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Walkaway Q inversion

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Two algorithms are presented to estimate Q from marine multi- offset VSP (walkaway) data. The walkaway geometry, where an array of 3C receivers remains fixed in a borehole for a line or pattern of shots, provides the opportunity to make many measurements of earth attenuation through the same depth interval. As with conventional VSP, high SNR direct arrivals are recorded for Q analysis but in the case of walkaways the additional attenuation due to moveout time difference is exploited to measure effective Q.

The first algorithm follows the classical spectral ratio approach but makes use of the data redundancy provided by the walkaway geometry. The second algorithm is a waveform inversion through inverse extrapolation and coherency optimization. Neither algorithm requires knowledge of the source spectrum. The two techniques are compared on a real data set and show good agreement

INTRODUCTION

Q is a parameter that quantifies frequency-dependent attenuation due to anelastic absorption, and VSP data have been used to estimate Q, the quality factor, for many years (e.g. Ganley and Kanasewich (1980)). The most popular method for doing so is based on spectral ratios, where data from two receiver depths straddling an assumed constant Q medium are selected. The spectral amplitude A at frequency f and time t_2 is related to the spectral amplitude at time t_1 by:

$$A(f,t_2) = A(f,t_1)e^{-\pi f(t_2-t_1)/Q}. \tag{1}$$

Rearranging and taking the logarithm,

$$\ln\left[\frac{A(f,t_2)}{A(f,t_1)}\right] = -\pi f(t_2 - t_1)/Q. \tag{2}$$

A linear regression of the left-hand side versus frequency therefore yields a slope which is equal to $-\pi(t_2 - t_1)/Q$.

Recently Dasgupta and Clarke (1998) proposed using a spectral ratio approach to estimate Q from surface seismic reflection data. In their approach the spectral ratios are computed between the source wavelet spectrum (reference) and windowed events in CMP gathers. The intercept of a linear regression to 1/Q values versus offset provides the *effective* or *cumulative* Q estimate down to the zero offset two-way time. The estimated Q values represent *effective* Q in that frequency-dependent scattering effects are rolled into the Q estimate. This is true for the algorithms presented here as well.

Among the problems with using surface data to estimate Q are NMO stretch, offset-dependent tuning of reflections and generally poor signal to noise due to multiples and mode conversions. Using an incorrect source spectrum will also bias Q estimates. Many of these problems are obviated if multi-offset VSP data are used.

The advent of multi-receiver 3C VSP tools has made multi-offset VSP (walkaway) surveys cost effective to acquire (particularly offshore), but this type of VSP data has only recently been used for Q estimation (Leaney and Hope (1998)). The walkaway geometry is actually ideally suited to estimating Q for a number of reasons: 1) a 3-component direct arrival is recorded with high signal-to-noise, 2) common shot velocity filtering attenuates reflections and downward traveling mode conversions, and 3) the receiver is essentially at a common depth point so estimated effective Q values are appropriate for use in prestack surface processing.

In this paper two algorithms are described to estimate Q from marine multi-offset VSP data. The first is based on spectral ratios while the second is a waveform inversion through coherency optimization. As with the CMP approach of Dasgupta and Clarke (1998), the assumption is that the same effective Q exists across the spatial aperture of the data and down to the event time window, but no estimate of the source spectrum is required. The performance of the two algorithms is compared on a real data set.

MULTI- SPECTRAL RATIOS

The classical spectral ratio approach described in the introduction for VSP data can easily be adapted to walkaway data by simply selecting the minimum time or offset trace and computing the spectral ratio Q value as a function of offset. To improve the statistical significance of these Q estimates shot points other than the minimum time or offset shot can be used as "reference" traces. Using different pairs of shot points gives more independent estimates of the effective Q down to the receiver. The total number of unique pairs of shot points available from N shots is N!/(2(N-2)!) or N(N-1)/2. In practice about half of all possible shot point pairs have insufficient time difference and can be discarded based on a quality of fit criterion. For a typical walkaway experiment with 150 shots, more than 3000 independent effective Q estimates are often available.

The preprocessing of the walkaway data for Q estimation includes first arrival maximum amplitude 3C rotation, common shot velocity filtering to attenuate reflections and downgoing mode conversions and log gap predictive deconvolution to attenuate multiples without altering the wavelet. The only input variables to the algorithm are the low and high frequency cut-offs (10-80Hz in this case) and optional coherency smoothing parameters. Figure 1 shows 2791 1/Q estimates versus shot-pair midpoint for a selected real data set with 119 shots. Estimates are color-coded based on slope standard deviation with smaller values being darker. The confidence–weighted Q estimate is 78 but considerable scatter is observed. Coherency filtering reduces the scatter (Figure 2) and exposes variations with offset which are due to interference with downward scattered diffractions not attenuated by the preprocessing. The multi-ratio algorithm is simple, exploits the redundancy afforded by walkaway data and naturally produces quality control plots, but results are quite sensitive to the selected frequency band.

