Alternative strategies for tackling scattered noise

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Summary

Scattered ground roll is one of the most serious noise problems in the Middle East and similar high-velocity areas. Meunier has shown that the noise of point scatterers can best be discriminated from the desired signal in 3D shot or 3D receiver gathers, whereas part of that noise looks like signal in cross-spreads. This paper makes a detailed analysis of the scattered noise problem, both for point and line scatterers, in 3D shot gathers and in cross-spreads. The findings of Meunier are confirmed and also apply to line scatterers. Then alternative strategies are proposed to solve the problem. The most successful method - acquiring data with areal geometry (3D shot or 3D receiver gathers) - is also the most expensive. As an alternative, orthogonal geometry can be used provided the receiver and/or source lines are laid out as 2D ribbons rather than 1D strings. This can be implemented using a single-point technique and also by using array-based acquisition. The array-based technique is the least expensive of the three alternatives.

Introduction

The traveltime surfaces of surface scatterers are circular cones in 3D shot gathers (Meunier, 1999), and - because of reciprocity - those surfaces are also circular cones in 3D receiver gathers. On the other hand, in cross-spreads those traveltime surfaces behave like rounded pyramids with rounded edges and a rounded top (Figure 1). As a consequence, 3D velocity filtering of those scatterers should perform best in 3D shot or 3D receiver gathers and be less successful in cross-spreads.

Based on these observations Meunier et al., (2008) conclude that orthogonal geometry is not suitable for tackling scattered noise. This means that areal geometry would have to be acquired, but areal geometry is woefully expensive for land data acquisition, even when using 12 single vibrators simultaneously as proposed in Meunier et al., (2008).

In this paper the problem of scattered noise is analyzed in further detail and alternative strategies for data acquisition allowing successful suppression of the scattered noise are proposed.

Description of problem

To illustrate the discussion, ground-roll velocity $V_{\min,N}$ is 900 m/s, maximum frequency of ground roll $f_{\max,N}$ is 45 Hz, and minimum signal velocity $V_{\min,S}$ is 2700 m/s throughout this paper.

Point scatterers

The behavior of the traveltime surface of point scatterers in a cross-spread as shown in Figure 1 can be explained with help

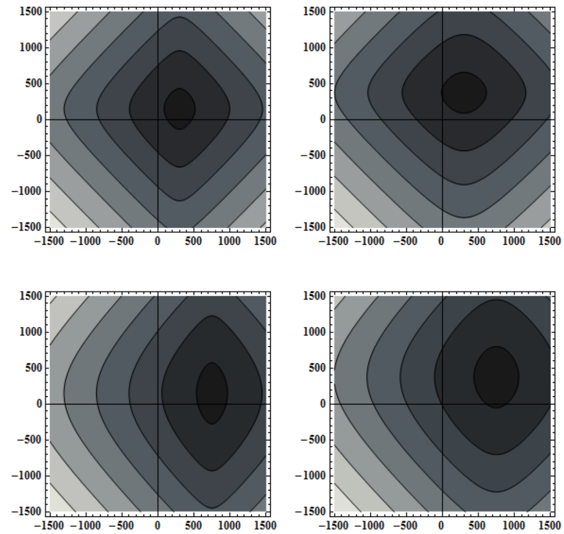

Fig. 1. Contour plots of traveltime surfaces in midpoint domain of 4 surface scatterers in cross-spread. The scatterers are located at (x, y) = (600, 300) and (600, 750) in top row and at (1500, 300) and (1500, 750) in bottom row. First contour around apex of scatterer is at time of apex plus 250 ms, contour interval is 1000 ms.

of Figure 2, which shows the square cross-spread used as a basis for Figure 1. Midpoint M at (800, 1050) is the position of the apex of the traveltime surface. The derivative of the traveltime with respect to shot or receiver position is zero in the apex; hence the top of the traveltime surface is rounded rather than sharp like the traveltimes in the 3D shot gather.

