Seismic noises by infrastructure fiber optics reveal the impact of COVID-19 measures on human activities

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Abstract

Recent world-wide quieting of seismic noise caused by COVID-19 lockdown measures has been observed by seismometers. However, current seismic network that has a few seismometers or none in a city-scale area is hard to reveal the spatiotemporal characteristic of seismic noise impacted by COVID-19 measures. Here, we show that a 5-km-long distributed acoustic sensing (DAS) array deployed in State College, PA is able to illuminate seismic noise variation in a broad bandwidth 0.01 - 100 Hz during March - June 2020. The temporal noise variation exhibits a 'decrease-increase' trend responding to 'decrease-increase' human activities caused by the COVID-19 measures - from stay-at-home to Phase Green. Our results reveal different types of human activities (including footsteps, road traffics, and machines) as noise sources, suggesting that DAS noise recordings using cite widely-installed infrastructure fiber optics could be used for quantifying the impact of COVID-19 measures on human activities in city block dimensions.

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Key Points:

- DAS data from underground fiber-optics in State College PA shows significant seismic noise variation during the COVID-19 pandemic.
- We find a systematic seismic noise variation in the broad frequency band (0.01-100 Hz).
- We present evidence of the spatiotemporal correlation between seismic noise and human activities impacted by progressive COVID-19 measures.

Abstract

Recent world-wide quieting of seismic noise caused by COVID-19 lockdown measures has been observed by seismometers. However, current seismic network that has a few seismometers or none in a city-scale area is hard to reveal the spatiotemporal characteristic of seismic noise impacted by COVID-19 measures. Here, we show that a 5-km-long distributed acoustic sensing (DAS) array deployed in State College, PA is able to illuminate seismic noise variation in a broad bandwidth 0.01 – 100 Hz during March – June 2020. The temporal noise variation exhibits a 'decrease-increase' trend responding to 'decrease-increase' human activities caused by the COVID-19 measures – from stay-at-home to Phase Green. Our results reveal different types of human activities (including footsteps, road traffics, and machines) as noise sources, suggesting that DAS noise recordings using cite widely-installed infrastructure fiber optics could be used for quantifying the impact of COVID-19 measures on human activities in city block dimensions.

Plain Language Summary

COVID-19 lockdown measures make the world quieter since people stay at home and make fewer noises. Current seismic networks can only detect the noise level averagely in urban areas. Distributed Acoustic Sensing (DAS) can convert existing telecommunication optic fibers that have been widely installed in the city in past decades into dense seismic sensors and provide high spatiotemporal resolution monitoring of seismic noise. Here we show the noise level changes caused by progressive COVID-19 measures from a 5-km-long fiber array deployed in the city of State College, PA. We find the same decrease-increase trend in both noise level and human activities. We distinguish noise generated by different types of human activities including footsteps, road traffics, and machines. This study shows that DAS can be used to track human activity with highly spatial resolution.

1 Introduction

COVID-19 pandemic has been impacting all aspects of our society particularly on public health and economy. To reduce the spread of coronavirus, the COVID-19 measures such as working from home, self-isolation, and community contact reduction were implemented and resulted in the severe disruption in human activities. In the initial stage of the pandemic, the lockdown measures were adopted regionally and globally, resulting in less human activities; After adopting the loose measure re-opening schools and the economy gradually increases human activities. Therefore, quantifying human activities may serve a potential way to evaluate the effectiveness of the measures and optimize measures in the future (Gupta et al., 2020; Jarvis et al., 2020).

Seismologically, human activities generate vibration noises with frequency above 1 Hz (referred to anthropogenic noise) (Bonnefoy-Claudet et al., 2006; Xiao et al., 2020). Several recent reports have shown that after COVID-19 lockdown seismometers detected a significant drop of high-frequency anthropogenic noise levels (roughly 1-20 Hz) directly corresponding to less human activities in the urban cities in the wide world (Xiao et al., 2020; Poli et al., 2020; Lecocq et al., 2020; Dias et al., 2020; Yabe et al., 2020). These studies commonly use seismic stations designed for recording low frequency earthquakes to track lockdown induced seismic noise changes. Apparently, a few seismometers (or even none) in many cities pose a technical challenge to characterize high-frequency seismic noise with a desired spatial and temporal resolution, considering highly spatial-varying and temporal-varying noises in urban environments.

Distributed acoustic sensing (DAS), a recent technology converting optic fibers to dense seismic sensor arrays, could provide high fidelity seismic strain/strain rate measurements at the meter spacing (Lindsey et al., 2017; Ajo-Franklin et al., 2019; Zhan et al., 2020). By using existing telecommunications infrastructure, particularly by plugging into "dark" or unused fiber that is already installed underground, these experiments greatly reduce the experimental cost and setup time as an interrogator simply needs to be plugged into one end of a stretch of fiber to being data acquisition. DAS has been demonstrated with tens of kilometers long telecommunication fiber cables for seismic monitoring (Martin et al., 2018; Lindsey et al., 2019; Zhu et al. 2020). Recent studies reported new recordings of vehicles, footsteps, and music, highlighting the sensitivity of DAS equipped dark fibers in the cities (e.g., Wang et al., 2020; Lindsey et al., 2020; Zhu et al., 2020).

Here we demonstrate the use of seismic recordings from an underground telecommunication fiber-optics DAS array in the cite of State College, PA, USA (Figure 1a) to reveal details of seismic noise variation caused by COVID-19 measures during March to June 2020. The timeline of the COVID-19 measures in State College, PA is summarized in Text S1. We show that seismic noises from 0.01 Hz to 100 Hz along the array are systematically impacted by the level of COVID-19 measures. We ascribe the noise reduction to the very-restrict stay-at-home and the noise recovery to less-restrict Phase Yellow/Green in State College. The linear correlation between seismic noises data and Google mobility data suggest that the use of seismic noise recordings by cite widely-installed infrastructure fiber optics provide a new way to quantify the level of human activities with high spatiotemporal resolution in a city.

