Distributed acoustic sensing applications for near-surface characterization and traffic monitoring

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Summary

The ability of DAS (Distributed Acoustic Sensing) systems to acquire data for large distances (>10 km) and with a dense sampling (<1 m) makes this technology very attractive for near-surface monitoring and characterization. We show two applications that illustrate the potential of DAS data for these purposes. First, by using interferometric principles, we compute virtual source gathers from the ambient noise recorded by a segment of fibre along a road. This process allowed us to reconstruct the surface-wave propagation that would have been recorded between two different points along the fibre simulating an active source experiment. Then, a dispersion spectrum was computed showing the ability of the DAS data to provide the necessary input for near-surface characterization methods like MASW (multichannel analysis of surface waves). A second application of DAS is explored using data acquired along the Ctrain tracks in the City of Calgary. From the raw data, it is possible to identify the signature of different sources propagating with different apparent velocities. Here, we compute the velocities of these signals by using a series of windowed τ-*p* transformations. Assuming that most of these signals are generated by vehicles driving along the roads next to the Ctrain tracks, this information can be used for monitoring traffic condition in terms of the velocity of the vehicles recorded at any time of the day. We also compute spatial average velocities, vehicle density, and estimated travel times that can be used to interpret changes in traffic conditions throughout the day in a given section of the road. These applications were explored during the Industrial Problem Solving Workshop 2018 organized by the Pacific Institute for the Mathematical Sciences.

Computing dispersion curves from DAS data

Here we used DAS data recorded from an optical fibre buried next to a road. The data was acquired with a channel spacing of 0.67 m and frequency sampling of 20 kHz. The maximum record length we used for this experiment was 30 s. Figure 1 shows the data recorded over a segment of 600 m. Surface-waves are excited by a person standing next to the fibre and dropping a rock. These are the events observed at 11 s, 17 s, and 23 s in the record in Figure 1. There we can see that the source is located close the channel located at 400 m from the origin of the segment.

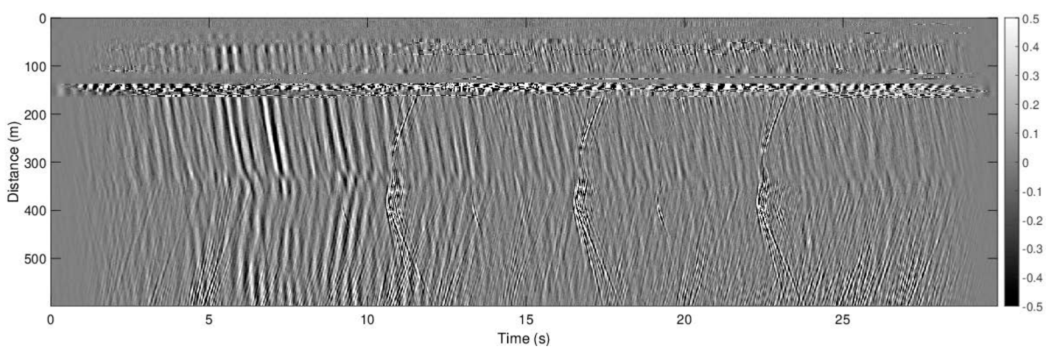

Figure 1. Raw DAS data used for virtual source gather computation.

We followed the workflow detailed in Bensen et al. (2007) to compute a dispersion spectrum using interferometric principles. First, the data in Figure 1 is split in windows of 4 s. Then, amplitudes are gained using an automatic gain process with a window length of 1 s. Next, the spectrum of the data is whitened by using a frequency domain deconvolution. In this process, the amplitude spectrum of each trace is smoothed, and its inverse is used as the deconvolution operator.

A virtual source gather was then created by taking the first trace in each window and crosscorrelating it with the rest of the traces in the data panel. The effect of the crosscorrelation operation is that of subtracting the traveltimes between the reference trace and each trace in the panel. This provides the traveltimes that would have been recorded if an active source had been fired at the location of the channel used as the reference source. This output is accumulated and stacked with the output of the previous data windows. This integration process allows the attenuation of random noise and the reinforcement of the coherent part of the signal present in each window.

Figures 2a and 2b show the final virtual source gather and its corresponding dispersion spectrum, respectively. In Figure 2b, it is possible to interpret two surface-wave modes. The fundamental mode is represented by the area of maximum energy with the lowest frequency content (4 Hz to 12 Hz). Then, the first higher mode can be identified between 12 Hz and 25 Hz with phase velocities between 280 m/s and 320 m/s.