As a consequence the traveltime surface around the apex has similar time dips as the reflection data of interest. Conventional filtering techniques will not be able to discriminate between primaries and noise. Yet, a large range of slopes, up to the minimum P-wave velocity is still steep enough to be suppressed by 3D *f-k* filtering. What is left after 3D *f-k* filtering are the slopes that are smaller. Figure 3 illustrates the corresponding areas around the scatterer.

Line scatterers

Yet another type of surface-wave noise is caused by surface discontinuities such as cliffs. Next I address that type of noise for the stylized situation of a straight-line discontinuity. I assume that source and receiver should be on the same (high) side of the cliff. For areal geometry (assume sparse shots and dense receivers) the situation is simple: from the virtual source at a position mirrored in the straight discontinuity a "direct wave" travels to all receivers. Hence, the traveltime surface is now formed by a (truncated) circular cone with its center at the

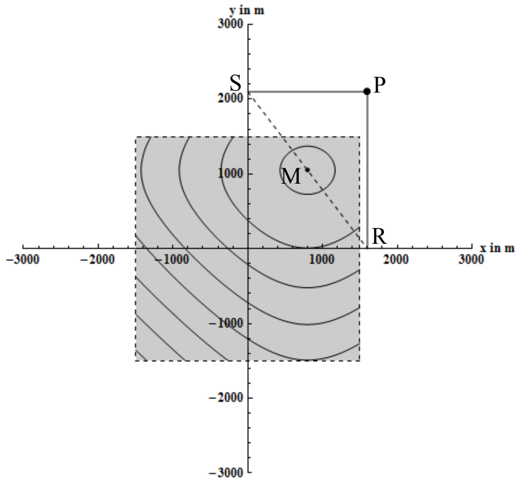

Fig. 2. Cross-spread used in Figure 1. A scatterer is located at (1600, 2100) and a contour plot of its corresponding traveltime surface is displayed in the gray midpoint area of the cross-spread. The travel path from shot S at (0, 2100) via scatterer at P to receiver R at (1600, 0) is the shortest path and the corresponding traveltime forms the apex of the traveltime surface.

virtual-source position. So, the traveltime surface is steep with constant time dip and the noise can be suppressed with 3D *f-k* filtering as before for the point scatterer in the 3D shot gather.

The situation is quite different and much more complex for orthogonal geometry. Now the shape of the traveltime surface depends on the orientation of the discontinuity with respect to the grid of acquisition lines. Figure 4 shows the gradients of the traveltime surfaces for a single cross-spread for four orientations of the line scatterer.

The top-left display in Figure 4 shows an area where noise and signal cannot be discriminated. The white contour lines represent the boundary between noise that can and cannot be removed by 3D *f-k* filtering. Areas of noise that cannot be removed by 3D *f-k* filtering are not present in the other three situations illustrated in Figure 4. For the bottom-right situation the traveltime surface is in fact a truncated circular cone producing constant gradient, similar as for the 3D shot gathers. This is the situation that the line scatterer is parallel to the receiver line.

From this analysis it is clear that the orientation of the shot and receiver lines with respect to a linear surface discontinuity makes a big difference in the ability to remove the noise with 3D *f-k* filtering. If the shot or receiver lines are parallel to the discontinuity, all noise can be removed; whereas when they make an angle of 45° with the discontinuity the noise is most serious with an area that cannot be removed. Figure 5 illustrates the areas that cannot be suppressed by 3D *f-k* filtering for the same acquisition geometry as used in Figure 3.

