Characterizing intrinsic and stratigraphic *Q* in VSP data with information measures

Siming Lv and K. A. Innanen, Department of Geoscience, University of Calgary, CREWES*

SUMMARY

The problem of distinguishing between intrinsic *Q* and stratigraphic filtering is a classical example of non-uniqueness in seismic data analysis. Two very different mechanisms affecting propagating waves – reverberations between thin layers and transformation of mechanical energy to heat – produce almost identical effects. A version of the Shannon entropy, defined on snapshots of a VSP wave field, has been proposed to analyze and compare these two influences. It has been used to argue that the distinction is not as meaningful as we might think, but here we take the opposite view: that with it we may separate the two effects. Besides the basic entropy measure, we further extend the entropy "attribute" to include conditional entropy, which incorporates correlations of seismic data points with their neighbouring values. Synthetic VSP data built from a range of well logs are used to investigate the separability of intrinsic/extrinsic sources of attenuation and dispersion. Progress of this kind may have impact on aspects of reservoir characterization such as viscosity estimation.

INTRODUCTION

Stratigraphic filtering (also referred to as extrinsic *Q*) is the term used to describe apparent amplitude attenuation caused by reflections, especially internal multiples, in contrast with the attenuation caused by the absorption factor *Q* (Aki and Richards, 1980). It has attenuating effects on the transmitted wave which resemble those caused by absorption: decaying and spreading of the waveform, reduction of the high-frequency content of the initial disturbance, and appending of an incoherent coda to the signal.

Ever since O'Doherty and Anstey (1971) pointed out the equivalent importance between stratigraphic and absorptive attenuation in periodic layering section, significant effort has been expended in distinguishing between them (Hauge, 1981; Spencer, 1977, 1982; Stewart, 1984; Walden and Hosken, 1985; Margrave, 2015).

One important reason why geophysicists would like to distinguish intrinsic and extrinsic *Q* is that one of them is connected to important rock properties, and the other one is connected more closely with structural changes of rock. For example, Vasheghani and Lines (2009) showed that the viscosity of a cross-well section can be linked to the intrinsic *Q* measurement by Biot-Squirt theory (Lines, Vasheghani and Bording, 2013). Therefore, estimation of intrinsic *Q* free from effects of extrinsic *Q* supports quantitative interpretation.

Innanen (2012) made the case that the disorder of the mechanical disturbances involved in a seismic wave was a common feature of both intrinsic and extrinsic *Q*. Treating each snapshot of a VSP wave field as a "sentence" written in an "alphabet" of allowable discrete values of the displacement, the Shannon entropy or information content of each snapshot could be calculated. He argued that this allowed a single measure of the wave field to smoothly characterize the transition smoothly from multiples, to multiples below the resolution of the data, and then to intrinsic *Q*.

The goal of this research is to use some of the same entropy ideas to analyze intrinsic and extrinsic *Q*, but to extend them and use them to do in effect the opposite thing, namely to help distinguish between the two attenuation mechanisms.

THEORY

Shannon Entropy

A wave field containing complex reflecting events can be thought of as carrying large amounts of information in it, whereas those without interbed multiples might be said to contain relatively small amounts of information. This point of view motivates the use of the Shannon entropy, which represents the amount of the information in a message, to characterize the amplitude distributions in seismic wave fields.

Shannon Entropy deals with uncertainty of a message. For a discrete random variable X with possible values $\{x_1, x_2, \dots, x_n\}$ and their corresponding probability distribution $\{P(x_1), P(x_2), \dots, P(x_n)\}$, Shannon defined entropy H about variable X as (usually take b=2):

$$H(X) = \sum_{i=1}^{n} P(x_i) I(x_i) = -\sum_{i=1}^{n} P(x_i) \log_b P(x_i) \, . \quad (1)$$

In this research we applied the entropy calculation on snapshots of a seismic wave field, that is, distributions of displacement values in space at a fixed instant of time. According to Innanen (2012), if each snapshot consists of N data points (i.e. responses from N receivers), and every datum represents the selection of a displacement value u_i from m possible values, we can define the probability of u_i's occurrence as:

$$P(u_i) = \frac{W(u_i)}{\sum_{i=1}^{m} W(u_i)} \quad (2)$$

Then, Shannon entropy is calculated as in equation (1):

$$\mathrm{H} = -\sum_{i=1}^{m} P(u_i) \log_2 P(u_i) \quad (3)$$

By inspecting this entropy definition, we observe that the larger the set of possible values the displacement can have, and the wider its probability distribution function (PDF) is, the bigger the Shannon entropy will be. Thus, H should be expected to go up when the disorder of the wave field increases. In our case, the disorder is caused by either inter-layer reverberations or wave dispersion. If we can understand how each one affects the entropy differently, we might be able to separate them.