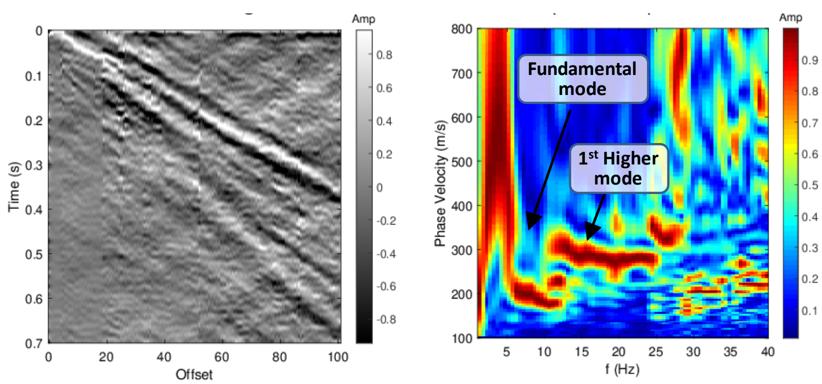

Figure 2. (a) Computed virtual source gather and (b) its dispersion spectrum.

These areas of high energy in the dispersion spectrum can be picked to create dispersion curves. These curves can be used as an input for computing near-surface S-wave velocity profiles using techniques like the multichannel analysis of surface-waves (Park et al., 1999). The inversion process needed to accomplish this goal was beyond the scope of this experiment and it will be explored in future studies.

Monitoring traffic conditions from DAS data

In this part of the study, we used DAS data acquired with an optical fibre currently used for communications. The optical fibre is buried next to the tracks of the light rail transportation network of the City of Calgary, also known as the Ctrain. Due to the large volume of data available, we re-sampled the data at 4 ms in time and 2.0256 m in space. Figure 3a displays the data recorded for about 10 minutes along 5 km of the fibre. The large amplitude signals in Figure 3a correspond to the displacement of the Ctrain cars along the tracks. We filtered these data using a FK filter to remove the high amplitude, very large velocity (> 300 m/s) noise introduced by the propagation of the Ctrain and to reveal the signals in the background.

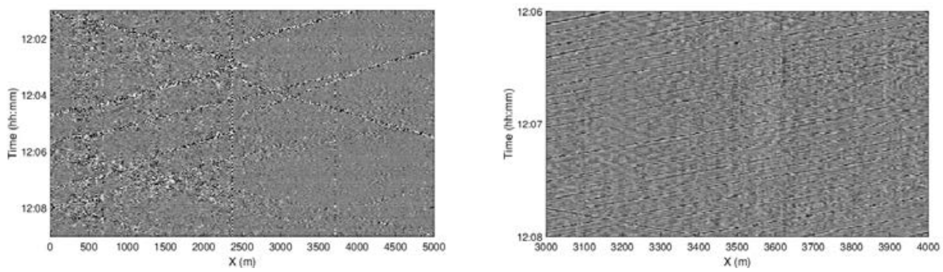

Figure 3. (a) Raw data recorded along a segment of the Ctrain tracks. (b) Zoom after filtering and amplitude balancing.

Figure 3b presents the data contained in a window of 2 minutes between the X-locations at 3000 m and 4000 m, after filtering and amplitude balancing. There, we can observe a series of linear events, most of them propagating from right to left, i.e. from north to south given the orientation of the fibre. Other events with opposite slope, but with less energy, can also be observed in the data. We interpret these coherent linear events as the signature of vehicles propagating in the highway parallel to the Ctrain tracks. Therefore, the slope of these events represents the apparent velocity of the vehicles as they displace on the road.

We estimated the velocity of these linear events by windowing the data in subsets of 100 m and 8 s (Figure 4a) and performing a τ-p transformation (Stoffa, 1989) over these data (Figure 4b). We then extracted the slowness p corresponding to the maximum energy of the τ slice intersecting the center of the window ($\tau = 0$ s). The slowness p was then transformed to velocity by taking its inverse, this corresponds to the velocity of the linear event captured in the window. We also extracted the maximum amplitude of the slice and use it as an indicator of the strength of any captured linear event.