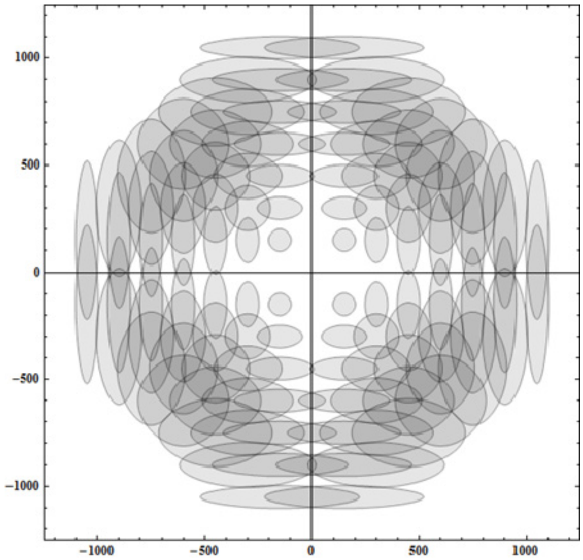

Fig. 3. Flat apex areas for single scatterer in origin in orthogonal geometry with 300-m line intervals. $V_{\min,N}$ = 900 m/s, cut-off velocity 2700 m/s, maximum time 3 s.

Alternative designs

I will discuss three alternative survey designs: single-point areal geometry, single-point orthogonal geometry and array-based orthogonal geometry. In single-point acquisition all noise removal takes place in processing, because field arrays are not applied. For those designs it is possible to sample the spatial domains using the adequate sampling interval (Baeten et al., 2000) rather than the basic sampling interval (Vermeer, 1990) needed for alias-free sampling of the 3D shots or the cross-spreads. The "adequate Nyquist wavenumber" can be computed from $k_a = f_{\max,N}(1/V_{\min,N} + 1/V_{\min,S})/2$. For the standard ground-roll parameters k_a = 0.033 m^{-1} or Δx = 15 m. This may be contrasted with a basic sampling interval in this case of 900 / (2 * 45) = 10 m.

In the following I compare the alternative designs using a "benchmark" survey that requires (for orthogonal geometry) about 200-m line intervals and 3000-m maximum inline and crossline offsets.

<u>Areal geometry</u>

Areal geometry may be implemented in two different ways: dense sources and sparse receivers or sparse sources and dense receivers. Meunier et al., (2008) propose the first solution. An adequate sampling interval of 15 m would require a 15 × 15 m grid of (single) sources, or, a source density of 10^6/(15 * 15) = 4444 VP/km^2.

The areal geometry equivalent to the benchmark survey would have a 200 × 200 m receiver station grid. However, for regular

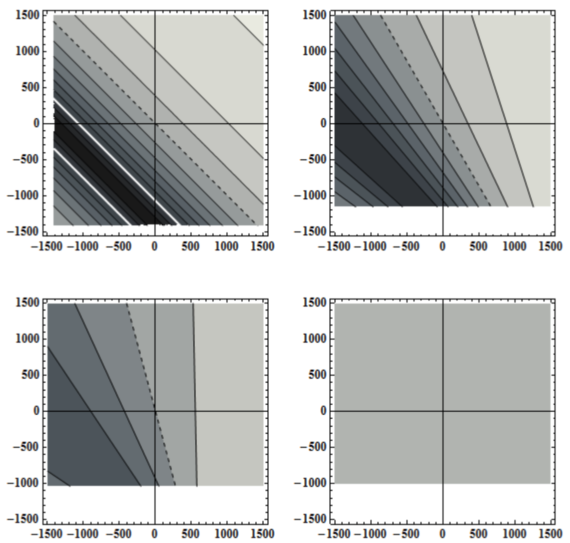

Fig. 4. Contour maps of slownesses of traveltime surfaces in cross-spread for four different orientations of line scatterer. Distance of line from center of cross-spread is 2000 m. Normals to line have angles 225, 240, 255, and 270° with positive *x*-axis). The contour interval is 1/ (9 * 450) s/m. The dashed contour line is for slowness 1/450 s/m. The white contour lines (in top left slowness map only) correspond to a slowness that is 3 times as small as for the dashed contour lines. (Slowness is measured in midpoint domain.)

geometry the grid interval should be an integer multiple of the station interval of 15 m. So, the sparse receiver grid might be chosen as 210 × 210 m. Acquiring the same fold as in the benchmark survey would require 30 * 30 = 900 receiver stations, each of which needs to record a total of 176,400 shots.

