Spectral Shaping during Acquisition of Seismic Reflection Data

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SUMMARY

It is the purpose of this paper to point out the difference between "broadband recording" and "recording broadband data" in reflection seismology. There can be a significant difference, and it should be noted that broad-band recording does not always result in broad-band data. Conversely, narrow band recording does not always result in narrow band data.

The information transmission rate of any discrete passband is never increased by data processing. All that can be accomplished in data processing is to improve the signal to noise ratio by eliminating part of the noise and scaling up the amplitude of the remaining signal. Consequently, it is in the best interest of the reflection seismologist, who deals in no more than a few seconds of data transmission from each shot, to transmit as much information as possible into the usable passband in the field prior to A/D conversion.

This can sometimes, but not always, be accomplished by careful selection of analog filtering in the field prior to analog to digital (A/D) conversion. Commonly, the upper band-edge of the recorded spectrum can be pushed upward by 10 to 30 percent by shaping the recording spectrum prior to A/D conversion.

INTRODUCTION

Figure 1 compares the amplitude spectrum of data recorded with a pre-emphasis lowcut filter and data recorded with open passband. Note the data obtained with the narrow passband have a substantially broader and flatter spectrum than the data recorded with open passband. The source location and geophone plant was identical, so information received by the geophone was invariant. The data recorded with open passband are actually more narrow band than the data recorded with the pre-emphasis filter. There is little significant energy greater than 250 Hz in the data recorded using the open passband. The low-frequency components of the signal saturated the system and the high-frequency components were insignificant by comparison. The pre-emphasis filter, on the other hand, attenuated the low frequencies sufficiently that the high-frequency components maintain a relative significance to frequencies greater than 400 Hz.

Such preconversion spectral balancing reduces the detrimental influences of the low-pass earth filter, improves the significance of the recorded data, and makes the recording of high-resolution data possible by attenuating to a manageable level the low-frequency signal that would saturate a flat-response recording system. The reader should note that resolution of seismic data depends on total bandwidth and on the presence of high frequencies.

The Ideal Source

To put the need for spectral balancing into perspective, I will discuss the theoretical aspects of the ideal seismic source. One might expect the ideal-source spectrum to be flat from zero Hz to infinity. That is not true, and one of the most important reasons for writing this paper is to get that point across. The ideal source would have a spectrum that increases at the high frequencies to exactly offset the low-pass nature of the earth with respect to seismic waves. In other words we want our source to provide more high frequency energy to make up for the earth's natural tendency to attenuate high frequencies. The result would be recorded data with a frequency spectrum that is flat from zero Hz to infinity (actually to the Nyquist frequency). (It is interesting to note that because of differential attenuation of various frequencies, this ideal source would only be ideal for one particular raypath length from source to receiver.)

Naturally, our ideal source will need an infinitely variable and controllable output energy. We only need that amount of energy that gives an acceptable signal to noise ratio in our data. We also want our source to have a totally linear method of coupling its energy into the ground, because stressing large volumes of earth beyond the elastic limit has a deleterious effect on our seismic data. It also can cause environmental damage, and our ideal source must produce zero environmental damage. We also want our source to produce absolutely no air-coupled waves, since these waves often obscure waves that come through the ground. Our ideal source must also be repeatable. We want our source to be safe so nobody will ever be injured by it.

We would like our source to have a minimum phase wavelet to stabilize some of the processing steps. Wait a minute, what processing steps? If we had an ideal source, there would be little need for processing, since there would be no ringing of the source wavelet, there would be no need to filter, there would be no need to use CDP methods. We might need to apply the normal moveout correction and to migrate the data to put things in their proper spatial perspective, but beyond that there would not need to be any processing done, and we could simply use either common offset methods, or single-fold coverage.

SHAPING THE RECORDED DATA SPECTRUM

Since dreaming about sources is a marginally productive exercise, we must move on to practical methods of simulating ideal sources. One method is to use nonlinear Vibroseis sweeps to enhance the higher frequencies. Another method is to shape the recording spectrum to compensate for the earth's attenuation of high frequencies. These two techniques complement each other and can be used together to improve resolution. Previously we noted that frequency bandwidth has an effect on resolution. High frequencies may be present but not detected if the dynamic range of the recording system is insufficient to represent both the high-amplitude low-frequencies and the low-amplitude high-frequencies simultaneously.

