Urban Sensing

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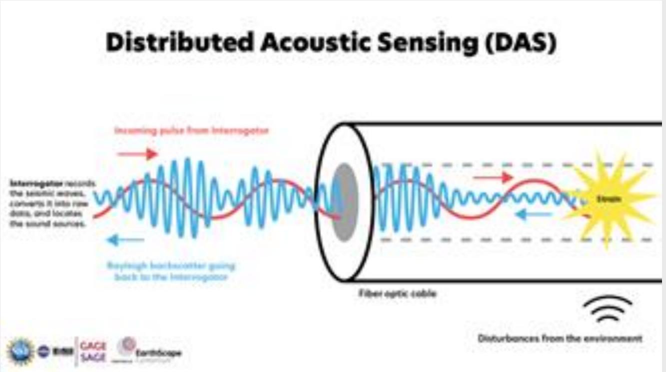
Background

- Cities draw a lot of interest to research ways of improving quality of life and sustainability based on urban “signals”
- Urban seismic signals have been used to monitor environmental conditions, traffic patterns, and cultural and social activities
- Urban activities at frequencies above 1 Hz are subject to scattering and attenuation
- Accurate seismic signals also require ultra dense seismic arrays which are not feasible to install in cities

Distributed Acoustic Sensing

- There exists a long fiber optic cable
- An interrogator sends pulses of light and imperfections/disturbances in the fiber disrupted the light pulse
- Some of the light will go back towards the interrogator (Rayleigh backscattering)
- The phase differences, amplitude, frequency, and arrival time of the backscattered light can be analyzed to determine where the strains occurred
- Combining data from points along the cable or multiple cables can improve analysis



Main Idea & Challenges

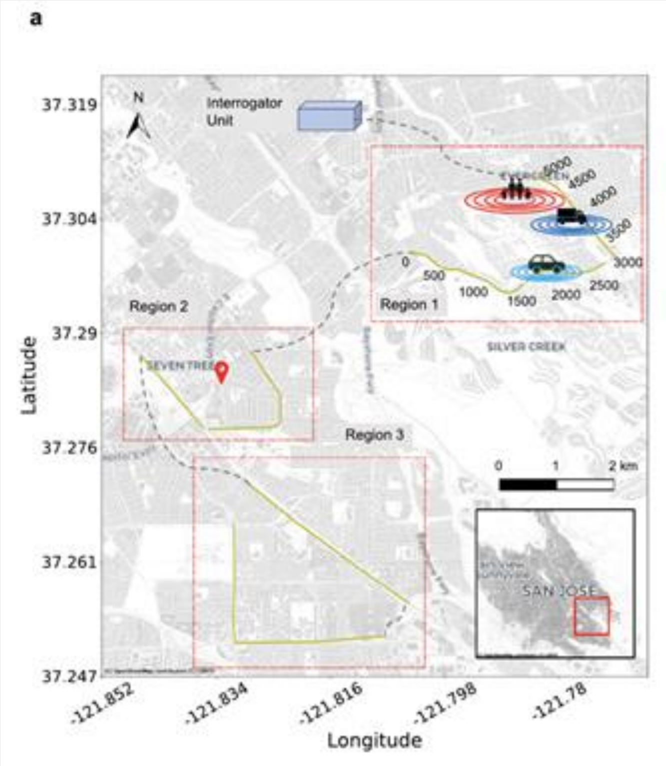
- Use existing fiber optic cables to sense urban activity using distributed acoustic sensing (DAS)
- DAS has been used prior to detect natural seismic activity (earthquakes, ocean waves) but has not been explored much for the purpose of urban science
- Limited by proximity sensing - activities that happen close to the fiber

Main Idea & Challenges

- Urban activity that causes disturbances in the fiber optic cables can be analyzed through DAS
- Seismic interferometry and beamforming can be combined to overcome proximity limitations
- Model propagation of seismic surface waves to estimate spatiotemporal distribution of seismic source power (SSP)
    - Defined as average seismic energy per unit time within an area

