Marchenko redatuming of the hDVS signal

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Introduction

- Heterodyne distributed vibration sensing (hDVS) is a technique for distributed acoustic sensing (DAS) to record seismic data using an optical fibre (Hartog et al., 2013).
- Conventional hDVS processing methods suffer from nonlinear response of the hDVS system to strain measurement, which may result from complex waveform interference and multiple-scattering process inside the fibre.
- Recent research on Marchenko redatuming (Wapenaar et al., 2013) has shown that the Green's response to a virtual source inside the medium can be retrieved from single-sided reflection measurement. Becker et al. (2016) first perform Marchenko focusing physically in a sound wave tube.
- We investigate Marchenko redatuming numerically on a fibre model. The redatumed Green's response can potentially improve hDVS data processing.

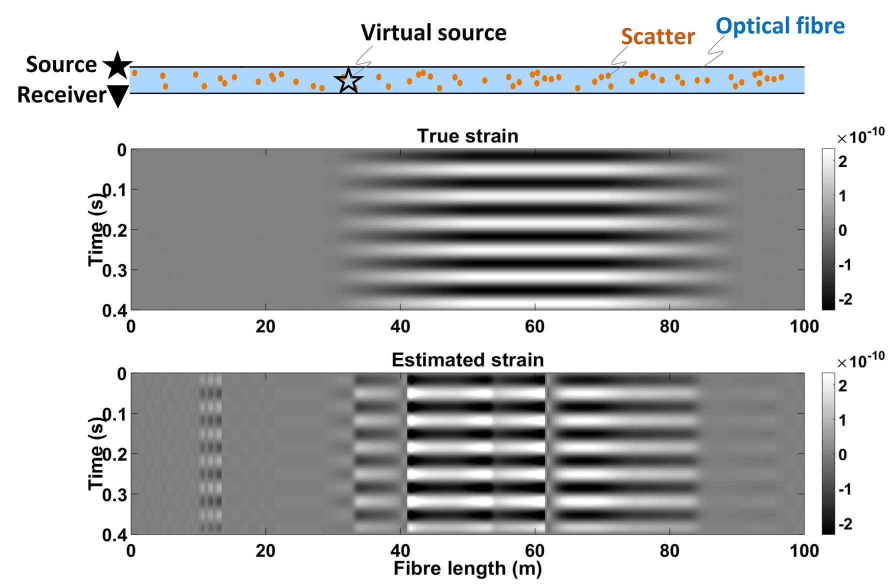

Figure 1. Numerical modelling shows nonlinear artefacts of the hDVS measurement.

Modelling the hDVS system

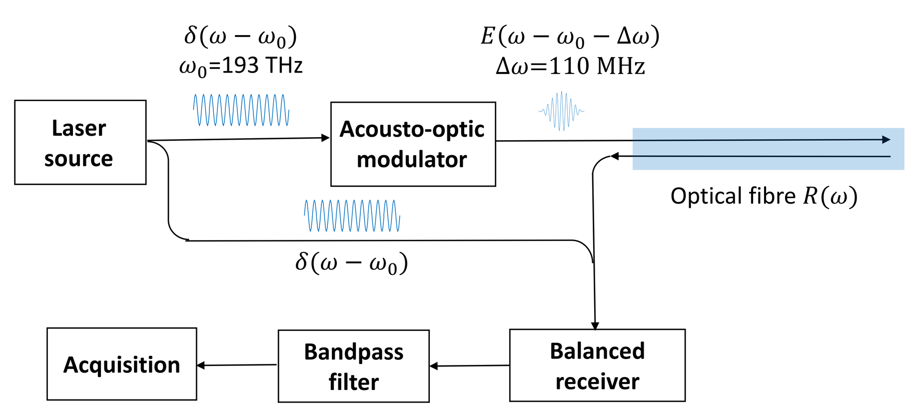

Figure 2. Block diagram of the hDVS acquisition system. The laser source emits monochromatic light at the optical frequency ω_0. An acousto-optic modulator shapes it to a short pulse and increases its frequency by an intermediate amount $\Delta\omega$. The pulse interrogates the fibre and is partially reflected by scatters. The backscattered signal is then mixed with the carrier signal, followed by bandpass filtering to be heterodyned down to the intermediate frequency .

We model the hDVS signal recorded from a static single-mode fibre in the frequency domain as

$$R^h(\omega) = E(\omega-\Delta\omega)R(\omega+\omega_0)$$

For reference, the conventional bandlimited signal without heterodyning process is

$$R^b(\omega) = E(\omega-\Delta\omega)R(\omega)$$

δ: Dirac delta function;

E: Envelope of the short pulse in the frequency domain, its max frequency $\omega_E \ll \omega_0$;

$E(\omega-\Delta\omega)$: An equivalent wavelet spectrum;

R: Fibre impulse response modelled with single- and multiple-scattering effects separately.