Seismograph Considerations

Seismic recording hardware used to shape the recording spectrum must be designed to extract and record high-resolution information with minimum distortion. This can be accomplished with properly designed analog filter circuits. Progress in solid state switching now allows variable slope on the shoulders of the filters. Classically, filters had a fixed number of poles that produced a constant filter slope of something like 12, 18, 24, or 36 dB/octave rolloff. The slope was fixed because each filter was implemented by a manual switching mechanism that contributed a significant amount of noise to the signal as it passed through. Modern solid-state switches add a very small amount of noise to the signal. Some new designs have multiple stages in the filters, which allow the operator to selectively shape the spectrum by varying the attenuation, corner frequencies, and slopes of the filters to meet the needs of a specific survey. One commercial seismograph that uses this approach is the I/O System One, in which the filters are called "spectral-shaping filters."

An important factor in maximizing transmission of information is to shape the energy passband so the seismograph digitizes data having a spectrum that is as flat and broad as possible. This involves lowcut filtering and high-frequency boosting of the data before A/D conversion so the magnitude of the prevalent low-frequency noise does not swamp the high-frequency signal. The objective is to permit boosting the amplitude of the high-frequency signals to fill a significant number of bits of the digital word. Judicious use of a lowcut filter is one element of this step, although geophone selection is also a factor because geophones have a -12 dB/octave velocity response at frequencies less than the resonant frequency of the spring-mass system.

Figure 2 shows a seismic reflection from a depth of 2.6 meters that was recorded as part of a high-resolution reflection survey near Great Bend, Kansas. Now notice that the pre-A/D lowcut filter used was 600 Hz with 24 dB/octave rolloff. Conventional wisdom of seismic data recording would predict that the reflection wavelets recorded under these parameters would ring. Note that the wavelet is not ringy, and in fact is a nearly perfect minimum-phase wavelet with a dominant frequency of 335 Hz. This is due to the broad bandwidth (270 Hz) of the data, which was obtained in spite of a recording pass-band that was only 2/3 of an octave wide (600-1000 Hz).

One of the least understood but most important concepts in instrumentation is that of dynamic range. *Dynamic range* was defined by Sheriff (1973) as "the ratio of the largest recoverable signal (for a given distortion level) to smallest recoverable signal." The effectiveness of a seismograph system in recording accurate seismic-reflection data is determined largely by the instantaneous dynamic recording range of the system, which is the ratio in decibels between the largest signal and the smallest signal that can be recorded simultaneously. For high resolution seismic reflection surveys, instantaneous dynamic recording range is of special significance because we are trying often to extract a very small high-frequency seismic-reflection-signal voltage from a very large voltage that is commonly dominated by ground roll.

Boosting high frequency in preamp can prevent reflections from being swamped by ground roll at the instant of A/D conversion. Further increase in frequency response can be obtained by sophisticated lowcut filters that selectively attentuate low frequencies instead of eliminating them altogether. These two techniques would serve to provide the best frequency response and instantaneous dynamic range. Such improvements are however predicated on noise levels in preamp filter sections being very low.

In the practical sense, reflection seismologists often deal with blackened wavelets on white paper. The dynamic range of the human eye is such that under suitable conditions, wave amplitudes in the range from 0.1 mm to about 1 cm can be transmitted simultaneously to the brain. This represents a dynamic range of 40 dB.

Consider a seismograph that uses 15-bit A/D conversion, not including sign. Such a system potentially has a dynamic range of 90 dB. Because its dynamic range is better than that of the human eye, it is possible that seismic reflections may be present on field seismograms in the data that are invisible to the eye. For example, consider figures 3, 4, 5, and 6. Figure 3 shows a seismogram recorded in the back yard of the Kansas Geological Survey. Figure 4 shows a seismogram from the same locality after pre-emphasis filtering with a 340 Hz lowcut filter. Notice that a reflection at about 48 ms is present on Figure 4 that is not even hinted at on Figure 3. We used this test site for eight years with many combinations of sources, geophones, offsets and filters, but did not see any reflections at all until we used the 340 Hz lowcut filters for the first time.

Figures 5 and 6 show two seismograms recorded without and with spectral shaping filters, with all other recording parameters held constant. Note that in Figure 6 (with spectral shaping) there are reflections between 1.0 and 1.1 seconds that are not even hinted at on Figure 5.

The degree of care required in designing the filter response depends in part on the resolution of the recording instrument. The merits of a recording system include its precision (number of bits digitized), its noise level, and its dynamic range at all preamplifier gains. The objective is to maximize the significance of all desired frequencies recorded within the signal band-pass. This means the total response of all components combined should be high-pass to counterbalance the low-pass filter characteristic of the earth. Hence, rather than requiring a flat instrument response, a high-pass instrument response that increases gain with increasing frequency is required.

