

# Noise reduction in phase-OTDR distributed acoustic sensing for railway monitoring applications

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*For the railway transportation sector phase-sensitive optical time domain reflectometry (phase-OTDR) is currently investigated as a commercial tool for train tracking and railway monitoring. Detection performance of different features relies on the noise suppression techniques and specific filtering applied. In this paper results from field measurements made on train passages over 2.6 km are presented, comparing the performance of two different noise reduction techniques.*

## Introduction

Distributed acoustic sensing (DAS) based on phase-OTDR ( $\Phi$ -OTDR) has found commercial applications for instance in perimeter security and oil well monitoring. Recently, the technique has drawn increased interest to the railway industry [1] due to its distributed properties, its sensitivity to external perturbations and the fact that trackside sensor fibers are already in place in the form of telecom cables. Typical railway applications are train detection and localization, rail and track defect detection, catenary wire short circuit detection, cable theft and trackside trespassing. Since phase-OTDR relies on interference of the weak Rayleigh-scattered light, noise suppression and filtering techniques are important in the process of event detection and localization. Common methods for phase-OTDR noise suppression are based on moving averaging [2], wavelet transforms [3], other transform techniques [4], image edge detection and spectral filtering. Depending on time and frequency characteristics of the targeted event, the most suitable denoising method and filtering can be applied. In this paper, based on field measurements, we compare two different noise suppression techniques, namely moving averaging and wavelet transform denoising, in the context of train detection performed on a 2.6 km long railway section.

## Measurement principles

The prototype phase-OTDR setup, corresponding to a typical direct detection scheme, is shown in Fig. 1(a). The core component is the high-coherence laser source (0.1 kHz linewidth, 40 mW continuous output power). Pulses of width 100 ns and a repetition frequency of 20.3 kHz are created using an acousto-optic modulator (AOM), driven by a 160 MHz RF signal. The pulses are amplified by a fiber amplifier (EDFA), followed by a 0.9 nm bandpass filter, resulting in a pulse peak power of 95 mW at the phase-OTDR output. Detection of the backscatter signal is made using a photo-receiver (5 MHz bandwidth) and the detected signal is sampled by a 100 MHz digitizer. As the emitted pulse is propagating along the fiber under test, in our case in the trackside cable in Fig. 1(b), the electric field backscattered from scattering centers within the resolution cell (equal to half the pulse width, 10 m), interferes at the photo-detector. The result is a registered backscattered power  $S(z)$  versus position  $z$  that is depending on the instant distribution of scattering centers within the resolution cell. Upon a local perturbation, resulting in a change in relative positions of the scattering centers in the perturbed zone,

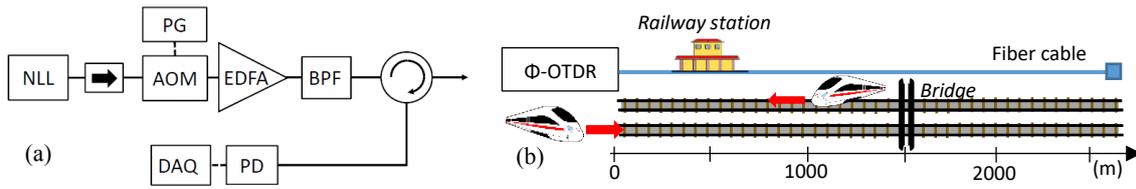


Fig. 1. (a) Phase-OTDR setup using direct detection: NLL = narrow linewidth laser, AOM = acousto-optic modulator, PG = pulse generator, EDFA = fiber amplifier, BPF = band pass filter, PD = photo-receiver, DAQ = data acquisition card,  $\rightarrow$  = isolator; (b) Measurement site layout with 2.6 km trackside fiber cable.

