# Vibroseis Harmonic Noise Cancelling By Time Varying Filtering With Reference

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## Abstract

**Keywords**: vibroseis, slip-sweep, harmonic noise, classes, multiple input/output, global, cascade, multi-reference, signal shaping.

In recent years, the demand of large 3D data volume, such as the high-density and wide-azimuth, leads the seismic companies to improve the productivity of their seismic crews. A significant increase of Vibroseis productivity, in 3D land survey, can be obtained using more than one group of vibrators shooting at the same time. The Slip Sweep technique offers a high productivity by enabling the recording of overlapping sweeps from different groups of vibrators. Unfortunately, this technique often suffers from data quality deterioration associated to the harmonic noise distortion, generated by the adjacent vibrators (caused by non-linear phenomena and vibrator-earth coupling problems).

The time between two consecutive sweeps, called slip-time, controls the productivity. A short slip-time allows obtaining a high productivity. However, if the slip-time was taken too short the more harmonic noise increased.

Because the quality of data should not be significantly affected by the technique used to speed up acquisition, several methods have been developed for reducing this harmonic noise. These methods are based on harmonic prediction operator for all harmonics calculated using Ground Force (GF) measurements (weighted sum the base plate and mass accelerations) and/or uncorrelated traces.

It is important to note that the estimation of harmonics using the Ground Force measurements is not entirely representative of the far field signature and the estimation by an operator calculated from several uncorrelated traces (range of offsets), is only representative of the signature of the selected range of offsets. Indeed, the evaluation of harmonics using a unique operator is found to be inaccurate.

In this paper we present a new method for the reduction of harmonic noise in slip-sweep data. The method consists of estimating each harmonic component of a seismic trace, at first, by applying a prediction operator of considered harmonic. The prediction operator is calculated using the representative emitted signal (GF) measured by the vibrator. The prediction operator can be calculated in frequency domain by a ratio of the cross-correlation of the considered harmonic and the fundamental components and the auto-correlation of the fundamental component of the Ground Force signal.

The harmonic components of each trace should be subtracted from the contaminated trace using band limited adaptive subtraction according to one of the following techniques:

a. Harmonic by harmonic with re-adaptation of the input (multi-layers)
b. All at once (multi-inputs interference cancelling).

The method was applied to a 3D vibroseis data, and the obtained results show excellent reduction of the harmonic noise both on the field records and on the stack section, which make obvious the robustness and the efficiency of this method.


# Background

Oil and gas industry still remain for a few more decades to come, the most used energy resources in the world. In order to maintain production at a high level, oil companies are increasing their exploration efforts by employing the most advanced methods to describe in great detail the geological structure of the reservoir and the rock properties that are more to extract the oil and to better develop the gas resource ; consequently, the demand for high-resolution 3D volume increases like in the  Wide and multi- Azimuth which greatly improving the seismic imaging using multiple sources and a spread of high-density recording. It is widely accepted that Wide-azimuth acquisition is the best geometry to improve imaging of complex and small traps. That is, may allow to a reliable characterisation of shale gas accumulation. That allows estimating anisotropy, then inferring rock parameters necessary to map fractures and stress distribution in rocks.

To meet this demand, geophysical companies have innovated in land as in marine acquisition. They propose High Productivity Vibroseis acquisition techniques in order to realize this volume data and reduce the cost. Therefore, the greatest development effort in desert operations was devoted to the reduction of the cycle time of vibration, which determines mainly the cost of a 3D seismic vibroseis survey. With a single group (fleet) of vibrators, the cycle of vibration is the sum of the duration of the sweep and the time required to move the vibrators to the next vibration point. The use of a second group (fleet) vibrator has almost double the production with the appropriate parameters, because that one group could move to the next vibration point while the other is vibrating. This technique, called 'flip-flop', is very effective especially in typical flat zone. The cycle of vibration is reduced effectively and the acquisition system can be put in 'automatic mode'. A higher productivity can be accomplished by further reducing the length of the sweep. Though, the corresponding decrease in the cycle time of vibration would not be proportional, because the vibrator in displacement would not be ready in time. In other words, the diminution in the data quality due to a sweep of a shorter length would not be recovered by a corresponding increase in productivity. In addition, the vibrators will spend more time displacing than vibrate. However, the use of more than one vibrator or group of vibrators vibrating at the same time allows a substantial increase in vibroseis productivity. Hence, many methods of high productivity vibroseis have been developed to speed up vibroseis acquisition data.

The slip-sweep technique is an attractive way of optimizing productivity to a level, which can keep the cost of increasing source density within reasonable limits. Refinements in harmonics noise reduction make it possible to take full advantage of its possibilities.

# Slip sweep technique

Slip sweep is a Vibroseis acquisition technique that was introduced by Petroleum Development Oman (Rozemond, H.J., 1996). The idea behind the recording slip-sweep is simple: a group of vibrator begins to vibrate without waiting for the previous group's sweep to terminate. Using this method, the cycle time can be reduced significantly and so the productivity can be doubled or tripled, of course additional vibrators are needed to achieve such an increase. In addition, the slip sweep method offers the most technical advantages in terms of simplicity and flexibility of operations. In this method, the data is recorded continuously, and the recording obtained is called the mother gather. In this, the interval between two consecutive sweeps is called slip times. The correlation acts as a filter in the time-frequency domain, allowing then the separation of individual records, cutting the correlated mother record in the appropriate time breaks (TBs) truly used. In Figures 1 and 2 we simulated the principle of the normal acquisition mode and that of the slip-sweep in time space (X-T) and in the time-frequency domain (F-T). In Figure 1 a conventional recording was represented with a linear up-sweep; 12 seconds and 4 seconds of listening time. The length of uncorrelated record is 16 seconds, corresponding to the minimum cycle time can be achieved in this normal mode of acquisition.
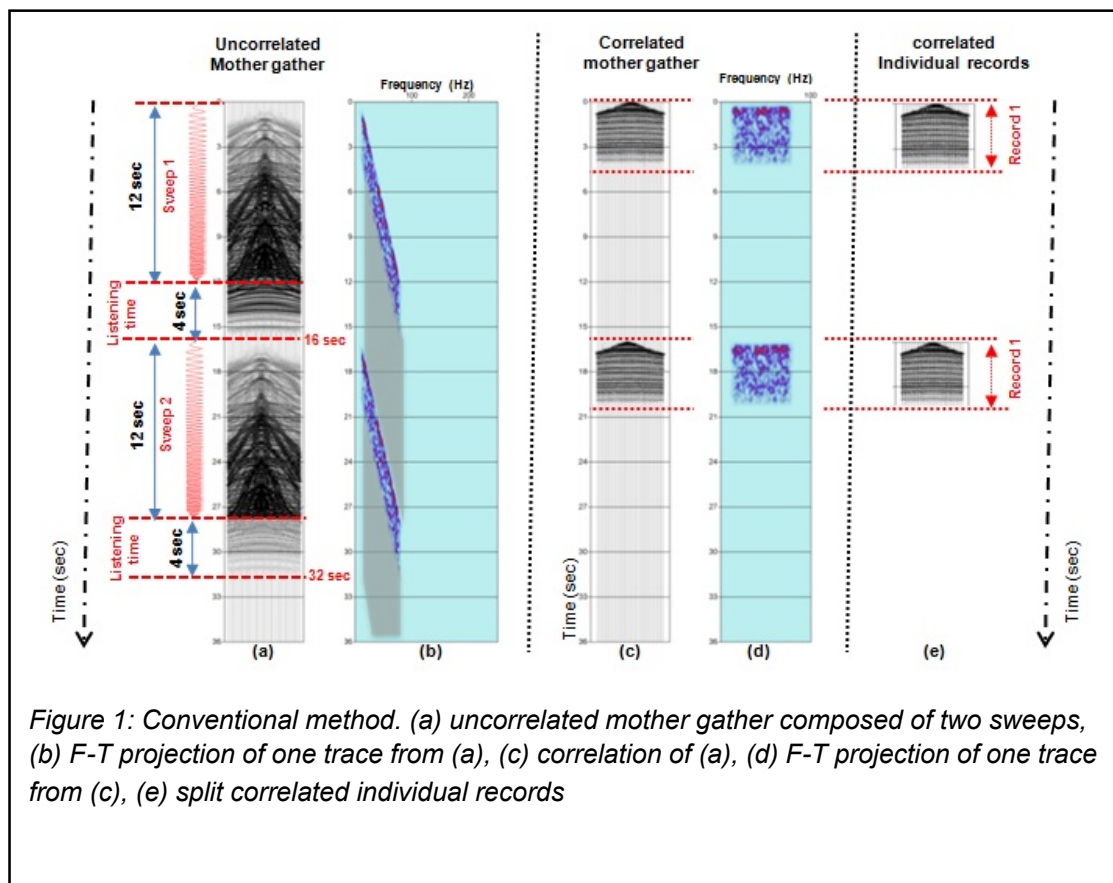