Use of Lowcut Filters

To improve resolution, application of lowcut filters prior to A/D conversion is often critical, for several reasons. Most elements of the seismic reflection system are working against the generation, transmission, and recording of high-frequency data. The high frequencies received at the geophone can be of such small magnitude compared to the low frequencies that they do not register in the A/D conversion. They are lost in the system noise, or they are smaller than the voltage value represented by the least significant bit of the A/D converter. Even if the high frequencies do register on one or two least significant bits, they are subject to large errors. To reduce the significance of the recording errors, it is necessary to fill several bits of the A/D converter with high-frequency reflection information. Applying a lowcut filter can improve this situation by attenuating the low frequencies to a level where their magnitude is comparable to the magnitude of the high-frequencies. This technique then allows one to emphasize the high frequencies by increasing the gain applied in the amplifiers.

There are times when use of spectral shaping is not appropriate. There are some localities where any degree of filtering of the low frequencies causes the data to ring unacceptably. If the dominant reflection frequency is near the natural frequency of the geophones, it may be necessary to pass more low frequencies. Some localities have a very broad natural spectrum of reflectors that can be degraded by spectral shaping.

The techniques used in shallow high-resolution reflection applications can easily be scaled to deeper petroleum exploration surveys. As noted in the introduction, spectral shaping prior to A/D conversion can often move the upper band-edge of the spectrum upward by 10-30 percent, depending on the specific site geology. This can often be done without losing more than an equivalent percentage of the lower band-edge, which effectively broadens the bandwidth and improves the associated resolution limits.

As a typical petroleum exploration example, assume that the data were relatively flat from 10 Hz to 60 Hz. If we can move both the upper and lower band-edges upward by 20 percent by spectral shaping, we can broaden our spectrum to 12 Hz to 72 Hz, which will improve resolution. Generally, spectral shaping can improve resolution more in good-data areas than in bad-data areas.

REFERENCES

Knapp, R.W., and Steeples, D.W., 1986, High-resolution common depth point seismic reflection profiling, instrumentation: Geophysics, 51, 276-282.

Sheriff, R. E., 1973, Encyclopedic dictionary of exploration geophysics: Soc. of Explor. Geophys.

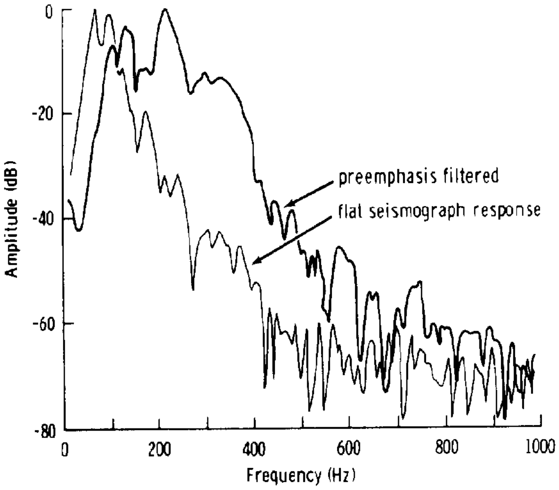
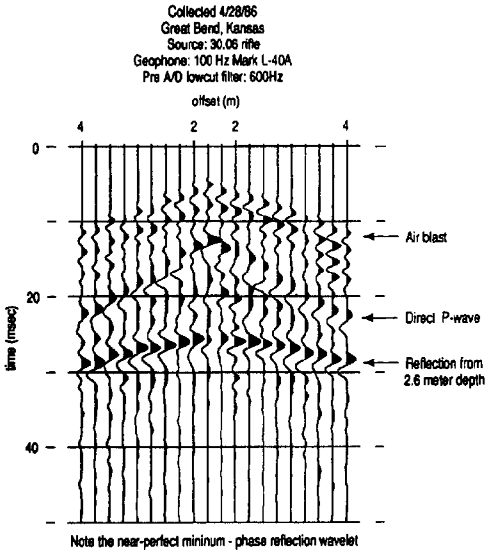


Fig. 1. Normalized amplitude spectra comparing data recorded with a pre-emphasis, 220 Hz lowcut filter applied prior to A/D conversion with data recorded with flat, broad-band seismograph response (from Knapp and Steeples, 1986).


Collected 4/28/86
Great Bend, Kansas
Source: 30.06 rifle
Geophone: 100 Hz Mark L-40A
Pre A/D lowcut filter: 600Hz

Note the near-perfect mininum - phase reflection wavelet

Fig. 2. Seismic reflection from a depth of 2.6 meters. Note that the lowcut filter was set at 600 Hz with 24 dB/octave rolloff. The reflection is a very clean wavelet with no ring, even though the dominant frequency was outside the nominal seismograph passband of 600 to 1000Hz.