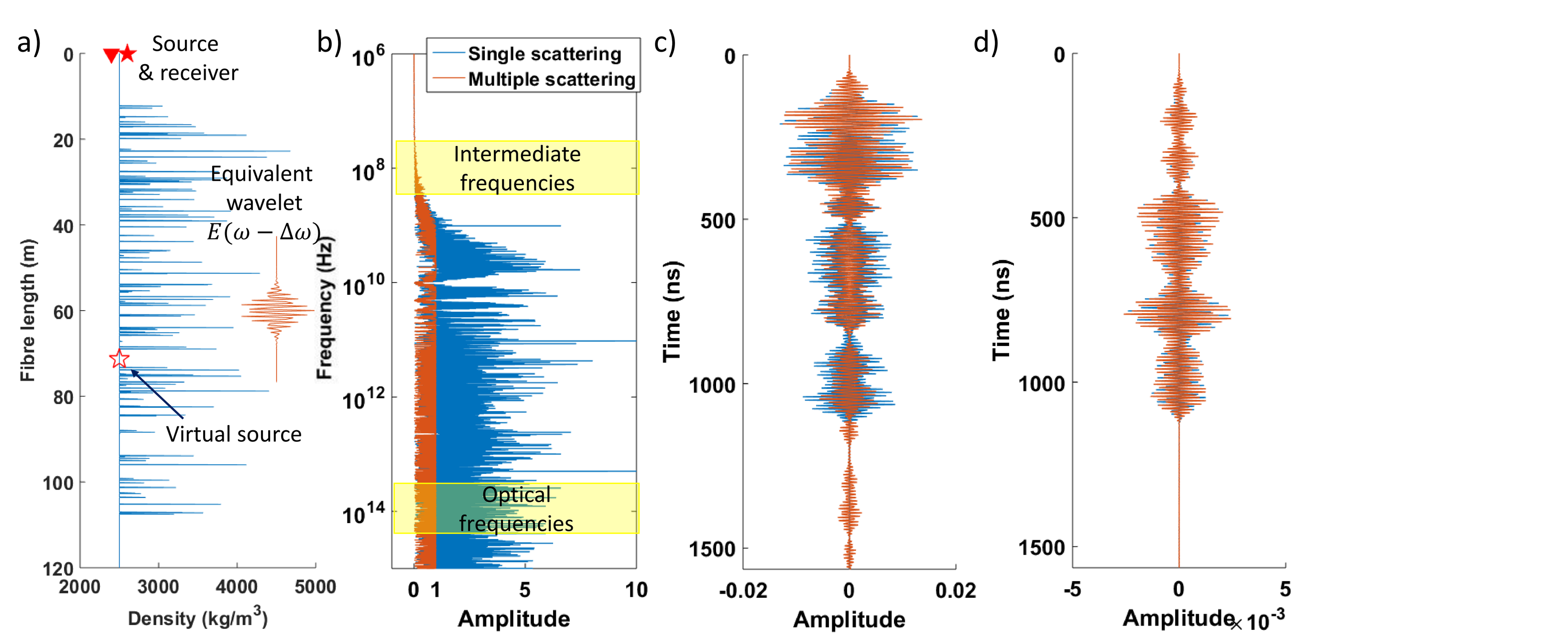

Figure 3. (a) The fibre is modelled as a 1D acoustic medium with random scatters, characterized as density contrasts with the fibre core material. (b) Fibre impulse reflection response $R(\omega)$ is modelled by the propagator matrix method (Margrave, 2015), with single- and multiple-scattering effects separately. (c) The hDVS signal R^h heterodyned from optical frequencies. (d) The bandlimited signal R^b at intermediate frequencies.

Marchenko redatuming of the hDVS signal

In Marchenko redatuming, the broadband focusing functions $f_1^{\pm}$ are defined on a truncated medium, which is the same as the actual medium above a desired virtual source and is reflection-free below it. The focusing functions relate the single-sided impulse reflection response R to the upgoing and downgoing broadband Green's response $G^{\pm}$ to a desired virtual source inside the medium. We rewrite the coupled Marchenko equations for the hDVS and bandlimited signals respectively. On a simplified fibre model, we directly calculate the focusing functions assuming its truncated medium was known. Then the redatumed Green's wavefields are retrieved for both signals.