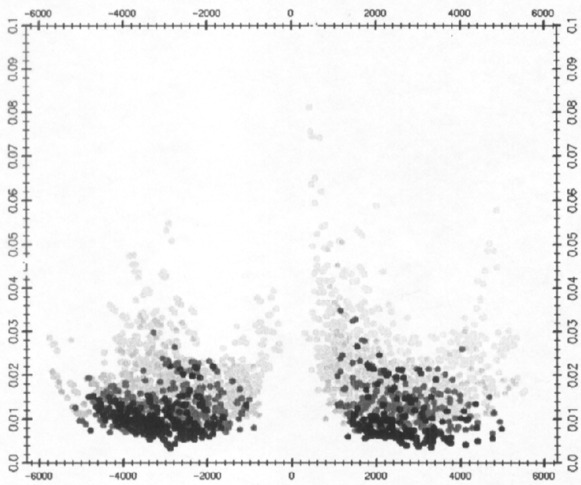
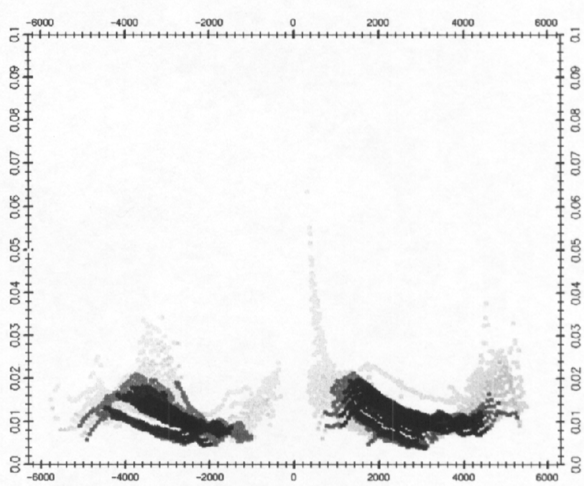



Figure 1. (Left) Multiple spectral ratio effective 1/Q estimates versus shot pair midpoint. Darker dots indicate greater confidence in the spectral slope. The confidence-weighted average 1/Q = .0128 or Q=78.
Figure 2. (Right) Same as Figure 1 but after coherency filtering. Variations with offset are due to interfering downward travelling diffractions.

WAVEFORM COHERENCY INVERSION

The waveform coherency inversion algorithm seeks to balance amplitudes with offset and so requires compensation for geometrical spreading. This can come from 1) a layered velocity model and ray theory, 2) higher order truncated series approximations to spreading (Ursin (1991)) using a layered velocity model, or 3) spreading derived from a non-hyperbolic fit to travel times. If the goal is to use the Q estimate for compensation in surface seismic prestack processing then the selection should be consistent with whatever offset-dependent spreading compensation is being applied there.

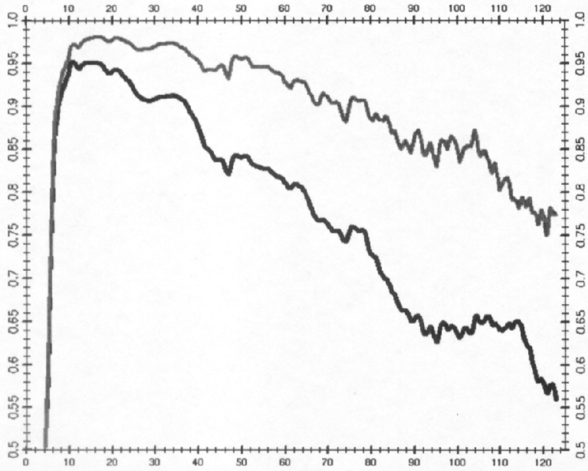
Once waveforms have been compensated for offset-dependent geometrical spreading the next steps are inverse Q extrapolation and coherency computation. The inverse extrapolation step is accomplished by applying a frequency domain operator to each offset trace. Following Valera et. al. (1993), the inverse extrapolation operator U is given by:

$$U(\Delta t, f) = \exp\left[\frac{\pi \Delta t}{Q}\left(f + i\frac{2f}{\pi}\ln(f/f_r)\right)\right], \quad (3)$$

where Δt is the time difference relative to 0 offset and f_r is the frequency to which phase delays are referenced.

Having applied the inverse Q wavefield extrapolation, semblance is computed at each frequency and averaged over the selected band. A simple line search is then carried out to find the Q value that yields the maximum semblance. Frequency and ray-parameter -dependent source ghost effects (Loveridge et. al. (1984))) can be included in the coherency optimization, but I have found them to have a small impact on the estimated Q value.

