## Chapter 1

# INTRODUCTION

### 1.1 The drill bit as a downhole seismic source

In a new type of seismic experiment, ambient acoustic energy is recorded with a multichannel array of geophones during the drilling of a well (Figure 1.1). During drilling, part of the energy applied to breaking the rocks is converted into elastic waves that propagate from the bottom of the borehole to the surface. The goal of this seismic experiment is to record the waves emitted from the drill bit — the tool that breaks the rocks at the bottom of the borehole — and extract information about velocities or reflectivities that is of interest to geophysicists and drilling engineers.

Depending on the goals of the seismic experiment performed during drilling, the wavefield along the surface can be sampled either coarsely with a few geophones or densely with a 2-D grid of geophones. Because this new seismic experiment does not interfere with drilling, it avoids two major drawbacks of conventional borehole surveys: the cost of interrupting drilling operations, and the risk of damaging the borehole by operating either a sonde of geophones or an active source in the borehole (Hardage, 1985 and 1988).

The challenge in this experiment is to extract useful information from a signal that is weak with respect to several other sources of noise, such as engines on the drilling platform, and over whose power and frequency there is little or no control. Perhaps the most attractive and unique applications of the seismic experiment performed during drilling would be the "real time" prediction of drilling hazards ahead of the bit and steering of the well towards a target.

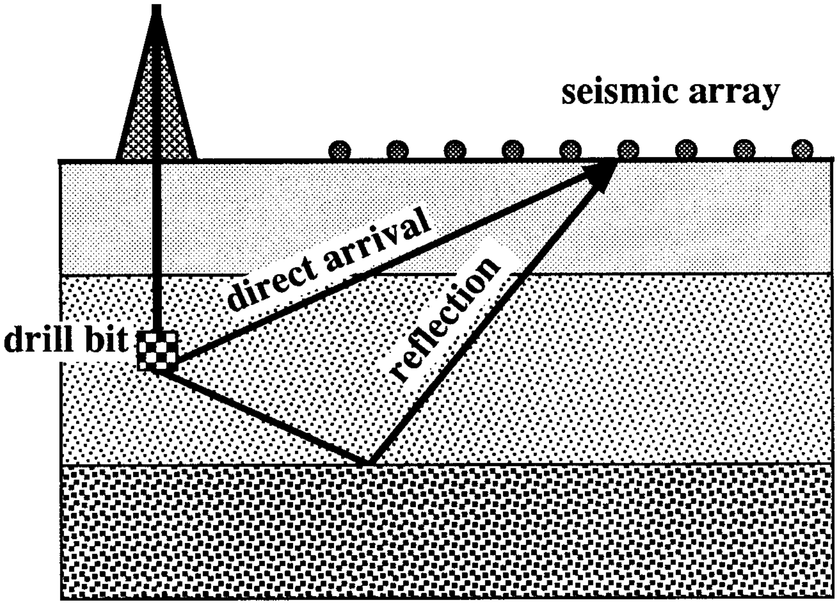

FIG. 1.1. A multichannel array records ambient noise during the drilling of a well. Part of the elastic energy released at the bottom of the borehole propagates through the formation to the surface as direct or reflected waves.

## 1.2 Experiments using the drill-bit signal

### 1.2.1 A single-channel experiment

In the early 1970's, Lutz and his co-workers at Elf-Aquitaine demonstrated that signals up to at least 150 Hz generated by the drill bit at the bottom of the well can be recorded with an accelerometer attached to the top of the drill string [1]. Theoretical studies have established that sound propagating in a string is dispersed (different frequencies travel at different speeds) and attenuated only when the material properties vary along the string (Lutz, 1972; Drumheller, 1989). Although the drill string is a non-uniform medium, the expected dispersion and attenuation remain small at the frequencies of interest in seismic experiments using the drill-bit signal. To illustrate this point, consider a signal of frequency, $f$, equal to 150 Hz. Its wavelength $\lambda$ is given by:

$$\lambda = v_{\mathrm{steel}}/f \geq 4875/150 = 32 \text{ m}.$$

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[1] The drill string is equal in length to the depth of the well minus the length of the bottom-hole assembly (approximately 100 m long). The drill string is built by connecting drill pipes each about 10 m in length, with tool joints which are roughly 0.5 m long and have a larger cross-sectional area.