	hDVS signal	Bandlimited signal (for reference)
Convolution type	$G^{-h}(\omega) = R(\omega+\omega_0)f_1^{+h}(\omega) - f_1^{-h}(\omega)$	$G^{-b}(\omega) = R(\omega)f_1^{+b}(\omega) - f_1^{-b}(\omega)$
Correlation type	$G^{+h}(\omega) = -R(\omega+\omega_0)f_1^{-h*}(\omega) + f_1^{+h*}(\omega)$	$G^{+b}(\omega) = -R(\omega)f_1^{-b*}(\omega) + f_1^{+b*}(\omega)$
Green's function	$G^{\pm h} = E(\omega-\Delta\omega)G^{\pm}(\omega+\omega_0)$	$G^{\pm b} = E(\omega-\Delta\omega)G^{\pm}(\omega)$
Focusing function	$f_1^{\pm h} = E(\omega-\Delta\omega)f_1^{\pm}(\omega+\omega_0)$	$f_1^{\pm b} = E(\omega-\Delta\omega)f_1^{\pm}(\omega)$

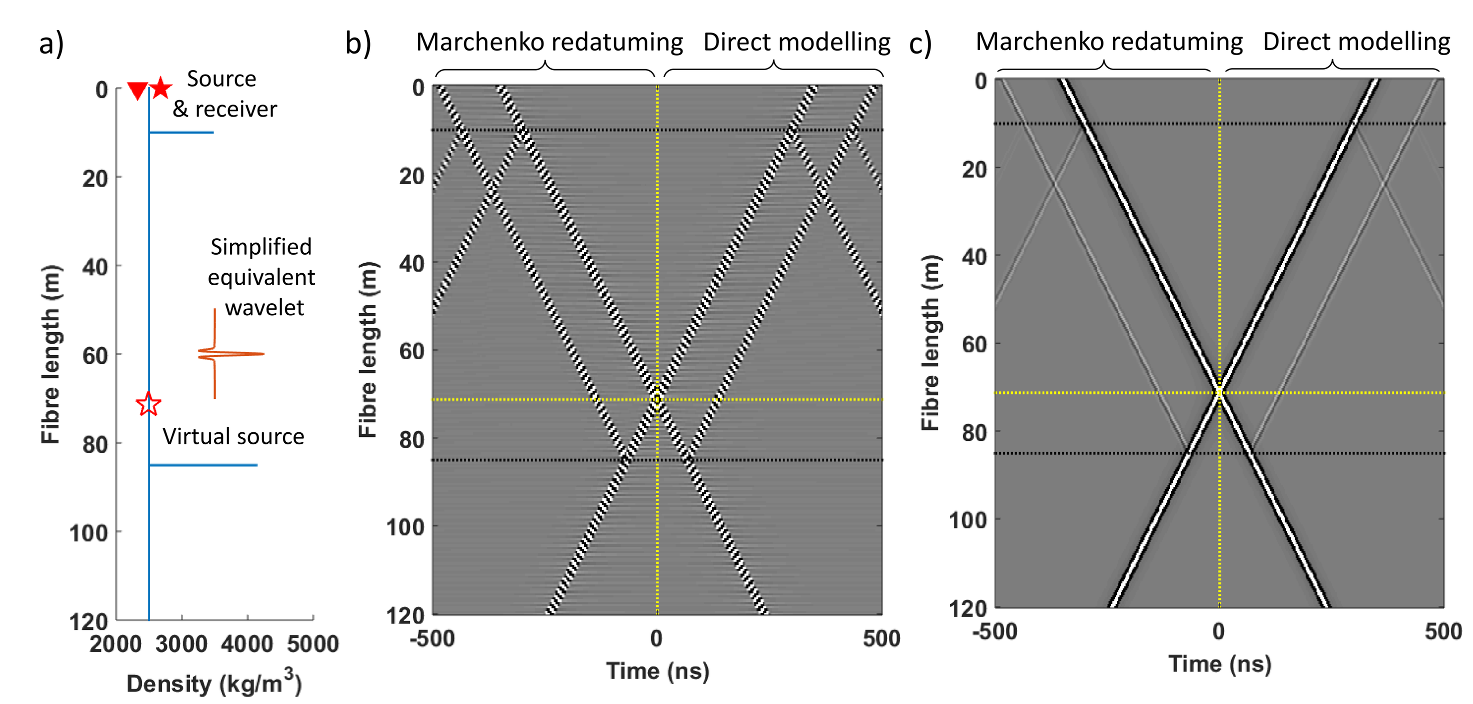

Figure 4. (a) The simplified fibre model with two scatters only and the equivalent wavelet with shorter wavelength. (b) Total Green's wavefield ($G^{+h}+G^{-h}$) for the hDVS signal. (c) Total Green's wavefield ($G^{+b}+G^{-b}$) for the bandlimited signal. In either case, the acausal wavefield is retrieved by Marchenko redatuming whereas the causal wavefield is directly modelled by igniting a real source at the virtual source location.