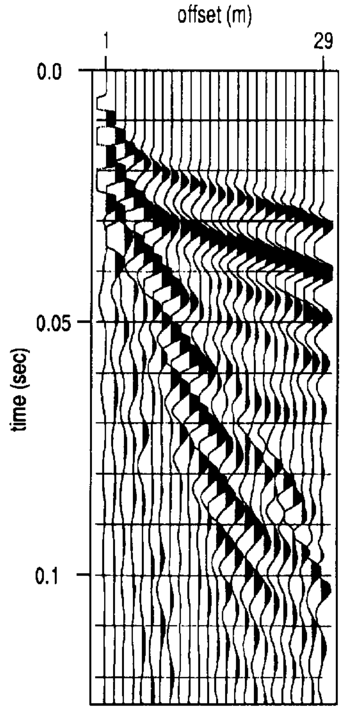


Fig. 3. Unprocessed field seismogram from the backyard test site at the Kansas Geological Survey. Lowcut filters were open for this seismogram. Note that no reflectors are visible.

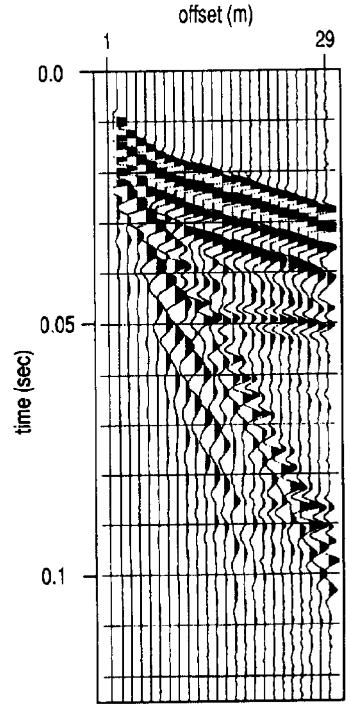


Fig. 4. Unprocessed field seismogram from same site and geophone plants as in Figure 3. Note reflection at about 45 ms.

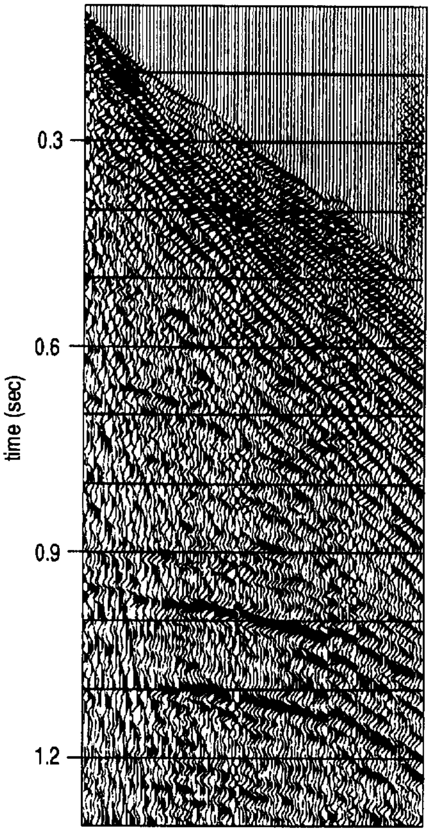


Fig. 5. Unprocessed field seismogram without spectral shaping filter.

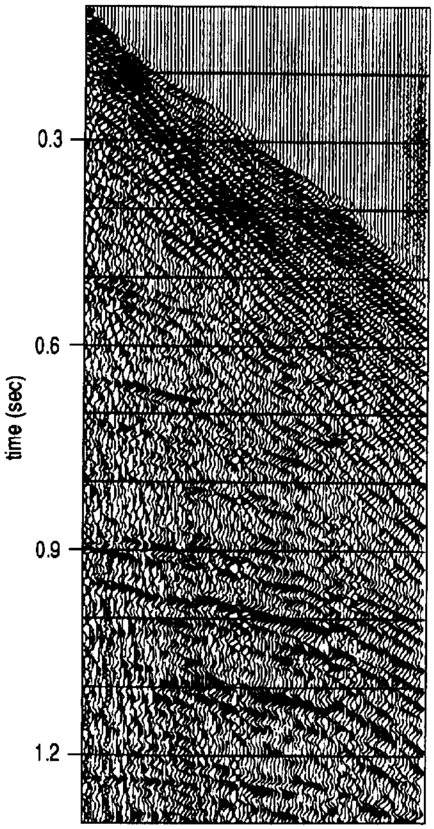


Fig. 6. Unprocessed field seismogram with spectral shaping. Note that several reflectors are visible that are not visible on Fig. 5.