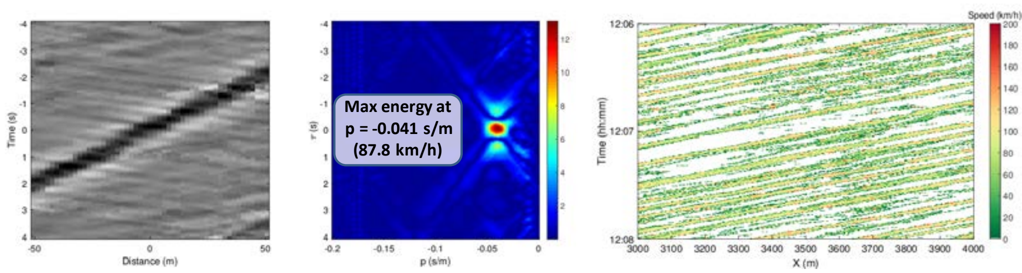

Figure 4. (a) Data window and its (b) τ-p representation. (c) Apparent speeds measured on the data on Figure 3b.

We then extended the velocity extraction process by moving the analysis windows over the entire dataset. Figure 4c shows a zoom in the same window presented in Figure 3b. From this attribute map, we computed three additional metrics over the full dataset. First, in Figure 5a we present the number of vehicles per minute detected at each location along the fibre. We computed this metric by counting the number of signals with velocities larger than zero in 1-minute windows. Second, we computed the average velocity (Figure 5b) using the same data windows. Finally, we computed the estimated total time it would take a vehicle to travel along the 5 km of the fibre (Figure 5c). This was done by simply integrating the average slowness map along the spatial axis. These plots allow us to understand the traffic flow at any given time of the day and at any segment of the road. No significant trends were identified in the 10 minutes of data that were analyzed. The application of the processing here explained to a large dataset spanning several hours or even days remains to be explored.

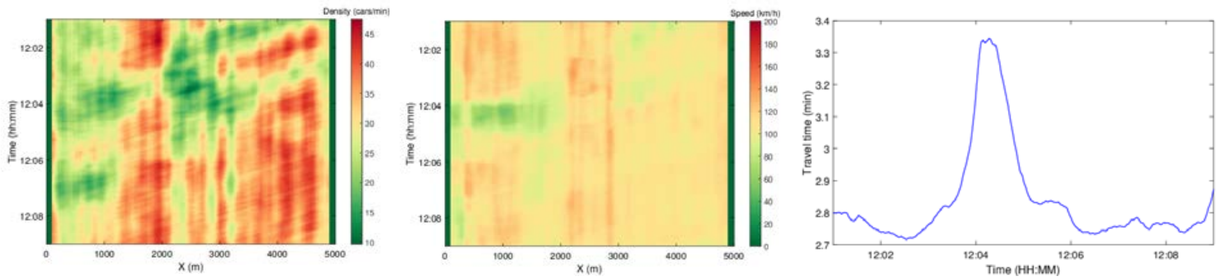

Figure 5. (a) Traffic density measured as number of cars per minute. (b) Average speed. (c) Estimated travel time along the 5 km segment of the fibre.

Conclusions

We showed how DAS data can be used to compute surface-wave dispersion spectra with a very inexpensive source effort. Dispersion curves can be extracted from these spectra and input into a S-wave velocity inversion algorithm. The very dense character of the DAS measurements reduces the spatial aliasing characteristic of most surface-wave data acquisitions. Furthermore, the permanent and continuous nature of the DAS data allow to repeat this experiment multiple times over long periods of time. By continuously computing S-wave velocity models, it is possible to detect changes in the sediments in the near-surface over time. Most of the processing used in this study requires very limited human intervention. This sets the stage for the development of automatic near-surface monitoring and early warning systems based on DAS measurements.

We also explored an application of the DAS data for intelligent transportation systems. In this realm, DAS measurements can also provide a cost-effective option for continuous monitoring of roads over large distances. More importantly, buried optical fibres offer high resistance to temperature, corrosion, and electromagnetic interference rendering their maintenance a very low-cost operation. Here, we used DAS data to compute the average velocity, vehicles density, and total travel time along a segment of 5 km of an optical fibre. Computing these parameters over large period of times can help to reveal transit flow patterns. These data can be critical for taking road management decisions oriented toward an efficient use of existing roads and the planning of future ones.

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