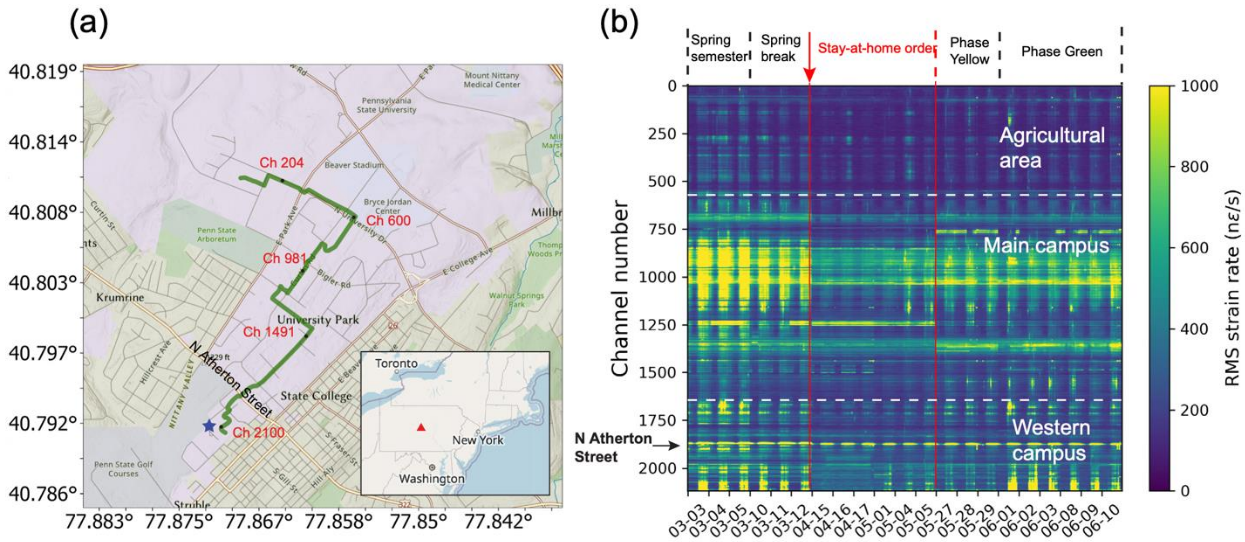

Figure 1. (a): DAS map. Dark fiber (Green line) is located beneath Pennsylvania State University campus in State College, Pennsylvania (inset, red triangle). Selected channels are indicated for referencing sensors' location. Blue start indicates the construction site. (b): Temporal variation of seismic noise across the DAS channels with showing the timeline of local conditions above. Red line marks the abrupt noise change during the implementation of stay-at-home order. Clear diurnal pattern shows that signals are mainly from human activities at daytime.

2 Calculation of the RMS noise level

We examine seismic noise data (March 3 – June 10 2020) recorded by the DAS array connected to underground telecommunication fiber optic cables, shown in Figure 1a. The DAS array makes continuous strain rate measurements at a 500 Hz sampling frequency with a 10 m gauge length and 2 m channel spacing, leading to all 2137 sensors along the array (detailed data description in Text S2).

To quantify seismic noise in different frequency bands, we first calculate the noise power spectral density (PSD) in each 5-minute window using McNamara's method (McNamara, 2004). We compute spectrograms, $\boldsymbol{A(f)}$, by discrete Fourier transform. The PSD estimate, $\boldsymbol{P(f)}$ is the square of the spectrogram with a normalization factor:

$$\boldsymbol{P(f)} = \frac{\boldsymbol{2\Delta t}}{\boldsymbol{N}}|\boldsymbol{A(f)}|^{\boldsymbol{2}}, \tag{1}$$

where $\boldsymbol{\Delta t}$ is the sampling interval (0.004 sec) and N is the number of data samples in each time series segments. The PSD estimate for each hour is obtained by averaging 12 segment PSDs. In this way, for each hour, we have a PSD estimate at each channel.

Then we calculate the RMS (root-mean-square) strain rate $\boldsymbol{e_{rms}}$ to represent the noise power by taking the square-root of the integral of the power spectrum over four interested frequency bands, 0.1-1Hz, 1-10 Hz, 10-50 Hz and 50-100 Hz:

$$\boldsymbol{e_{rms}} = \sqrt{\int_{\boldsymbol{f_{min}}}^{\boldsymbol{f_{max}}} \boldsymbol{P(f)df}}, \tag{2}$$

Then the time-lapse noise change is defined as follows:

$$\boldsymbol{N_{TL}} = \frac{\boldsymbol{e_{rms}} - \boldsymbol{e_{rms}^{baseline}}}{\boldsymbol{e_{rms}^{baseline}}} \times \boldsymbol{100\%}. \tag{3}$$

The baseline noise level $\boldsymbol{e_{rms}^{baseline}}$ as reference is selected in the time period of 8 am to 6 pm and is averaged over a week of spring semester (February 3-7 2020).

3 Spatial distribution of noise variation during COVID-19

We first present a meter-scale spatial variation of seismic noise (RMS strain rate) across the 5-km DAS array, shown in Figure 1b. Spatially, during the entire period the seismic RMS noise data was impacted mostly on the main campus, exhibiting the least variation in agricultural/sports fields, and the intermediate variation on western campus. A significant drop of seismic RMS noise is observed after the implementation of the stay-at-home measure (red line in Figure 1b). After Phase Yellow seismic noise recovers but maintains at a relatively low level.