Implementation

- DAS data was collected over six days
- Luna - OptaSense QuantX interrogator unit connected to one end of 50-km long dark fiber in San Jose, CA
- 50000 DAS channels
- 10m gauge length
- 200 Hz sampling rate
- Recorded seismic signals from the fiber optic cables in 3 key regions
- Regions were selected where there was a loop of cable (provided geometric constraint)



Pre-Processing

- Bandpass filter (1 to 20 Hz)
- Data is segmented into 10 minute windows
- Large amplitude outliers are replaced with median value from a 50 channel spatial window centered at the problematic channel
- 10x subsampling in spatial domain

Seismic Source Power Estimation

- Seismic source at $\mathbf{x_s}$
- DAS array with N channels
- $p(\omega;\ \mathbf{x_r})$ is the seismic signal recorded by r-th DAS channel at $\mathbf{x_r}$ and frequency ω
- $s(\omega)$ is the seismic amplitude at the source at frequency ω
- $a(\omega;\ \mathbf{x_r},\ \mathbf{x_s})$ is the transfer function that accounts for signal attenuation and phase delays at frequency ω

$$p(\omega; \mathbf{x}_r) = a(\omega; \mathbf{x}_r, \mathbf{x}_s)s(\omega), \tag{1}$$

Assuming a monopole source with a frequency-independent attenuation, the transfer function is defined as:

$$a(\omega; \mathbf{x}_r, \mathbf{x}_s) = \frac{1}{\sqrt{r_{s,r}}}\exp\left(-\frac{\omega r_{s,r}}{2Qv_\omega}\right)\exp\left(-\frac{i\omega r_{s,r}}{v_\omega}\right), \tag{2}$$

where $r_{s,r} = |\mathbf{x}_s - \mathbf{x}_r|$ denotes the Euclidean distance between the source and the DAS channel at $\mathbf{x}_r$, v_ω is the wave propagation velocity at frequency ω, and Q is the attenuation quality factor. Phase distortion due to the attenuation is not considered here. The vector of seismic signals at the DAS array at frequency ω due to a source at $\mathbf{x}_s$ is given by $\mathbf{p}(\omega) = \mathbf{a}(\omega; \mathbf{x}_s)s(\omega)$, where vector $\mathbf{a}(\omega; \mathbf{x}_s)$ includes all individual transfer functions and compensates for the time delays and attenuation of the seismic wave traveling from the source to the N DAS channels.

Seismic Source Power Estimation

- Frequency domain beamforming to identify source location and source power
- Additional assumptions: DAS directionality is ignored, seismic signals from multiple sources are considered to be uncorrelated
- Before beamforming can occur, Q (attenuation quality factor) and v_ω (wave propagation velocity at frequency ω)

$$S(\omega, \mathbf{x}_t) = \mathbf{h}^H(\omega; \mathbf{x}_t)\mathbb{E}\left[\mathbf{p}(\omega)\mathbf{p}^H(\omega)\right]\mathbf{h}(\omega; \mathbf{x}_t), \tag{3}$$

where the superscript H denotes the Hermitian transpose, and $\mathbb{E}[\cdot]$ is the expectation operator. The cross-spectral matrix $\mathbb{E}\left[\mathbf{p}(\omega)\mathbf{p}^H(\omega)\right]$ has dimensions $N \times N$, with each element at the i-th row and j-th column corresponding to the cross-spectrum density function of the signals between the i-th and j-th DAS channels at frequency ω. The cross-spectrum function is the Fourier transform of the cross-covariance function of the time-domain signals between these channels. The steering vector $\mathbf{h}(\omega, \mathbf{x}_t)$ is to calculate the weighted sum of the DAS signals using complex-valued weight factors at the location $\mathbf{x}_t$ and frequency ω. Applying this steering vector maximizes output power when the assumed and actual source positions match: $S(\mathbf{x}_t = \mathbf{x}_s) > S(\mathbf{x}_t \neq \mathbf{x}_s)$. The calculated output power also should approximate the source power, i.e., $S(\omega; \mathbf{x}_t = \mathbf{x}_s) \approx \mathbb{E}[s(\omega)s^H(\omega)]$. Various steering vector formulations exist; we adopt the formulation as suggested in refs. 57,58:

