Proposal for a polychromatic seismic survey

Charles P. Ursenbach, John C. Bancroft, Malcolm B. Bertram, Henry C. Bland, Arnim B. Haase, Don C. Lawton, Gary F. Margrave and Robert R. Stewart

ABSTRACT

Monofrequency data can in principle be obtained from vibrator sources. Several monochromatic sweeps at various discrete frequencies may be collectively termed a *polychromatic survey*. The primary motivation for a polychromatic survey is to generate benchmark data to help develop methods for extracting *Q* from surface seismic. Other possible applications include benchmarking nonstationary transforms, extracting time-traces with novel wavelets, obtaining signal in noisy environments and to experiment with new methods for obtaining subsurface images. An initial survey is proposed over a shallow oilfield with both surface and VSP receivers.

INTRODUCTION

Seismic sources are normally designed to generate a wide range of frequencies, either through impulse or sweep. A monochromatic source would in most situations be considered a step backward. However such a survey can be useful for certain applications. Most prominently, monochromatic sweeps have been used with phase-difference calculations to estimate subsurface velocities (Aki et al., 1970; de Fazio et al., 1973; Ward and Hewitt, 1977; Solov'ev, 2000).

The purpose of this proposal is to suggest a feasible approach for carrying out a polychromatic survey into both borehole and surface geophones. The primary motivation is to contribute to the development of methods for extracting *Q* from surface seismic data, and to study the commonly assumed frequency independence of *Q*. A number of other potential applications for such data are outlined as well.

POLYCHROMATIC SURVEY DESIGN

What constitutes a polychromatic survey?

Vibratory source equipment can be used in various ways to produce the monochromatic sweeps that would make up a polychromatic survey. We consider three specific possibilities for monochromatic sweeps:

1. **Very long sweeps on single frequencies.** This is the most intuitively obvious approach. A truly monochromatic sweep would be of infinite length, so the longer the sweep, the more accurate the realization. However, because of resonances and machine limitations, extremely long sweeps (several minutes) may be challenging. Still monochromatic sweeps much longer than common practice are feasible.

2. **Short sweeps on single frequencies.** This would be of a length typical for vibratory sweeps, and cross-correlation would be necessary to remove finite-length effects. Records from repeated sweeps would be stacked.

3. **Narrow frequency band sweeps.** The object here would be to design a range which is narrow enough to approximate a single frequency (i.e., a small fraction of typical seismic bandwidth) but large enough to damp out mechanical resonance within that range. Again cross-correlation would be required. A narrow-band Gaussian sweep may provide a Klauder wavelet which is optimally compact in both time and frequency.

4. **Dual frequency sweeps.** Shaping a high-frequency sweep by a low-frequency envelope is equivalent to the superposition of two closely-spaced frequencies, i.e. $\sin(\omega_{\mathrm{lo}})\sin(\omega_{\mathrm{hi}})=[\cos(\omega_{\mathrm{hi}}-\omega_{\mathrm{lo}})-\cos(\omega_{\mathrm{hi}}+\omega_{\mathrm{lo}})]/2$. This would provide a built-in taper, and the response to the two frequencies $\omega_{\mathrm{hi}}-\omega_{\mathrm{lo}}$ and $\omega_{\mathrm{hi}}+\omega_{\mathrm{lo}}$ is a good approximation to the response to ω_{hi} if ω_{lo} is small.

To define a polychromatic survey one must also define the frequencies at which monochromatic sweeps will be carried out. A range of possibilities exist, such as

1. A single frequency.
2. A few representative frequencies, sampling above, at, and below the center of a typical seismic band.
3. A regular sampling throughout the seismic band.

The actual choice of frequencies would be dictated by the desired use of the data.

Are polychromatic surveys feasible?

The primary concern in carrying out a polychromatic survey is protecting equipment from mechanical failure. This occurs through either excitation of resonances or prolonging a sweep to mechanical limits.

