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Quality-factor and reflection-coefficient estimation using surface-wave ghost reflections from subvertical structures

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ABSTRACT

Seismic interferometry can retrieve the Green's function between receivers from the cross-correlation and summation of recordings from a boundary of surrounding sources. Having the sources only along a boundary is sufficient if the medium is lossless. If the medium is dissipative, the retrieved result using cross-correlation contains non-physical (ghost) arrivals. When using receivers at the surface and transient sources in the subsurface for the retrieval of the reflection response in a dissipative medium, it has been shown that the retrieved ghost reflections are characteristic of the quality factor of the subsurface. The ghost reflections are caused by internal reflections inside subsurface layers. It has been shown with numerical examples for recordings in a borehole from a surface source that a ghost reflection can be discriminated from physical reflections and tied to a specific subsurface layer. After connecting the ghost reflection to a specific layer, the quality factor of the medium above this layer and the reflection coefficient at the layer interface can be estimated. In this article, we show how the above principles can be adapted and applied for surface waves. Due to intrinsic losses in the medium, surface-wave ghost reflections are retrieved from internal scattering between subvertical boundaries. We demonstrate the method on an ultrasonic dataset recorded on a sample composed of a PVC block and an aluminum block. The aluminum block has a groove parallel to the PVC/aluminum interface. Using a surface-wave ghost reflection between the groove and the PVC/aluminum interface, we estimate the quality factor of the PVC and the reflection coefficient at the PVC/aluminum interface. We also show that the ghost reflection can be identified and tied to the layer between the groove and the PVC/aluminum interface, thus confirming previous numerical findings.

1. Introduction

When propagating through the earth, the seismic waves experience intrinsic losses due to internal friction, viscous drag and other mesoscopic and microscopic mechanisms. The effect of the loss of energy can be expressed by the dimensionless quantity Q, which is called quality factor. Determining spatially detailed knowledge of Q is important for accurate interpretation of processes inside the earth and the composition of the earth at different scales. For example, Solomon (1972) showed that the knowledge of the Q-values for Rayleigh and Love waves can be used to interpret partial melting in the upper mantle; Klimentos (1995) showed that the ratio of the Q-values for P- and S-waves can be used to distinguish between gas and condensate from oil and water saturation in reservoir rocks; Zhubayev and Ghose (2012a,b), showed that a joint inversion of frequency-dependent P- and S-wave velocity and their Q-values could be used for characterization of the flow properties in water-saturated soils.

A traditional method for estimating Q is the spectral-ratio method (e.g. Jannsen et al., 1985; Portsmouth et al., 1993; Tonn, 1991). It can be applied to transmission measurements using recordings at multiple seismic receivers from the same seismic source (common-shot gather) or from multiple sources at the same receiver (common-receiver gather). In both of these cases, the ratio between the spectra of the direct arrivals is computed and then used to estimate the Q-value of the medium between the receivers or between the sources. The method can also be applied to a measurement at a single receiver from a single source. In this case, the spectral ratio is estimated between a direct arrival and a primary reflection, which has reflected at a boundary. When only one reflector is present, the Q-value is estimated between the receiver and the reflector. The same technique could be used on a multilayer sample (subsurface), but in this case, the Q-estimate would be the

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apparent quality factor of the medium between the receiver and the reflector whose reflection is used.

Recently, Draganov et al. (2010) proposed an alternative method for estimating Q. This method makes use of non-physical arrivals retrieved from seismic interferometry with transient sources. Seismic interferometry is a method that allows the retrieval of the Green's function between two receivers, as if one of them were a source, using recordings from sources that effectively surround the receivers (e.g. Campillo and Paul, 2003; Schuster, 2001; Schuster et al., 2004; Snieder, 2004; Wapenaar, 2004; Wapenaar et al., 2002). The retrieval is most popularly performed by the process of cross-correlation: recordings at the two receivers from all surrounding sources are cross-correlated and the resulting correlations are summed over all sources to obtain the final retrieved Green's function. The theory with cross-correlation, with sources on a surrounding boundary, is derived for lossless media. When a medium causes intrinsic losses, the retrieved result will also contain non-physical (ghost) arrivals. When seismic interferometry is applied to receivers at the surface to retrieve the reflection response of the subsurface using subsurface boundary sources, the ghost events would be in the form of reflections that appear to have propagated only inside a subsurface layer and measured with source and receiver directly on top of that layer. In the correlation process, the ghost reflections are retrieved from arrivals that have experienced single or multiple reflections inside that layer. Draganov et al. (2010), used such body-wave ghost reflections to estimate Q of the medium above each subsurface layer, from inside which a ghost reflection is retrieved. The accuracy of their estimated values would depend on the signal-to-noise ratio of the later arrivals in the recordings that have experienced multiple reflections inside the layers in question. As a remedy, Ruigrok (2012) proposed to utilize only the earliest such arrivals, and using their amplitudes, the author estimated Q above and the reflection coefficient at the top of a layer that caused a ghost to be retrieved. When the subsurface is homogeneous or contains only one layer above a homogeneous half space, ghost reflections would not be retrieved even when there are intrinsic losses in the medium.

