Filter design for directional geophone arrays in seismic data acquisition

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Resumen

Los arreglos de geófonos típicamente usados en adquisición sísmica, no aprovechan totalmente las posibilidades de los arreglos de sensores. En este trabajo proponemos una metodología preliminar para el diseño de arreglos direccionales de geófonos para su uso en adquisición sísmica.

Summary

Geophone array techniques, typically used in seismic acquisition, do not take full advantage of the array capabilities. In this work, we propose a preliminary methodology for designing directional arrays suitable for seismic acquisition.

Introduction

Geophone arrays have been traditionally used with the objective of improving the signal to noise ratio by attenuating ground roll and random noise, and their use have not exploited in full all the advantages and possibilities that a sensor array can offer.

Traditionally, the design of geophone arrays was just limited to variations of the spatial configuration of geophones. Additionally, none, or almost none, processing was performed to individual geophone signals previous to their combination. As a consequence, two of the most important capabilities of sensor arrays, directivity and adaptability, are lost.

There exists a large amount of sensor array processing techniques that have been successfully used in many applications (Widrow & Stearns, 1985). An adequate use of sensor array processing techniques allows to: first, maximize the signal to noise ratio by taking advantage of directiveness (beamforming and super resolution techniques); second, perform real time array configuration according to the given circumstances (adaptive arrays); and third, process data in order to spatially localize events of interest (target detection).

Recently, the use of array signal processing techniques in seismic acquisition have been gaining more and more popularity (Hu & White, 1998; Ozbek, 2000).

In this work, we propose a preliminary methodology for designing directional geophone arrays, which is based on the concept of beamforming (Widrow & Stearns, 1985), suitable for seismic acquisition. First, a brief discussion on detector arrays, directivity patterns and beamforming is presented. Also, a methodology for designing prototype filters is proposed. Then, these filters are used in a synthetic data set in order to demonstrate the many possibilities of geophone array processing.

Finally, we discuss the most important economical and technological implications of this proposition into the present acquisition industry, as well as, the future developments that must follow in the years to come.

Array processing and beamforming

In this section, a brief discussion on geophone arrays and directivity patterns is presented. Also, it is illustrated how directivity can be achieved by weighted summation and filtering, and at the end of the section, a simple technique for designing prototype filters to construct directive arrays of detectors is proposed.

Uniformly Weighted Arrays

Typically, in conventional seismic acquisition, each channel records a prestack seismic trace which is the result of adding the signals of a group of geophones. Such a group of geophones constitutes a geophone array, which has the main objective of attenuating noise and enhancing the signal of interest. In this way, the channel signal is given by:

$$S_{channel}(t) = \sum_{n=1}^{N} S_n(t), \qquad (1)$$

where $S_n(t)$ is the output signal at geophone *n*, and *N* is the total amount of geophones in the array.

In addition to the attenuation of random noise and the enhancement of the signal, the processing implied by equation (referencia) has some important implications on how the array *sees* the wavefield at different frequency values. This is illustrated in figure 1.

In the figure, the responses of a six geophone linear array at 20, 30 and 40 Hz are shown. The wave velocity used for this example was 1000 m/s and the separation between consecutive geophones was 4 m.

As seen, due to the summation, a directivity pattern has been imposed to the geophone array. This means that the response of the geophone array varies with the incidence angle of the seismic wavefield. In the particular case illustrated in figure 1, the array's main lobe is focusing the array response into the vertical direction.

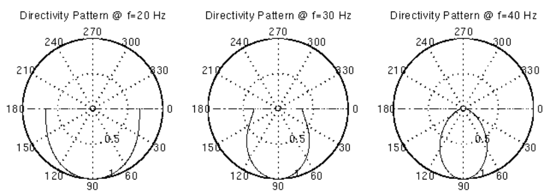

Figure 1: A Six Geophone Array Directivity Pattern.

Directivity constitutes a very important property of sensor arrays. However, as presented here (which is the way their are commonly used in seismic acquisition), two important limitations apply. First, the directivity pattern is different at each different frequency (the directivity pattern of a sensor array is indeed a function of the frequency, the wave propagation velocity, and the spatial configuration of the sensors in the array). Secondly, the only parameters of such a directivity pattern that are available to the operator are those related to the spatial configuration of the array. In order to overcome this two limitations and take more control over the array's directivity pattern, some processing of the individual sensor signals before the summation are required.

Weighting, Shifting and Filtering

In this section, the basic concepts in sensor array processing are discussed. First, the operations of weighting and shifting, which are enough for dealing with narrow band signals, are presented. Then, the filtering operation, which is required for the treatment of wide band signals (which is the case of seismic signals), is discused.