Figure 1: Conventional method. (a) uncorrelated mother gather composed of two sweeps, (b) F-T projection of one trace from (a), (c) correlation of (a), (d) F-T projection of one trace from (c), (e) split correlated individual records

At any time, only a limited number of frequencies can be recorded. For example, at time t = 12 seconds, only the high frequency band of the sweep reaches the recording system.

The areas shown in light gray correspond to free space in the time-frequency domain, that is to say that the frequency at a given time, are not used.

The technique of slip-sweep principle is illustrated in figure 2. A new sweep starts early as the start frequency of the previous sweep was extinguished, which would ideally after the listening time (4s). As the same sweep is used by all groups of vibrators, there will be no overlap in the time-frequency domain. Although at first glance, a complex band pass filter in variable time seems necessary to separate the different records from the uncorrelated mother record.

The reality is much more elegant: simply by correlating the mother record with the sweep pilot to get a recording that is primarily the individual correlated records placed one after the other. In other words, the records of the various shot points will be extracted by simply cutting the correlated record at the appropriate time breaks (TBs).
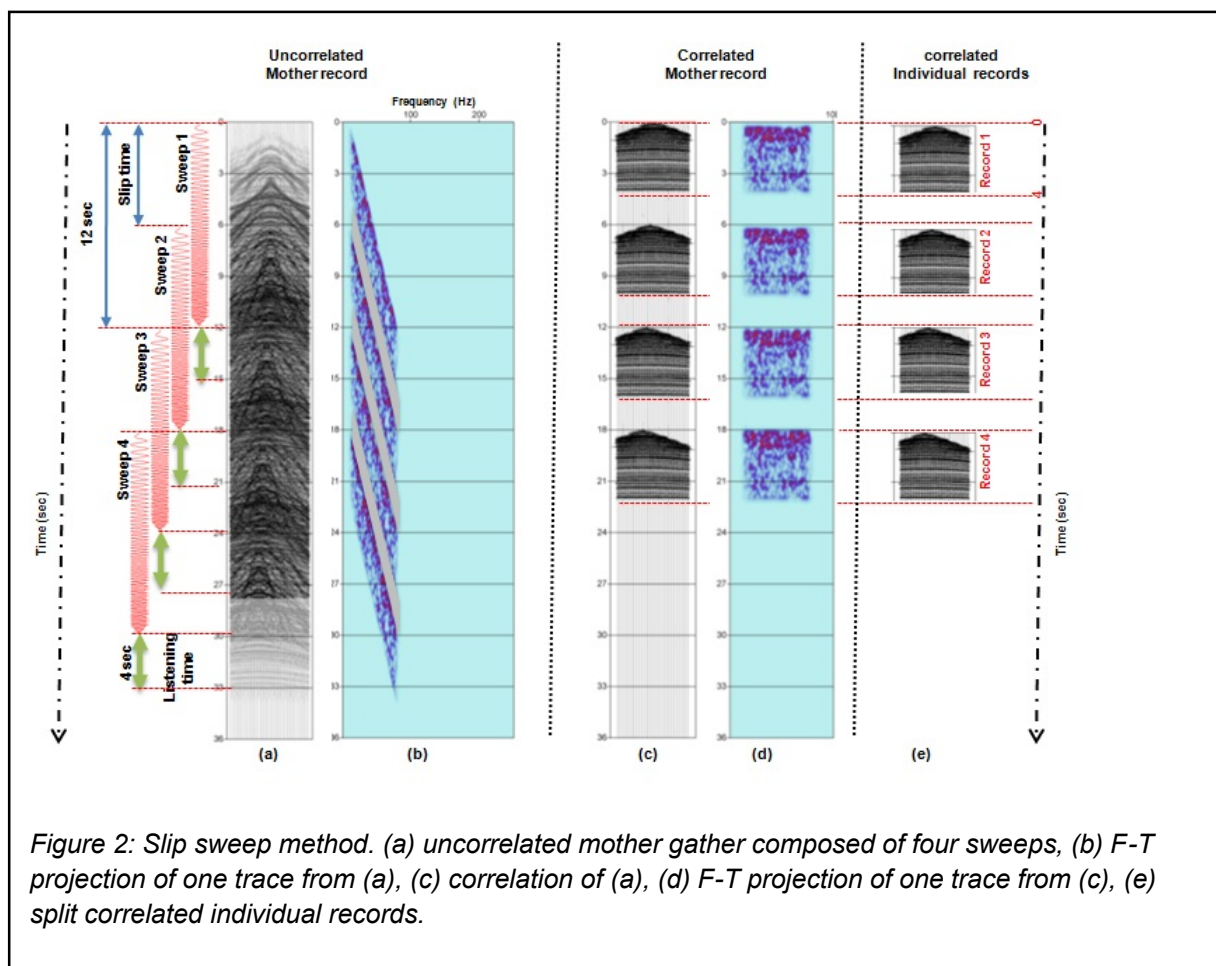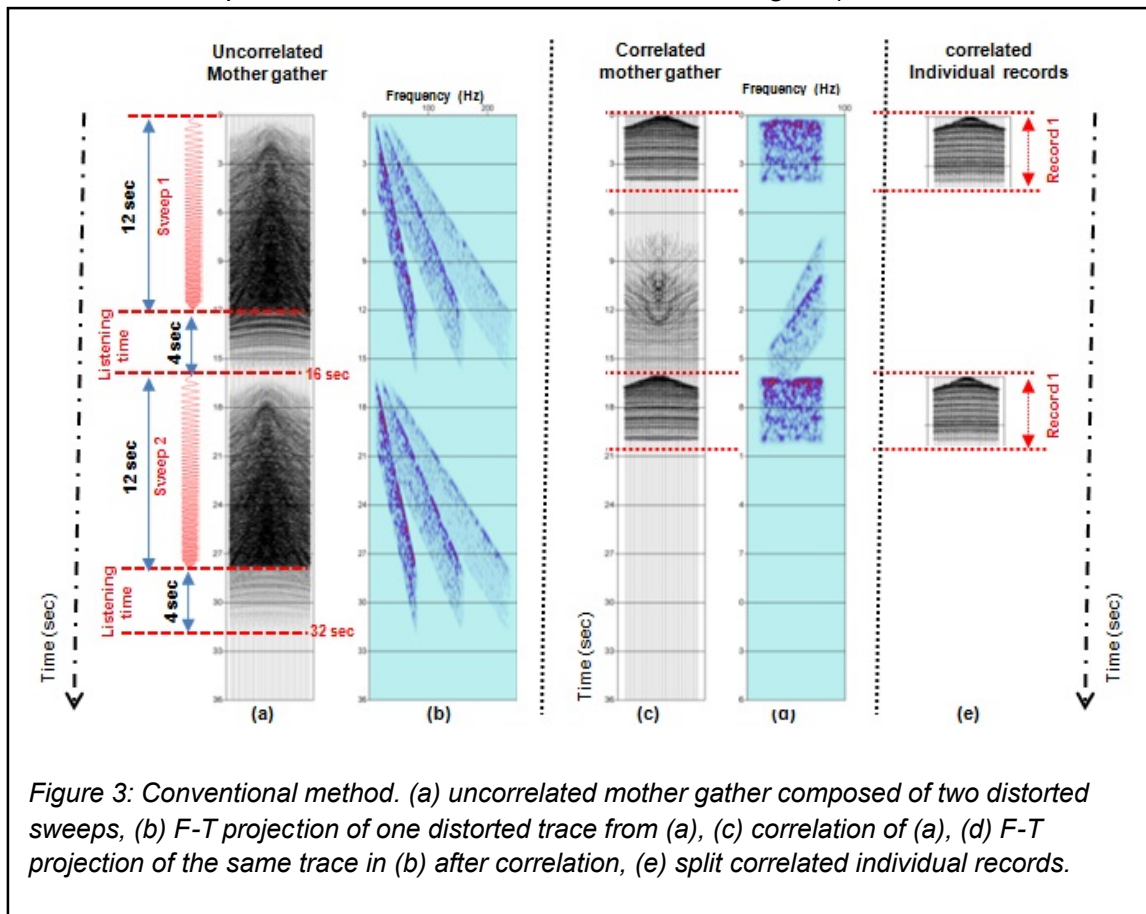


