Appendix B

Acquisition geometry for the OGS experiment

B.1 Introduction

The seismic experiment that provided the data for my work was performed by the *Osservatorio Geofisico Sperimentale* (Trieste, Italy) in the spring of 1988. The goals of the experiment were (1) to test equipment such as accelerometers, geophones, and types of drill bits; (2) to sample the ambient noise field in several places on the drilling platform, at varying depths, and at far offsets (Figure B.1); and (3) to detect the drill-bit signal (OGS, 1988).

In practice, the acquisition geometry resulted from a compromise between the various goals of the experiment and the limited resources available. The main hardware limitations for the OGS survey were the number of seismic channels (about 130) and the the time in which recording could be made without interruption (25 seconds).

In describing the acquisition geometry for the OGS experiment, this appendix follows the stages of one decision process by which the experiment could have been designed.

B.2 Surface seismic array

A surface seismic array can be used as a powerful antenna to focus on weak sources of signal and attenuate strong interferences. In this seismic experiment performed during drilling, the sampling rate in time and the spacing of geophones along the array are chosen by arguments similar to those applied in surface seismic exploration (Anstey, 1986); first the expected maximum frequency of the signal determines the sampling rate in time,

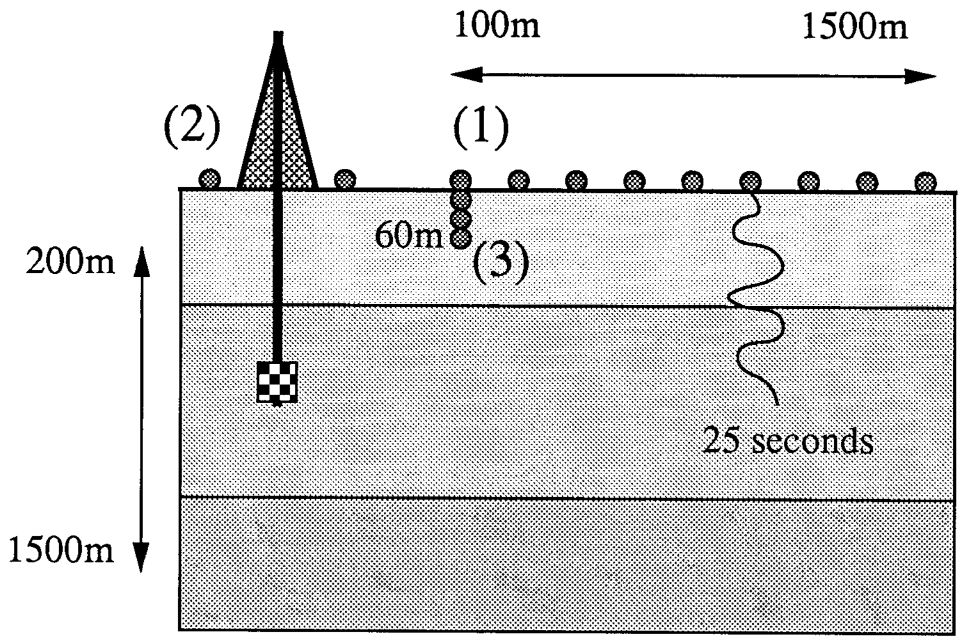

FIG. B.1. Data for this experiment were collected by (1) a surface array of geophones at distances from the well ranging from 100 m to 1500 m, (2) geophones on the drilling platform near strong sources of noise, (3) geophones buried up to depth of 60 m. The data were recorded for depths of the drill bit between 200 m and 1500 m.

then velocity and dip information are added in order to derive bounds on the wavenumber spectrum and determine a sampling rate in space. Specific issues to this kind of experiment are the choices of the sampling rate in depth and the record's length in time.

Sampling rate in time

The signal emitted from the drill-bit source is expected to contain broadband components from the crushing of the rock, at least up to 100 Hz and perhaps higher (Lutz et al., 1972). Therefore a sampling rate of 2 ms and a high-cut filter at 125 Hz, typical for surface seismic experiments, were also chosen for the OGS experiment.

What seismic array?

Even when a limited number of channels are used for the array, there are many possible options for the array geometry — one or several linear arrays, one or several circular arrays, or a 2-D grid; and, for the orientation of the geophones — vertical or horizontal components.

The OGS experiment was performed in a region of flat, horizontally layered sediments, mainly sands and clay. The sources related to the drilling — equipment on the drilling platform and downhole sources — were located close to the vertical axis of the borehole. The elastic wavefield emitted by these sources in a horizontally layered medium is expected to be symmetric with respect to the axis of the borehole.

