# Analysis of the Slip Sweep Technique

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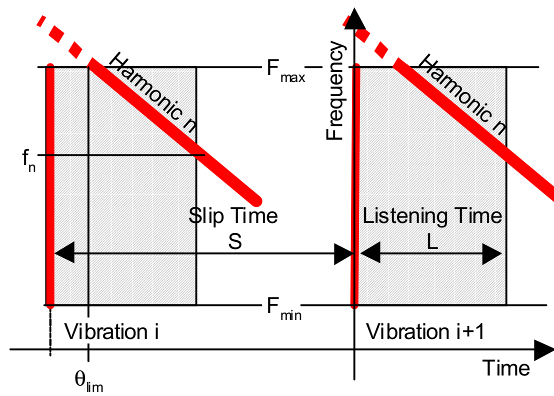
**Summary**
A 2D slip-sweep simulation experiment was recorded in the Mabruk field in Libya. In order to prepare this experiment, a preliminary analysis was conducted using synthetic data. Various types of noise were isolated and the corresponding data contamination analyzed. Signal-to-noise ratio maps were generated for various slip-sweep configurations. The same analyses were conducted on the actual data after slip sweep simulation, correlation and standard processing. Considering a 10 second slip time, the noise added to the data was lower than -20 dB.

**Introduction**
The method introduced by Petroleum Development Oman in 1996 essentially "consists of a vibrator group sweeping without waiting for the previous group's sweep to terminate"[1]. Its implementation is remarkably simple. Vibrator electronic systems have been adapted to offer the Slip sweep technique. And yet, outside its motherland of Oman, the proportion of 3D seismic surveys recorded with the Slip Sweep technique remains relatively modest. A possible cause of this slow penetration is the fear that harmonic noise generated by the method affects data quality. Several experiments were carried out, in Oman and elsewhere, to compare conventional acquisition with Slip sweep. Some of them have been related in literature or presented at conventions. For A. McGinn [2] "the slip-sweep method doubled production levels but did not affect data quality". P. Burger [3] introduced an implementation of the technique within an advanced acquisition system. P. Ras [4] conducted an interesting analysis of the method and tested its limits. P. Thacker presented an aggressive experiment in the Egyptian western desert [5]. They all concluded that it was relatively easy to deal with harmonic noise. The aim of the present study is to quantify the noise created by the slip-sweep technique and evaluate ways of reducing it. The first step is an analysis using synthetic data. The result of this analysis led to the definition of a life-size 2D experiment in Libya, which was subsequently recorded and validated the conclusions of the synthetic analysis.

**Analysis on synthetic data**
When a vibrating truck generates frequency f, because of harmonic distortion in the mechanism and in the [vibrator-earth] coupling, it also generates harmonic energy at frequency 2f, 3f, …nf. . In conventional vibroseis™ operations, signals of increasing frequency ("up-sweeps") are used and the correlation process rejects harmonic energy at negative time where it is relatively harmless to the data.




In slip-sweep operations, the interval between 2 consecutive sweeps, the slip-time, is too short to prevent interference between the harmonic noise and the previous record (see fig. 1). This interference can be described mathematically (P. Ras et al. 1999) as follows:

$$f_n = \left[\frac{n}{n-1}\frac{(F_{max} - F_{min})}{T}(S-L)\right] \qquad (1)$$

$$\theta_{lim} = S - \frac{n-1}{n} \times \frac{T.F_{max}}{F_{max} - F_{min}} \qquad (2)$$

Equation 1 gives the maximum frequency $f_n$ without interference of the harmonic n. It is a function of the sweep limits $F_{min}$ and $F_{max}$, the sweep length T, the slip time S and the listening time L. The harmonic noise-free portion of the data is then limited in frequency by $F_{min} \le f \le f_n$.
Equation 2 describes the time limit $\theta_m$ beyond which the seismic data will be affected by harmonic n. Equations 1 and 2 concern a source wavelet at time 0. For a particular event at TWT time $t_0$ , $f_n$ and $\theta_{lim}$ should be modified as follows :

$$f_n^{t_0} = f_n\left(\frac{S-L+t_0}{S-L}\right)$$

and $$\theta_{lim}^{t_0} = \theta_{lim} + t_0$$

# Analysis of the Slip Sweep Technique.

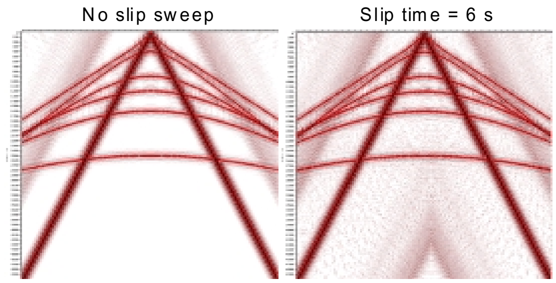



Fig.2 Comparison of conventional and slip-sweep data. In this example, radial noise is the major source of harmonic noise.