*Figure 2: Slip sweep method. (a) uncorrelated mother gather composed of four sweeps, (b) F-T projection of one trace from (a), (c) correlation of (a), (d) F-T projection of one trace from (c), (e) split correlated individual records.*

In conventional method, the correlation with sweep pilot puts the harmonic noise, in the case of an up-sweep, at the negative times relative to the time zero of the signal. The removal is then performed using as a signal the correlated causal part, Figure 3.

## Slip sweep problem

Slip-sweep technique offers great potential for improving the productivity in vibroseis. Nevertheless it suffers from a degradation of data quality caused by harmonic noise

contamination generated by this method. When a vibrator generates the frequency f, and because of the mechanism vibrator imperfection and coupling [vibrator-ground], it also generates energy harmonic frequency 2f, 3f, ..., nf. Traditionally, the correlation process would project the harmonics of an up-sweeps to negative time recording. Harmonics are eliminated by truncating the record at t = 0. The problem of harmonic distortion for the technique "slip sweep," is that a long record of continuous recording (Mother-gather) containing multiple sweeps. And why, the harmonics will not be eliminated by the truncation, as they also contaminate the records of previous sweeps, Figure 4. This is because the slip-time is too short to prevent harmonics interference with the signal (harmonic contamination



*Figure 3: Conventional method. (a) uncorrelated mother gather composed of two distorted sweeps, (b) F-T projection of one distorted trace from (a), (c) correlation of (a), (d) F-T projection of the same trace in (b) after correlation, (e) split correlated individual records.*

inter-record). However, the most affected part in a record is in the later times, especially the high frequency part (HF), ex: deep reflexions.

By analysing slip-sweep correlated data with the presence of harmonic distortion, it becomes clear how we can reduce the effect of harmonics: increasing slip time, increasing the frequency bandwidth, decreasing the sweep length, or bringing closer the vibrator groups to avoid large differences of amplitude coming from consecutive shot points.

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From operational point of view and to reduce the effect of harmonics noise we must increase the slip time (to detriment of productivity) and / or reduce the sweep length (to detriment of

quality). From these two alternatives, increasing the slip time would be the easiest solution; however it would therefore have a negative impact in terms of productivity.
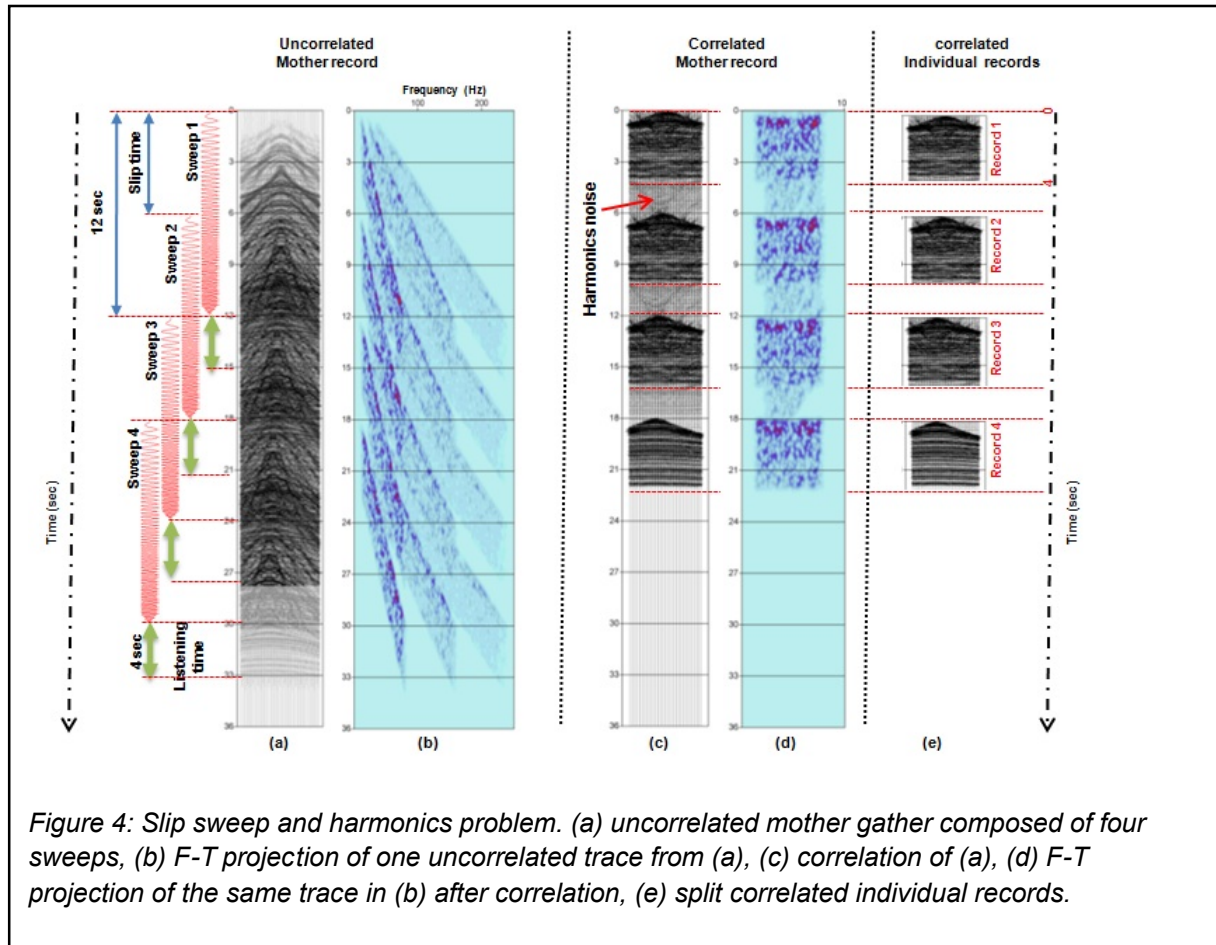