To understand the spatial variation of seismic noise in 2-meters spacing over the entire array, we calculate the RMS strain rate over 10 hours from 8 am to 6 pm and then calculate the time-lapse noise change on March 5 (spring semester), April 16 (during the stay-at-home measure) and June 4 (business reopening) (all Thursdays), to highlight seismic noise spatiotemporal variation responding to different COVID-19 measures, shown in Figure 2. By analyzing noise in four frequency bands (0.01-1 Hz, 1-10 Hz, 10-50 Hz, and 50-100 Hz), we aim to distinguish which frequency band of noises is affected by the COVID-19 measures most.

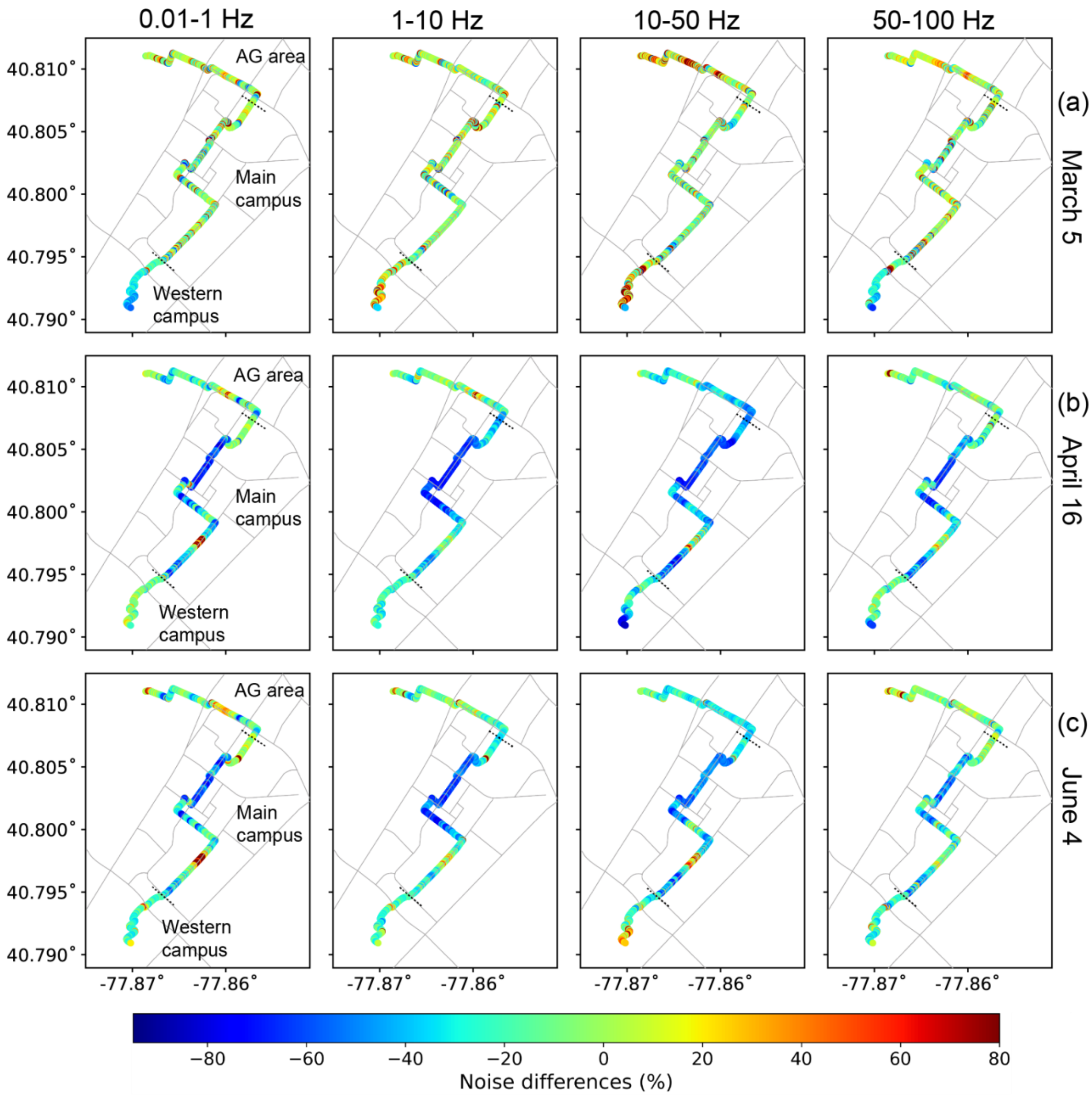

Figure 2. Time-lapse noise variation across the DAS array. Time-lapse noise difference is calculated on a given day (top to bottom: March 5, April 16 and June 4 2020).

First, the biggest noise variation was detected on the main campus (Figure 2b). The peak noise reduction appears in all frequency bands on April 16 under the stay-at-home measure. This reduction is as much as 90% in the frequency band 1 – 10 Hz. With the gradual relaxation of the COVID-19 measure policies, the noise level on the main campus is increased but still stay at the lowest level (about 60% in 1-10 Hz).

In the agricultural/sports fields and western campus with less school activities, the noise variation is relatively small in all frequency bands and the largest noise reduction is in 10 – 50 Hz. This reduction could be caused by the decrease of traffics (e.g., school bus) due to the

COVID-19 measures. On the western campus, it is interesting to note that significant noise variation in the array end is likely caused by construction-associated human activities, i.e., shut-down of construction sites after the stay-at-home order and reopen of construction sites in Phase Green (details will be discussed in Figure 3).

We also find that channels just around the intersections detect large noise variation in the frequency band below 50 Hz while noise level of adjacent channels away from the road remains unchanged, which indicates that our fiber array is able to identify the exact places where traffic noise is dominant.