Conditional Shannon Entropy

If $H(Y|X = x_i)$ is the conditional entropy of variable Y given X taking on a certain value $x_i (i = 1,2, \ldots n)$. The PDF of X is $P(x_i)$, the conditional PDF of Y is $P(y_j|x_i)$ (where y_j represents every possible value of Y), then the conditional entropy is defined as:

$$H(Y|X) = \sum_{x_i} P(x_i) H(Y|X = x_i) = -\sum_{x_i} P(x_i) \sum_{y_j} P(y_j|x_i) \log P(y_j|x_i) \quad (4)$$

In our experiments, at each fixed time, we took each VSP amplitude value U_0 as a given, and computed the conditional probability distribution of the amplitudes U_i following it throughout the whole data set.

METHOD

We designed a controlled series of Shannon entropy calculations using four different synthetic VSPs generated from the well logs: a) with only primaries; b) with primaries and internal multiples, c) with primaries and absorption and d) with primaries, internal multiples and absorption. Artificial intrinsic *Q* distributions are generated from P-wave velocity and density logs using an empirical relationship (Margrave, 2014a), beginning with

$$Q_v(z) = Q_0 \frac{v(z) - v_1}{v_0 - v_1} + Q_1 \frac{v(z) - v_0}{v_1 - v_0} \quad (5)$$

$$Q_\rho(z) = Q_0 \frac{\rho(z) - \rho_1}{\rho_0 - \rho_1} + Q_1 \frac{\rho(z) - \rho_0}{\rho_1 - \rho_0} \quad (6)$$

and determining the final *Q* log from:

$$\frac{1}{Q(z)} = \frac{1}{2}\left(\frac{1}{Q_v(z)} + \frac{1}{Q_\rho(z)}\right) \quad (7)$$

With (7), we computed synthetic VSP data sets by a propagator matrix method (Margrave and Daley, 2014b).

Our study first used the same measure of entropy proposed by Innanen (2012), then moved to the conditional entropy algorithm. The calculation of the Shannon entropy of wave field snapshots requires us to define a range of possible amplitude values and amplitude bins to classify these values, which makes choosing bin size a key step in the experiment.

EXAMPLES

Well log data from 7 wells have been collected from a range of areas to be used in the analysis, to minimize the possibility that the results are special to one area. We took results from well “Blackfoot 1227” (Hoffe et al., 1998) for analysis purpose.

PDFs from snapshots of the VSP wave field are computed and shown in Figure 1. The following observations were made from comparisons among 1a, 1b, 1c and 1d:

(1) Internal multiples tend to extend the breadth of the PDFs to later arrival times and wider amplitude range;
(2) Absorption shrinks the amplitude variation to a smaller range and consequentially tends to restrict the dispersion effect to earlier arrival times;
(3) With internal multiples and *Q* operating at the same time, amplitude attenuation and dispersion lies between 1b and 1c where internal multiples and absorption are acting individually.

Outcome (3) appears to depend on the relative strength of internal multiples and absorption. But (1) and (2) suggest that the information measure H may be sensitive enough to distinguish between the two attenuation mechanisms.

The entropy variation with time for all wave fields is shown in Figure 2. In this figure, for all systems, the entropy rises with increasing time in reaction to the amplitude dispersion evolving in the wave field. However, differences among peaks of the H curves reveals clues to distinguish intrinsic and extrinsic *Q*.

Without stratigraphic filtering in the system, the yellow and blue curves have low peak entropies between 0.2s and 0.3s. Comparing the yellow and blue curves, absorption in the system causes an even smaller peak value. After internal multiples are added to the system, the entropy curves (purple and red in Figure 2) reach higher peak entropies at times around 0.4s, in contrast to the other two curves.

Stratigraphic Filtering Analysis

The effect of absorption is to counteract some of the scattering effects of the internal multiples, by attenuating them, which explains why the purple curve lies between red and blue ones.