A simple test for resonances could be carried out by attaching geophones to various parts of the vibrator and its vehicle and conducting a wide-band sweep. Resonances would appear as amplitude anomalies. If a sufficient set of “safe frequencies” can be identified, then sweeps of gradually increasing length up to a maximum consistent with the vibrator design specifications would help to define an appropriate sweep length. Alternatively, if there are no resonance-free zones, then sweeps of gradually decreasing bandwidth could be used to define a limited-range sweep.

In carrying out testing as described above, it would be best to first investigate behavior at high frequencies, as damage to equipment would be less likely to occur in this regime. Initial monochromatic tests have been carried out without incident (8 seconds at 50 Hz, 100 Hz and 120 Hz) using vibratory source equipment owned by the University of Calgary. This suggests it would now be appropriate to test a wider range of frequencies.

APPLICATIONS

The investigation of Q is the primary motivation for undertaking a polychromatic survey, but it would be of interest to analyze the data thus obtained to further understand other aspects of the subsurface. We first describe *Q* studies and then consider additional applications.

1) **Attenuation and frequency dependence –** *Q* is a valuable rock property employed in estimating the fluid content of subsurface rocks. Most work on estimating *Q* has focused on VSP data, so that estimation can only be carried out in the vicinity of wells. Estimation of *Q* from surface seismic data is a present challenge of interest to researchers, as it would provide insight into much larger subsurface volumes.

Polychromatic data can play a valuable role in the development of technologies for extraction of *Q* from seismic data. *Q* values obtained from polychromatic surveys can be used as benchmarks to test methods for extracting *Q*, as well as for testing theories of frequency dependence of *Q*.

Attenuation implies frequency dependence on traveltime, which can then form the basis for a method of extracting *Q* from polychromatic data. How this is effected depends on the view we take of the signal. If it is viewed as truly monochromatic, then there is no zero-time information, and the phase-difference approach referred to in the introduction is appropriate. No signal is truly sinusoidal however, and it will have a beginning and an end, which could be employed to determine the timing of arrivals at various locations. Thus in principle two methods exist to estimate time differences between different geophones.

For true steady-state signals one can carry out VSP experiments with monitor geophones at various depths and offsets (in different holes) in-line with the source. Then as the wave sweeps by a receiver we can look at the direct phase shift with respect to the next receiver. The velocity is then given by

$$v = \omega r / \Delta\phi, \tag{1}$$

where ω is frequency, *r* is the distance between adjacent sensors (assuming they are connected by a single raypath), and $\Delta\phi$ is the phase difference between them. This would assume that most of the energy is in the downgoing direct arrivals, which is probably reasonable. The primary challenges of this approach are that a) accuracy is dependent on the length of the signal (DeFazio, 1973), which at this point is unknown, and b) the signal is assumed to be dominated by a single mode. This latter point would provide an extra challenge in extending the experiment to a surface-seismic analogue, where the signal would include unwanted direct arrivals. It may be beneficial to amplitude modulate the signal over time, as in the dual-frequency sweep, as this may help with phase detection.

Alternately one can use the finite-length characteristics of the train to identify arrival times for various events. These events would need to be correlated between data obtained with differing frequencies, as well as with well-logs to establish depths. Then a frequency dependent velocity can be established and *Q* extracted from an empirical equation such as (Aki and Richards, 2006)

$$\frac{v(\omega_1)}{v(\omega_2)} = 1 + \frac{1}{\pi Q} \ln \frac{\omega_1}{\omega_2}, \qquad (2)$$

where v is velocity. Such measurements can in principle reveal different Q's for different layers, and even the anisotropy of Q. The drawback of this method is that the more impulsive the wave-train is, the less pure its frequency content becomes. Filtering out frequencies beyond a narrow range degrades the ability to define an initial onset, while leaving them in mixes together traveltimes for a range of frequencies. Clearly some theoretical work needs to be done to clarify the conditions required to produce useful information.

