Symmetric Sampling of Multiple-Coverage Seismic Data

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SUMMARY

The pre-stack seismic data set is in its simplest form a function of three independent variables: shot coordinate x_s, receiver coordinate x_r, and time t. A linear transformation links the spatial coordinates x_s, x_r to the midpoint coordinate x_m and the offset coordinate x_o. For each spatial coordinate there is a corresponding wavenumber: k_s, k_r, k_m and k_o.

Consideration of the properties of the pre-stack wave field leads to the definition of the symmetric sampling technique as the preferred way of recording 2-D multiple-coverage seismic data.

The effects of asymmetric spatial sampling are discussed and illustrated with an example of asymmetry in the common midpoint gather of a center-spread geometry.

Symmetric spatial sampling is compared with the stack-array approach proposed by Anstey. Symmetric sampling will lead to better data quality, especially in case of complex geology or strongly varying groundroll.

The combined effect of field arrays and CMP array is to be analysed in the two-dimensional (k_m, k_o) domain, rather than as a function of only one wavenumber. Examples of the total stack response are discussed.

INTRODUCTION

In recent years the seismic data acquisition technique has received renewed interest through Anstey's publication of the stack-array approach (1986a, 1986b), and Ongkiehong and Askin's universal seismic acquisition technique (1988). Vermeer (1990) introduces the concept of symmetric spatial sampling on basis of an assessment of the physical properties of the wave field to be recorded. The present paper discusses some aspects of symmetric and asymmetric sampling.

SYMMETRIC SAMPLING

To establish spatial sampling requirements we need to consider the physical properties of the (hypothetical) continuous wave field to be sampled.

The continuous wave field for a straight seismic line is a function of shot coordinate x_s, receiver coordinate x_r, and recording time t. It is the ensemble of all possible common shot panels. The wave field can also be described in terms of the midpoint coordinate x_m, offset x_o, and recording time t, and the two coordinate systems are related by:

$$x_m = (x_s+x_r)/2 \quad \text{and} \quad x_s = x_m+x_o/2$$

$$x_o = x_s-x_r \qquad\qquad x_r = x_m-x_o/2$$

The properties of the wave field in each common shot panel follow from elastic wave theory. Assuming reciprocity, the properties in the common receiver panel are identical to the properties in the common shot panel. As a consequence, the **sampling requirements for the shot coordinate are identical to the sampling requirements for the receiver coordinate.**

The smallest phase velocity V_{min} of all events in the common shot panels, together with the maximum frequency f_{max}, determines the maximum receiver wavenumber k_{rmax}, with

$$|k_{rmax}| \leq f_{max}/V_{min}, \text{ and, because of}$$

reciprocity

$$|k_{smax}| \leq f_{max}/V_{min}.$$

It follows that in (k_s, k_r, f) the energy of the continuous wave field is confined to a pyramid, the base of which is a square at $f=f_{max}$ with edges $k_s, k_r = \pm f_{max}/V_{min}$. Hence to achieve alias-free spatial sampling of the continuous wave field the shot and receiver sampling intervals should both be equal to or smaller than $0.5/k_{rmax}$.

Unfortunately, alias-free sampling requires sampling intervals that are too small to be practical (e.g. for f_{max} = 75 Hz, V_{min} = 300 m/s the shot and receiver intervals should be 0.5*300/75 = 2 m). As a compromise field arrays are to be used. **The arrays act as a resampling operator, and a shot array is as necessary to resample the shot coordinate as the receiver array is to resample the receiver coordinate.**

This reasoning leads to the optimum compromise acquisition technique set up according to the symmetric sampling criterion (Vermeer, 1990):

- equal shot and receiver intervals, and
- equal shot and receiver arrays.

Using different reasoning and terminology Ongkiehong and Askin (1988) recommend the **same** acquisition technique. Provided the sampling intervals are small enough, a shooting geometry allowing the construction of a symmetric data set from the recorded data might produce even better results (e.g., individual recording of each shot), at some extra cost.

SOME EFFECTS OF ASYMMETRIC SAMPLING

Deviations from symmetric sampling lead to an asymmetric distribution of samples in the (x_s, x_r) coordinate system. Figure 1 illustrates the sample distribution for some common center-spread shooting geometries. Each symbol represents an elemental shot/receiver combination. Each group (3 or 9) of equal symbols represents one trace. The (x_s, x_r) coordinate system has been rotated over 45 degrees for ease of display. Horizontal lines represent common offset, vertical lines represent common midpoint. (For a representation in the (x_m, x_o) coordinate system the vertical scale should be twice as large.) Figure 1a represents a symmetric sampling geometry with shot and receiver arrays each having 3 elements. It shows a regular coverage of the (x_s, x_r) coordinate system. Figure 1b shows the same geometry as Figure 1a, but without a shot array. In this (asymmetric) case large areas of (x_s, x_r) are not sampled. Figure 1c has no shot array and a shot interval three times the receiver interval.