This wavelength (and to a greater extend the wavelengths of lower-frequency signals) is large compared to the smaller scale inhomogeneities along the drill string. This explains why in Lutz's experiment the accelerometer record (SNAP-log) was comparable to sonic logs without further processing, and why in later experiments (Tomex survey, page 3) dispersion and attenuation effects have not been considered.

In principle, even single-channel records of a downhole source could be used to detect strong reflectors, because the interference between waves propagating arriving at the surface with different traveltime delays, corresponding to different paths of propagation, modifies the temporal autocorrelation of the signal. A theory, developed by Claerbout (1985a) and relevant to the interpretation of earthquake seismograms, states how to recover the impedance profile of a stack of layers (bounded by a uniform medium and a free surface), from a seismogram observed at the surface and a model for the autocorrelation of the incident waveform. In the seismic experiment performed during drilling the signals from the drill bit are much weaker than several other sources of noise, and therefore such single channels methods are not applicable.

### 1.2.2 A two-channel experiment

Instead of measuring the relative traveltime delays between the weak direct arrival from the drill bit and the even weaker reflections, another idea is to record ambient noise with two geophones placed at some distance apart. Then the relative traveltime delay between the direct arrivals recorded at the two different locations should change as the depth of the drill bit increases. Widrow (1988) has suggested signal-processing methods that would measure the change of the recorded signals with time and infer from them the position of the drill bit, or of reflectors. Again, this method has not been applied successfully to field data.

A variation on the previous concept has been pursued by several companies and led to a successful industrial application — the Tomex[2] survey (Rector et al., 1988; Staron et al., 1988). In the Tomex survey, an accelerometer at the top of the drill string replaces one of the two previous geophones and provides a record of the drill-bit signal in a noise environment that is *different* from the noise traveling along the surface.

To emphasize the model for the signal and noise that underlies the processing of data

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[2] The Tomex survey is a Registered Trademark of Western Atlas International, Inc.

from a Tomex survey, I will discuss that processing sequence in some detail following Rector (1988). The sampled drill-bit signal is defined in terms of its Z transform[3], BIT(Z). The drill-bit signal propagates through the drill string to the accelerometer, and through the earth to the geophone. The propagation effects through each of these two media — drill string and earth — are modeled as linear filters, DS(Z) and EARTH(Z), convolved with the drill-bit signal. Thus, the discrete time-domain signal received at the accelerometer is:

$$\mathrm{PILOT}(Z) \;=\; \mathrm{BIT}(Z) \times \mathrm{DS}(Z),$$

and the discrete signal received at the geophone is:

$$\mathrm{GEO}(Z) \;=\; \mathrm{BIT}(Z) \times \mathrm{EARTH}(Z). \qquad (1.1)$$

Cross-correlation of the signals recorded by the accelerometer and by the geophone yields:

$$\mathrm{XCOR}(Z) \;=\; \mathrm{PILOT}(1/Z) \times \mathrm{GEO}(Z) \;=\; \mathrm{DS}(1/Z) \times |\mathrm{BIT}(Z)|^2 \times \mathrm{EARTH}(Z). \qquad (1.2)$$

The earth response is obtained by deconvolution of the cross-correlated data, with the following assumptions:

1. The spectrum of the drill-bit signal is white, hence $|\mathrm{BIT}(Z)|$ is constant at all frequencies:

$$|\mathrm{BIT}(Z)|^2 \;=\; \mathrm{cst}.$$

2. The impulse response of the drill string is minimum phase, and therefore can be deconvolved with a minimum phase inverse wavelet obtained from the autocorrelation of the accelerometer signal:

$$\mathrm{AUTO}_{\mathrm{Accelerometer}}(Z) = |\mathrm{BIT}(Z)|^2 \times |\mathrm{DS}(Z)|^2 \;=\; \mathrm{cst} \times |\mathrm{DS}(Z)|^2. \qquad (1.3)$$

