

Pitter, patter, gurgle, burble: measuring the acoustics of rainfall using DAS in urban environments

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Author contributions: *Conceptualization:* Jonathan Ajo-Franklin, Valeriia Sobolevskaia. *Software:* Valeriia Sobolevskaia. *Formal Analysis:* Valeriia Sobolevskaia. *Investigation:* Valeriia Sobolevskaia, Brianna Miranda. *Writing - Original draft:* Valeriia Sobolevskaia, Jonathan Ajo-Franklin, Brianna Miranda. *Visualization:* Valeriia Sobolevskaia. *Funding acquisition:* Jonathan Ajo-Franklin.

Abstract Accurate precipitation data is one of the key inputs for hydrological models, yet traditional ground-based rain gauges and remote sensing data often lack the necessary spatial coverage and/or resolution for local environmental applications. This study demonstrates the potential of distributed acoustic sensing (DAS) as a tool for rainfall detection and quantification with high spatiotemporal resolution. We evaluate data from two distinct fiber-optic deployments in Houston, Texas: a surface cable in a controlled environment at Rice University campus and a 12-km urban dark fiber array. Rain induces high-energy broadband noise in DAS data with a strong correlation between the precipitation rate and mean DAS energy, consistent with past studies using traditional seismic sensors. However, DAS sensitivity to rain is heavily influenced by several external factors, including burial conditions, deployment depth, cable coupling, and seasonal ground coverage. In complex urban environments, where the signal is coupled directly from surface impacts on utility infrastructure, fiber sensitivity appears to be limited to spatial domains where the cable resurfaces from the deep conduits. Ultimately, our study shows that DAS can serve as a scalable alternative to traditional seismic sensors for distributed rain sensing across urban networks after identifying network portions with environmental sensitivity.

Non-technical summary Accurate rainfall measurements are essential for predicting floods and managing water resources, yet traditional rain gauges and satellite data often do not provide enough detail at the local scale. This study explores whether fiber-optic cables, which are commonly used for telecommunications, can help measure rainfall. Using a technology called distributed acoustic sensing (DAS), we analyzed ground vibrations recorded along fiber-optic cables at two locations in Houston, Texas: one in a controlled campus setting and another along a 12-km urban cable network. We found that rainfall produces clear acoustic signals in the cables, and the strength of these signals increases with rainfall intensity. However, how accurately the system detects rain depends on how and where the cable is installed. Factors such as cable burial depth, its connection to the ground, and surface conditions affect its sensitivity. In cities, the cable is primarily sensitive to rainfall when it is close enough to the surface. Overall, the results show that fiber-optic networks could serve as large-scale, high-resolution rain sensors, especially in urban areas where traditional monitoring is limited.

Epigraph

*Like Rain it sounded till it Curved
And then I knew 'twas Wind—
It walked as wet as any Wave
But swept as dry as Sand—
When it had pushed itself away
To some remotest Plain
A coming as of Hosts was heard
That was indeed the Rain—
It filled the Wells, it pleased the Pools
It warbled in the Road—
It pulled the spigot from the Hills
And let the Floods abroad—
It loosened acres, lifted seas
The sites of Centres stirred
Then like Elijah rode away
Upon a Wheel of Cloud.*

– Emily Dickinson

Production Editor:
Andrea Llenos
Handling Editor:
Wenbo Wu
Copy & Layout Editor:
Ethan Williams

Received:
March 26, 2026
Accepted:
July 21, 2026
Published:
August 29, 2026

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1 Introduction

Over the last 50 years, disasters related to water have exacted significant economic and human tolls across the world (World Meteorological Association, 2021). Floods and storms account for 44% and 22% of all natural catastrophes worldwide, respectively, making them the two most common types of disasters (van Loenhout et al., 2020). Between 2000 and 2019, the number of reported floods more than doubled, while the number of storms rose by a third compared to the previous 20 years, and cumulatively they caused over two trillion USD in economic damage, affecting 2.4 million people (van Loenhout et al., 2020). Climate change and socio-economic development in flood-prone areas inevitably increase the frequency and severity of these events (Winsemius et al., 2016; Wing et al., 2018). As a result of these trends and impacts, understanding flood risk is critical for developing effective strategies for disaster preparedness, response, and mitigation (Parliament and Council of European Union, 2017).