*Figure 4: Slip sweep and harmonics problem. (a) uncorrelated mother gather composed of four sweeps, (b) F-T projection of one uncorrelated trace from (a), (c) correlation of (a), (d) F-T projection of the same trace in (b) after correlation, (e) split correlated individual records.*

Moreover, if the slip time is random (reality in the field), harmonic noise contamination will arrive at random times and thereby mitigate them by the summation process. This attenuation increases with fold coverage.

In addition, the desire to optimise productivity leads to search the times interval between vibrations as short as possible (slip-time very close to the listening time). Under these conditions, the obtained records have a signal-to-noise degraded compared to that which would be obtained using the conventional method. A simple band-pass filter would not have distinguished the fundamental and harmonic energy. Hence we need to design a processing method enabling the reduction of harmonic noise. In recent years, various techniques of harmonic noise reduction have been proposed.

## New harmonic noise removal method

In recent years, various techniques of harmonic noise reduction have been proposed, Fleure (2002), Meunier and Bianchi (2002), Moerig (2007), Moro et al. (2007). Such techniques are based on: the calculation of the spectral ratio of the global harmonic component over the fundamental component, the estimation of reduced spectral weight functions (computation operators) and estimation of the harmonic noise (application operators) and its subtraction.

The problem of representativeness of the filter is laid in these methods: in fact, the evaluation of harmonics based on a single operator may be inaccurate because of the nature of the signal source (non-stationary). The contribution (weight) of each harmonic changes from one trace to another, the estimation of the operator from several non-correlated traces (range of offsets), is representative of the signature of this range of offsets, measurements of GF's are not fully representative of the signature of far traces. It's all a single operator calculated in this way does not provide an accurate estimation of the harmonics. Other scientists have proposed improvements that have a solution to the problem of overlapping harmonics with the fundamental component of the previous shot, evaded by the first method. These improvements are based on a calibration of the estimated harmonic noise from outside the overlap interval. But that does not entirely solve the problem of representativeness of the filter for the same reasons mentioned above.

Compared to previous methods, that neglect the variation of the operator to estimate the harmonic noise as a function of offset, we propose in this paper a new method of harmonic noise attenuation that makes improvements in the estimation of noise by the implementation of finer techniques decomposition of the transmitted signal and a new process that uses an attenuation of time-varying with reference filter and limited dynamic band.

## Harmonic noise filter estimation from seismic trace model

We denote by $x^k(t)$ the signal recorded by one of the geophones G. This signal is the result of the convolution of the signal $x^k(t)$ emitted at the base plat of the source $S^k$ (GF), the reflectivity function r(t) of the earth, which is the chronological sequence of the different geological interfaces reflection coefficients encountered:

$$x^k(t) = s^k(t) * r(t) + n(t) \qquad (1)$$

And ,
$$s^k(t) = \sum_{i=1}^{n} s_i^k(t) \qquad (2)$$

Where $s_1^k(t)$ is the fundamental component assumed to be very close to the recorded pilot sweep $p(t)$, $s_2^k(t), s_3^k(t), ..., s_n^k(t)$ the harmonic components of 2, 3, ..., n order, contained in the transmitted sweep issued and $n(t)$ the additive random noise.

After correlation with the pilot sweep, and neglecting the component relative to random noise, the recorded signal becomes:

$$z^k(t) = \sum_{i=1}^{n} \left[ s_i^k(t) * p(-t) * r(t) \right] \qquad (3)$$

where: * denotes the convolution operation.

$z^k(t)$ is a non-causal signal that the correlation gives the reference sweep, in the case of using an up-sweep, a map of harmonics $s_i^k(t) * p(-t)$ for $i > 1$, located in negative time from the time zero signal. The recording system delivers a correlated causal trace. In doing so, much of the harmonic energy is eliminated because the correlated trace obtained is then equal to:

$$y^k(t) = z^k(t).U(t) = s_1^k(t) * p(-t) * r(t) \qquad (4)$$

where $U(t)$ denotes Heaviside function.

In order to realize filtering with reference, we propose in this paper a new method based on the extraction of harmonics noise in the form of subsets, called harmonic classes. The simplest case is to estimate the harmonics one by one. The proposed algorithm is to determine the optimal filter which, from the fundamental component, $s_1^k(t) * p(-t) * r(t)$, given by applying the reference noise $b_i(t)$ corresponding to class of order i, which satisfies the equation:

$$b_i(t) = s_i^k(t) * p(-t) * r(t) \qquad (5)$$

The desired optimal filter $h_i$, satisfies the equation is written using only the components of the GF (fundamental and harmonic of order $i$):

$$\jmath_{s_1^k.s_1^k}(t) * h_i(t) = \jmath_{s_i^k.s_1^k}(t) \qquad (6)$$

where $\jmath_{s_1^k.s_1^k}(t)$ is the autocorrelation function of the fundamental component of the Ground Force and $s_1^k$ and $\jmath_{s_i^k.s_1^k}(t)$ the cross-correlation function key component $s_1^k$ and the harmonic component of order $i$, $s_i^k$ of the Ground Force.

Non-causal version of this filter can be calculated using the Wiener-Levinson algorithm. Equation 6 accepts in the frequency domain, a solution equal to the ratio of spectral densities.

$$H_i(f) = \frac{f_{s_i^k s_1^k}(f)}{f_{s_1^k s_1^k}(f)} \qquad (7)$$

The estimated harmonic noise of order i is given by:

$$b_i(t) = y^k(t) * h_i(t) \qquad (8)$$

The algorithm described above has the advantage of treating the harmonics, one by one, or block. The estimated noise $b_i(t)$ (generated by the source $S^k$) is then subtracted from the trace itself $y^k(t)$ and the trace of the same geophone $y^{k-1}(t)$ at the point of previous shot $S^{k-1}$.