Asymmetric sampling is more or less the norm in marine data acquisition, as shot layouts are usually not designed to be similar to receiver arrays. As a consequence, left- and right-dipping events are affected differently by this shooting geometry, leading to a different appearance of parallel lines shot in opposite directions. This effect also causes jitter in the crossline direction of 3-D surveys.

Asymmetric sampling may have quite disturbing effects on center-spread recording. Within one CMP half the number of traces have been shot updip, and the other half has been shot downdip. If the arrays are not symmetrical then the same event will be affected differently depending on the shot-receiver direction. In Figure 2 the left panel is a CMP, sorted according to increasing absolute offset, recorded with 25 m shot and receiver intervals and array lengths, whereas the right panel shows the same data after simulation of a 75 m receiver array. All events that are dipping as a function of midpoint show an odd/even effect as a function of offset in the right panel. Obviously this effect will adversely affect the stack. The phenomenon is explained in Figures 3a and b in terms of a destruction of reciprocity. In Figure 3a rectangles ABCD and EFGH represent the convolution of shot and receiver arrays, they are not reciprocal. The averaging effect of a rectangular array on a dipping event (represented by two constant traveltime curves in Figure 3b) is different on either side of zero offset as illustrated in Figure 3b.

THE STACK-ARRAY APPROACH VS. SYMMETRIC SAMPLING

The stack-array approach as proposed by Anstey (1986a) leads to a much better data quality than older techniques that still use shot intervals three or four times as large as group intervals. Anstey (1986b) formulates the stack-array criterion as "an even, continuous, uniform succession of geophones across the CMP gather" and recommends particular shooting geometries for center-spread and end-on configurations. Morse and Hildebrandt (1989) demonstrate the advantage of an even distribution of geophones over the CMP gather.

The stack-array approach does not require the use of a shot array, hence it is an asymmetric sampling technique. (Figure 1b would represent a shooting geometry according to the stack-array criterion.) **Symmetric sampling not only requires an even, uniform sampling of geophones, but also of shots along the whole seismic line** (Figure 1a).

Anstey (1986a) suggests that shooting noisespreads is no longer necessary with the stack-array approach. However, a prescription of regular spatial sampling does not yet say anything about the length of the sampling intervals. The shorter the intervals the more costly the acquisition. A compromise must be reached taking into account the geological and the geophysical problem (groundroll energy, structural complexity, near-surface effects, character play). Testing, including shooting noisespreads, will help to establish the best compromise.

THE STACK-ARRAY RESPONSE

The combined effect of field arrays and CMP stack should be described in the two-dimensional wavenumber domain, rather than as a function of only one wavenumber.

Figure 4 shows the response in the midpoint/offset wavenumber domain of the following configurations:

Figure	shot array	receiver array	CMP array	NMO
4a	25 x 2m	25 x 2m	no	no
4b	25 x 2	25 x 2	24 x 50m	no
4c	no	25 x 2	24 x 50	no
4d	25 x 2	25 x 2	12 x 100	no
4e	no	25 x 2	12 x 100	no
4f	25 x 2	25 x 2	24 x 50	yes

Figure 4a shows the response of the field arrays only. It shows that in the (k_m, k_o) system the zero-crossings of the array responses run at oblique angles with the coordinate axes. Note that this is also the response of the acquisition geometry for a perfectly NMO corrected and stacked event, as the stack does not affect such events.

Figure 4b shows the total plane wave stack response (no NMO correction) for a center-spread configuration with 50 m shot and receiver spacings and 25 elements in shot and receiver arrays. The CMP array has its zero-crossings parallel to the k_m axis, with the first zero-crossings at $\pm 1/1200\ m^{-1}$. The first alias (secondary pass band) of the stack occurs at $\pm 1/50\ m^{-1}$. The total stack response shows the effect of all three spatial filters on the original continuous wave field. The energy passed by these filters will end up in the final stack.

Figure 4c shows the total plane wave stack response for the same configuration as for Figure 4b, but without a shot array. More energy will now be passed by the spatial filters, the amount of passed energy depending on the energy distribution in the continuous wave field. Figures 4d and 4e repeat Figures 4b and 4c, respectively, but now with twice the element spacing in the CMP (off-end shooting).