One of the fundamental tools in flood risk assessment are physically-based distributed hydrological models (Wood et al., 1988; Su et al., 2008). These computational models require distributed hydrological data, including precipitation, that can be challenging to acquire, especially at a large scale (Alferi et al., 2015; Vorogushyn et al., 2018; Pavesi et al., 2024). Rainfall estimation products come from three main sources: ground-based measurements, remote sensing, model-based reanalysis, or a combination of them (Omar et al., 2024). Rain gauges are the most accurate source of precipitation data (Kidd et al., 2017). However, databases based solely on surface rain gauge data (e.g., Menne et al. (2012)) have inadequate spatial coverage and resolution for environmental risk assessment (Saltikoff et al., 2019; Crum and Albery, 1993). Datasets derived from satellite data, such as passive microwave, infrared, and radar sensors data, can provide near-global coverage including remote and ungauged areas (Funk et al., 2015; Ashouri et al., 2015; Joyce et al., 2004). Yet, their spatial resolution may be too coarse for local hydrological applications (Behrangi et al., 2011; Ashouri et al., 2015). Lastly, precipitation estimates can be obtained through atmospheric reanalysis, which integrates weather observations with numerical models to produce spatially complete precipitation fields (Hersbach et al., 2020; Gelaro et al., 2017). However, similar to remote sensing methods, these datasets are more appropriate for global rather than local flood risk predictions (Hirabayashi et al., 2013).

In addition to being a source of water, rain is also a source of seismic energy, as each raindrop hitting the surface induces a tiny ground motion. The total amount of energy coming from raindrops is an important research topic as it affects soil erosion and other landscape changes (Brandt, 1988; Fornis et al., 2005; Guo et al., 2013). Rain signature observed in seismic data has traditionally been treated as noise as it can decrease the detectability of coherent seismic phase observations and reduce data quality (Nørmark, 2011; Brittan et al., 2008; Burtin et al., 2011). Recently, a number of studies have demonstrated how rain-induced seismic signals,

as measured by inertial sensors, can be used to monitor natural phenomena. For example, fluvial processes following intense rain, such as bedload, fluid transport, and others, have been monitored using locally installed seismometers (Burtin et al., 2011; Schmandt et al., 2013; Gimbert et al., 2014; Roth et al., 2016). On a larger scale, permanent seismic stations have demonstrated the ability to capture storms through flood waves (Chmiel et al., 2022) and rivers discharge (Díaz et al., 2014). For direct rain observation, several studies have utilized surface geophones and established that recorded seismic energy shows a power-law relationship with precipitation rate and raindrops' kinetic energy (Dean, 2017; Bakker et al., 2022). Due to noise decay with depth (Dean, 2017) and changing attenuation of seismic energy depending on soil type, the observed seismic signature varies from site to site (Rindrahariasona et al., 2022). Other research suggests that the bandwidth of the rain seismic signal also depends on the tool and the deployment conditions (Dean, 2017; Díaz et al., 2023); however, the exact wave modes that are excited by rain are not well studied.

Considering demonstrated seismic sensitivity to local rain events, it should be possible to monitor local and regional storms using large-N seismic sensor arrays. However, very few studies have successfully demonstrated that, particularly on a significant scale or in an urban environment. Hua et al. (2023) and Díaz et al. (2023) utilized dense seismic nodal arrays to obtain precipitation maps with high spatiotemporal resolution, and the results appeared promising. However, their utilization of a large-scale nodal network suggested limitations since such deployments are not a trivial undertaking due to demanding logistics and costs for deployment and retrieval, making it challenging to scale up for monitoring purposes. Nodes also have limited battery life and data storage space, lack options to monitor instrument health or response in real time, and it may not be feasible to properly install nodes in areas with restricted space availability or strict permitting requirements.