$$\mathbf{h}(\omega; \mathbf{x}_t) = \frac{1}{\sqrt{N}} \frac{\mathbf{a}(\omega, \mathbf{x}_t)}{\sqrt{\mathbf{a}^H(\omega; \mathbf{x}_t)\mathbf{a}(\omega; \mathbf{x}_t)}}. \tag{4}$$

Surface Wave Velocity Estimation

- Vehicles travel along a roadside DAS array and produce two types of signals: quasi-static deformation (<1 Hz) due to vehicle weight and vehicle induced surface waves (1 Hz to 20 Hz)
- Quasi-static deformation + special Kalman filter are used to track vehicle locations
- This is used to select surface wave windows (**isolated vehicles with 25 seconds of separation**)

Surface Wave Velocity Estimation

- Virtual Shot Gathers (VSGs) are created by cross-correlating the pivot trace with other traces in the surface-wave windows (figure out how much lag makes the signals match up)
    - Cross correlation contains information about wavefield assuming one channel is a source and the other is a receiver
- VSGs from many vehicles are stacked to improve SNR
- Vehicles generate forward and backward propagating waves

$$C(\mathbf{x}_s, \mathbf{x}_r, \tau) = \begin{cases} \int_{t_s+c}^{t_s+c+\Delta t} u(t+\tau; \mathbf{x}_r) \cdot u(t; \mathbf{x}_s)\, dt, & \mathbf{x}_r < \mathbf{x}_s \\ \int_{t_r+c}^{t_r+c+\Delta t} u(t-\tau; \mathbf{x}_r) \cdot u(t; \mathbf{x}_s)\, dt, & \mathbf{x}_r \geq \mathbf{x}_s, \end{cases} \tag{5}$$

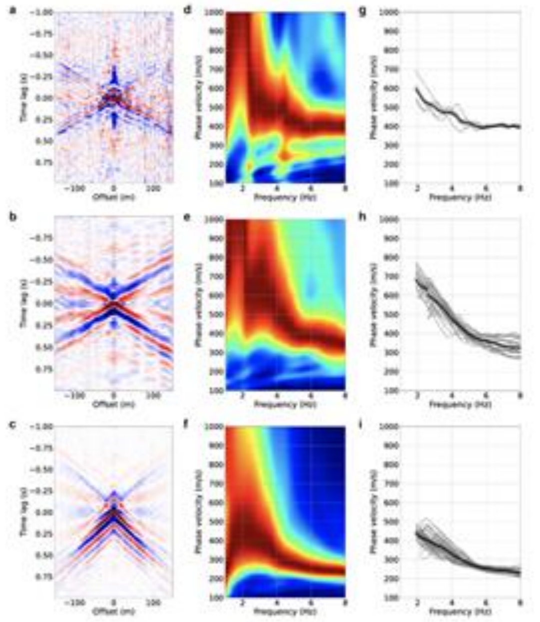
Cross correlation for backward propagating waves

Surface Wave Velocity Estimation

- Assume uniform velocity model (fundamental mode dispersion curve) in each region
- The velocity models in each region are estimated by averaging results across VSG locations in each region

$$C(\mathbf{x}_s, \mathbf{x}_r, \tau) = \begin{cases} \int_{t_s+\epsilon}^{t_s+\epsilon+\Delta t} u(t+\tau; \mathbf{x}_r) \cdot u(t; \mathbf{x}_s)\,dt, & \mathbf{x}_r < \mathbf{x}_s \\ \int_{t_r+\epsilon}^{t_r+\epsilon+\Delta t} u(t-\tau; \mathbf{x}_r) \cdot u(t; \mathbf{x}_s)\,dt, & \mathbf{x}_r \geq \mathbf{x}_s, \end{cases} \tag{5}$$