We investigated 3 methods of harmonic noise reduction: randomization of the slip-time as proposed by Rozemond [1], phase rotation of consecutive records and use of non-linear sweeps. Synthetic data sets were then generated, with various acquisition parameters: constant slip-time, randomized slip-time, phase shifts and non-linear signals. Results are summarized as follows.

a)*constant slip time:* As expected, harmonic noise moves up in the data when the slip time gets smaller; After stack, for an [8-80 Hz] 12 second-linear sweep, the harmonic noise remains below –50 dB even with a slip-time as short as 6 s. (fig. 3) Harmonic noise increases as $F_{max}$ decreases (for a same sweep length) and as the sweep length is shortened (for a given $F_{max}$).

b) *randomized slip time:* If the slip time is random, harmonic contamination will occur at a random time and be attenuated by the stacking process. This attenuation increases with the stacking fold. After a 60-fold stack, the signal-to-noise ratio gain was less than 3 dB.

c) *variable phase shifts:* This technique did not show a significant improvement. Consequently, it was decided not to include it in the field tests.

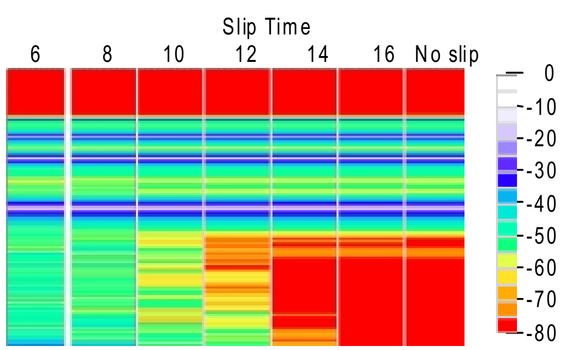



Fig.3 Variation in harmonic noise with slip time: The signal is an [8-80] 12s-linear sweep with 20% of H2 and H3, 12% of H4, 10% of H5 and 5% of H6. Data are NMO corrected and stacked (fold 60). Harmonic noise is found after the last reflection in blue.

d) *effect of log sweep:* A change in the time-frequency relationship produces a change in the interval contaminated by harmonic noise and in the amplitude of the contamination. On our synthetic data the contamination was significantly attenuated.

We also investigated the behavior of ambient noise in the slip-sweep process. If it is random, its amplitude after correlation is proportional to the square root of the recording time. Since, for a given source energy, the recording time is shorter in slip-sweep operations, should not slip-sweep data be less affected by ambient noise than conventional data? We modeled this effect and observed no difference. In fact, in the correlation process, only part of the correlated seismogram is kept and the advantage of a shorter recording time disappears. The second question is the behavior of ambient noise in a simulated slip sweep experiment. Such a simulation is the shifted addition of two or several records. In the common time gates, ambient noise belonging to the input records will be summed whereas in actual operations, ambient noise is recorded only once. For a salvo of 8 records of 20s. with a slip time of 6s., simulated noise can be as much as 4dB greater than actual noise.

**Data acquisition**

A 2D line acquired in Libya in April 2000 served as input for the slip sweep simulations. The station interval was 25m and the nominal fold 120. Three 45000-lb vibrators and two 16-second [8-92 Hz] sweeps were used. The 2D profile was recorded twice, with a linear up-sweep and with a logarithmic up-sweep. The data were not correlated in order to allow the simulation. The shot gathers evidenced a rather high distortion level due to a poor coupling with the unconsolidated surface sands. (Fig. 4)

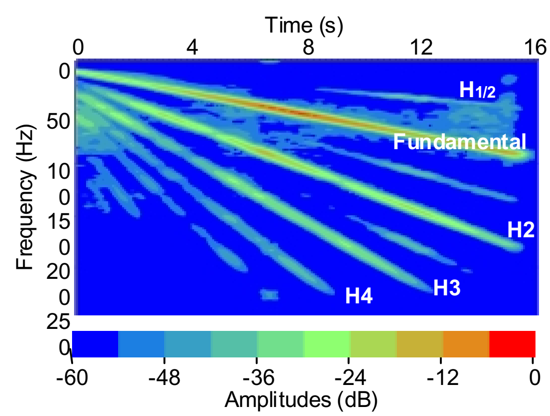



Fig. 4 Time frequency map of uncorrelated data. Note the relative strength of harmonics and sub-harmonics: the second harmonic rises from –24 dB at 30 Hz up to –12 dB at 80 Hz , the third harmonic is more consistent at –24 dB . The $4^{th}$ and $5^{th}$ as well as the sub-harmonics remain below –30 dB.

