, clean, vibroseis acquisition. *Geophysical Prospecting*, *58*(1), 123–153. https://doi.org/10.1111/j.1365-2478.2009.00843.x

Castor, K., Bianchi, T., Winter, O., & Klein, T. (2015). Efficient harmonic-distortion mitigation on vibro-seismic sources. In *EAGE Workshop on Broadband Seismic – A Broader View for the Middle East* (pp. 1–5). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.201414418

Dean, T. (2016, October). High productivity vibroseis techniques: A review. *Preview*, pp. 36–40. https://doi.org/10.1071/PVv2016n184p36

Donati, M. S., & Stewart, R. R. (1996). P-and S-wave separation at a liquid-solid interface. *Journal of seismic exploration*, *5*(2), 113-127.

ENAGEO. (2011). *Méthode d'atténuation des distorsions harmoniques*. [Internal report – no public DOI]

Howe, D., Foster, M., Allen, T., Taylor, B., & Jack, I. (2008). Independent simultaneous sweeping: A method to increase the productivity of land seismic crews. *SEG Technical Program Expanded Abstracts 2008*, 2826–2830. https://doi.org/10.1190/1.3063932

Huo, S., Tsingas, C., Kelamis, P. G., Pecholcs, P. I., & Xu, H. (2012). Unconstrained simultaneous source land data processing. *Geophysical Prospecting*, *60*(4), 608–617. https://doi.org/10.1111/j.1365-2478.2012.01074.x

Ikelle, L. T., & Amundsen, L. (2005). *Introduction to Petroleum Seismology*. Society of Exploration Geophysicists. https://doi.org/10.1190/1.9781560801702

Kalinski, M. (2007). Effect of Vibroseis arrays on ground vibrations: A numerical study. *Journal of Geotechnical and Geoenvironmental Engineering*, *133*(12), 1523–1533. https://doi.org/10.2113/JEEG12.3.281

Krohn, C., & Johnson, M. (2006). HFVS: Enhanced data quality through technology integration. *Geophysics*, *71*(2), E13–E23. https://doi.org/10.1190/1.2187730

Liu, D., Li, X., Wang, W., Wang, X., Shi, Z., & Chen, W. (2022). Eliminating harmonic noise in vibroseis data through sparsity-promoted waveform modeling. *Geophysics*, *87*(3), V183–V191. https://doi.org/10.1190/geo2021-0448.1

Mahmood, U. (2012, June). Investigating Different Approaches of Deblending. In *74th EAGE Conference and Exhibition incorporating EUROPEC 2012* (pp. cp-293). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.20148885

Makama, A., Kuladinithi, K., & Timm-Giel, A. (2021). Wireless geophone networks for land seismic data acquisition: A survey, tutorial and performance evaluation. *Sensors, 21*(15), 5171. https://doi.org/10.3390/s21155171

Meunier, J., & Bianchi, T. (2005, November). Cost-effective, high-density vibroseis acquisition. In *SEG Technical Program Expanded Abstracts 2005* (pp. 44–47). Society of Exploration Geophysicists. https://doi.org/10.1190/1.2142239

Pecholcs, P. I., Lafon, S. K., Al-Ghamdi, T., Al-Shammery, H., Kelamis, P. G., Huo, S. X., Winter, O., Kerboul, J.-B., & Klein, T. (2010). Over 40,000 vibrator points per day with real-time quality control: Opportunities and challenges. In *SEG Technical Program Expanded Abstracts 2010* (pp. 111–115). Society of Exploration Geophysicists. https://doi.org/10.1190/1.3513041

Rozemond, H. (1996). Slip-sweep acquisition. *SEG Technical Program Expanded Abstracts 1996*, 64–67. https://doi.org/10.1190/1.1826730

Sallas, J. (1984). Seismic vibrator control and the downgoing P-wave. *Geophysics, 49*(6), 732–740. https://doi.org/10.1190/1.1441701

Sheriff, R., & Geldart, L. (1995). *Exploration Seismology* (2nd ed.). Cambridge University Press. ISBN 978-0-521-46826-5

SONATRACH. (2017). *Design d'une étude sismique 3D et technique d'acquisition haute productivité.* SONATRACH. [Internal report – no public DOI]

Taieb, M., & Belbachir, A. (2020). *High-productivity seismic acquisition techniques and harmonic noise attenuation.* Technical report. ENAGEO. [Technical report – no public DOI]

Yilmaz, Ö. (2001). *Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data* (2nd ed.). Society of Exploration Geophysicists. https://doi.org/10.1190/1.9781560801580

Zhang, H. J., Zhou, H., Abd El-Aal, A. E. A. K., & Zhang, J. (2012). The anti-correlation method for removing harmonic distortion in vibroseis slip-sweep data. *Applied Geophysics, 9*(2), 159–167. https://doi.org/10.1007/s11770-012-0325-5