4 Identification of noise sources associated with human activities

Our dense DAS array at 2 m spacing enables us to identify noise sources – footstep signals, passing vehicles and industrial noise, by comparing seismic noise variation before and after the COVID-19 restriction. We select 1-hour data (local time 10 am – 11 am) from a subarray beneath a pedestrian-only path on the main campus at the same three days as section 3 (Figure 3). Intuitively, these linear events (arrow in Figure 3a) are walking signals appearing in almost every minute on March 5. After stay-at-home order was issued (April 16), very fewer linear signals (Figure 3b) can be seen on this path. In Phase Green (June 4), the footstep signals are almost not recovered despite of less restriction measures. This almost-no-recovery is confirmed by the average spectrum plot in Figure 5d, showing the absence of peaks at 2 Hz and 4 Hz in both April 16 and June 4 curves, which are considered to be the footstep signals (Zhu et al., 2020).

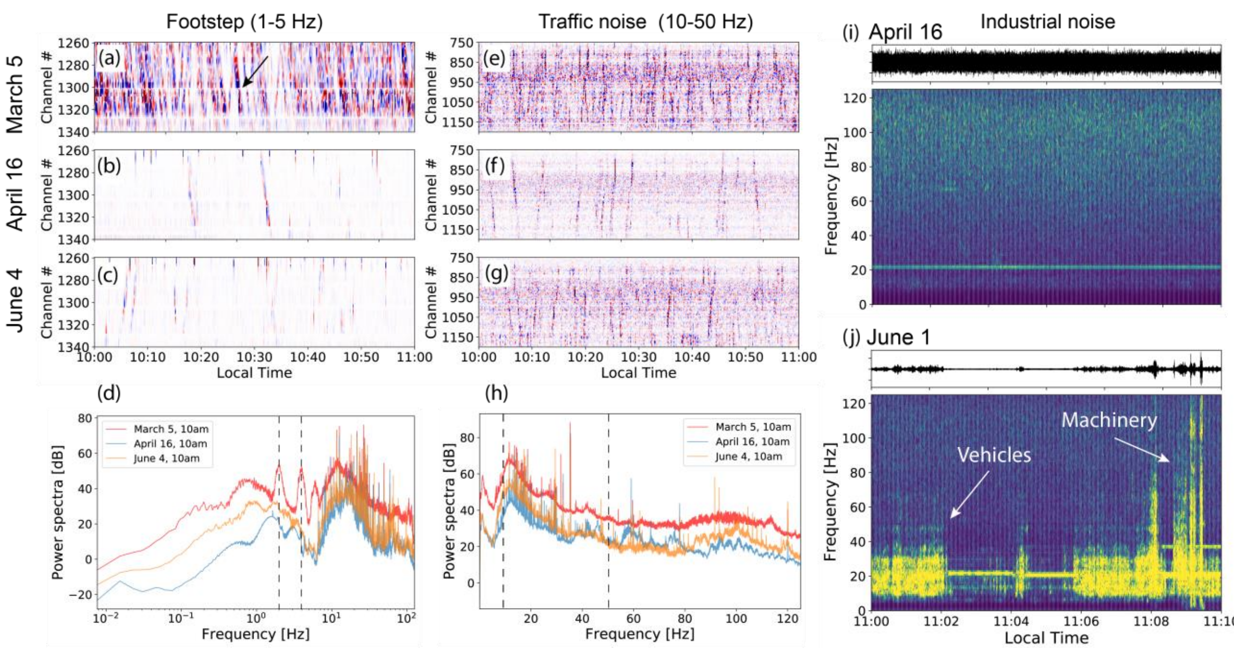

Figure 3. DAS recordings and spectrums of footstep (a-d) and traffic noise (e-h) on March 5, April 16, and June 4. Comparisons of construction-associated seismic noises in the stay-at-home measure (April 16 2020) and in the Phase Green (June 1 2020). We select DAS recordings at channel 2100 next to the construction site (its location is indicted in Figure 1a). Raw strain rate data and their time-frequency spectra maps on (i) April 16 2020 and (j) June 1 2020.

Similar trend ‘decrease-increase’ can be found in traffic noise recordings (Figure 3e-h) from a subarray beneath Curtin Road, the main road on campus. A significant decrease of passing vehicles can be observed by comparing data on March 5 with April 16. This is because the shutdown of the university prevented people from traveling to campus and the bus service was also reduced. On June 4, a few more linear signals indicate more passing vehicles. This is apparently different from almost-no-recovery of people movement. The frequency spectrum (Figure 3h) confirms this trend: a significant drop of the power spectra between 10 - 50 Hz from traffic vehicles about 30 dB, then an increase by 10 dB.

In addition, we find higher frequency noises associated with construction activities. On the western campus, a new parking garage and utility upgrades nearby the fibers were planned to be conducted from December 17, 2019 to April 20, 2021. Due to the suspension of the industrial activity during the stay-at-home measures, the data on April 15 shows no detected events (Figure 3i). After re-opening industrial activities since May 7 (Phase Yellow), we can observe strong industrial noises on June 1 in Figure 3j, which are identified in the spectra plot as the broadband impulses (10 – 100 Hz) between 11:09 – 11:10 am from machines distinguished from the construction vehicles noise in the frequency band of 10-30 Hz.

5 Temporal noise variation during COVID-19

While significant noise variation across the array is detected, we here show the complete temporal noise variation from March 3 to June 10 2020.