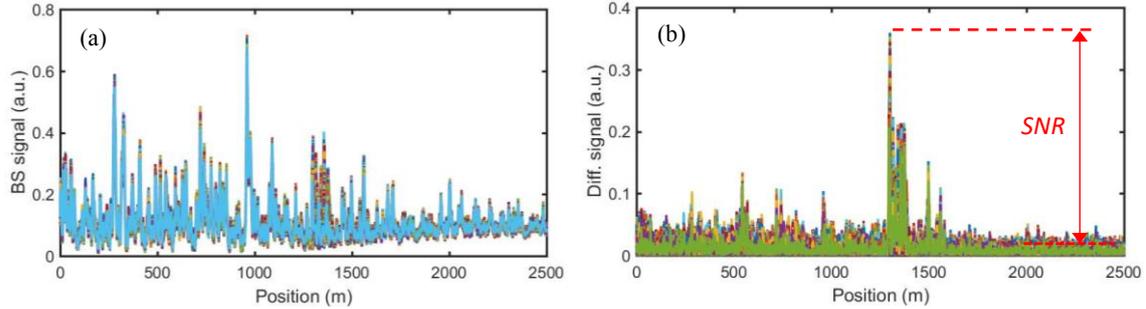


Fig. 2. (a) 1280 superimposed backscatter traces  $S_i(z)$  and (b) corresponding 1279 difference traces  $\Delta S_i(z)$  from a phase-OTDR measurement made with a train present around the position 1340 m, also showing the SNR definition.

the registered backscattered power from that zone will change as indicated in Fig. 2(a), obtained during the passage of a train at position 1340 m. Subtracting each trace  $S_i(z)$  with a reference trace  $S_r(z)$ , taking the absolute value and forming a set of difference traces  $\Delta S_i(z)$  will result in a dominant peak around the point of perturbation as shown in Fig. 2(b). The width of the peak will correspond to the size of the perturbation, in this case a train with a length of about 100 m. Depending on the amount of noise present in the data, the peak will be more or less dominant. Also, due to the random nature of the scattering process, the detected intensity is not necessarily proportional to the magnitude of the perturbation. For the spectral characterization of a perturbation event, FFT analysis can be performed along the time axis on the recorded set of traces  $S_i(z)$  at the position of the event. Such an analysis can also help categorizing events and discern real events from perturbations considered as noise.

## Measurement case and method

For the study of the noise suppression we use a set of 1280 backscatter traces and the corresponding 1279 difference traces formed as shown in Fig. 2. The total measurement time is 63 ms (equal to 1279 times the pulse separation), during which the train moves less than 2 m. The train perturbation zone is identified as 1290-1390 m, and we define an unperturbed zone to be 2100-2400 m. As a measure of the noise suppression, a signal-to-noise (SNR) value is calculated from the collection of difference traces  $\Delta S_i$ :

$$SNR = 10 \cdot \log \left( \frac{\max(\Delta S_i[pert])}{\max(\Delta S_{i,rms}[noise])} \right) \quad (1)$$

where, among all traces,  $\max(\Delta S_i[pert])$  is the maximum difference signal in the perturbation zone and  $\max(\Delta S_{i,rms}[noise])$  is the maximum root-mean-square (RMS) value in the unperturbed region. This gives a reference value of 17.0 dB for the raw trace data. The SNR was also calculated for the peaks at 540 m (railway station) and 1500 m (road bridge) to 12.7 dB and 13.3 dB, respectively. Further, spectral analysis using FFT was