This of course influenced subsequent slip sweep simulations.

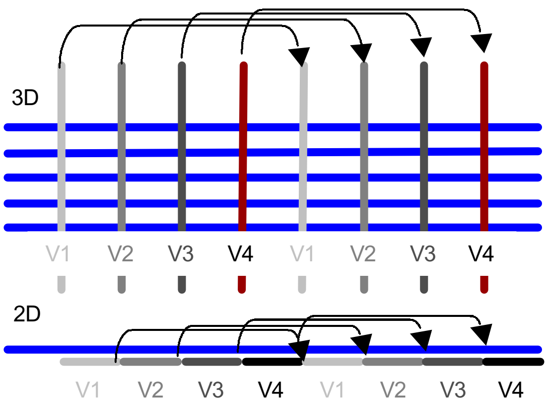



Fig. 5 4-group Slip-sweep simulation
Top: 3D implementation: each group on a different line
Bottom: 2D simulation: all groups on the same line

**Data Processing**

The advantage of the slip-sweep method is most obvious in 3D acquisition. For instance, N groups of vibrators would operate on N consecutive source lines. To somehow simulate this type of acquisition using uncorrelated 2D data, we generated slip-sweep salvos of 8 records separated by 10 stations (fig. 5). Uncorrelated data were then merged to simulate slip sweep salvos of 8 SPs with various slip times. Fig. 6 represents a correlated SP between time –20s and +20s. The black rectangle (e) is the useful part of this SP. It is the time gate which is kept after conventional correlation. On this record, noise can been classified into three categories:

(a) Harmonic noise observed essentially at negative times (for an up sweep) and generated by correlation of (integer) harmonics with the pilot. The velocity of this noise indicates that it consists essentially of ground roll energy. In slip-sweep operations, this noise will contaminate the previous record(s)

(b) Sub-harmonic noise observed at positive times and generated by the correlation of (fractional) sub-harmonics with the fundamental. This noise also mainly consists of ground roll. It was not modeled in our preliminary study. It was unexpected and particularly energetic in this survey. In slip-sweep operations, it will contaminate the next record(s).

(c) Uncorrelated noise produced by the vibrator engine and hydraulic pump. This noise affects mainly the traces with one geophone next to one vibrator during the VP. Its amplitude is 24 dB greater than the signal amplitude.

(d) Ambient noise responsible for the vertical stripes on the records. Its RMS amplitude is 20 to 30 dB below the signal amplitude.

It is important to keep in mind the difference between such a simulation and an actual 3D implementation. In 2D, vibrators move along the line, close to the geophones and generate high amplitude uncorrelated noise. This simulation poorly models the uncorrelated noise (c). It is far less cumbersome in 3D where vibrators move across receiver lines instead of along them. Moreover, it contaminates records acquired with a short slip time more than records acquired with a longer slip time whereas the real contamination would be the same on both. Indeed, we consider it as the major weakness of the simulation. For this reason, we removed all traces with one geophone close to one vibrator during any sweep of the VP which, in this particular case, amounted to 6 traces.

Besides various slip-sweep simulations, the data were also conventionally correlated. All data sets were subsequently processed with identical parameters up to CMP stack. These stacks were obtained without any particular processing to reduce slip-sweep noise. Although the slip time was only 5 s., no significant difference can be seen between the sections obtained using conventional correlation (reference section) and slip-sweep simulation before correlation. The noise generated by the slip-sweep method can be estimated as the difference between these two pictures. The signal-to-noise ratio is then computed as the ratio of filtered envelopes of the difference section and the conventional sections. Figure 8 shows such ratios expressed in dB.