Figure 4 shows the time-lapse noise change recorded by channel 981 located beneath Curtin Road on the main campus (channel 204 in Figure S1 and channel 1491 in Figure S2). As a comparison, all the results are plotted against the Google mobility data from workplaces and transport (Text S3). First, we can see that noise experienced a slight drop (up to 10%) in the spring break compared to normal spring semester in the low frequency band (0.01 - 10 Hz). In 10-50 Hz the noise change in both channel 981 (Figure 2c) and channel 1491 (Figure S2c) remains flat before the stay-at-home order while the change in channel 204 (Figure S1) drops down. In the high-frequency range (50-100 Hz) the noise change drops down only in channel 1491 (Figure S2d). We interpret that the reduction of low frequency noise (<10 Hz) is attributed to least school activities during spring break (i.e., many students left school and there were few school activities). The only reduction in the intermediate frequency (10-50 Hz) primarily caused by traffics may be due to lack of school activities (e.g., reduced services of daily school buses) and the stop of the machinery noise (probably from a construction site nearby channel 1491) may cause the drop in Figure S2d.

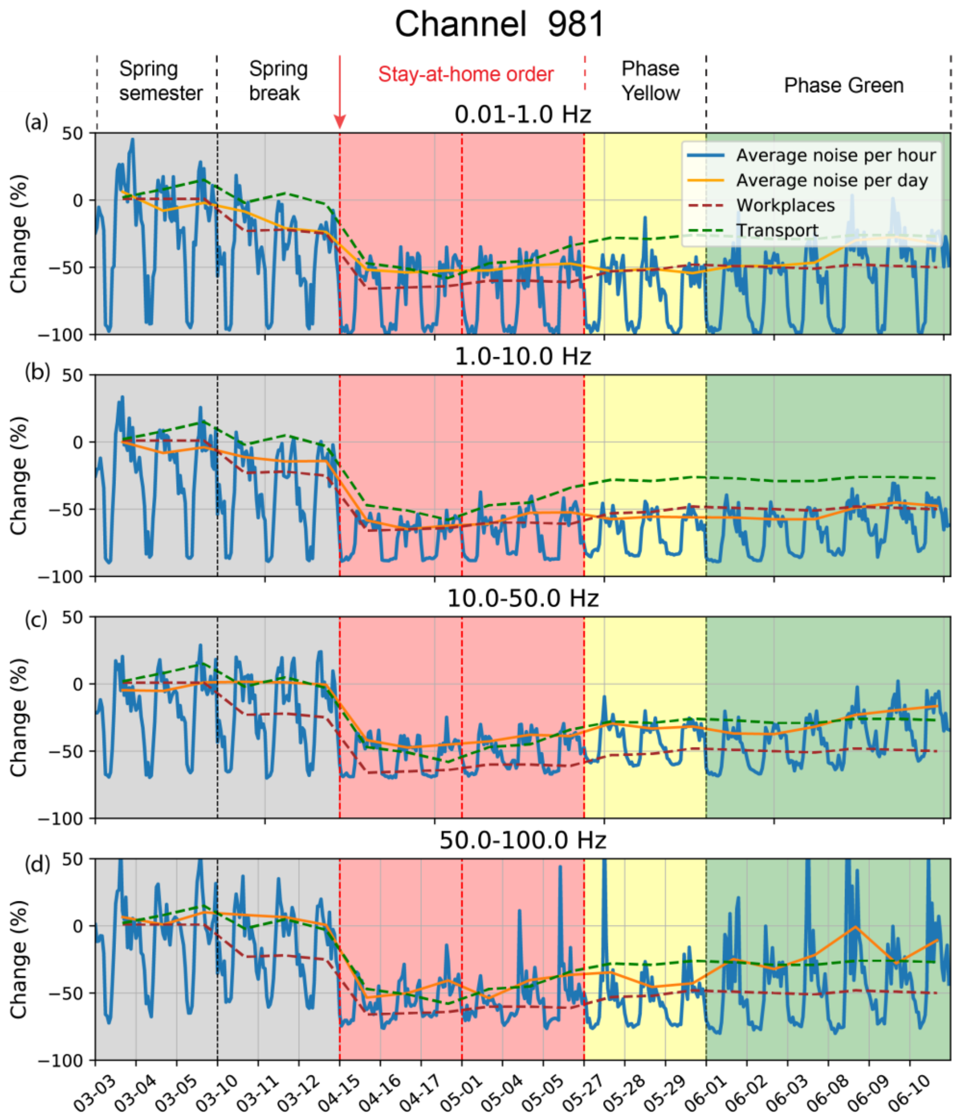

Figure 4. Noise change at channel 981 in the frequency range of (a) 0.01-1 Hz, (b) 1-10 Hz, (c) 10-50 Hz and (d) 50-100 Hz. The daily average noise change (orange) as well as the mobility data provided by Google (dashed line) are plotted.

After the university closure on March 18, we observe a distinct drop (up to 60% daily average) of noise level falling to the lowest level in the whole period of the stay-at-home phase (Figures 2 and S1 and S2). Moreover, this universal noise reduction in all frequency bands (0.01 – 100 Hz) reflects the quieter period and the disappearance of noise sources due to the stay-at-home order. There were almost no human activities.

After Phase Yellow on May 27, the noise level gradually recovered with less restriction measures. The noise level (0.01-10 Hz) still stay flat at the lowest level (50%~60% reduction) until the Phase Green. This feature implies that local residents still followed the stay-at-home order (e.g., working at home). Interestingly, the noise level (10-100 Hz) increase gradually, which is similar to the mobility data (transport), suggesting the recovery of road traffics and industrial activities (e.g., shopping and construction business). After Phase Green, the noise in all frequency band gradually increases by a few percent (1-10 Hz) to 20% (0.01-1 Hz).