In contrast to traveltime methods, an amplitude-based method for extracting Q would determine how the attenuation of various frequencies differs from strict geometrical spreading and then relate this to Q via the relation

$$A(t) = A_0 \exp\left[-\frac{\omega t}{2Q}\right]. \qquad (3)$$

This observation however is intermingled with other amplitude-changing effects which would need to be carefully taken into account.

Broadening of the frequency spectral band is also a predicted consequence of anelasticity. That is, if a single frequency is put into the earth, a slightly broadened spectral band should be observed. Measuring this effect could provide an estimate of Q.

We next briefly consider other potential applications of polychromatic data.

2) **A 'window' into non-stationary data** – The Fourier transform of a typical trace assigns for each frequency an intensity which is independent of time. Methods such as the Gabor transform and spectral decomposition use windowing to define the frequency content at each point in time, but do so non-uniquely. Polychromatic data would show differing levels of depth penetration for each frequency, and thus could serve as a unique benchmark to validate nonstationary transforms.

3) **Saturation of seismic response** – To approximate an infinite sinusoid the sweep should proceed until the signal recorded at the geophones achieves a steady state, i.e., an unchanging sinusoid at each geophone, when all reflection energy is below a signal-to noise ratio (SNR) threshold. How long is required for such saturation to occur? Our ability to investigate this question depends on the operating specifications of the vibe. Obtaining such a signal would lead to other investigations described below.

4) **Novel seismic wavelet** – Assuming saturation is achievable, a sufficiently long trace could be divided into three segments: (a) approaching saturation, (b) saturation, and (c) decay from saturation, as shown in Figure 1.

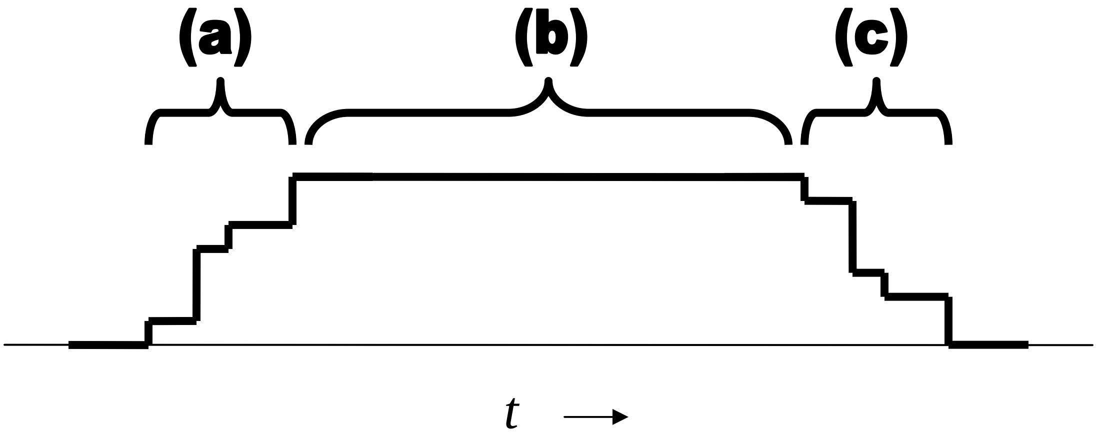

FIG. 1: A schematic diagram illustrating the progress toward, through, and from saturation of a monochromatic seismic signal. The (a) and (c) segments represent signal in which the amplitude and phase change as various reflections appear or disappear. The (b) segment has constant amplitude and phase.

Ideally, these three segments should obey the relation (a)+(c)=(b), as can be seen from the diagram of Figure 2:

FIG. 2: A schematic diagram similar to Figure 1, but with a shifted portion (c) of the signal shown with a dotted line. Summing (a) and an appropriately shifted (c) yields the equivalent of (b).

This relation would not be obeyed perfectly, though, as both the initial appearance and the final disappearance of a signal for a given event in a trace would not be as nearly sinusoidal as at interim times. Thus the combination (a)+(c)–(b) should result in cancellation of the principal sinusoid to leave behind what would essentially be a time trace whose wavelet is some combination of the incipience and vanishing of the monochromatic signal. It would be interesting to see if this can be detected.