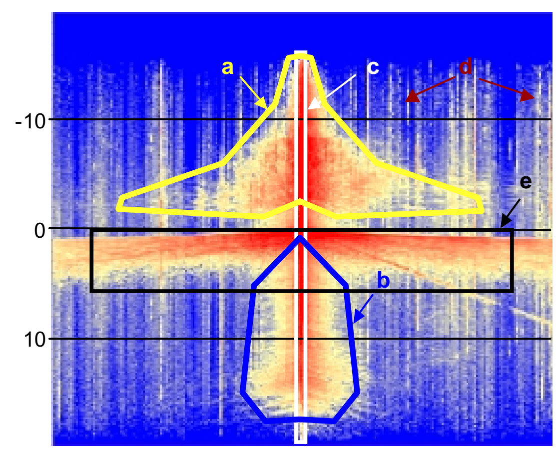



Fig. 6 Correlated SP (Up sweep)

| | | | |
|---|---|---|---|
| a | Harmonic noise | b | Sub-harmonic noise |
| c | Uncorrelated noise | d | Ambient noise |
| e | Useful correlated gate | | |

**Conclusions**

This study allowed us to classify various type of noise and to describe the effects. Despite inherent limitations, namely, inexact analysis of ambient and uncorrelated noise, this simulation presents the unique advantage of providing a reliable signal-to-noise ratio estimate. Since data contamination by both ambient and uncorrelated noise would be smaller in an actual 3D slip-sweep recording, these ratios are a low estimate of the actual case. In this example, we found a ratio larger than 20 dB for a slip time of 10 s everywhere signal can be recognized in the data. A slip time of 5 s removes less than 5 dB from this ratio. The signal-to-noise ratio gained by slip time randomization was less than 3 dB. Utilization of a logarithmic sweep did not improve the result in this case.

## References

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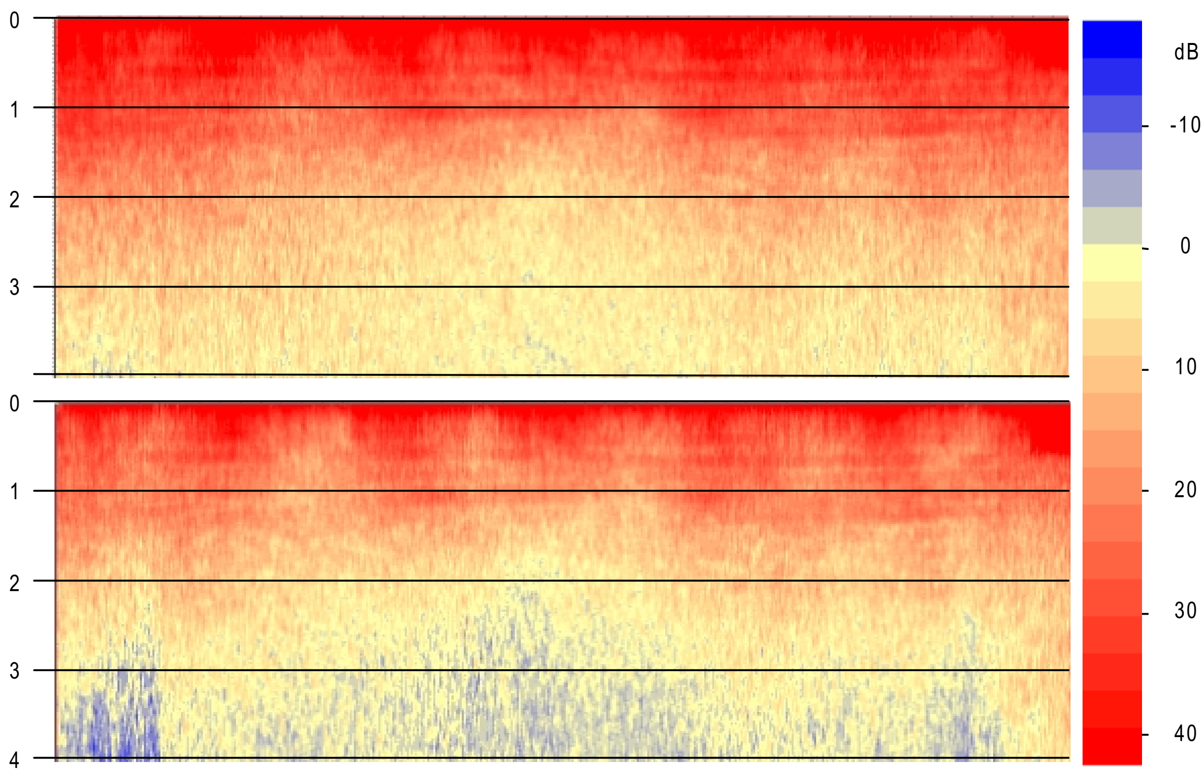


Fig 7 Slip-sweep noise evaluation Signal to noise ratio (in dB)
[Envelope of (reference - simulated slip-sweep)] / [envelope of reference]
Top: slip time10 s. Bottom: Slip time 5 s.