Iterative Marchenko scheme of the hDVS signal

In real hDVS acquisition, we have no access to the truncated fibre information. However, the underdetermined Marchenko equations can be solved by exploiting the causality of the focusing and Green's functions. The heterodyned focusing and Green's functions calculated from the known truncated fibre medium shows the same causality as the conventional bandlimited signal, so that we can retrieve the heterodyned Green's functions by iterative substitution (van der Neut et al., 2015). This numerical example converges after 8 iterations.

$$\theta\{R(\omega+\omega_0)[f_{1d}^{+h}(\omega)+f_{1m}^{+h}(\omega)]\} = f_1^{-h}(\omega)$$
$$\theta\{R(\omega+\omega_0)f_1^{-h*}(\omega)\} = f_{1m}^{+h*}(\omega)$$

f_{1d}^{+h}: Initial focusing function, i.e., direct arrival of f_1^{+h};

f_{1m}^{+h}: Coda of f_1^{+h};

t_d: Direct arrival time from the virtual source to the real source/receiver, denoted by the vertical dotted lines.

θ: Windowing operator which removes all the events arriving at and after t_d as well as all the acausal events.

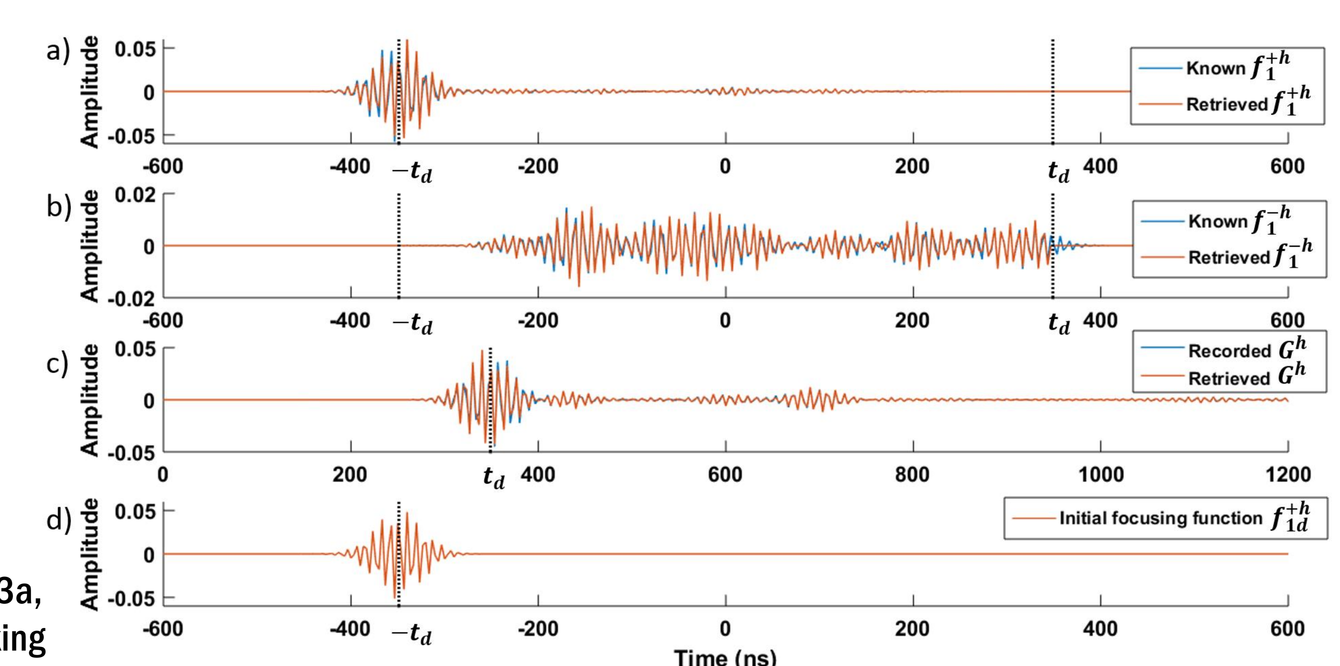

Figure 5. We perform iterative Marchenko on the fibre model of Figure 3a, assuming that the only knowledge of the fibre medium is R and t_d. Taking the equivalent wavelet being advanced to $-t_d$ as the initial focusing function (d), we retrieve the heterodyned focusing (a and b) and Green's functions (c).

Conclusions

- We derive a forward model of the hDVS signal recorded from a static single-mode fibre.
- The theory of Marchenko redatuming is valid in the optical frequency regime, where the laser pulse propagates physically inside the fibre and multiple-scattering effects leave a strong imprint on the data.
- The causality holds for the heterodyned focusing and Green's functions, so that the heterodyned Green's response can be iteratively retrieved from the hDVS signal recorded at one end of the fibre with limited knowledge of the fibre medium.
- We need to improve initial focusing function estimation and the windowing operator to accommodate the fibre medium of complex inhomogeneity.
- The ultimate goal is to utilize this redatumed Green's response to clean up hDVS raw data, handle multiple scattering and finally improve strain estimation.

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