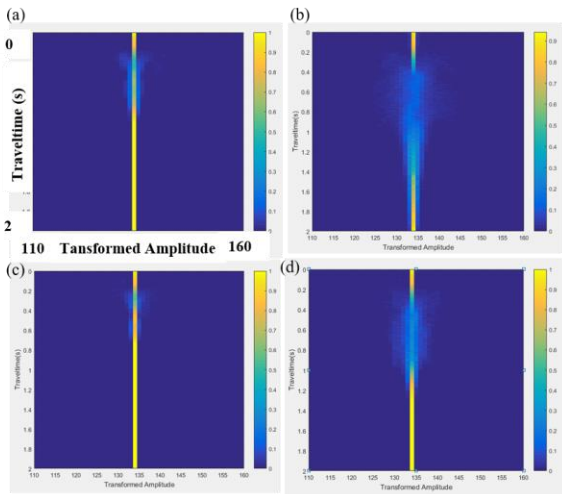

Figure 1. "Zero-order" PDF from VSP data sets (a) primaries with no absorption or internal multiples (b) primaries with only internal multiples (c) primaries with only absorption (d) primaries with both absorption and internal multiples built from Blackfoot 1227.

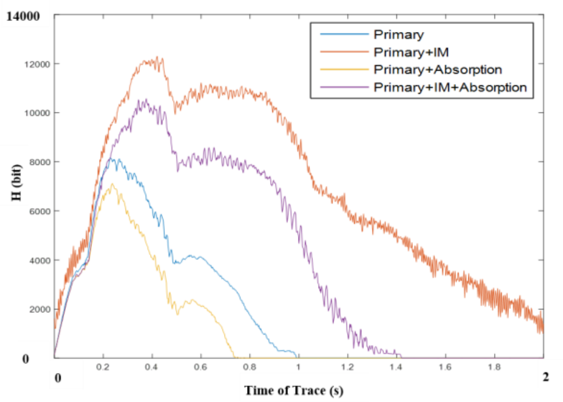

Figure 2. The amplitude entropy variation comparison of wave fields built from Blackfoot 1227.

Conditional entropy algorithm

We calculated the entropy of wave field snapshots following the workflow in Figure 3. In Figure 4 the conditional probability distributions are plotted; the probabilities distribute along the diagonals, which means each datum correlates strongly with its preceding value. This is a consequence of the continuity of seismic waves, and should hold true for most wave fields.

The entropy variation is shown in Figure 5. Comparing these new results with the originals in Figure 2, we find:

(1) The magnitude of the entropy values is significantly reduced owing to the use of conditional probabilities, which means the PDF histograms contain far fewer entries;

(2) Entropy peak values affected by internal multiples (red and purple curves) are now smaller than those from systems with no internal multiples (yellow and blue curves), in contrast to the results in Figure 2.

This seems unexpected at first, however, by using the conditional entropy, the effect of the continuity of the waveform appears to play a much larger role. Each event adds a correlated sequence of amplitudes, so that more events makes any amplitude more likely to correlate with its next amplitude, which leads to a smaller entropy. Internal multiples increase the complexity of the wave field while absorption does the opposite by attenuating amplitudes and blending different events (i.e. primaries, internal multiples, etc.) together. This explains the tighter probability distribution in circled region of Figure 5b than 5c;

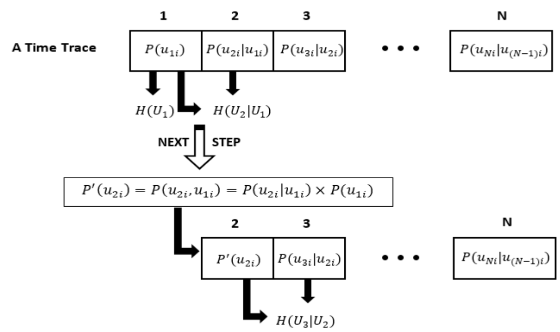

Figure 3. Workflow for computing conditional entropy.

Footprint of Bin Size

Because of the effect of bin size on the character of the PDFs, we tested different sizes to understand their influence on the ability of entropy to characterize attenuation, particularly to understand if it could suppress or obscure the opposing entropy reaction caused by intrinsic and extrinsic *Q* that we have observed. The results suggest that this information measurement is more stable than we thought. No matter big or small, stationary or flexible bin size we choose, the conclusion of this research stays trustworthy.