Figure 4f shows the effect of the three spatial filters on a linear event with apparent velocity V_o = 600 m/s, after NMO correction with V_{nmo} = 1500 m/s. Relative to the original wave field the notches of the CMP array move outward, leading to a less good energy suppression along the k_o axis and better suppression of energy in other areas of the (k_m,k_o) plane. Again, the actual effect depends on the energy distribution in the continuous wave field, but it is likely that the effect is insignificant as compared to not using a shot array.

Finer sampling (shorter shot and receiver arrays) pushes the filter notches out toward larger wavenumbers. As a consequence a larger part of the original wave field will fall in the pass band of the combined field arrays. In that area more of the suppression of the unwanted events is then left to the stack, and to other digital processes. Other digital processes such as (k,f) filtering in common midpoint and common offset panels may be required to compensate for the loss of the effect of the two field arrays.

CONCLUSIONS

Symmetric spatial sampling is the preferred way of gathering seismic data. The actual parameters are a compromise and need to be established after evaluation of the geological and geophysical problems at hand.

A better understanding and knowledge of the energy distribution in (k_m,k_o,f) would help to predict the effect of any choice of the acquisition parameters. Noisespreads and very densely sampled multiple-coverage data can help to gain such insights.

ACKNOWLEDGEMENTS

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REFERENCES

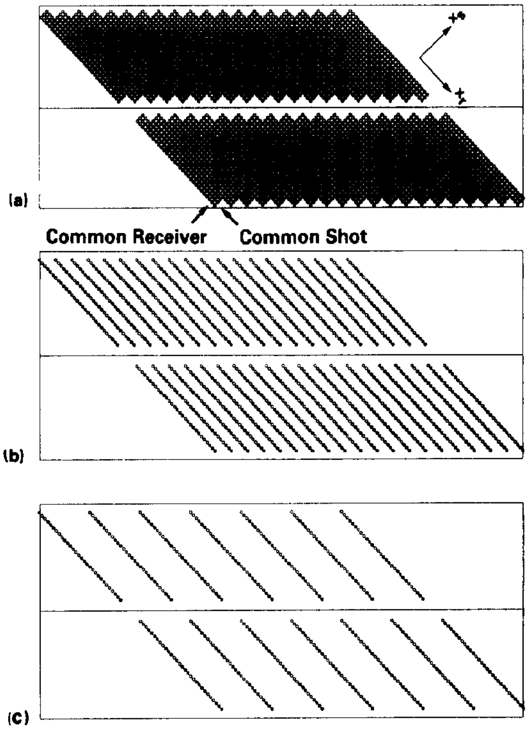
Anstey, N.A., 1986a, Whatever happened to groundroll?: Leading Edge, 5, No.4, 40-45.

Anstey, N.A., 1986b, A reply by Nigel Anstey: Leading Edge, 5, No.12, 19-21.

Morse, P.F., and Hildebrandt, G.F., 1989, Ground-roll suppression by the stack-array: Geophysics, 54, 290-301.

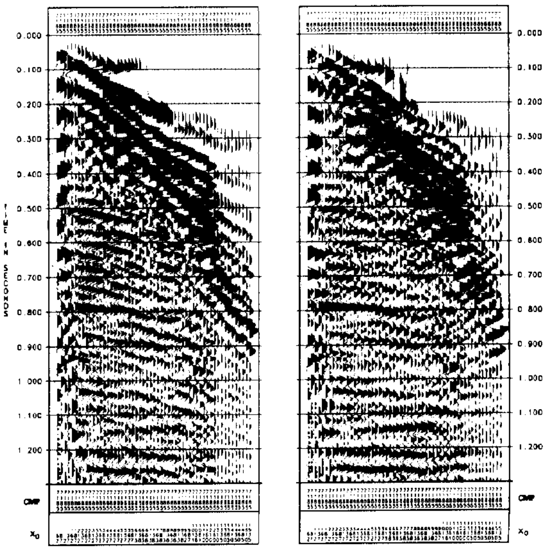
Ongkiehong, L., and Askin, H., 1988, Towards the universal seismic acquisition technique: First Break, 6, 46-63.

Vermeer, G.J.O., 1990, The four domains - Some acquisition and processing fundamentals for multiple-coverage seismic data: SEG Reference Series (in press).