Cross correlation for backward propagating waves



Supplementary Fig. 2 Constructed virtual short gathers (VSGs) and the estimated shear wave velocity (v_s) across the three regions. a-c, Averaged VSGs for Regions 1, 2, and 3, respectively, illustrating Rayleigh wave energy generated by passing vehicles. **d-f**, Dispersion images computed using the phase-shift method for the three regions. **g-i**, Fundamental mode dispersion curves of Rayleigh surface waves for the three regions. Gray lines represent dispersion curves picked from VSGs at different locations and dates along the fiber in each region, while the black line indicates the averaged wave velocity. VSGs were obtained at 2, 5, and 8 locations by stacking signals from 485, 2,520, and 3,492 vehicles along the fiber in Regions 1, 2, and 3, respectively. The variation in the number of vehicles isolated for VSGs is due to differences in fiber layouts and traffic volumes across the studied regions.

Attenuation Quality Factor Estimation

- Assume constant attenuation quality factor in each region
- Transform truck induced DAS signals to frequency domain using FT
- Attenuation is impacted by subsurface factors, ground coupling of fiber and directional sensitivity of wavefield
- Q hat is an approximation of these factors

$$\ln\left(\frac{A(\omega;\mathbf{x}_i)}{A(\omega;\mathbf{x}_j)}\right) = -\frac{\omega r_{i,j}}{2Qv_\omega} + C, \tag{6}$$

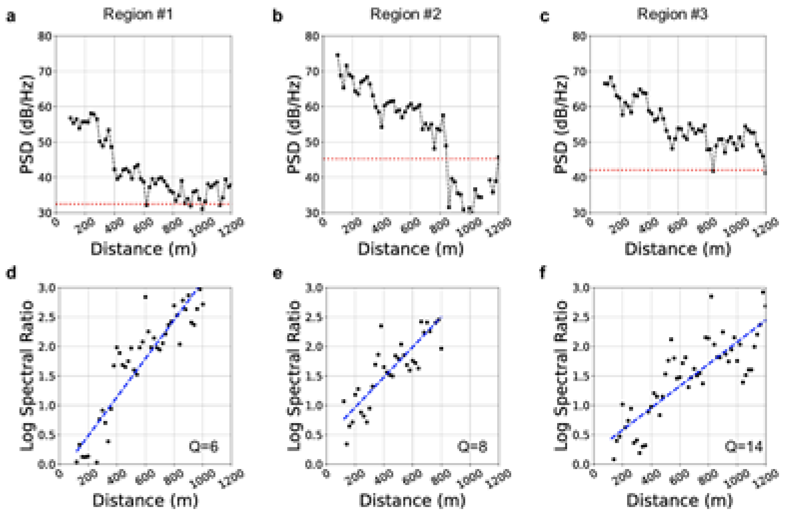
where $A(\omega;\mathbf{x}_i)$ and $A(\omega;\mathbf{x}_j)$ represent the energy of seismic waves at frequency ω at locations $\mathbf{x}_i$ and $\mathbf{x}_j$, respectively. The constant C is an intercept term, and $r_{i,j} = |\mathbf{x}_i - \mathbf{x}_j|$ denotes the Euclidean distance between the two locations.