Figures 3, 4 and 5 show the results of this algorithm applied to the same data as was used previously to generate figures 1 and 2. Shown in Figure 3 is semblance versus frequency for the no Q and best Q cases. Figure 4 shows semblance versus Q with the inverted value of 82, in close agreement with that estimated using the multi-ratio algorithm (78).



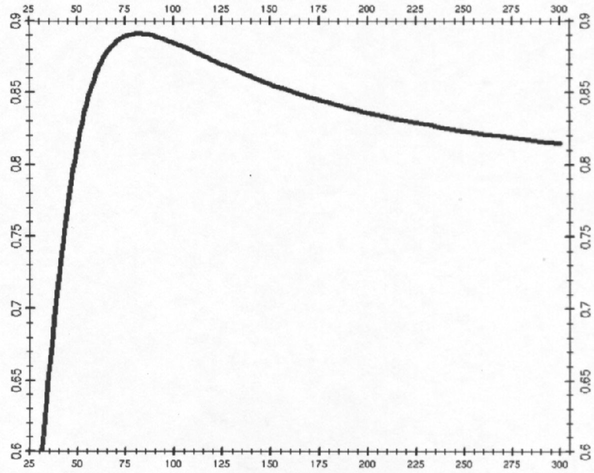


Figure 3. (Left) Semblance versus frequency for no Q (black) and best Q (gray).
Figure 4. (Right) Semblance versus Q showing the best Q=82.

Figure 5 shows input waveforms, waveforms after offset-dependent geometrical spreading compensation and after inverse Q filtering with the determined best Q value. In contrast to the multi-ratio algorithm, coherency Q inversion is relatively insensitive to the chosen frequency band.

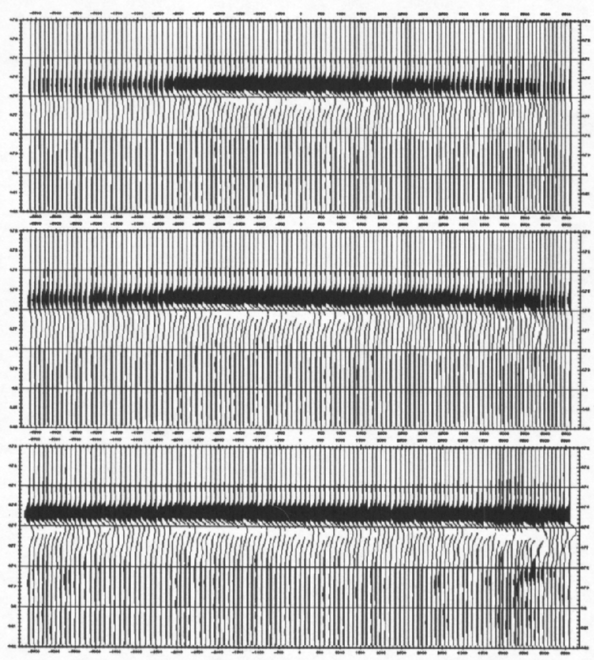


Figure 5. Walkaway waveforms through coherency Q inversion. Top: pre-processed input downgoings; middle: input downgoings after offset-dependent geometrical spreading compensation; bottom: final balanced downgoings including inverse Q filtering with Q=82.

DISCUSSION

The algorithms presented here have been applied to multi-offset VSP data acquired at a single array tool depth, but both algorithms are equally applicable, with slight alteration, to conventional VSP data. The advantage of the VSP geometry is that it permits Q(z) to be determined. If walkaway lines are acquired for multiple depth settings then Q(z) can be determined using either of the algorithms discussed here. Q for shear waves can also be determined using these algorithms, but to determine Q-shear as it affects sea-bed recording, for example, mode conversion at the seabed is required and this doesn't always occur. The multi-offset / multi-azimuth / multi-depth VSP (walkaway) geometry may also provide the best data to study Q anisotropy. These are areas for future work.

CONCLUSIONS

The marine multi-offset VSP or "walkaway" geometry arguably provides the best data for accurate Q estimation. The main advantages are: 1) high SNR scalar downgoing arrivals are recorded; 2) many shots acquired with the same receiver positions provides data redundancy and statistical confidence; and 3) the geometry is similar to surface seismic in that the receiver is essentially at a common depth point.

To exploit these advantages two new Q estimation algorithms have been developed for walkaway VSP data. The first algorithm is a variation on the familiar spectral ratio approach but makes use of all reliable shot point pairs, providing a Q estimate with natural quality control outputs. The second algorithm employs inverse Q extrapolation and coherency optimization to balance offset-dependent amplitudes and is insensitive to the frequency band selected. Neither algorithm requires knowledge of the source wavelet.

The two algorithms were shown to give consistent results on a real data set. Both algorithms are applicable to conventional VSP data, and walkaways acquired at multiple depth settings together with these algorithms should yield more accurate Q(z) results.

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