## Noise removal methods with multiple input /output

During the propagation and because of non-stationarity of the sweep there can be a distortion phenomenon that makes the transmitted signal non-stationary used for different signal processing in the trace (variation with time on the same trace and depending on offset), therefore the filters conventionally calculated from the GFs are not fully representative of all traces. Therefore, the use of Ground Force as a signal, can give an inaccurate estimation of the noise $b_i(t)$, where a simple subtraction will leave a residual, energy which can sometimes be very strong compared to the signal, especially for the HF component of this residual.

In this paper, we propose an adaptive subtraction applied to each order harmonic separately, that is, harmonic by harmonic with support of dynamic frequency band. This is justified by the

fact that distortions neglected, differ from one harmonic to another, and the proposed processing effectively eliminates the desired noise $\hat{b}_i(t)$ of the previous trace $y^{k-1}(t)$ is:

$$\hat{y}^{k-1}(t) = y^{k-1}(t) + \hat{b}_i(t) \qquad (9)$$

Where: $\hat{y}^{k-1}(t)$ : contaminated trace by harmonics noise of the trace $y^k(t)$

$y^{k-1}(t)$ : the filtered trace

$\hat{b}_i(t)$ : the real harmonic noise coming from trace $y^k(t)$ of the next shot point of ($S^k$).

The proposed algorithm is to determine the optimal filter $w(t)$, from the harmonic class $b_i(t)$ as the reference noise, given by the application, a signal that accurately represents the harmonic distortion $\hat{b}_i(t)$. So the filtered trace becomes:

$$y^{k-1}(t) = \hat{y}^{k-1}(t) - \hat{b}_i(t)$$

$$= \hat{y}^{k-1}(t) - b_i(t) * w(t) \qquad (10)$$

For the calculation of the filter $w(t)$, a version of the Wiener-Levinson filter in time-varying with dynamic limitation bandwidth has been implemented. It is working on the signal by sliding window to estimate the noise.

**Way of applying the method**
By subdividing the harmonic components into classes, as described above, the proposed algorithm can handle harmonics, one by one, or by block, in one of the three methods described below. These methods of multiple inputs / outputs estimate the harmonic noise and subtract it from the contaminated previous record. They can be made using one of these three time-variant versions.

**Global version**: This is a subtraction method that estimates and removes, in global manner, the noise on the class containing all harmonic components.

**Cascade version** : This is a multi-subtraction method (multi-layers) with rehabilitation of the input which estimates and removes, one by one, and recursively the noise related to each considered class.

**Multiple-reference version**: It is a method to mitigate interference to multiple inputs (multi-input Canceling interference), which estimates and removes, simultaneously the noise on each class.

# Ground Force decomposition

## Using adaptive filter

The filter for estimating the harmonic of order $i$, $h_i(t)$, is as a function of on the fundamental component $s_1^k(t)$ and the harmonic component of order $i$, $s_i^k(t)$ of the transmitted signal (GF). This requires an accurate decomposition of the GF. In the following we propose two methods for extracting the harmonic of order i from the GF using as reference the pilot sweep.

The first method is to determine an optimal filter $g(t)$, from the reference signal, $p_i$ of order $i$, given by applying the harmonic component of order $i$ of the GF signal, taking the GF as the desired signal. Where:

$$p_i(t) = a(t).\cos(i.f(t)) \qquad (11)$$

Where $a(t)$ et $f(t)$ denote the envelope and instantaneous phase of the pilot sweep $p(t)$.

Figure 5 illustrates the extraction process of any harmonic order i. It has as input the distorted sweep in which we look for the component that looks best to the reference sweep. As output, the harmonic component was extracted and the residual of the sweep which represents the other remaining components. For the extraction of all components is performed first to extract the fundamental component (the energetic one) from the GF by choosing as the reference sweep the pilot sweep $p_1(t) = p(t)$.

For the harmonic component of order 2, we take as input the residual signal from the previous step as a reference signal and the sweep $p_2(t)$ calculated from the pilot sweep $p(t)$ according to Equation 11.

## Decomposition in Time Frequency domain

The second method is based on the separation of the different components of sweep in Time Frequency domain, which requires the use of a reversible transformation F-T and with good resolution.

let $|S(t, f)|$ the amplitude image of distorted sweep in F-T domain. Applying a mask $M_i(t, f)$ adapted to the component of order i that we would separate and extract, the term phase is retained as it was.

This technique has the advantage of allowing calculation of the mask automatically, without needing to know the mathematical expression of the instantaneous frequency settings or pilot sweep parameters, this calculation will be made only from the registered pilot sweep and the desired harmonic order (Equation 7). Figure 6 explains the process of separation and extraction of the harmonic component of order 1 (fundamental). Is performed initially to transform the GF sweep in the F-T plan. Then we compute a mask from the pilot sweep in the F-T domain (using the same parameters of the first transformation). The result is obtained after multiplication of two images and an F-T inverse transformation is applied. For other components, the reference sweep is calculated previously from the pilot sweep according to Equation 7.

The two proposed methods have the distinction of being well suited to frequency-modulated signals like sweep. In addition, they allow to extract the different components in a cascade diagram, where GF signal taken as the desired signal, is rehabilitated by subtracting the

estimated component in the previous stage, which makes discrimination between the new component to extract and the remaining easier.
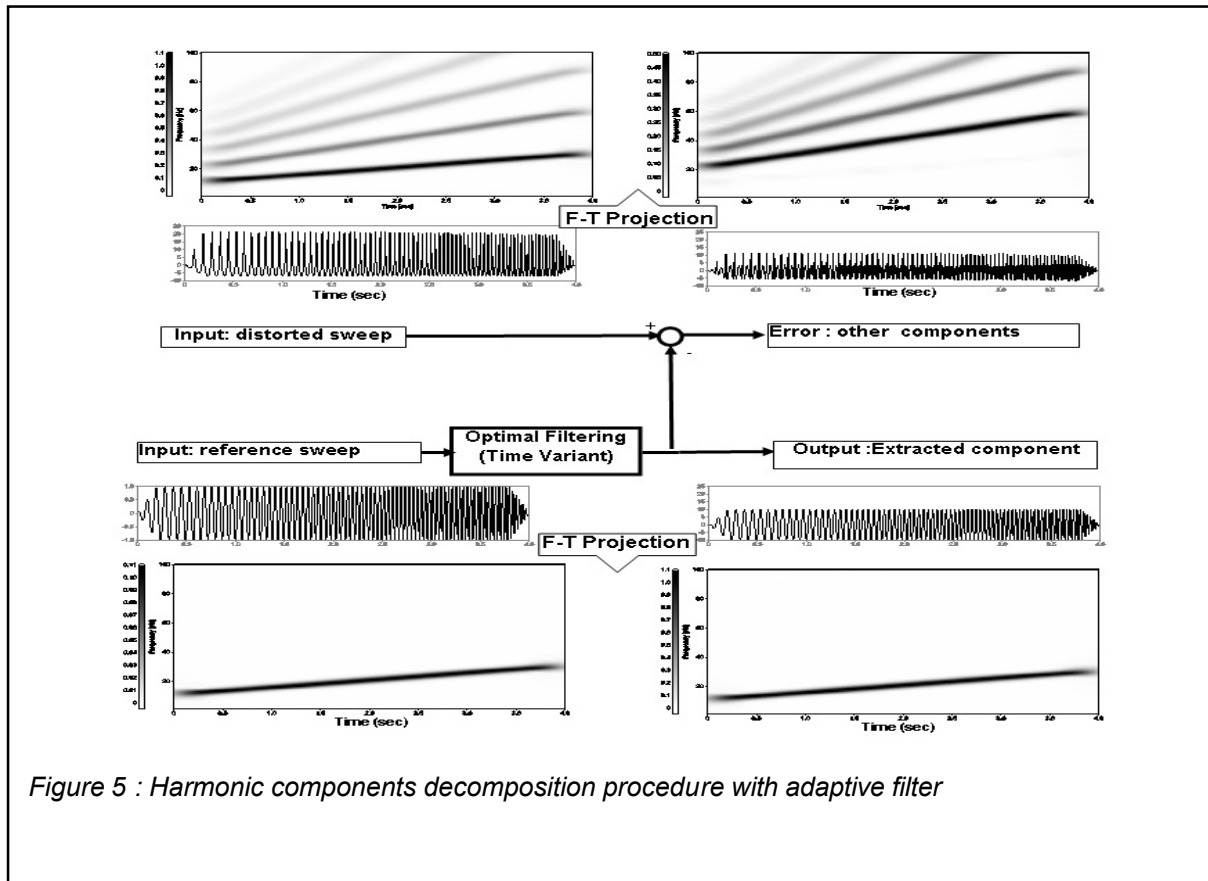