transform for each DAS signal. Based on Eq. (6), Q is then estimated by solving the following least square problem:

$$\hat{Q},\hat{C} = \arg\min_{C,Q} \sum_{\omega}\sum_{r}\left[\ln\left(\frac{A_0(\omega)}{A_r(\omega)}\right) + \frac{\omega r}{2Qv_\omega} - C\right]^2, \tag{7}$$

where $A_0(\omega)$ is the reference power spectral density (PSD) of DAS signals at frequency ω. This reference energy is computed as the average PSD from DAS channels located at a distance of 50 to 90 meters from the truck source to avoid signal clipping near the source that could underestimate the energy. $A_r(\omega)$ is the average PSD of signals from DAS channels within a distance of $r - d/2$ to $r + d/2$ from the reference signals' center, with d set at 10 meters. This calculation also

Attenuation Quality Factor Estimation



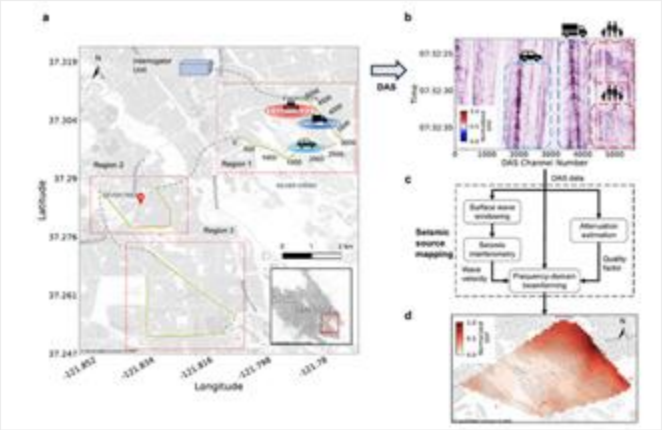
Supplementary Fig. 6 Estimation of the attenuation quality Q factors for seismic signal attenuation across three regions. We use truck-induced seismic signals to estimate Q factors, as they are the most common seismic sources with known locations among all three regions. **a-c**, The average PSD values of the truck-induced seismic signals in the 2.8 to 3.4 Hz frequency range decrease as the distance from the truck source increases for the three regions, respectively. The red dotted lines represent the background noise levels. We calculate the logarithmic spectral ratios of the PSD values and plot the ratios at various distances from the seismic source in the scatter plots **d-f**. The dashed lines in these plots represent the least-squares fit to the data, where the slope of the line is proportional to Q^{-1}. The calculated Q factors for the respective regions, obtained by solving the least square problem in Eq. 7, are 6, 8, and 14 for regions 1, 2, and 3, respectively.

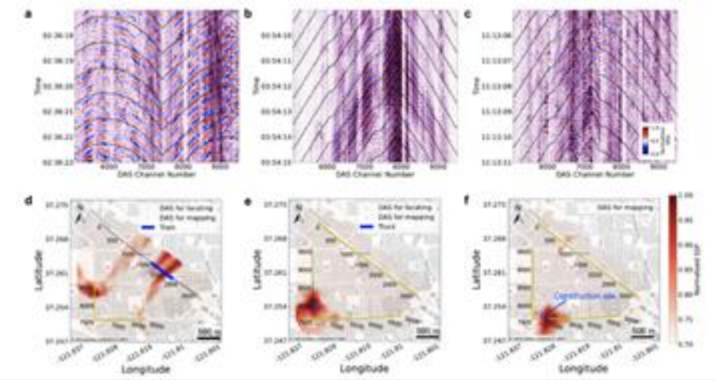
Seismic Source Mapping

- 50 m x 50 m grid cells
- Power spectrum in 1.5 Hz to 8 Hz frequency range estimated with equation (3)
- Source power for each cell is estimated by DAS channels at least 100 m away to avoid near field effects
- Seismic source mapping is either done at a given frequency or across all frequencies by aggregating data

