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Attenuation estimation using high resolution time–frequency transforms

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ABSTRACT

Wave attenuation is often measured using spectral techniques such as the spectral ratio method and the frequency shift method, comparing the spectral content of pairs of waveforms along the ray path. The recent introduction of novel highly-localized time–frequency transforms leads to high-resolution but discontinuous spectra. It prevents the use of these time–frequency transforms with conventional attenuation measurement methods. We show how three highly-localized time–frequency transforms, namely basis pursuit, the synchrosqueezing wavelet transform, and complete ensemble empirical mode decomposition, can still be used to estimate attenuation using the peak frequency method. Assuming a Ricker source wavelet, the decrease in peak frequency of a wave spectrum as it propagates in a given medium is used to estimate attenuation. When applied to a synthetic benchmarking signal corrupted by Gaussian white noise, the three transforms show different degrees of performance and robustness for different signal-to-noise ratios. The developed methodology is suitable for geophysical investigations, but may also find application in other fields such as biomedicine, acoustics and engineering.
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1. Introduction

Attenuation refers to the loss of energy as a wave propagates through a given medium. In the case of seismic waves in the Earth, attenuation is usually separated into intrinsic losses, connected to the conversion of seismic energy into heat or fluid flow [32], and apparent attenuation corresponding to various physical processes such as scattering effects [34]. Intrinsic attenuation is connected to various medium and fluid properties such as fluid content, viscosity, and permeability [5], which makes it a potential monitoring tool (e.g., [36,6]). Attenuation measurements have also a wide range of applications outside of geophysics, such as in acoustics [22,17], biomedicine [2], archeology [21], astrophysics [28] or engineering [27,9].

For a propagating wavelet, the quality factor Q is commonly defined as the total wave energy divided by the loss of energy per cycle. Attenuation, inversely proportional to the quality factor, is assumed to be approximately constant in the frequency band relevant for seismic waves in the Earth [29]. However, higher frequencies decay more rapidly than lower frequencies simply because attenuation corresponds to a certain absorption value per signal period [42]. The disappearance of higher frequencies leads to a shift of the dominant frequency toward lower frequencies and a relative widening of its main lobe (Fig. 1a, b).

Attenuation can then be measured either in the time domain, using the amplitude decay of signals with distance/time, or in the frequency domain by quantifying spectral changes. The two main spectral methods are the spectral ratio method and the frequency shift method [33]. Both operate by comparing the spectra of a pair of arrivals, for instance at different locations along the ray path. Several other methods were developed to estimate quality factors from a single frequency estimate, such as the peak frequency method [48] and the analytical signal method [42,14]. The peak frequency information should be preserved by highly-localized time–frequency transforms, even though bandwidth information is lost.

New highly-localized time–frequency transforms representations were developed recently, such as basis pursuit (BP) [10], empirical mode decomposition [25] and the synchrosqueezing wavelet transform (SST) [12]. See Tary et al. [38] for more background on their rationales and performances. High-resolution time–frequency transforms improve the readability of time–frequency representation by focusing the spectral information around the main frequency content of the signal. This can be useful in a variety of applications, encompassing climate time series [40], solar physics [1], seismic data analysis [50,24], and signal denoising [45]. The high spectral localization, on the other hand, prevents or compli-

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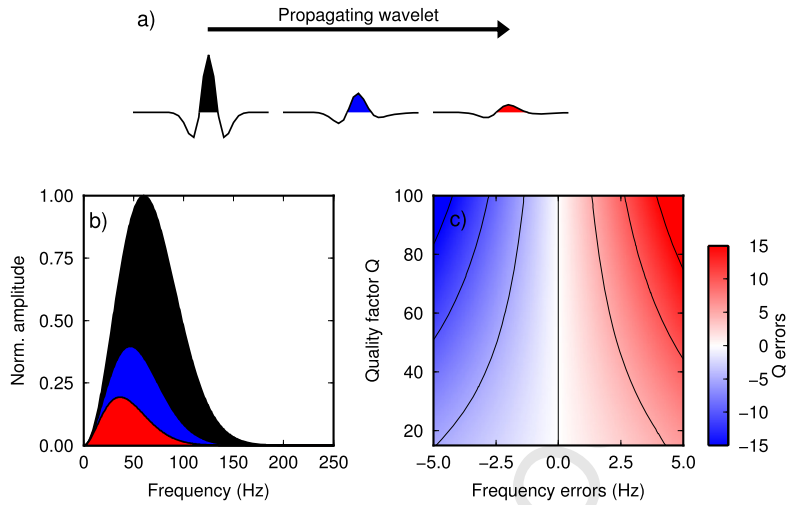