In general, the alterations introduced by a sensor array to the measured wavefield are the result of the differences among individual sensor signals. There are only two factors responsible for these differences, they are attenuation and delay. In this way, array signal processing is based on adjusting both attenuations and delays of the individual sensor signals in order to gain control over the array's response.

The first element to be incorporated in this analysis is weighting, which is used to handle attenuation. In this way, equation (1) is reformulated as follows:

$$S_{channel}(t) = \sum_{n=1}^{N} W_n.S_n(t)., \quad (2)$$

where each individual sensor signal is weighted by a factor W_n before summation. Control over the thickness of the response lobes is gained by incorporating the weights.

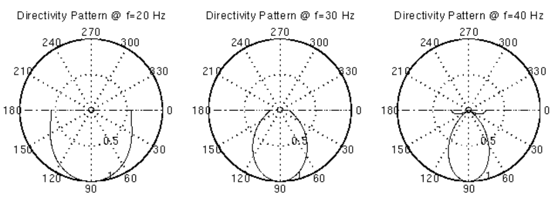

Figure 2: Six Geophone Array Directivity Pattern with Weighting.

Weighting makes the response of the array more or less selective in the direction of the main lobe. Figure 2 illustrates the effects of weighting for the same six geophone linear array described before. In this case, the individual sensor signals have been weighted as follows: W_1=W_6=1.5, W_2=W_5=1.0 and W_3=W_4=0.5.

As can be noticed from the figure, the obtained directivity patterns are more selective than those presented in figure 1. Notice how the thickness of the lobes has been substantially reduced.

The second element to be incorporated in this analysis is shifting, which is used to handle delays. In order to incorporate shifting, equation (1) has to be reformulated as follows:

$$S_{channel}(t) = \sum_{n=1}^{N} S_n(t-\tau_n)., \quad (3)$$

where each individual sensor signal is shifted by a delay term τ_n before summation. By incorporating shifting, control over the orientation of the lobes is gained.

Shifting gives directivity to the response of the array by orienting the main lobe in a particular direction. Figure 3 illustrates the effects of shifting for the same six geophone linear array described before. In this case, the individual sensor signals have been shifted by using the following

delay terms: $\tau_n = (n-1)\ d/v\ sin(\pi/6)$ *for n=1,2,…N;* where n is the number of geophone, d is the distance between geophones (4m) and v is the wave velocity (1000 m/s).
As can be noticed from figure 3, due to the delays introduced, the main lobe of the obtained directivity patterns has been oriented thirty degrees to the right of the vertical direction.

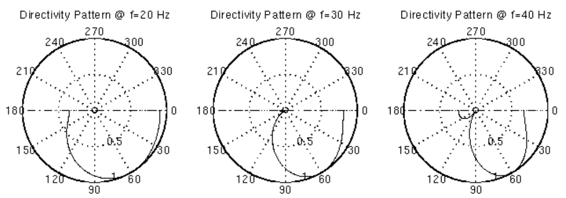

Figure 3: Six Geophone Array Directivity Pattern with Shifting.

Both, directivity and selectivity, can be simultaneously controlled by performing weighting and shifting. In this way, equations (2) and (3) can be combined as follows:

$$S_{channel}(t) = \sum_{n=1}^{N} W_n.S_n(t-\tau_n).. \qquad (4)$$

However, the control gained over the response of the array by using equation (4) is still very limited. The delay and weight parameters allow to adjust the array's directivity pattern for a given frequency value only. For this reason, this kind of processing is appropriate for narrow band signals only.

For the case of wide band signals, adjusting delay and weights according to equation (4) is not enough. In this case, parameters for each different frequency values must be adjusted independently, and this is why filtering is required (Ozbek, 2000). Filtering provides means for associating different weight and delay values at each different frequencies. In this way, equation (4) is rewritten as:

$$S_{channel}(t) = \sum_{n=1}^{N} F_n(t). * .S_n(t)., \qquad (5)$$

where $F_n(t)$ is the filter associated to geophone n and * represents the convolution operator.

Then, equation (5) provides means for designing directive sensor arrays when dealing with wide band signals, which is the case of the seismic wavefield, where the design problem itself is reduced to the design of the filters $F_n(t)$.

Prototype Filter Design

This section presents a preliminary filter design technique for constructing directional geophone arrays. Although the problem of filter design for directional arrays is very broad and it can be approached in many different ways, here we will concentrate in the particular problem of attenuating signals coming from a given direction while enhancing signals coming from another direction of interest. However, the ultimate goal in seismic acquisition should be the availability of adaptive arrays.