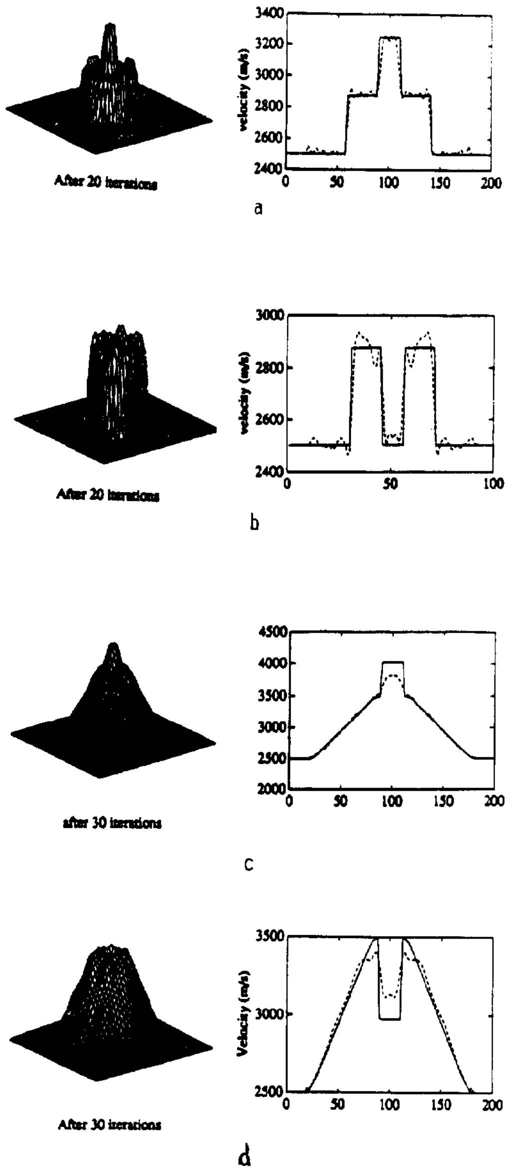


Figure 3. Reconstructions of velocity model A, B, C, and D shown in figure 1 by WTW inversion.
a. Velocity reconstruction of velocity model A
b. Velocity reconstruction of velocity model B
c. Velocity reconstruction of velocity model C
d. Velocity reconstruction of velocity model D

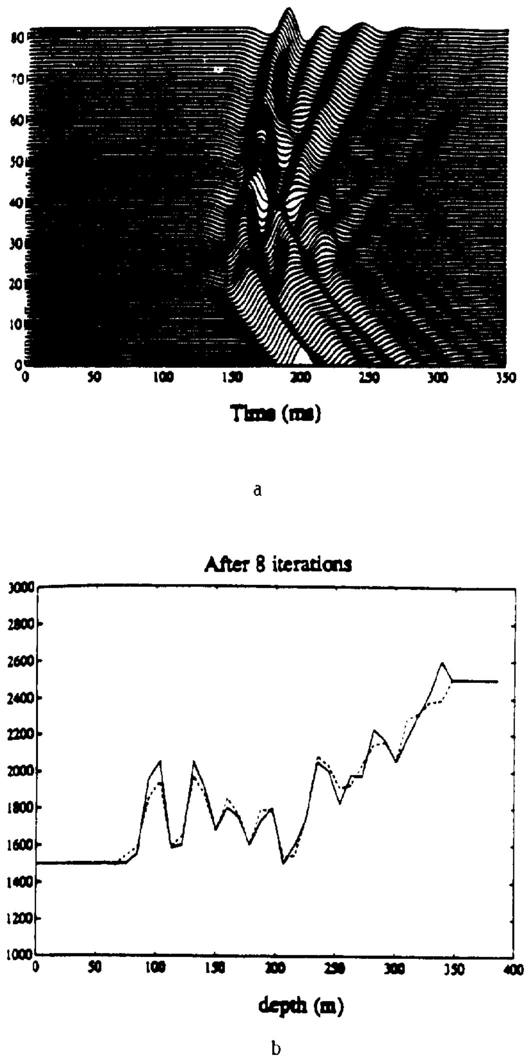


Figure 4. (a) Cross-well synthetic seismograms for Langan velocity profile. (b) 1-D Langan velocity profile (solid line) and WTW reconstruction (dashed line) after 8 iterations.