The symmetry around the axis of the borehole implies that a 1-D linear array in the plane of the borehole should adequately record the wavefields emitted by sources close to the borehole axis. However there will be ambiguity in the source location (Figure 3.1), which could be reduced by either the use of two or more lines of vertical-component geophones, or the use of two-component geophones along a line. Another way of separating the drill-bit source from a source at the surface is by tracking changes in the moveout as the depth of the drill bit increases.

In the OGS experiment, data were recorded with a linear, 1-D array of vertical-component geophones, located on only one side of the well. An array of horizontal-component geophones, with a coarser spacing of channels and without field arrays, was also laid alongside the vertical-component array. This particular choice for the geometries of the array was probably dictated by the limited number of available seismic channels.

Summary of the array parameters in the OGS experiment

The offset range was modified when the depth of the well reached 1 km: the nearest and farthest offsets were increased respectively from 0.1 km to 0.385 km, and from 1.4 km to 2.1 km. The parameters of the seismic array are summarized in Table B.1, where (A) and (B) refer to the initial and final configurations of the array.

Sampling and resolution of 1-D linear arrays

Figure B.2 displays the group and channel arrays responses to monochromatic plane waves. The array responses for linear arrays are discrete sinc functions,

$$A(k) = \frac{\sin(k\delta x N/2)}{\sin(k\delta x/2)}, \tag{B.1}$$

where k is the wavenumber, N the number of channels in the array, and δx is the spacing between channels. Using the above equation, the following important physical properties of

Offset range	(A) 0.1 to 1.5 km ; (B) 0.385 to 2.1 km
Channel spacing, vertical component:	20 m
Channel spacing, horizontal component:	100 m
Number of vertical component channels	(A) 72 ; (B) 90
Number of horizontal component channels	(A) 14 ; (B) 18
Groups	12 geophones per group, spaced 1.66 m apart
Geophone natural frequency	10 Hz
Lowcut acquisition filter	10 Hz
Highcut acquisition filter	125 Hz
Recording Parameters	
Sampling rate in time	0.002 seconds
Length of records	10 or 25 seconds
"Shot spacing"	vertical movement of the drill bit 1 to 5 m
Number of "shot" gathers	1200
Array data available for this study	
(A) Depth of drill-bit 376-476 m	33 gathers, each 10 sec. long
(A) Depth of drill bit 777-980 m	130 gathers, each 25 seconds
(B) Depth of drill bit 1300-1400 m	95 gathers, each 10 seconds
(B) Depth of drill-bit 1291-1393 m	61 gathers, each 10 sec. long
Storage for the array data	400 Megabytes

Table B.1. Parameters of the surface array.

linear arrays can be expressed in terms of acquisition parameters (Dudgeon and Mercereau, 1984):

- Periodicity

  The array responses are periodic in wavenumber and symmetric around zero wavenumber. The period is equal to twice the Nyquist wavenumber K_{Nyq},

$$2 \times K_{\mathrm{Nyq}} = \frac{1}{\delta x},$$

  For the OGS experiment, the spacing between channels, δx, is equal to 20 m and the Nyquist frequency K_{Nyq} is equal to 25 km^{-1}.

- Resolution

The resolution ΔK of the array is typically defined as half the width of the main lobe of the array response,

$$\Delta K = \frac{1}{N\delta x} = \frac{1}{L},$$

where N is the number of channels, and L is the length of the array.

- Wavenumber in terms of physical parameters
  The wavenumber is related to the frequency ω, the velocity v, and the angle between the normal to the wavefront and the vertical by the equation

$$K = \frac{\omega \sin(\theta)}{v}.$$

Figure B.2 shows the array responses for the group and channel arrays in the OGS experiment, while Table B.1 summarizes the acquisition parameters in that experiment.

Sampling in depth

The sampling in depth should be dense enough in order to detect changes in the moveout across the array as the depth of the drill bit increases. For the surface seismic experiment, an order of magnitude for the vertical resolution is one quarter of the wavelength; that is about 15 m for a source with dominant frequency of about 30 Hz in a medium of velocity 2 km/s.