The alternative areal geometry (sparse shots and dense receivers) would require 176,400 receiver stations in the template. Currently, this is not yet feasible.

Single-point orthogonal geometry

In areas with much scattered noise, orthogonal geometry does not provide a simple solution to the removal of that noise. The problem is that the flat part of the noise cannot be readily distinguished from signal.

The problematic horizontal parts of the traveltime surfaces are caused by noise that is traveling perpendicular to the shot line *and* to the receiver line. Small apparent velocities only exist in this perpendicular direction to the acquisition lines. It is common practice to exploit the larger time variations across the acquisition lines by using areal arrays. An alternative to using areal arrays is to use ribbon-like lines, in which those lines have also a dimension across the lines, i.e., the lines are 2D ribbons rather than 1D strings. In practice this means that each acquisition line may consist of two or more parallel sublines.

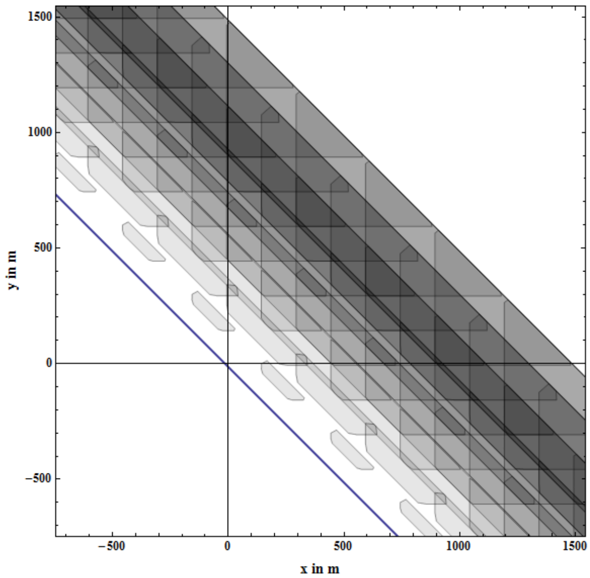

Fig. 5. Flattish apex areas of traveltime contours for line scatterer (heavy line) in orthogonal geometry with 300-m line intervals. Cut-off velocity 2700 m/s, maximum time 3 s.

Designing the dimensions of the acquisition lines has to meet two main objectives: the distance between the sublines should be chosen small enough to prevent aliasing of the noise to be removed (10 m in our case), and the total time difference of the noise across the subline traces should be large enough to allow discrimination against the signal. Assuming a minimum frequency of 8 Hz and that at least half a period is required for successful noise removal, the time difference should be in the order of 60 ms. This can be achieved by an effective width of about 55 m of the group of subtraces.

Satisfying both requirements may be achieved by using 6 shot/receiver combinations, either a single shot line and 6 receiver sublines or 2 shot sublines and 3 receiver sublines. In the latter case, the two shot sublines may have a distance of 10 m and the three receiver sublines should then be spaced at 20 m. This would produce an effective width of 60 m for the 6 traces in each group.

The sampling of the shots and receivers along the lines can be carried out with the adequate sampling interval. This would allow removal of the flanks of all noise traveltime surfaces with 3D *f-k* filtering in each one of the 6 sub-cross-spreads. After this noise has been removed, the remaining tops of the traveltime surfaces can be suppressed using a filtering operation on each group of 6 traces.

For regular geometry with 210-m line intervals and maximum offsets of 3150 m, each receiver line with 3 sublines would require 3 * 6300 / 15 = 1260 single geophones. A complete 30-line template would need 37,800 geophone stations. The receiver density would be 3 * 10^6 / (15 * 210) = 952 geophones / km^2; the source density would be 635 VP/km^2. A full-swath roll technique would be the best option to implement this design (Vermeer, 2002; 2004; Rached , 2007).