Stratigraphic Filtering Analysis

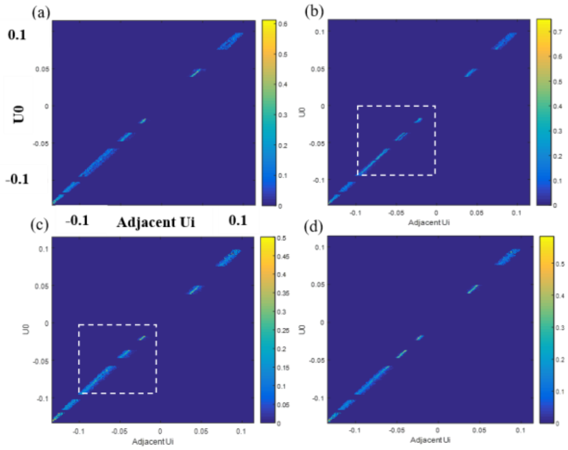

Figure 4. Conditional PDFs (several points near zero amplitude are muted).

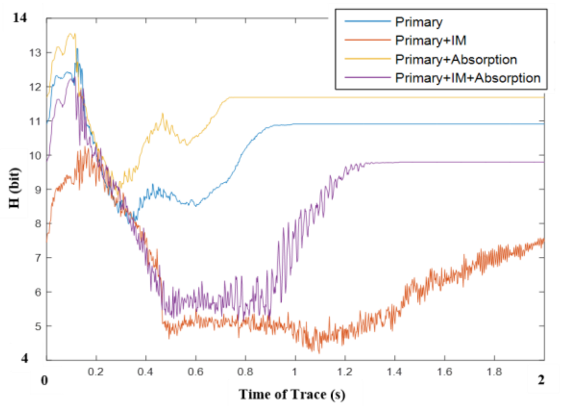

Figure 5. Comparison of conditional entropy variations of wave fields built from Blackfoot 1227.

Seven well logs comparison

Figures 6 and 7 show comparisons of the zero-order entropy and conditional entropy measurements amongst all wells. Our results are robust across at least three randomly selected analysis areas.

CONCLUSIONS

Although stratigraphic filtering and absorption produce very similar effects on propagating waves, they are ultimately based on different physical processes, and seeking measures that bring these differences out (when both processes are operating) and help distinguish them is an important task. The Shannon entropy defined on VSP time snapshots appears to serve as a magnifier that enhances their differences, and translates them into a visible and measurable form.

Comparison of two entropy algorithms show how different information measures can be. However, reverberations and absorption tend to influence entropy variations in opposing ways, and we see this as a promising starting point from which to develop techniques to separately determine intrinsic attenuation and stratigraphic filtering parameters.

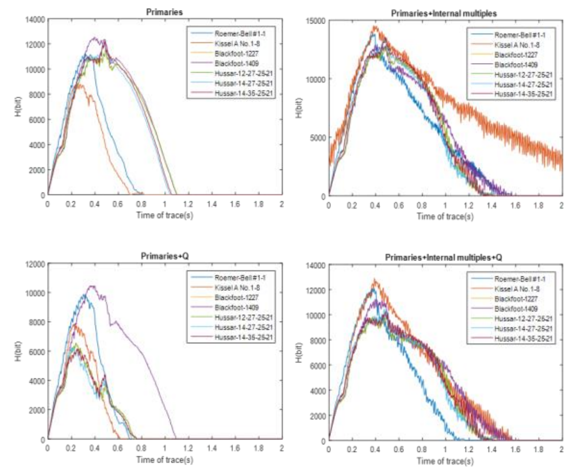

Figure 6. Seven well log zero-order entropy comparison.

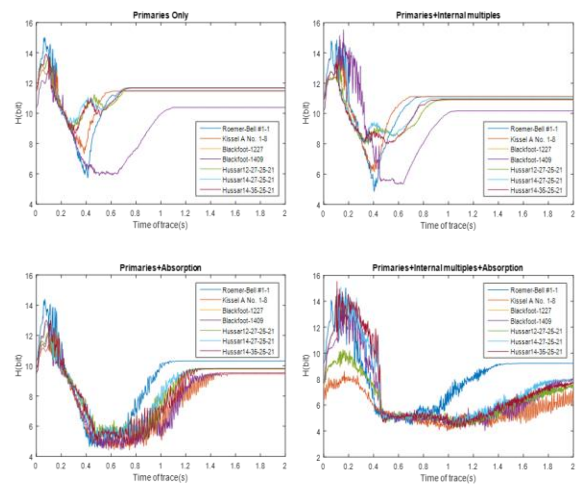

Figure 7. Seven well log conditional entropy comparison.

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