A more precise computation determines the array response to a monochromatic point source of angular frequency ω, located at zero-offset and depth z, and emitting compressional waves in a medium of velocity v. For such a source, the wavefield recorded at offset x will be:

$$d(x,\omega) = A(x,z)e^{j\omega\frac{\sqrt{x^2+z^2}}{v}}, \tag{B.2}$$

where $A(x,z)$ is an amplitude factor that depends on the distance from source to receiver. In the following computation, I will neglect variations in amplitude with offset, assuming that there is one dominant event in the data and that the power in each trace has been normalized. Then, the power of the stack along a trajectory defined by a pair of velocity and depth parameters (v_s, z_s), which differ from the parameters (v, z) describing the signal,

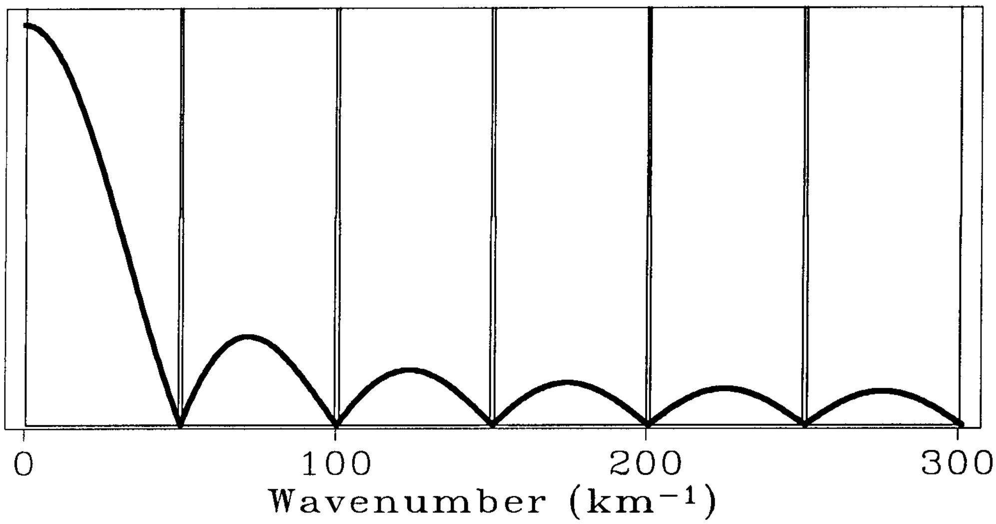

FIG. B.2. Amplitude responses to monochromatic plane waves of group and channel arrays for the OGS experiment.
The amplitude response for the group array is a sinc function (fat curve), readily apparent on the scale of the plot. The number of geophones in each group (12) determines the peak amplitude of the array response and the number of sidelobes. The spacing between geophones (1.66 m) determines the periodicity of the array response (600 km^{-1}).
The amplitude response of the channel array is also a sinc function (thin line). Only the main peak of the channel array response is apparent on the scale of the plot. There are 72 channels, spaced 20 m apart; therefore the peak amplitude of the channel array is 36 times ($(72/12)^2$) larger than the peak amplitude of the group array, and the period of the channel array is 12 times (20/1.66) smaller than the period of the group array.
The spacing between channels is equal to the length of the group array; therefore the zeros of the group array cancel exactly the main lobes of the channel array.

will be expressed as

$$S(\omega, z, v) = \frac{1}{M}\left|\sum_{x=1}^{M} e^{j\omega\times\left\{\frac{\sqrt{z^2+x^2}}{v} - \frac{\sqrt{z_s{}^2+x^2}}{v_s}\right\}}\right|^2 . \tag{B.3}$$

Figure B.3 displays the response of the array used in the OGS experiment to the wavefield radiated by a point source at depth of .8 km in a medium of constant velocity, 2 km/s. The dominant frequency of the source wavelet is 30 Hz, and the array responses computed by Equation B.3 are averaged over frequency. The figure shows a strong depth-velocity ambiguity discussed further in Chapter 3. For a given depth of the source, the width of the main-lobe is also about 15 m — a result obtained by neglecting noise, and valid only for the method of parameter estimation by stacking.

In the OGS experiment the sampling rate in depth varied between 1 and 3 m. The oversampling in depth attempted to compensate for the length of the records in time — 10 or 25 s, which was presumed to be too short.

Length of the records in time

The length of the records in time is perhaps the parameter that is hardest to specify without reference to the actual noise level in the experiment. For the OGS recording geometry, the expected traveltime difference between near and far offsets for events emitted by the drill bit is about 1 second. When noise is suppressed with multichannel methods, the length of the records in time is not crucial, as long as the event is not truncated in time, which would have the effect of reducing the effective aperture of the array. Lengths of the records of the order of 10 to 30 s as in the OGS survey seem reasonable and compatible with current recording and multiplexing systems.