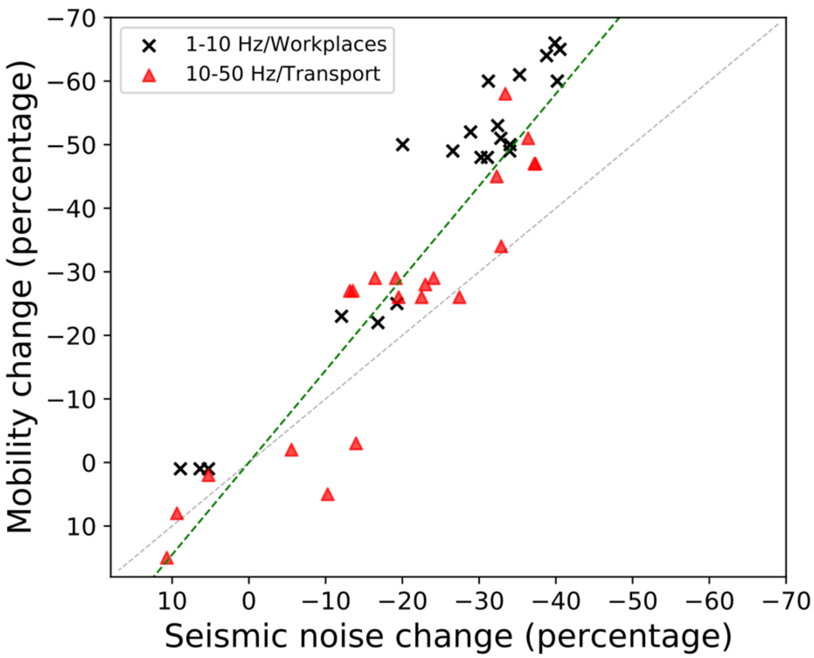

Figure 5. Plot of time-lapse changes in seismic noise (1 - 10 Hz and 10 - 50 Hz) from all channels against with Google mobility data from workplaces and transport, respectively.

To verify our seismic noise reduction, we adopt a similar strategy from previous studies (Lecoq et al., 2020) by using Google mobility data (Google, 2020), although the Google mobility data counts the whole Centre County and detailed information near the fiber is unavailable. Figure 5 shows a crossplot between the noise data (daily average) and Google mobility data, including workplace and transit station (transport) in the Central County, PA (Text S3). The noise reduction in the frequency band of 1-10 Hz over all DAS channels is against the workplace mobility data while the 10-50 Hz noise level reduction is compared with transport mobility data. We can identify a linear correlation between mobility change and changes of seismic noise level with a ratio around 1.5. This linearity implies that the seismic noise variation (1-50 Hz) is linearly proportional to the amount of human activities including people movement and road traffics.

6 Discussion and Conclusions

Our study using dense fiber-optics seismic array offers high spatiotemporal details of seismic noise variation across the city of State College PA (USA) during the COVID-19 pandemic. Our results show a strong relation between seismic noise temporal variation and the timeline of the COVID-19 measures from stay-at-home (March-April 2020) to Phase Yellow/Green (May-June 2020). Spatiotemporally, significant noise reduction as much as 90% in the frequency band 1-50 Hz on the main campus is attributed to least local concentrated human activities (including people movement and road traffic) due to the very-restrict stay-at-home measure in State College PA. Similar noise reduction was also discovered in many other cities reported by previous studies (Xiao et al., 2020; Poli et al., 2020; Lecocq et al., 2020; Dias et al., 2020; Yabe et al., 2020).

In addition, our results reveal many new and detailed features of seismic noises caused by progressive COVID-19 measures. First, the seismic noise variation in broad frequency bands (0.01 – 100 Hz) shows the 'decrease-increase' trend, which is caused by 'decrease-increase' human activities during stay-at-home (March-April 2020) and Phase Yellow/Green (May-June 2020). This trend correlates well with the county mobility data released by Google (Google, 2020). Second, in Phase Yellow, the noise stay-flat (0.01-10 Hz) implies that local residents still followed the stay-at-home order (e.g., less people movement) while the rapidly increased noise level (10-100 Hz) implies the recovery of road traffics and industrial activities (e.g., shopping and construction business). Third, seismic noises at frequencies below 1 Hz where anthropogenic noise is weaker are also impacted by the COVID-19 measures which was not reported in previous studies using seismometers (Xiao et al., 2020; Lecoq et al., 2020; Poli et al., 2020). We note that, Lindsey et al. (2020) also observed a reduction in the very-low-frequency seismic noise (0.01 – 1 Hz) using fiber sensors in Stanford, CA during COVID-19, and proposed that this reduction is likely to be the geodetic response of the roadbed to decreased vehicle loading (Jousset et al., 2018). This discovery may provide an additional constraint to quantify the number of passing vehicles using dense seismic noise data. Furthermore, our results of the time-lapse noise variation reveal the noise reduction zones in the kilometer scale. In the local noise reduction zone (main campus) we can distinguish footsteps, single passing vehicle, and high-frequency industrial noises associated with construction activities.

A linear correlation between mobility change and changes of seismic noise level implies that seismic noise could be used for quantifying human activities in a city. Looking forward, the fiber-optics array using existing telecommunication fiber networks makes it much more cost-effective and practical in urban areas than other types of seismic sensors. This suggest the superior of using city infrastructure fiber-optic cables to the mobility data for monitoring and quantifying the human activity in a city (e.g., estimation of people movement and the number of vehicles) with high spatiotemporal resolution. The high-resolution quantification could further serve as an innovative approach for evaluating the impact of the COVID-19 measures in populated areas.

In summary, our results show key connections between the progressive COVID-19 measures and spatiotemporal seismic noise changes using a dense fiber array in a city scale. One implication of this research is that seismic noise recorded by infrastructure DAS fiber networks could be a factor considered by policy makers to monitor the effectiveness of measures and compliance of the population with these mobility restrictions and optimize the COVID-19 measures in the future pandemic.