The deconvolution of the drill string impulse response attenuates multiples generated by reverberations in the drill string or in the bottom-hole assembly. A further correction is needed to account for the traveltime delay from the drill bit to the accelerometer through

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[3] For a definition of the Z transform, see Claerbout (1985a).

the drill string. After minimum phase deconvolution of the accelerometer signal, time-delay correction, and cross-correlation with the record from the geophone at the surface, the data from the Tomex survey are comparable to data recorded in a conventional experiment with an impulsive source.

Noise terms, if included in the above model, would in general modify the interpretation of the cross-correlation and autocorrelation functions defined by Equations 1.2 and 1.3. However, two conditions under which the above equations and processing sequence would remain valid, even in presence of noise, are that (1) the noise components of the accelerometer and geophone signals are mutually uncorrelated, as well as uncorrelated with the drill-bit signal; and, (2) the noise on the accelerometer record is small with respect to the drill-bit signal.

Published results on the Tomex survey include processed data of quality comparable to that of conventional VSP's, evidence for shear waves emitted by the drill bit, and the accurate location of the drill bit in real time (Rector, 1988, 1989a, 1989b). The successful results obtained by the Tomex survey confirm that in several situations the hypothesis of uncorrelated noise at the accelerometer and at the surface geophones has been appropriate. On the other hand, the Tomex survey requires long cross-correlation times (on the order of several tens of minutes) to effectively attenuate noise, and in some cases the noise attenuation is still not sufficient (Rector, 1989c).

### 1.2.3 A multichannel experiment

The preceding single-channel and two-channel experiments using the drill-bit signal have demonstrated that signals from the drill bit can be recorded with accelerometers at the top of the drill string or with geophones on the surface. A further observation is that detection of a weak signal is the main challenge in experiments using the drill bit as a seismic source.

Thus, a logical extension of previous experimental work is to apply beamforming or other array-processing techniques to separate signal and noise from data recorded with a multichannel array. The *Osservatorio Geofisico Sperimentale* (OGS) carried out such a multichannel seismic experiment during the drilling of a well and provided experimental data for the study in this thesis (OGS, 1988). Appendix B describes the acquisition geometry of the OGS experiment in detail.

There have been relatively few reports using multichannel filtering to separate signal from noise in seismic experiments performed during drilling (Haldorsen, 1986; Miller and Haldorsen, 1987; Kostov, 1989; OGS, 1988). Two reasons for the limited attention given to multichannel methods could be the higher acquisition and processing costs of a multichannel experiment, and the observation that data collected with one or with a few channels along the surface are similar to conventional VSP data and therefore sufficient in many applications, ranging from time-to-depth conversion to 2-D structural imaging (Hardage, 1988; Christie and Dangerfield, 1987).

On the other hand, arguments in favor of multichannel experiments are twofold: (1) multichannel processing could improve resolution and/or reduce the length of recording time with respect to two-channel experiments, and, (2) such experiments would provide multifold data of interest for seismic imaging, particularly of 3-D targets.

## 1.3 Methodology of the investigation

The new concept investigated in this thesis is the separation of drill-bit signal from noise by using multichannel acquisition and processing. In the course of the investigation, I ask the following questions: What are the signal-to-noise ratios in field experiments; What processing should be applied to detect the drill-bit signal; and, What geophysical information could be obtained from the processed data.

My answers to these questions are derived from the analysis of data from the OGS experiment — each suggested signal-processing algorithm is applied to experimental data and each conclusion is based on experimental evidence. While this approach emphasizes facts over speculations, it also raises the issue of the relevance of the conclusions from a single experiment.