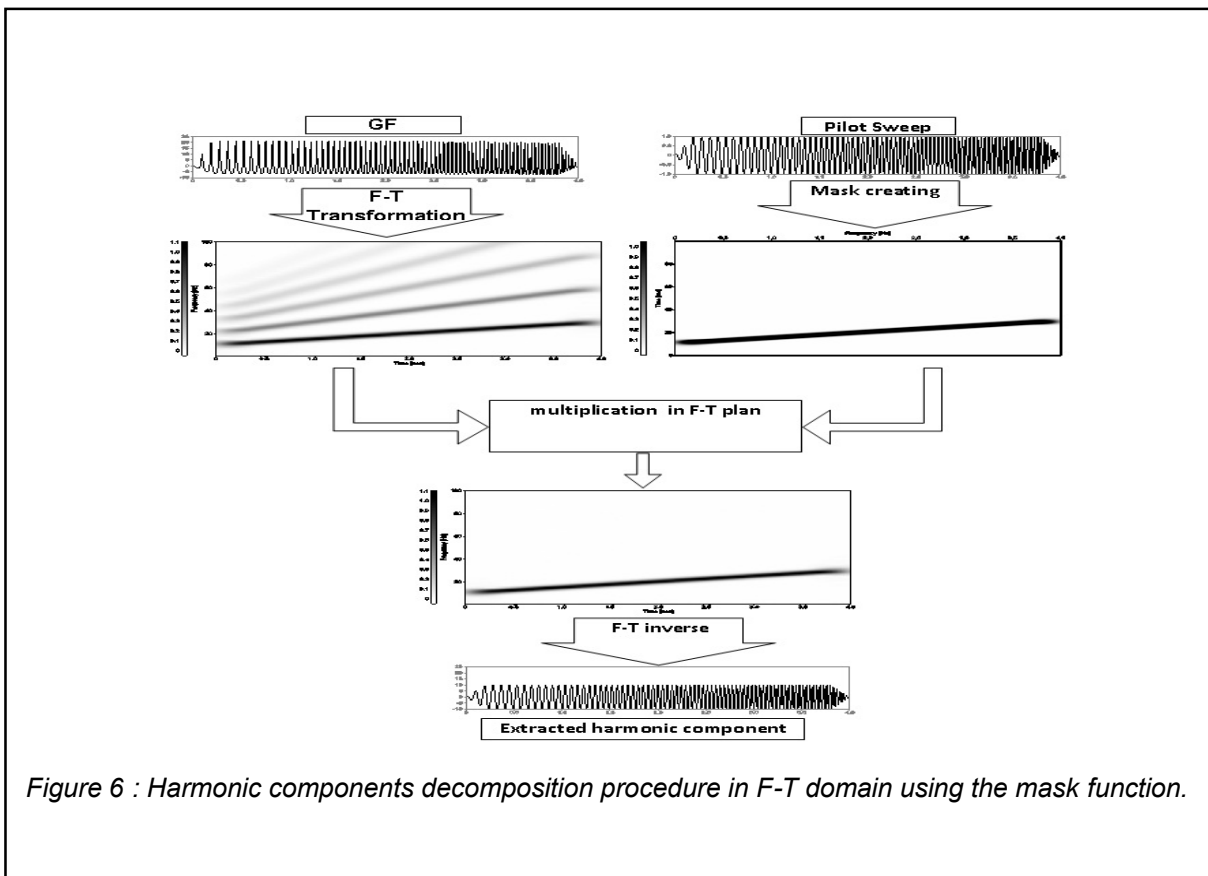*Figure 5 : Harmonic components decomposition procedure with adaptive filter*
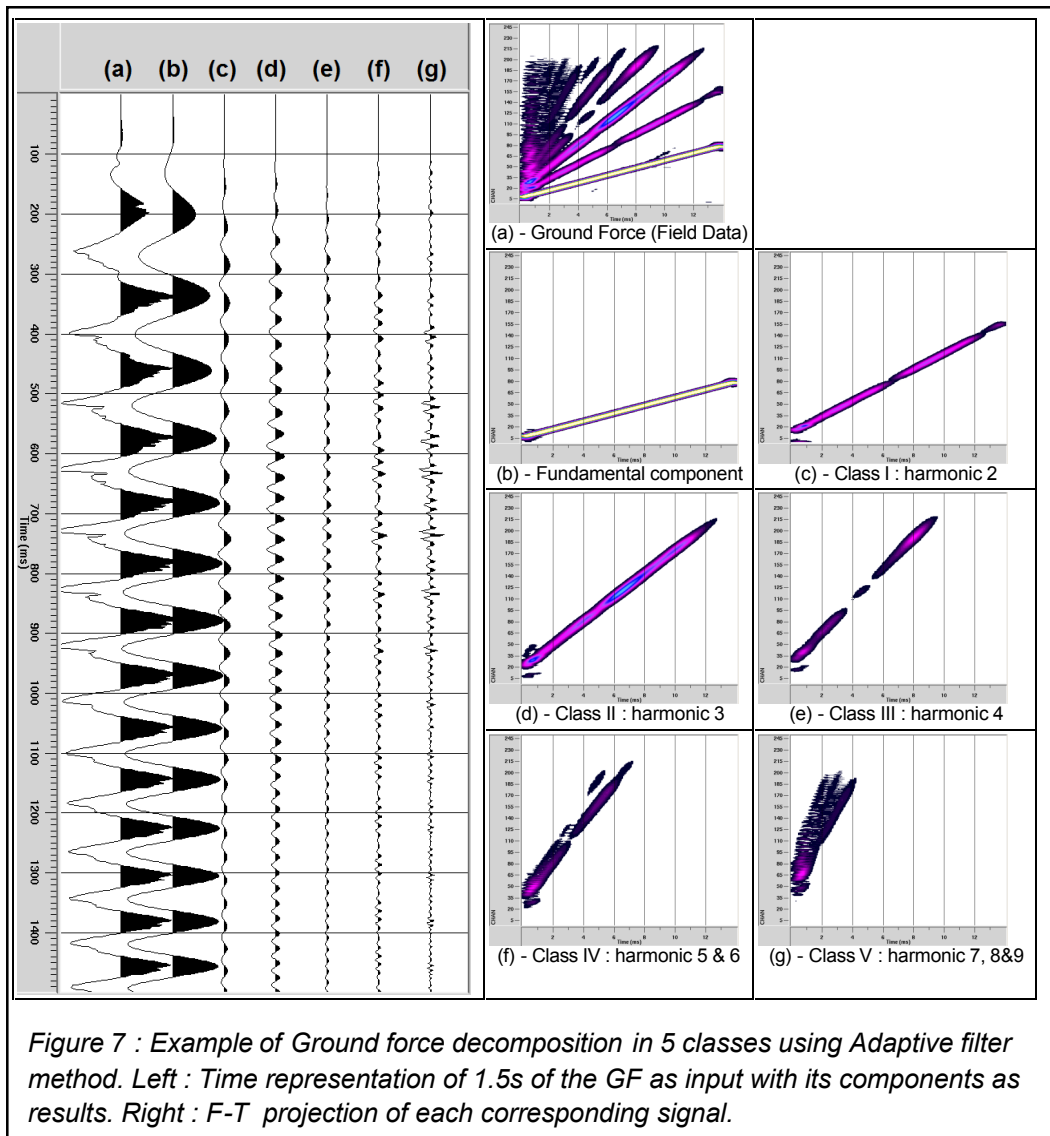