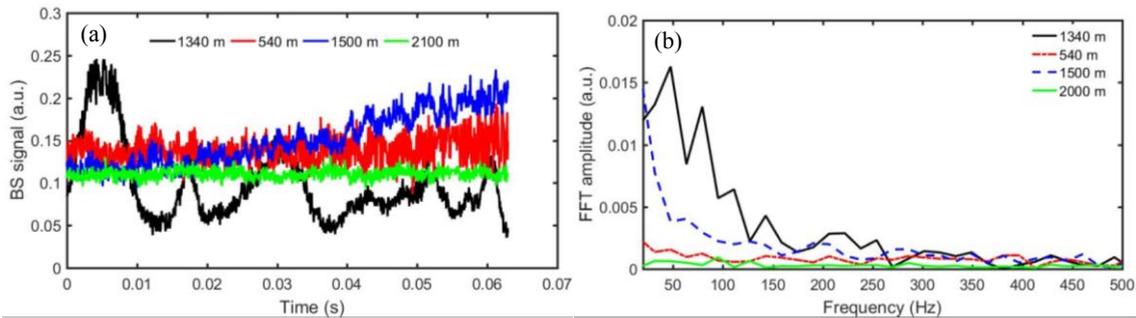


Fig. 3. (a) Time evolution of the backscatter signal at four positions and (b) corresponding FFT results.

performed at four positions: at 1340 m (train position), 540 m (railway station), 1500 m (road bridge) and 2100 m (unperturbed region). The time evolution of the backscatter signal at these target positions and the corresponding FFT results are shown in Fig. 3.

For the noise reduction, parameters were chosen to give maximum SNR at the train position according to (1). *Moving averaging* was applied on the  $N$  original traces by averaging within a sliding time window consisting of  $M$  traces, resulting in a set of  $N-M+1$  moving average traces [2]. From this set,  $N-M$  difference traces was formed by subtracting a reference trace, here set as every  $M$ :th trace in the set of averaged traces. Compared with straight-forward averaging, the moving averaging is less harmful to the frequency content of the signal, but the impact should nevertheless be considered. For the case studied  $M=51$ , resulting in 1230 moving average traces, was a good compromise between denoising and frequency content preservation. *Wavelet transform* denoising, based on the decomposition of the signal into wavelet components, thresholding and finally reconstruction of the signal [3], was performed using Matlab library routines for 2-dimensional fast wavelet transform (FWT). Key variables (values used) are wavelet family (Coiflets, ‘coif2’), decomposition level ( $l = 7$ ), thresholding method (‘rigrsure’) and thresholding type (‘soft’). Of these key variables, the thresholding method turns out to have the highest impact on the SNR result once the decomposition level exceeds  $l = 6$ .

## Results and discussion

Results from the moving averaging denoising are shown in Fig. 4. For the difference traces in Fig. 4(a), the train perturbation stands out better before other fluctuations present in the raw data of Fig. 2(b). The resulting SNR for the train as given by (1) is 21.8 dB, i.e. an increase by 4.8 dB compared with raw data, while the SNR for the station (bridge) has decreased by  $> 2$  dB to 10.4 (10.8) dB. For the spectral analysis shown in Fig 4(b), the suppression of higher frequencies is visible in comparison with the original spectrum in Fig. 3(b). Higher  $M$ -values will result in further suppression in the range 100-300 Hz.

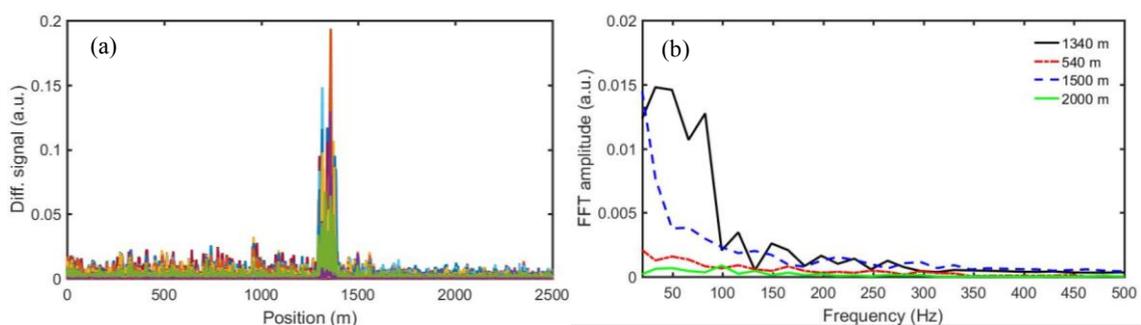


Fig. 4. (a) Difference traces after moving averaging and (b) FFT results for the target positions.