Validation of Seismic Source Mapping

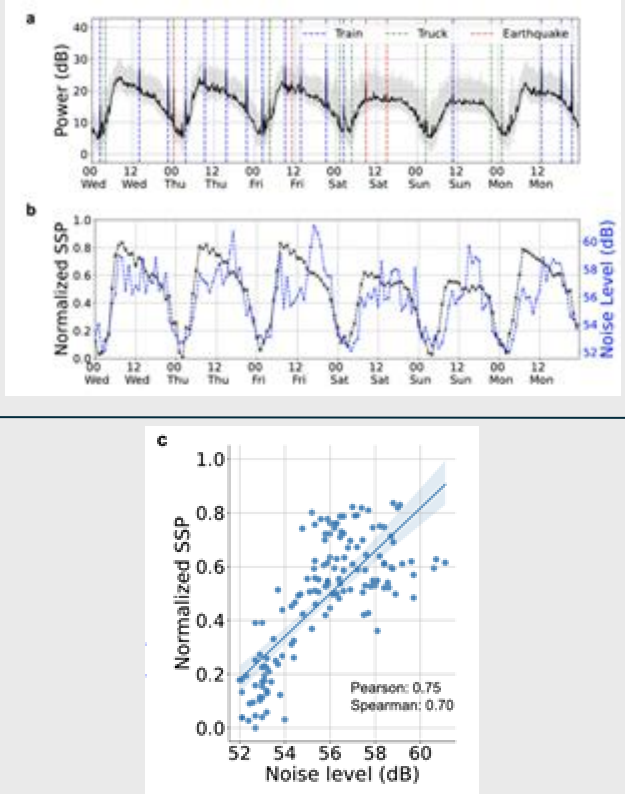
- Ground truth urban activity determined by fiber next to roads and railways to estimate positions and timings of seismic sources
- Remote fibers used for mapping the sources
- Truck, train, construction based seismic activity detected relatively accurately by remote fibers





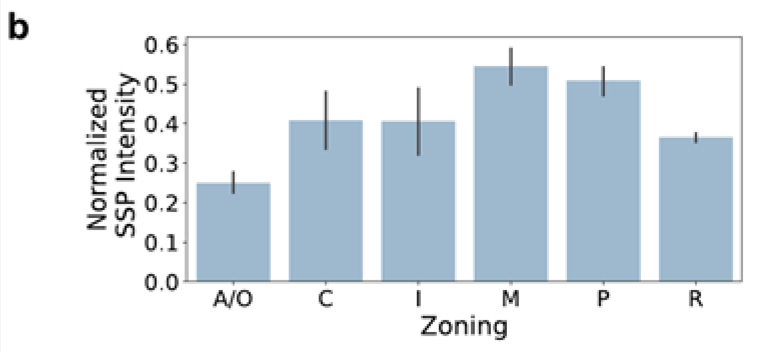
Validation of Seismic Source Mapping

- SSP maps align with areas/times of heightened activity
    - Identified earthquakes, activity near schools during school hours, more regular activity during weekdays
- Strong correlation between SSP and environmental noise