Acknowledgments

We thank Chris Marone for his warm support to convince the Penn State Institute of Natural Gas Research to provide seed money to the DAS fiber array. We thank Todd Myers, Ken Miller at Penn State University, Thomas Coleman from Silixa Inc. who help setup the fiber-optic DAS array. The DAS array was supported by Penn State Institute of Environment and Energy seed grant and Institute of Natural Gas Research. Figure 1a is plotted with ArcGIS Pro.

Data Availability Statement

The DAS data used in this paper are available for download (at https://doi.org/10.5281/zenodo.4072484)

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Geophysical Research Letters

Supporting Information for

Seismic noises by infrastructure fiber optics reveal the impact of COVID-19 measures on human activities

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Text S1. Timeline of COVID-19 in State College, PA

After Pennsylvania announced to close schools on March 13th, Pennsylvania State University moved to remote-learning on March 18th right after spring break. Closure of the university caused a large number of people, most students, leaving the town, which lead to a big drop of population. Soon after that, a statewide stay-at-home order was applied on April 1st. The strictest quarantine policy, only life sustaining business was allowed, led to the lowest level of human activities. Then Phase Yellow was issued on May 7, which marked that human activities (including traveling and building construction) started to return to normal gradually. From May 29 until the time of completing this paper, State College PA was put in Phase Green. All the businesses reopened under certain conditions.

Text S2. Description of fiber-optic seismic data

The continuous data we use was collected by the Penn State FORESEE array of underground telecommunication fiber optic cables. The DAS array makes continuous strain rate measurements at a 500 Hz sampling frequency with a 10 m gauge length and 2 m channel spacing, leading to all 2137 sensors. The fiber route pictured in Figure 1 consists of two fiber optic sections spliced together (around channel 1340), a total fiber length of approximately 5 km. These fibers are sitting in a buried concrete conduit at a depth of roughly 1 meter underneath the city of State College, PA. The details of the DAS array installation and calibration can be found in the paper (Zhu et al., 2020).

500 samples per second fiber-optic data enable us to study seismic noise in a wide frequency range. However, high sampling rate yields over 200 GB/day. We downsample the data to 250 Hz considering the efficiency in terms of computation and storage. Owing to the unexpected power disruptions, there are no recordings between March 16 - April 15 and May 06-26. We analyze seismic noise variation of 21 weekdays at 7 distinct time periods (3 days for each group) from March 3 – June 10 2020, covering normal spring semester, spring break, quarantine after the stay-at-home order was issued and the gradual relaxation of the COVID-19 measures.

Text S3. Mobility Data

Mobility data we use are from Community mobility reports in Centre County, PA, released by Google (Google, 2020). The reports chart daily percentage changes of visits by geography, across different categories of places such as retail and recreation, groceries and pharmacies, parks, transit stations, workplaces, and residential. The baseline is the median value during Jan 3-Feb 6, 2020. For a college town like State College, the most common social activities are school activities and transportation. In our study we pick out "transit stations" category (Mobility trends for places like public transport hubs such as subway, bus, and train stations) as Transport and "workplaces" (Mobility trends for places of work) as Workplaces.