*Figure 6 : Harmonic components decomposition procedure in F-T domain using the mask function.*
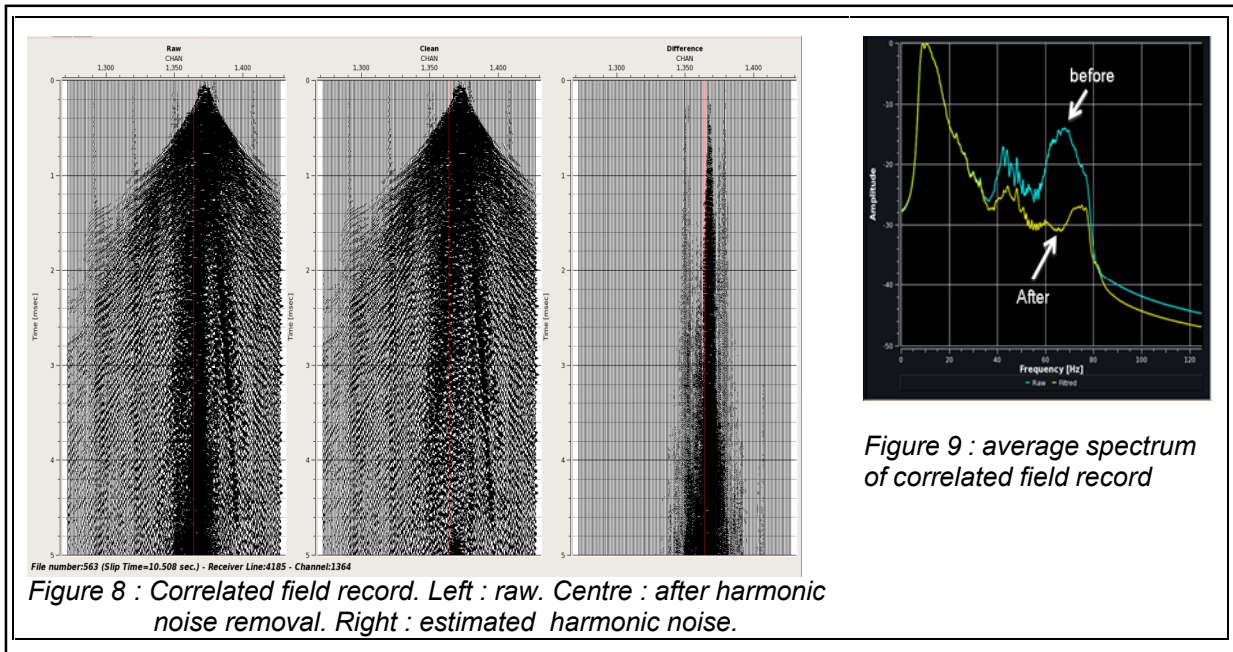
We give in Figure 7 an example of GF signal decomposition using the adaptive filter method.



*Figure 7 : Example of Ground force decomposition in 5 classes using Adaptive filter method. Left : Time representation of 1.5s of the GF as input with its components as results. Right : F-T projection of each corresponding signal.*
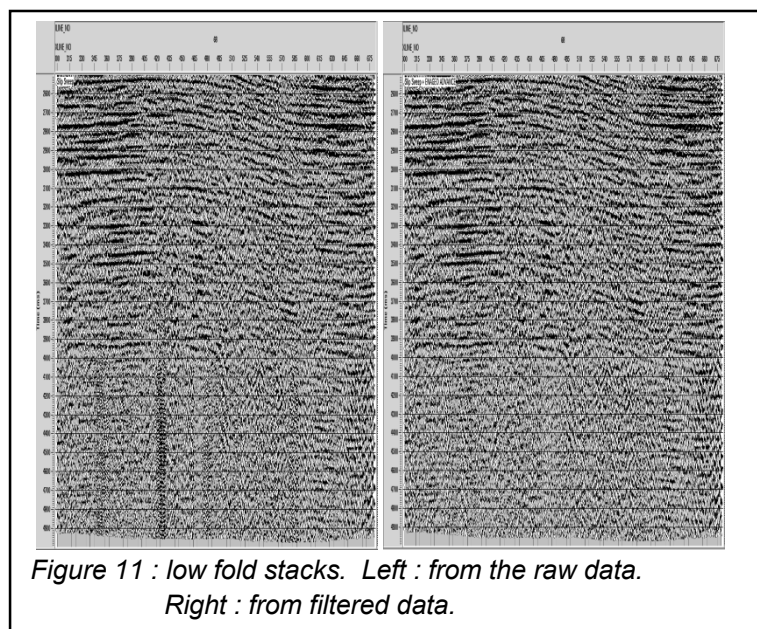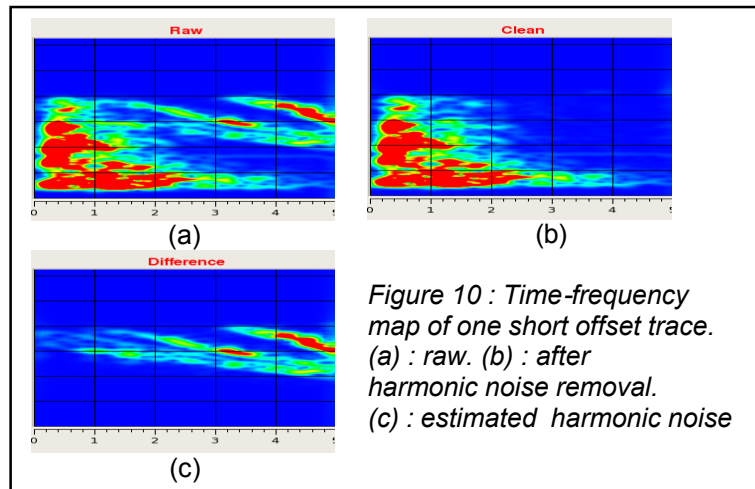
## Field application