Figure 4 illustrates two seismic wavefronts, A and B, impinging at two different angles on a geophone array of four elements. As seen from the figure, both of the wavefronts arrive first at the left-most geophone in the array. Then, each wavefront arrives to the rest of the geophones in a sequential way with a characteristic delay that responds to the geometry of the problem.

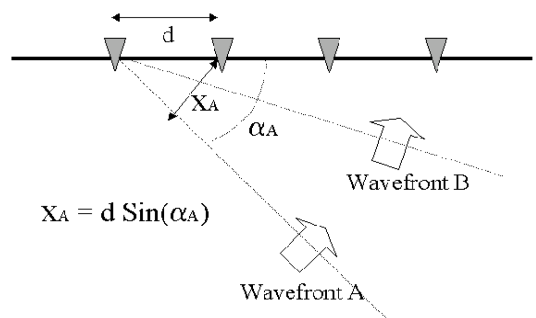

Figure 4: Directional Array Filter Design.

Suppose that the geophone array is desired to look at wavefront B. One way of achieving this is to design the filters in order to get a null of the directivity pattern in the direction of wavefront A. This can be easily achieved by introducing the following phase function:

$$phase_n(f) = -2.\pi.(n-1).\left(\frac{f.d.sin\alpha_A}{v} + \frac{1}{2}\right)., \qquad (6)$$

where d is the distance between adjacent geophones, v is the wave propagation velocity, f is the frequency and α_A is the incidence angle associated to wavefront A.

Notice from equation (6) that the phase function associated to each geophone is a function of frequency and incorporates two terms. The first term compensates the delay resulting from the difference in travel paths among geophones, and the second term adds an additional delay of a half period to the odd geophones. In this way, the phase function defined in equation (6) guaranties cancellation of signals of any frequency arriving at the wavefront A

direction. The only restriction is that the array must contain an even amount of geophones.

Although equation (6) guaranties cancellation of wavefront *A*, at this point there is no control over the response of the array in the direction of wavefront *B*, which is the signal of interest. In fact, distortion of the wavefront *B* must be expected unless some additional restrictions are imposed to the filters. These can be done by introducing a gain or amplitude function:

$$amplitude_n(f) = \frac{1}{r(f, phase_n(f), \alpha_B)}, \quad (7)$$

where $r(f, phase_n(f), \alpha_B)$ is the response of the geophone array at frequency f in the direction of wavefront *B* when incorporating the phase function described in equation (6).

Notice that equations (6) and (7) are actually functions of frequency and they describe how the amplitude (weights) and the phase (delays) must vary with frequency. Then, it follows in a very straightforward way that, equations (6) and (7) constitute samples of the Fourier transform coefficients of the desired filter impulse responses. This is illustrated next with a simple design example.

Consider the same four geophone array illustrated in figure 4 and assume a wave velocity of v = 2200m/s, an even geophone separation distance of d = 10m, a sampling period of dt = 0.5ms and incidence angles of $\alpha_A = 0.39\pi$ rad and $\alpha_B = 0.11\pi$ rad for wavefronts *A* and *B*, respectively.

Figure 5 illustrates the computed values for the amplitude and phase functions defined in equations (7) and (6) in order to force a zero for the directivity pattern in the direction of wavefront *A* and simultaneously maintain a constant unit gain in the direction of wavefront *B*.

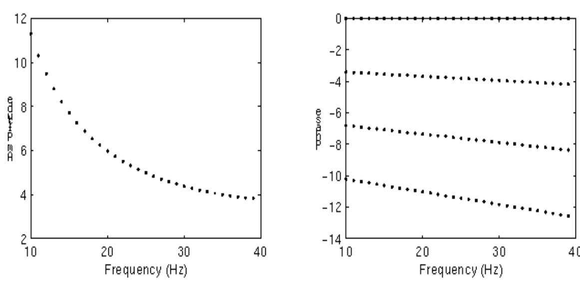

Figure 5: Amplitude and Phase Function Values.

As seen from the figure, the values of the amplitudes and phases where computed at intervals of 1 Hz in the range between 10 Hz and 40 Hz. Then, by using spline interpolators, both functions where resampled to the complete range of frequencies according to the defined sampling period of 0.5 ms. Also, during this resampling process, the responses of the filters where drop to zero in the intervals out of the frequency range of interest. Finally, the filter impulse responses where obtained via discrete inverse Fourier transform, after which a phase linearization process was included in order to obtain symmetrically centered impulse responses. These responses are shown in figure 6.