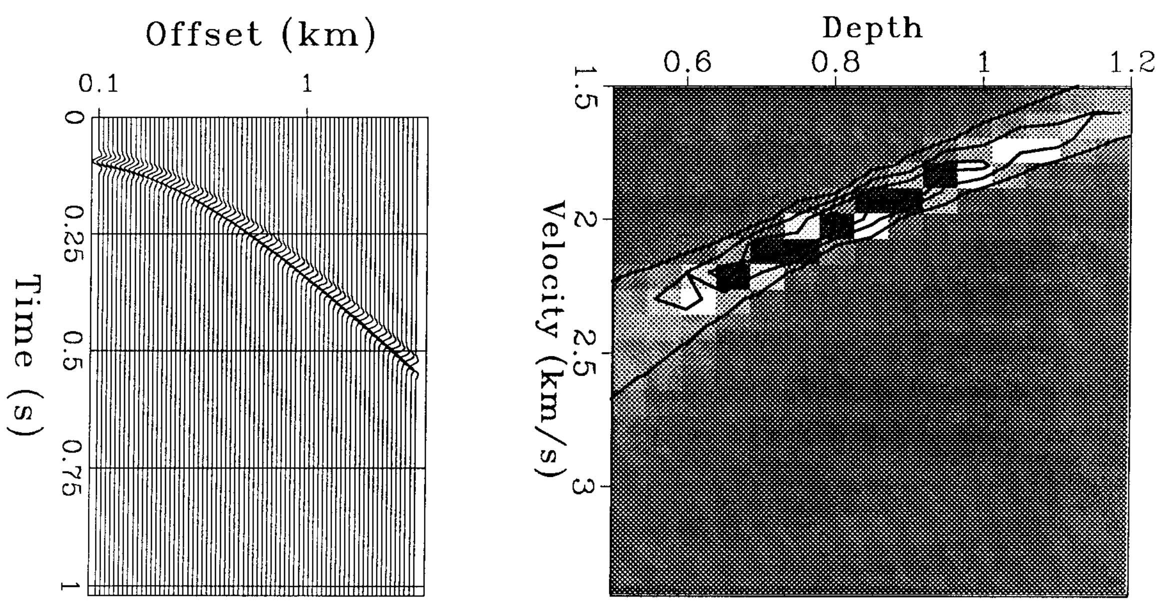

FIG. B.3. Array response to a broadband pulse with dominant frequency of 30 Hz emitted by a point source at depth of 0.8 km in a medium of velocity 2 km/s; these depth and velocity parameters are close to the ones expected from the drill-bit signal in the OGS experiment. The figure on the left is the synthetic seismogram in the time-offset domain (Equation B.2), while on the right is the array response.
Black pixels indicate clipped amplitudes above the 98^{th} percentile; high positive amplitudes are plotted in white.

B.3 Other measurements

Other sources of data for this experiment were (1) geophones on the drilling platform, (2) geophones buried up to 60 m deep, (3) standard drilling logs and (4) stacking velocities from surface seismics (Figure B.1) (OGS, 1988; Kostov, 1988).

Sampling of the noise field on the platform

To determine the frequencies produced by different engines, noise on the drilling platform was recorded with five geophones: one vertical-component and one horizontal-component geophone near the top of the borehole, one near the trailer, another near the pumps, and a final one near the mud pits.

Geophones in a nearby vertical well

Three three-component geophones were buried in a shallow well at the near-offset of the seismic line, 100 m away from the well. The depths of the geophones were 20 m, 40 m, and 60 m. The purpose of these geophones was to estimate the attenuation of surface waves with depth (OGS, 1988). Another possible use of deeply buried geophones would be as a vertical seismic array.

Drilling logs

The drilling logs list several parameters measured at intervals of about 2-3 minutes, not necessarily related to the times when the geophones were recording. The list of parameters includes depth of the well, time of measurement, weight on bit, rotations per minute, torque, rate of penetration, flow rate, injection pressure, and volumes of mud in the pits. The power transferred to the drilling assembly is given by the product of the torque times the rotation frequency (Lutz et al., 1972). Qualitatively one would expect strong signal from the drill bit when a hard formation is being drilled, for the weight on bit, torque, and rotation rates are high. Some parameters from the drilling logs are summarized in the following table:

Stacking velocities from a surface seismic survey

Some values for stacking velocities from a surface seismic survey near the survey site

Parameter	min	max	typical
Weight on bit (tons)	1	8	3
Rotations per minute	30	100	70
Torque (kgm)	10	350	80
Rate of penetration (m/h)	6	500	60

Table B.2. Parameters from the drilling logs.

are shown in Table B.3:

Time T (s)	RMS Velocity V (km/s)	Depth Z = V × T / 2 (km)
0.1	1.65	0.083
0.4	1.675	0.033
0.7	1.825	0.64
0.85	1.88	0.8
1.	1.95	0.975
1.2	2.1	1.26
1.52	2.325	1.77

Table B.3. Stacking velocities from a surface seismic survey.