ENAGEO conducted a 3D field tests survey recorded in slip sweep and conventional mode, in Hassi Messaoud (south of Algeria). For the case illustrated here, the production source configuration consisted of two fleets of four vibrators operating in flip-flop mode, whilst the slip-sweep configuration was four fleets of three vibrators. Data was acquired with both configurations using the same receiver spread (50 m group interval and 300 m line spacing). With three sweep/VP of 12s the two fleets conventional crew achieved 52 VP/hr with a 56 m VP interval on 200 m spaced lines. The slip-sweep operation used a 14s single sweep, and achieved 162 VP/hr with the same VP interval and source spaced lines. Another test, in conventional mode, has been conducted in the same area using the same configuration as slip-sweep (the same fleet number and the same sweep length), and achieved 120 VP/hr.

Compared with flip-flop acquisition using two fleets of vibrators, the slip-sweep acquisition achieved a 212% gain in productivity with no deterioration in seismic data quality (Figure 12),

Figure 9 : average spectrum of correlated field record

*Figure 8 : Correlated field record. Left : raw. Centre : after harmonic noise removal. Right : estimated harmonic noise.*
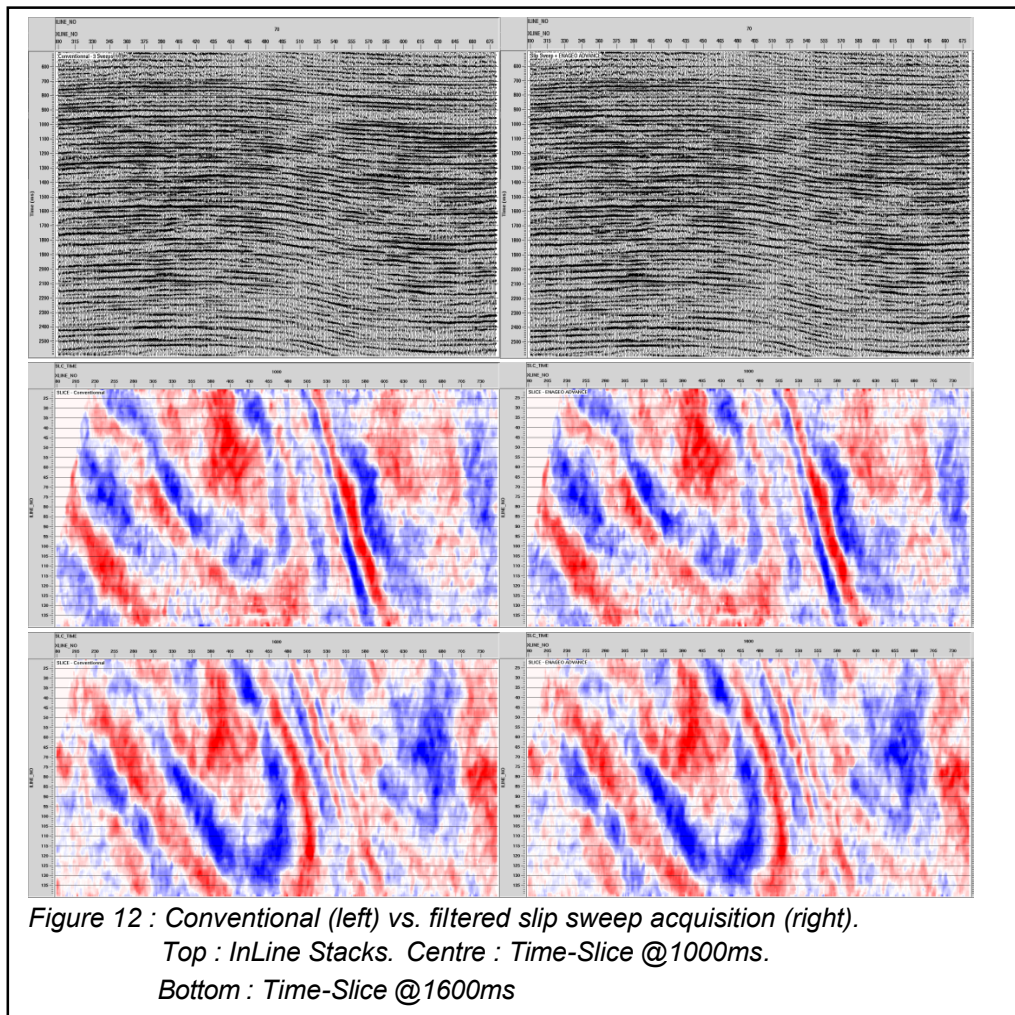
and 36% gain in productivity compared to conventional acquisition realized with the same parameters. This gain in productivity was supported by the efficiency and robustness of the new approach filtering presented in this paper that allowed reducing effectively the harmonic noise. Figure 8 illustrates a field record, before and after filtering and the estimated harmonic noise. The figure 9 shows the average spectrum for the same record before and after filtering in which we notice that the contaminated part is in the High frequencies. Harmonic noise appears in the F-T plan as negative dip alignments as it is shown in figure 10 which presents the F-T projection of one short offset trace before and after noise and the difference projection. Also the useful signal, shown as vertical energy, is preserved.

As is shown in Figure 11, slip sweep technique leads to a weak deterioration of the data quality in



*Figure 10 : Time-frequency map of one short offset trace. (a) : raw. (b) : after harmonic noise removal. (c) : estimated harmonic noise*



*Figure 11 : low fold stacks. Left : from the raw data. Right : from filtered data.*

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the stack section, particularly in the later times. This deterioration was reduced by CDP stack. However, the application of the harmonic noise attenuation method, on the field records resolves this problem effectively. To separate the effect of the stack and that of the harmonic filtering we performed a comparison between two sections with low fold. The first one is obtained from the raw data and the second from the filtered data, Figure 11.

Finally, the comparison between the In-lines and the time-slices in Figure 12 obtained from conventional data and filtered slip sweep data shows an equivalent quality. Consequently the slip sweep acquisition was achieved with a 36% gain in productivity without seismic data quality deterioration.



*Figure 12 : Conventional (left) vs. filtered slip sweep acquisition (right).*
*Top : InLine Stacks. Centre : Time-Slice @1000ms.*
*Bottom : Time-Slice @1600ms*

# Conclusion

A significant reduction in harmonic noise was achieved using the new harmonic noise removal approach. That is allows the implementation of slip sweep method properly without any data quality deterioration. So we can consider the data obtained using slip sweep technique after noise removal equivalent to conventional data.

We conclude that the slip sweep method offers the advantages to reduce the cost per km²
with the same parameters, or to improve the seismic image resolution by acquiring a higher
source density data with no extra cost.

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