Despite widespread industrial interest in experiments using the drill-bit signal, this thesis is the first public report on the analysis of data recorded with multichannel seismic arrays during drilling. The experiment for this study was carefully planned and well documented, and therefore the acquisition geometry is repeatable (OGS, 1988; Appendix B). On the other hand, unknown factors specific to the experimental site (such as the hardness of the rocks being drilled, the near-surface conditions, and the level of ambient noise) restrict the scope of the conclusions.

From this first analysis of experimental data, I expect to identify the important signal-processing issues and formulate a processing sequence that will also be relevant for future experiments. I attach less importance to the particular values of signal-to-noise ratios quoted; further iterations between experiments and processing should provide a background for comparing signal-to-noise ratios and assessing the potential of the method for industrial applications.

The algorithms included in my processing sequence are closely related to algorithms developed in the field of surface seismic exploration. My contribution consists mainly in identifying goals and signal-processing issues in this new type of seismic experiment, and in assembling a processing sequence from these familiar algorithms. In addition, I have developed a new class of algorithms that considerably improve the accuracy and efficiency of computing least-squares inverses of time-invariant linear transforms, such as the slant stack transform. Such least-squares transforms are essential components of my algorithms for velocity-filtering, and their application to large volumes of data, as in the seismic-while-drilling experiment, would not have been practical with previously existing methods (Appendix C).

I obtained the best results from the OGS data with the following processing sequence: first, I use multichannel processing methods to attenuate time-coherent and space-coherent noise on the surface-array data; then, I cross-correlate the filtered data with a "reference" signal recorded at 40 m depth. After cross-correlation, direct arrivals from the drill-bit signal can be identified, and the moveout of these arrivals can be measured. These results are encouraging and of interest for applications such as time-to-depth conversion and tomographic velocity analysis. On the basis of these results, I recommend that in future experiments data be recorded with a vertical seismic array in a nearby shallow well (rather than with only a few geophones at depth) as well as with seismic arrays on the surface.

## 1.4 Thesis overview

Chapter 2 begins with the description of several types of noise observed on a typical window[4] of drill-bit data; hyperbolic events that might be generated by a source at depth

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[4] The data are recorded as a function of time and offset (distance away from the well). A "window" refers to a subset of the data, corresponding to a limited range of times (here 1 s out of 10 min) or of offsets.

are barely visible. A processing sequence, developed in that chapter, is shown to attenuate time-coherent and space-coherent events with moveout that differs significantly from the expected hyperbolic moveout of the drill-bit signal.

To illustrate this processing sequence, I display all intermediate results for several control windows chosen for their widely varying noise patterns, as well as for a window of synthetic data. As a result of this processing, hyperbolic events 10 db below the original ambient noise become apparent on several control windows. I the question of whether these hyperbolas are drill-bit signal for the next chapter, and conclude Chapter 2 with three checks on the processing sequence. In the first test, to check that no spurious coherent events are created, I apply the processing sequence to spatially uncorrelated data. In the second and third tests, to determine noise has been well attenuated in a large volume of data, I compare amplitude and dip spectra before and after the applying the processing sequence.

In Chapter 3, I define a velocity transform and apply this transform to measure the moveout of the events with hyperbolic coherency that were revealed previously. The results of the moveout analysis indicate that these hyperbolic events are emitted by a source located on the surface and that their energy is about 3 db above a background noise with a broadband spectrum of dips. The failure of velocity analysis to detect the drill-bit signal implies that the background noise has larger power than the drill-bit signal. The velocity transform is generally applicable to non-impulsive signals, or to impulsive signal for which the time-origin is unknown.

To further enhance the drill-bit signal, I average cross-correlations between data from the surface array and data from a geophone at a depth of 40 m. When these cross-correlated seismograms are averaged, the signal and noise waveforms are compressed into short time-windows, and thus conveniently separated. The average cross-correlation, computed from a 10 min long sequence of data, finally reveals hyperbolic events whose moveout is as expected for direct arrivals from the drill-bit source.