VARIOUS SHOOTING GEOMETRIES

Each symbol represents an elemental shot/receiver pair. A group of 3 or 9 equal symbols represents one trace. Fig. 1

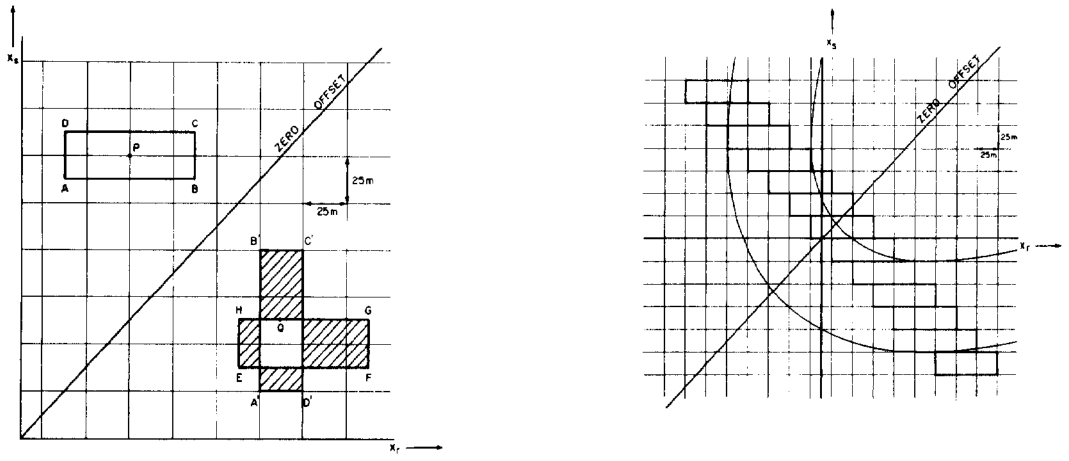


(a) symmetric sampling

(b) asymmetric sampling

Fig. 2

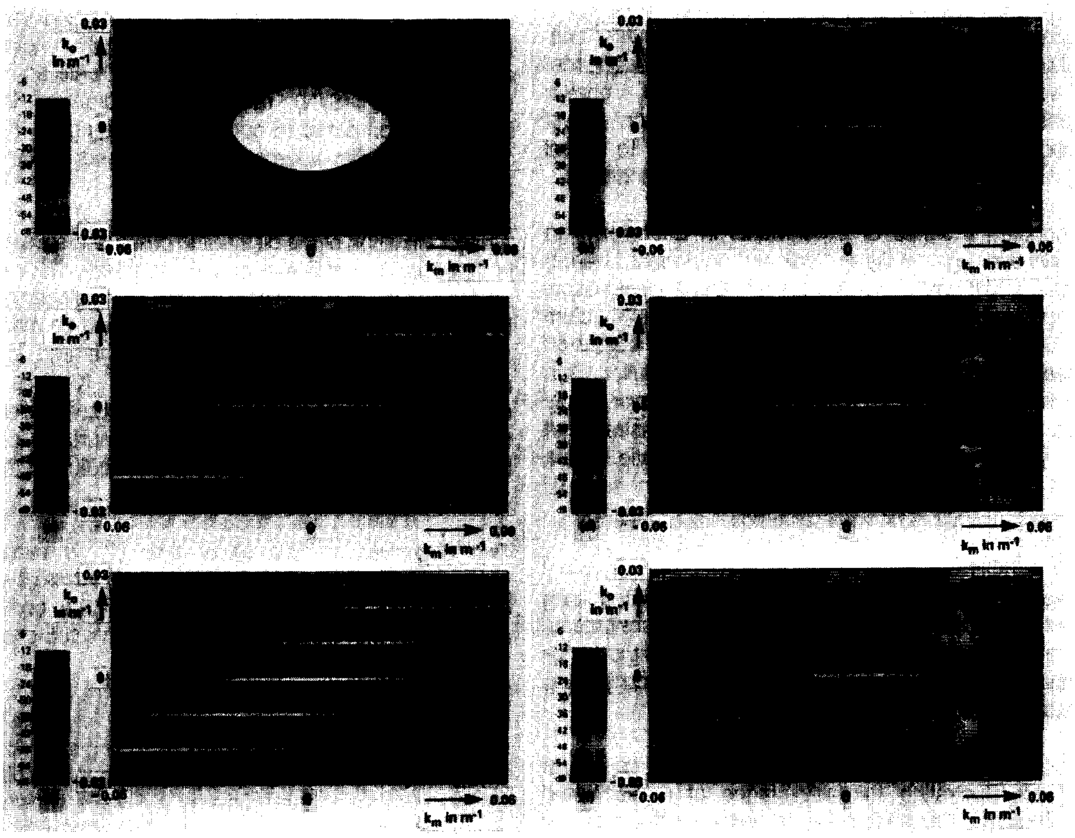
Explanation of odd/even effect in Figure 2



(a) Rectangles ABCD and EFGH represent convolution of 25 m shot pattern and 75 m receiver pattern.

(b) Rectangles on either side of zero offset have different averaging effect on dipping events.

Fig. 3



TOTAL STACK RESPONSES

Fig. 4