Fig. 1. a) Waveforms of a source Ricker wavelet with a peak frequency of 60 Hz (black) and two attenuated wavelets after 0.25 (blue) and 0.5 s (red) propagation time using a quality factor of 45. The wavelets are sampled at 500 Hz. b) Normalized Fourier spectra of the three wavelets shown in a). c) Errors in quality factor Q estimations due to errors in peak frequency, using the peak frequency method of Zhang and Ulrych [48] and different quality factors. The black lines correspond to Q error contours (every 5 Hz). We first use eq. (3), a source peak frequency of 60 Hz, and a given quality factor to estimate theoretical peak frequencies. An error is then introduced in these values in the range between −5 and 5 Hz, and the quality factor is computed using eqs. (4) and (5). The true quality factors are then subtracted from the quality factor estimations to get the Q errors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cates the use of the most common spectral estimation techniques for attenuation measurements since these often require either a continuous spectrum or a bandwidth estimate [42].

In principle, attenuation could still be estimated by high-resolution time–frequency transforms using the peak frequency technique. In the following, we first describe the peak frequency technique and three time–frequency transforms: BP, SST and empirical mode decomposition. We then test the performance of the peak frequency method in combination with these three high-resolution time–frequency transforms for accurate and precise attenuation estimation using a controlled synthetic experiment.

2. Quality factor estimation

The amplitude spectrum of a signal recorded at a given receiver $A_R(f)$ can be approximated as a multiplication of the source amplitude spectrum $A_S(f)$, amplitude modifications due to transmission/reflection at interfaces in addition to instrument and medium responses $G(t, f)$ (e.g., geometric spreading, source/instrument transfer function, radiation pattern), and attenuation [33], producing

$$A_R(t, f) = G(t, f)\, A_S(f)\, \mathrm{e}^{-\frac{\pi f t}{Q}}, \tag{1}$$

where f is frequency, t the travel-time and Q the quality factor grouping all sources of attenuation. We then assume that the attenuation is constant between the source and the receiver, and that $G(t, f)$ has no significant influence on the receiver spectrum in the frequency band of interest.

The individual arrivals are represented using the Ricker wavelet spectrum given by:

$$A_S(f) = \frac{2}{\sqrt{\pi}} \frac{f^2}{f_0^3} \mathrm{e}^{\frac{-f^2}{f_0^2}}, \tag{2}$$

with f_0 the peak frequency of the Ricker wavelet. Equating the derivative of eq. (1) with respect to frequency to 0 and using the Ricker spectrum as the source spectrum, the peak frequency f_p of latter arrivals after attenuation is [48]

$$f_p = f_0^2 \left[\sqrt{\left(\frac{\pi t}{4Q}\right)^2 + \left(\frac{1}{f_0}\right)^2} - \frac{\pi t}{4Q} \right]. \tag{3}$$

Eq. (3) is then used to estimate quality factors. The change in peak frequencies between signals is directly related to the quality factor by

$$Q = \frac{\pi t f_p f_0^2}{2\left(f_0^2 - f_p^2\right)}. \tag{4}$$

In addition, the peak frequency of the source wavelet[1] f_0 can be determined using the peak frequencies at two different times using

$$f_0 = \sqrt{\frac{f_{p1} f_{p2}\left(t_2 f_{p1} - t_1 f_{p2}\right)}{t_2 f_{p2} - t_1 f_{p1}}}, \tag{5}$$

for wavelets recorded at times t_1 and t_2 with peak frequencies f_{p1} and f_{p2}. This also assumes constant attenuation between measurements at times t_1 and t_2.

The peak frequency method for estimating Q is relatively sensitive to systematic errors in peak frequency estimations (see Fig. 1c). Systematic errors toward higher frequencies for example, for the same travel-time and frequency difference between wavelets, lead to quality factor overestimations because higher frequencies are attenuating faster compared with lower frequencies. The method is also more sensitive for higher quality factors since peak frequency changes are smaller compared to those arising from lower quality factors for identical propagation times. For example, considering quality factors comprised between 15 and 100, a peak frequency for the source wavelet of 60 Hz, and attenuated wavelets after a propagation time of 0.25 and 0.5 s, the errors in quality factor range between −9 and 9.4 in the case of an error of ±2.5 Hz (Fig. 1c). In the case of multiple layers, the quality factors are estimated successively from layer to layer by layer stripping (see Zhang and Ulrych [48] for more details). Errors in the estimations of quality factors from previous layers are then propagated to those of the following layers.

[1] For clarification, the source wavelet is the initial wavelet at the point of origin and the observed wavelet is the recorded wavelet after it has propagated over some distance. These terms should not be confused with the mother wavelet, that is, the template used in continuous wavelet transforms or associated time–frequency transforms.

UNCORRECTED PROOF

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