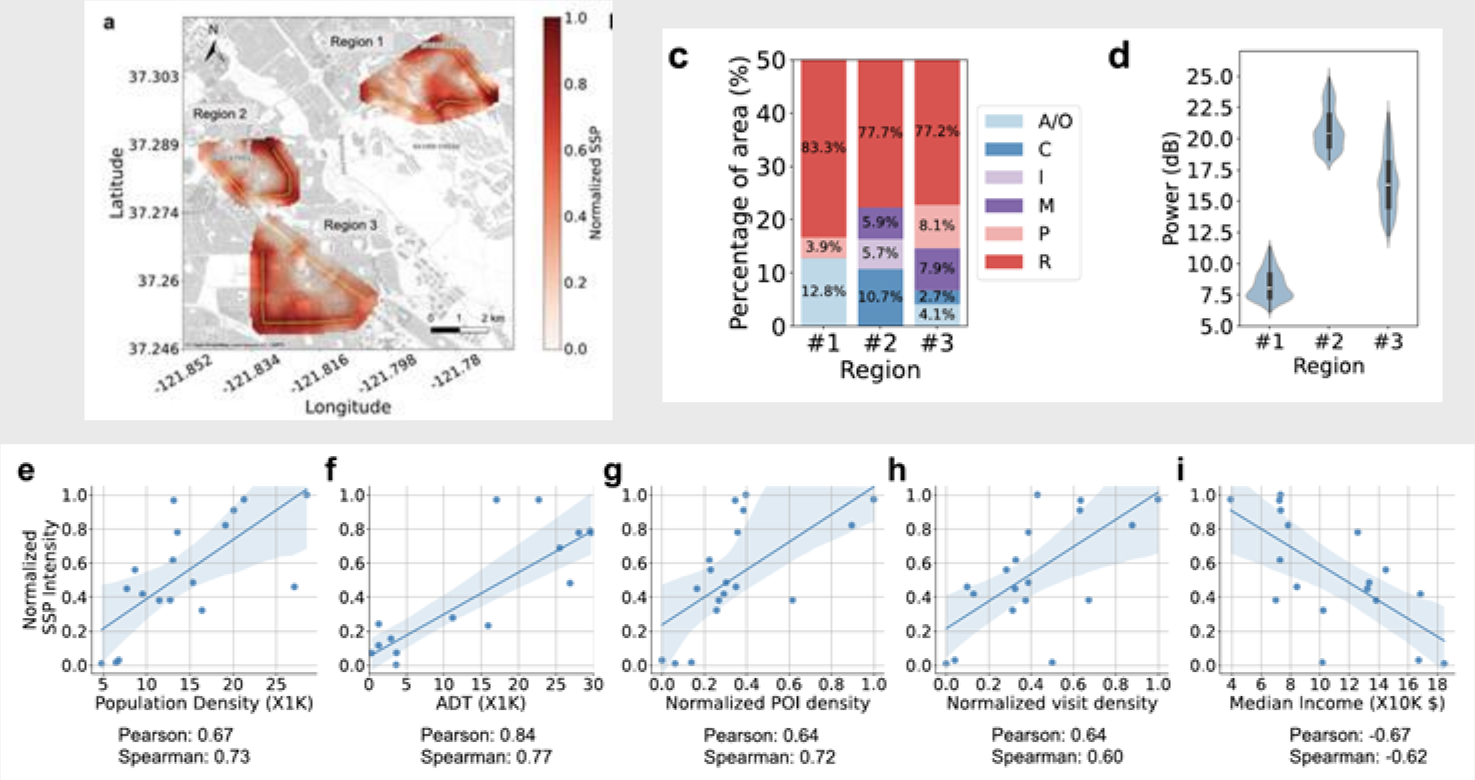
Portraying Persistent Urban Features

- Mixed use lands cultivate urban activities (highest SSP levels)
- Commercial, industrial, and public lands show moderate SSP levels
- Agricultural or open lands show the lowest SSP levels
- Higher residential population density also corresponds to higher SSP levels



A/O -> agricultural/open
C -> commercial
I -> industrial
M -> mixed use
P -> public
R -> residential

Portraying Persistent Urban Features



General Purpose Urban Sensing

- DAS based urban sensing is more generalizable, cheaper, more efficient, easier to less, while maintaining sensing coverage
- Crowd sensing approaches based on phone or vehicle data suffer from biased sampling and privacy concerns

Limitations, and Future Work

- Up-front cost (interrogator costs range from 5 to 6 figures)
- Requires existing fiber optic cable
- Methods require some assumptions about wave propagation
- Results depend on layout of fiber optic cable (fiber encircling region is most optimal)
- Near-field impacts may not be completely mitigated
- Dark fiber calibration
- ML pattern recognition for automated urban activity monitoring

Summary of Perusall

https://app.perusall.com/courses/cos597e_f2025-advanced-topics-in-computer-science-neural-sensing-modeling-and-understanding/urban-sensing?assignmentId=sb6q3zpgs6R22SkXe&part=1