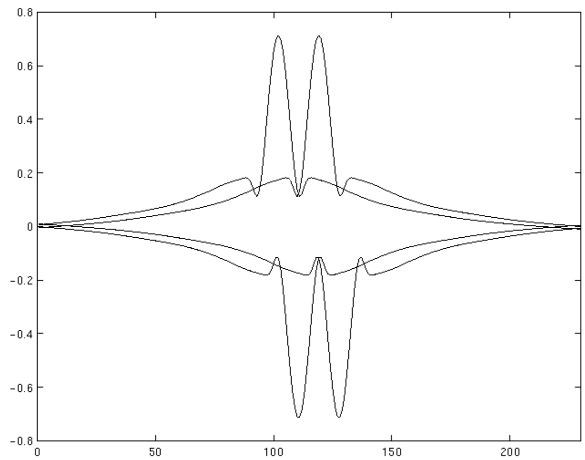

Figure 6: Filter Impulse Responses.

Synthetic data example

This section illustrates with a synthetic data example how the filters designed in the previous section can be used to give directivity to a geophone array.

Geological Model and Acquisition Data

The geological model used consisted of two different reflectors, a horizontal reflector and a dipping reflector. The model was designed such that, at the region of interest, both of the reflected wavefronts arrive simultaneously and with angles of 0.39π rad and 0.11π rad (Segovia, 2000). Figure 7 shows the model under consideration with the approximate shot location and the surface region where both wavefronts arrive simultaneously.

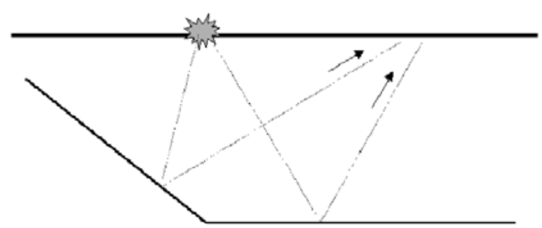

Figure 7: Geological Model Considered (Segovia, 2000). A synthetic seismic section, which is presented in figure 8, was acquired from this model. The upper layer model's velocity was set to 2200 m/s and geophones where uniformly spaced at intervals of 10 m in the region of interest. The synthetic data was computed by using a finite difference method. The presented time interval was cropped to include only the arrivals of the reflected wavefronts.

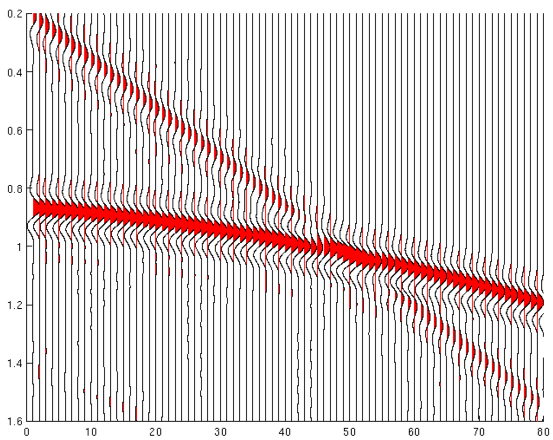

Figure 8: Synthetic Seismic Acquisition Data.

Directive Array Data Processing

By processing the obtained synthetic traces, which are shown in figure 8, in groups of four and using the filters designed in section in the previous section, the seismic section presented in figure 9 was obtained.

Notice form figure 9 how the wavefront corresponding to the dipping reflector was totally attenuated while the one corresponding to the horizontal reflector was preserved. However, it can be noticed that some phase alterations have been introduced (in fact, when designing the filters, no condition was imposed for preserving the phase of the recovered signal).

In the same way, filters were designed for canceling the reflection coming from the horizontal reflector and recover the one coming from the dipping one. In this case, the processing had to be done in five subsections since the horizontal wavefront presents an important variation of its incidence angle along the considered offset range. Each subsection was processed independently with filters designed to cancel signals with incidence angles of 0.07π, 0.08π, 0.09π, 0.10π and 0.11π radians, respectively. The resulting seismic section is presented in figure 10.