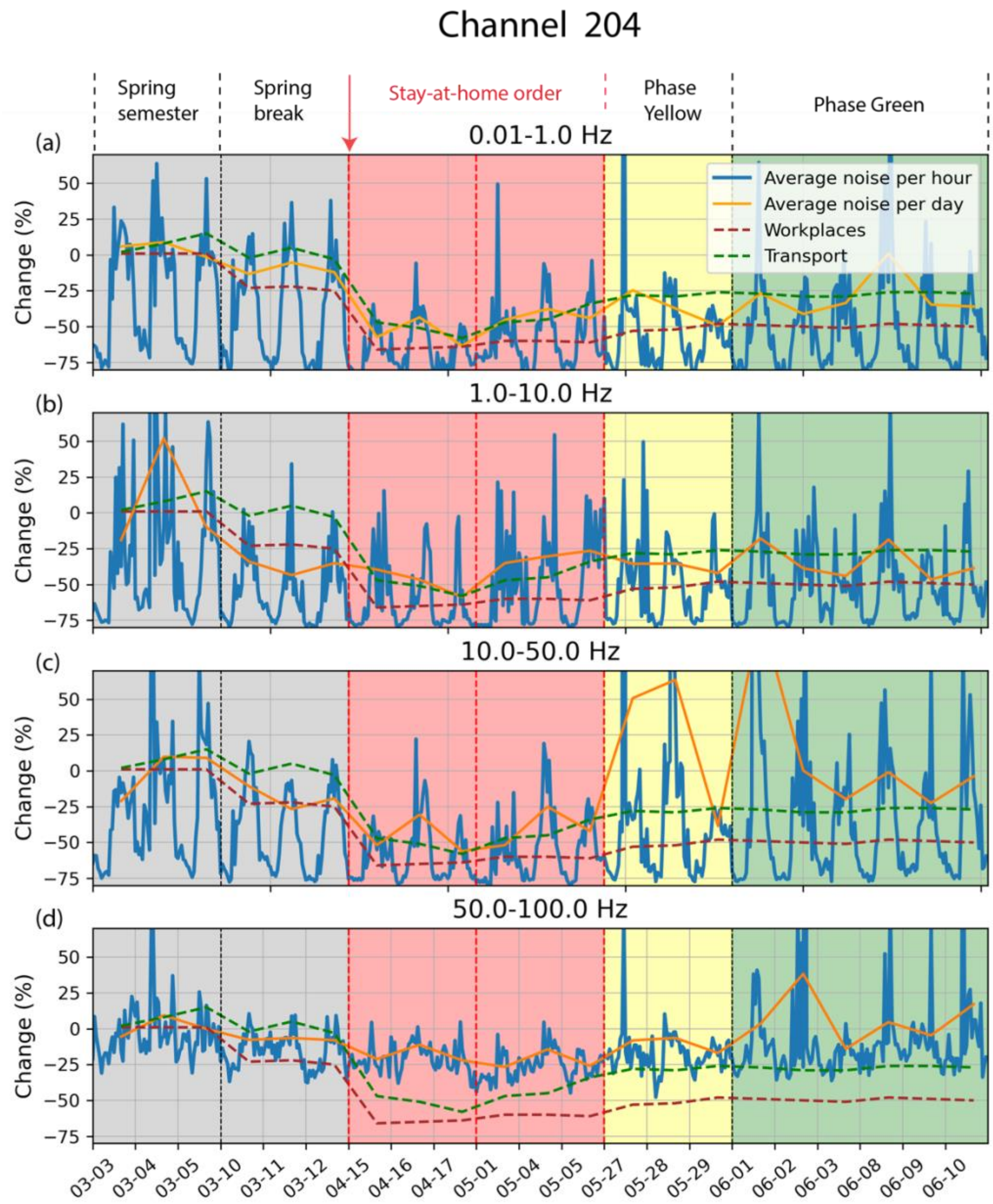

Figure S1. Noise change at Channel 204 in the frequency range of (a) 0.01-1 Hz, (b) 1-10 Hz, (c) 10-50 Hz and (d) 50-100 Hz. The daily average noise change (orange) as well as the mobility data provided by Google (dashed line) are plotted

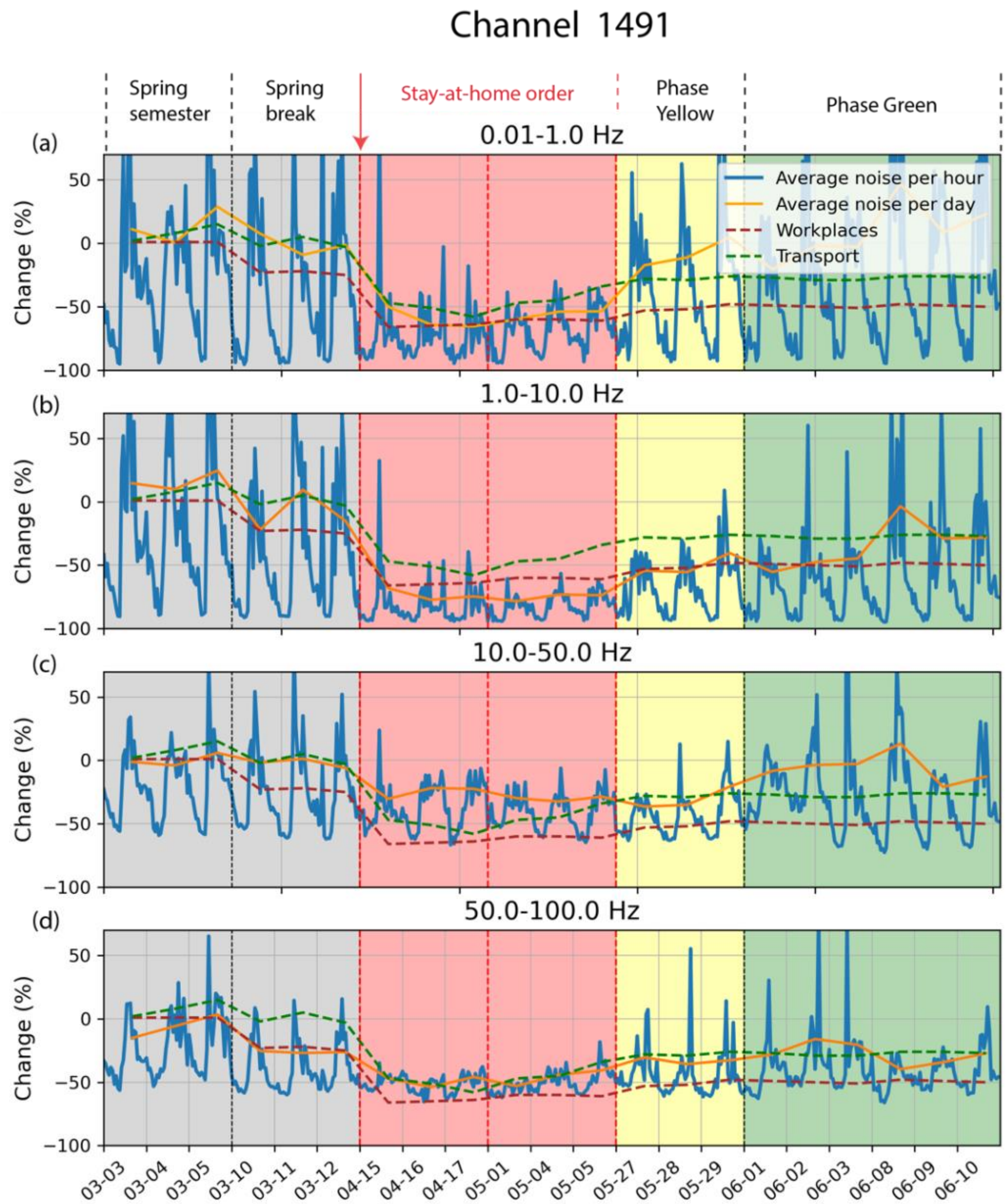

Figure S2. Noise change at Channel 1491 in the frequency range of (a) 0.01-1 Hz, (b) 1-10 Hz, (c) 10-50 Hz and (d) 50-100 Hz. The daily average noise change (orange) as well as the mobility data provided by Google (dashed line) are plotted

References From the Supporting Information

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