The loss-related ghost reflections are akin to the spurious reflections that appear in lossless media due to one-sided illumination of the receivers from an open boundary of sources (Draganov et al., 2012; King and Curtis, 2012; King et al., 2011; Snieder et al., 2006). Note that in media with intrinsic losses, ghost reflections would appear in the retrieved Green's function even when the transient sources effectively surround the receivers.

In the following, we show how the method from Ruigrok (2012) can be adapted and applied to estimate the surface-wave Q-value of the subsurface. This method can be seen as an alternative to the spectral-ratio method for cases when the latter method alone does not provide sufficiently reliable results. This might be the case when the recording geometry consists of sparse receivers in a medium with lateral changes in the seismic parameters, e.g. in volcanic settings or in the presence of a subvertical fault zone (e.g. Ghose et al., 2013). In such cases, the spectral-ratio method should be applied at single stations to estimate the Q-value between the station and a reflector, thus using a direct and a reflected arrival, to avoid erroneous results when the different receivers would be in media characterized by different intrinsic losses. In such cases, the method we propose could be applied at the same stations to obtain an alternative estimate of the Q-value. As will be shown in the last section, with our method we also estimate the reflection coefficient of the reflecting boundary, which supplies extra information about the media.

2. Method

For the explanation of the method we propose, we use the sketch in Fig. 1. It represents a plan view of a recording geometry with a seismic receiver (triangle) and two transient sources of plane waves (gray and black starts) placed at the earth's surface. The model consists of three vertical layers separated by two vertical interfaces (thick black lines). This makes the model 1D for surface wave. Because the model is vertically homogeneous, propagating surface waves will not experience dispersion.

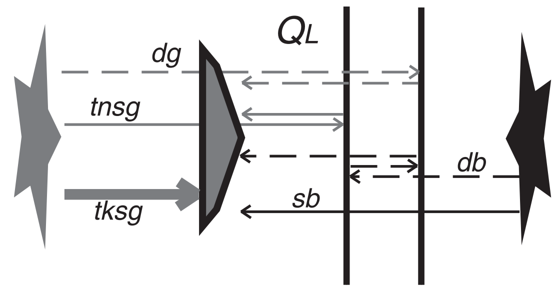

Fig. 1. Plan view of a vertically homogeneous earth model with a receiver (triangle) and two plane-wave sources (gray and black stars) at the surface, where the two thick black lines depict two reflective interfaces. The sources and receiver are elongated to illustrate the different arrivals. The symbol Q_L indicates that there are intrinsic losses in the left layer. The abbreviations label arrivals following different travel paths (arrows): sb — solid black; db — dashed black; tksg — thick solid gray; tnsg — thin solid gray; dg — dashed gray.

By applying seismic interferometry using cross-correlation to the recordings at the receiver from the two sources, we obtain a retrieved recording at the receiver from a virtual source collocated with it. To retrieve the surface-wave part of the Green's function, we would need to effectively surround the receiver, i.e. we need to have recordings from transient sources on each side of the receiver. If surface waves experience dispersion, to retrieve all the modes of the surface waves using cross-correlation correctly, the theory requires that also recordings be made from sources in the shallow subsurface down to a depth, at which the eigenfunctions become negligible. When only sources at the surface are used, only the fundamental mode of the surface wave will be retrieved correctly (Kimman and Trampert, 2010). For retrieval of the fundamental mode of the surface wave by seismic interferometry using cross-correlation from the surrounding transient sources, the arrivals at the receiver from each of the two sources need to be recorded separately. Then, the recordings from each source are correlated (in our case autocorrelated) separately and the two correlation results are summed.

To correctly retrieve the fundamental mode of the surface wave, the two plane-wave sources should have the same strength, same source mechanism (i.e. radiation pattern) and should emit energy with the same frequency content. As we assume plane-wave sources, there is no geometrical spreading, and the damping of the energy depends on transmission and reflection at parameter discontinuities and on the presence of intrinsic losses. Correlation of the direct (thick solid gray) arrival with the reflected (thin solid gray) arrival from the left interface of the middle layer will effectively eliminate the common travel path of the two arrivals (the thick solid gray path) and will retrieve a physical reflected surface wave. Note that the source in the right layer does not contribute to the retrieval of the physical reflection. Correlation of the thin solid gray with the dashed gray (the reflection from the right interface of the middle layer) arrivals will eliminate their common travel path. This will result in a retrieval of a reflected surface wave that kinematically would appear to have propagated only inside the middle layer. As such an arrival cannot be physically measured with collocated source and receiver at the position of the physical receiver, we call the arrival a non-physical (ghost) reflection. Correlation of the solid black with the dashed black arrival will also result in the retrieval of a ghost reflection from inside the middle layer. This ghost reflection, though, will have an opposite polarity compared to the gray ghost reflection. In the summation process of the correlated results from the two sources, the two retrieved ghost reflections will interact destructively. Together