Array-based orthogonal geometry

The designer of an array-based geometry has to consider two array parameters, its length along the acquisition line and its width across the line. If the array length is equal to station interval, the first notch of the array response (which is at k = 1/(Length array)) will be at $k = 2\ k_N$, k_N being Nyquist wavenumber corresponding to the station interval. Hence, the noise that is suppressed most by the array effect folds back on the signal where it would hurt most if not suppressed. The noise that stays outside the signal cone may still be removed by 3D *f-k* filtering. The shorter the station interval/ field array, the better the 3D *f-k* filtering effect will be. An interval of 25 m looks like a good compromise in the example situation.

The suppression of the apices of the traveltime surfaces of the scatterers has to come from the array effect itself. For a lowest frequency of 8 Hz the corresponding wavelength is 112.5 m. For suppression of this noise the array has to be at least as long as this wavelength. In 3D all shot-receiver azimuths are present requiring short array dimensions in all directions to prevent loss of high frequencies. This is a dilemma that cannot be solved simply: the signal requires short arrays and the scattered noise needs wide arrays.

The solution for this problem requires a number of arrays across the acquisition line. For the example situation one may select three subarrays side-by-side, each having an effective length of 25 m and an effective width of 20 m. Each subarray may consist of 3 geophones in the inline direction spaced 25/3 = 8.3 m and 2 geophones in the crossline direction spaced 10 m. On the source side an array of four vibrators may be used arranged in a square box with sides 12.5 m.

Because station intervals of 25 m are now proposed, line intervals of 200 m and maximum inline and crossline offsets of 3000 m can be chosen. In this case there will be 3 * 6000/25 = 720 channels per active receiver spread and a total of 21,600 channels per template. The number of geophones in the template would be 6 times as large. The source density in this case would be 10^6 / (25 * 200) = 200 VP/km^2.

Discussion

In this paper I have addressed one of the most notorious problems in Middle East seismic data acquisition. To illustrate various alternatives I have used parameters that are typical for that area. Yet, the implementation of the ideas has to be adapted to circumstances.

Table 1 gives an overview of the main requirements of the alternative solutions. Geophysically, the most attractive solution is to use areal geometry, either with sparse receivers (Areal-1) or with sparse sources (Areal-2). The next best solution is to use single-point orthogonal geometry. Last in line is the array-based orthogonal geometry. With this geometry, noise suppression with field arrays would reduce the success of this technique to some extent.

Table 1 Main requirements of alternative solutions (assuming benchmark survey parameters)

Geometry	Source density in VP/km^2	Number of receiver stations in template	Remarks
Areal-1	4444	900	Hexagonal sampling would reduce requirements by factor 0.866
Areal-2	22.7	176,400	
Single-point orthogonal	635	37,800	Number of VP/km^2 would increase for full-swath roll implementation
Array-based orthogonal	200	21,600	

In areal geometry line scatterers can be suppressed just as well as point scatterers by 3D *f-k* filtering. However, in orthogonal geometry it is best to orient either source lines or receiver lines parallel to any line scatterers (cliffs) as much as practically feasible.

Unfortunately, increasing order of geophysical attractiveness is also increasing order of cost and effort. Areal geometry 2 is way beyond current potential of recording systems, whereas Areal geometry 1 would take an inordinate amount of time. Single-point and array-based orthogonal geometry both require a large number of channels to make it work.

The array-based solution might provide quite satisfactory results. So, before going for the silver-plated single-point solution or for the gold-plated areal geometry alternative, it may be best to try out the bronze-plated solution first.

Conclusions

This paper addresses the problem of ground roll scattered by near-surface discontinuities, both point scatterers and line scatterers. The problem is most serious for high-velocity ground roll as occurring in the Middle East and for orthogonal geometry. Areal geometry would allow complete noise removal provided adequate spatial sampling is used. Unfortunately, areal geometry would be extremely expensive and time-consuming. Fortunately, with proper design single-point orthogonal geometry can also be made suitable for scattered noise removal. This requires the use of ribbon-like acquisition lines. The least expensive technique is array-based orthogonal geometry. This geometry would require separate recording of subarrays.

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