Note that in the absence of saturation (a)+(c) should still approximate a sinusoid. In this case (b) could be replaced by a best fit sinusoid.

5) **Naturally blocky traces** – A piecewise sinusoidal signal such as (a) or (c) would have a piecewise constant envelope and phase. Such a representation could be of help in distinguishing different events.

6) **Signal enhancement in noisy and dispersive areas** – Incoherent noise cannot be directly removed from the seismic band, rather it can only be diminished through stacking. By focusing all source energy into a single frequency however it is possible to filter out all noise except within a very narrow range around the desired frequency. Within this narrow range the SNR should be greatly enhanced, and permit us to observe events which are normally obscured. This could equally well apply to a portion of a signal. A typical signal obtained with conventional sources could be supplemented with several high-frequency monochromatic sweeps to extend the bandwidth and increase resolution.

These same ideas could be applied in an area where a conventional source is sufficient, but is not permitted. In this case a smaller monochromatic source may be allowed and sufficient.

We note that cross correlation can provide a huge increase in the SNR and/or dynamic range. (Cross correlation of sign bit data provided dynamic ranges over 100db.) Perhaps conventional 32 bit numbers are not adequate to recover some signals with conventional correlators.

One specific area of application is to surface carbonates where there are usually no seismic events recorded. If this is due to dispersion, then a polychromatic survey may reduce dispersive effects that could smear a conventional signal. Is it possible that the dispersive effects are frequency domain convolution that limits recordings in some way? Would extremely long sweeps or constant frequency sweeps be a way of side-stepping the dispersive effects? Perhaps we could learn more about these areas.

7) **Extraction of amplitude and phase** – If one is interested in simply extracting the amplitude and phase of segment (b) (see Figure 1) then it is further possible to stack all recurring periods into a single fragment of length $2\pi/\omega$, reducing the noise influence even further. This fragment could then be replicated to be of equal length to (a) and (c) to carry out the difference procedure in 4), or the amplitude and phase alone could be employed in other ways. A variety of methods exists for extracting the amplitude and phase. Cross-correlation in the steady-state will produce these values, as would fitting of sinusoids.

8) **Time-independent imaging** – Given complete saturation, the information of each trace can be reduced to a single magnitude and phase. With static data such as this, the imaging problem could perhaps be reduced to minimization of a single functional, with the magnitude and phase for each frequency-source-receiver combination as input, and earth properties as output. In a world of high risk and high uncertainty, it is worthwhile to seek subsurface images which may be complementary to those obtained from dynamic data.

IMPLEMENTATION

The ideal first application of this methodology would be over a shallow reservoir. A number of monochromatic sweeps would be executed, and a conventional sweep encompassing all of the single frequencies would also be carried out for comparison.

Signals will be recorded into both surface and VSP receivers. The rationale for this is that extraction of *Q* from surface seismic data is a promising but still undeveloped objective. Indeed the present proposal is intended to contribute to this enterprise. On the other hand, a number of techniques already exist for extracting *Q* from VSP data (Tonn, 1991), which would provide control for the experiment, and CREWES has already developed expertise in this area (e.g., Haase and Stewart (2005)). We are also collaborators with Dr. Swavik A. Spiewak of the Mechanical Engineering Department at the University of Calgary, who specializes in estimation of attenuation of materials from monochromatic signals.

CREWES has access to a vibrator source and acquisition system owned by the Department of Geology and Geophysics at the University of Calgary, and this equipment would be employed. Industry partners would also greatly strengthen the project by providing access to an appropriate site and wells.

Because this is a relatively unexplored facet of seismic exploration, an initial small-scale acquisition should be carried out first, the results of which would guide further efforts. CREWES is uniquely suited to carry these initial experiments, which could be undertaken in the near future.

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