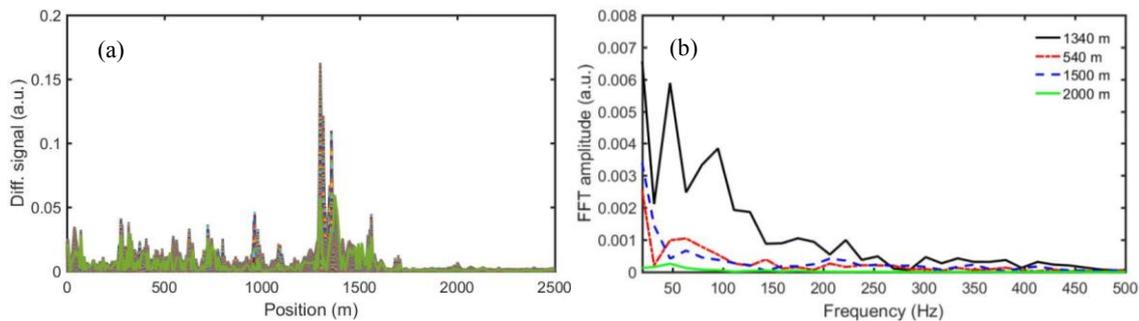


Fig. 5. (a) Difference traces after wavelet transform denoising and (b) FFT results for the target positions.

The wavelet transform denoising results in Fig. 5(a) show an even higher SNR value of 25.8 dB for the train position, and also better preserved spectral content comparing Fig. 5(b) with Fig. 2(b). However, as the wavelet transform is more shape preserving, the SNR at the station (bridge) positions increase by  $>5$  dB to 18.0 (18.7) dB, giving an overall worse impact from a train detection perspective. The better performance of the moving averaging for our train detection application is further visualized by applying the results on the full measurement sequence over 108 s and arranging the traces successively in a matrix that is converted into an image of the difference signal as shown in Fig. 6.

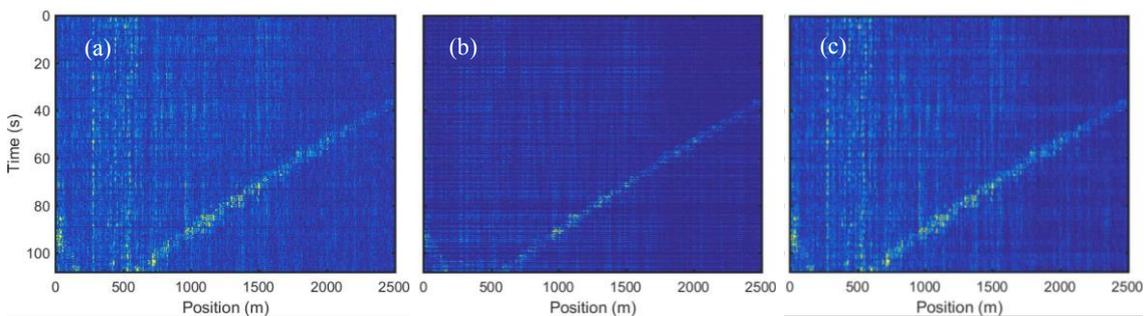


Fig. 6. Intensity images representing difference traces for the full measurement sequence over 108 s, showing one (later two) train(s) approaching the station: (a) raw data, (b) moving averaging results and (c) wavelet transform denoised data. The traces studied correspond to a 62 ms time slot at 78 s.

## Conclusions

Two methods for denoising, the moving averaging and the wavelet transform techniques, have been applied to raw phase-OTDR data for train detection. It is shown that the moving averaging is the most suitable in our case for visualization of train location over time.

## Acknowledgments

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