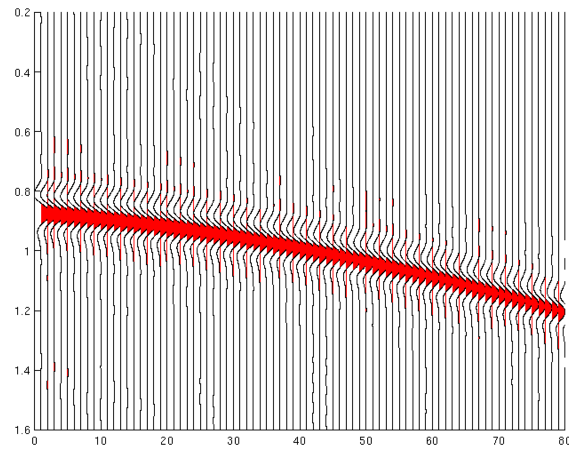

Figure 9: Processed Seismic Section with the Dipping Reflection Cancelled.

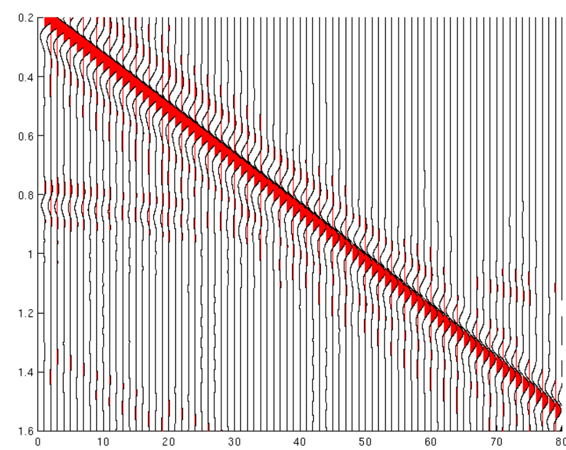

Figure 10: Processed Seismic Section with the Horizontal Reflection Cancelled.

Limitations and impact

Nowadays, the ideas presented here are not feasible to acquisition industry basically due to economical limitations. This is because the processing required by directive geophone arrays has some important implications on field strategies and operations, as discussed latter.

Nevertheless, not so far in the future, cost reductions resulting from the advances in electronics will make viable the implementation of directive geophone arrays in seismic acquisition operations.

There are basically two alternatives for implementing directive arrays in seismic acquisition; first, channel per element recording, and second, in-field adaptive processing. In the channel per element recording scheme, a seismic trace is recorded for each element in the array. This increases the total data volume by a factor equal to the amount of elements per array, however the full seismic wavefield is available for further processing and reprocessing. In this way the seismic survey can be always be reprocessed in order to vary the array responses; virtually, an infinite amount of different surveys can be generated.

In the in-field adaptive processing scheme, the array processing is performed during the acquisition. In this case, processing power is required at each individual station and, once the data have been acquired, the seismic survey cannot be focused in a different direction. By using this scheme, the total recorded data volume remains exactly the same as in a traditional seismic survey.

The impact of directional geophone arrays is evident in many acquisition applications and problems. As an example of such applications we can mention:

Seismic exploration in areas close to mountain fronts, where situations similar to the one described in figure 7 may be expected. In this cases, directional geophone arrays will help to discriminate the energy actually coming from the objective of interest.

Seismic surveying in areas with a highly heterogeneous weathered layer. In this cases, multiple scattering due to the heterogeneities is responsible for a very low signal to noise ratio. Then, directional geophone arrays can be used to increase the signal to noise ratio by focusing the survey in a given direction of interest.

Medium and far offset seismic acquisition. In this cases, refractions from shallow events can mask the reflections coming from deep objectives. Again, directional geophone arrays can be used to increase the signal to noise ratio by focusing the survey in a given direction of interest.

Conclusions and future work

Although the preliminary results presented here clearly illustrate the viability of the technique, there are still many questions to be answered.

As seen from figures 9 and 10, the designed filters accomplish the objectives of canceling one of the reflections and preserving the other one, however the phase of the preserved reflection is altered. The solution of this problem requires imposing conditions on the phase response when designing the filters. In fact, the best approach for designing the filters is by defining an optimization problem, in which the filter coefficients can be adjusted in order to satisfy a given set of conditions (Segovia, 2000).

There are still some important problems that must be studied in the area of directional geophone arrays. For example, wavefront horizontalization due to the low velocities associated to the weathered layer can make more difficult directional discrimination. Modeling should be used to study how a low velocity whethered layer affects directional geophone array processing. In general, the performance of the proposed technique must be evaluated by using models with more lithological and/or structural complexities than the one presented in figure 7. Another important problem to be studied is how the use of directional geophone arrays affects the problem of correction of statics.

In reference to the filter design problem more research is also required. For example, the incorporation of global search methods and more sophisticated adaptive algorithms requires some attention, as well as processing algorithms capable of detecting the direction of an incoming wavefront.

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