Given these limitations, distributed acoustic sensing (DAS) might be a better alternative to traditional seismic sensors for storm monitoring for a number of reasons. DAS utilizes fiber-optic cables, which are one of the least expensive, robust, yet highly sensitive seismic sensors (Lindsey et al., 2020; Lindsey and Martin, 2021). Using DAS, it is also possible to repurpose existing decommissioned telecommunication cables (called dark fiber), which makes this tool especially attractive in an urban environment with limited tool deployment options (Ajo-Franklin et al., 2019; Rodríguez Tribaldos and Ajo-Franklin, 2021). More recent advances have also demonstrated DAS recording on lit telecom cables, which are even more abundant than dark fiber footprints (Shi et al., 2025; Jia et al., 2021). DAS also benefits from high spatiotemporal resolution and has successfully been used for a range of environmental applications (Sobolevskaya et al., 2024; Cheng et al., 2022; Rodríguez Tribaldos and Ajo-Franklin, 2021; Shadoan et al., 2023). However, there are few studies using DAS for rain monitoring. Taweessintananon et al. (2023) reported identifying distant storms using an ocean-bottom telecommunication cable by trac-

ing ocean swells. To monitor a local storm, [Shen and Zhu \(2023\)](#) utilized an urban underground cable and recorded wind- and rain-induced noise following moderate and heavy rain events. However, they attributed the observed signal to water flow in stormwater drainage systems and observed no direct rainfall signature.

In this study, we utilize fiber-optic cables in different settings to monitor rain activity using noise signals in passive DAS data. At the first site, the cable is deployed in soil in a strictly controlled environment, while the second cable is an urban dark fiber array. We analyze the data collected over several months and demonstrate that DAS can record direct rain signatures under favorable conditions. Using data from the first site, we evaluate the effect of the type of deployment, burial conditions, burial depth, and ground cover on the recorded rain signature. Then, a similar analysis of the dark fiber data highlights the differences in rain signature observed in urban telecom network data compared to the experimental setting. Our analysis demonstrates the potential of using DAS in combination with dark fiber for distributed rain gauging across large distances while preserving high spatiotemporal resolution.

2 Experiment set up, tools, and methods

The data analyzed in this paper were collected at two distinct sites. The first dataset comes from a research test facility on the Rice University campus. There, we used a short cable installed in a carefully controlled environment in two dimensions—in a shallow surface trench and behind the casing of a wellbore. The site is instrumented with a meteorological station for continuous measurement of local precipitation and other environmental variables. The second dataset was recorded on a dark fiber array that begins on campus and extends over several kilometers across the city of Houston. The cable deployment conditions vary depending on the location, but predominantly it rests in an underground conduit with horizontally drilled sections beneath major infrastructure. These networks represent different monitoring conditions, and each has its strengths for evaluation. We will show how differences in the cable configuration produce significant variations in the observed seismic rain response.

2.1 Rice Subsurface Test Facility

Rice Subsurface Test Facility (RSTF) is a research well test site located on the Rice University campus in Houston, TX. It was originally developed to conduct hydrogeophysical experiments targeting shallow aquifer response and to test new geophysical instruments. For a full description of the site readers are referred to [Sobolevskaia and Ajo-Franklin \(2025\)](#). We collected data using a single-mode fiber-optic cable installed behind the casing of two wells (Figure 1a-b). In this paper, we focus on the surface portion of the cable as well as the shallowest portion of the cable in the wells. During installation the well cable was taped to the PVC casing and

then cemented to the walls. The surface portion of this cable was placed in a flexible plastic tubing and buried in soil between the wells and under the gravel as the cable approached the instrument trailer. In addition to preexisting equipment, we installed a separate cable on the surface extending over 140 m (tight-buffered cable with 4 single-mode fibers, aramid yarn, and HDPE jacket, Figure 1c). The cable formed a loop starting from the trailer, going to the meteorological station, then reaching the northwest edge of the site, turning around and following a straight line towards the southeast edge of the Rice campus, and then returning back to the site following the same path towards the weather station and back to the trailer. A short section of the cable between the trailer and the weather station was installed in a plastic tubing (for cable protection) buried under the gravel. The rest of the cable was placed in a shallow trench (5–10 cm deep) back-filled with original soil (Figure 1d). The soil type varied from soft dirt at the RSTF to a combination of hard-packed rocky soil, sand piles, and soft dirt between the RSTF and Main St. To facilitate simultaneous data recording across the wells and the surface portion of the cable, all cables were spliced in the instrumentation trailer. In addition to DAS, an array of 3C geophone nodes (IGU-16HR 3C Smart Seismic Sensors, natural frequency of 5 Hz, SmartSolo Inc.) was installed in a straight line along the surface fiber-optic cable with 2-m spacing. When possible, the nodes were placed in 20-cm-deep holes flush with the ground; however, in places with hard-packed and rocky soil they were deployed shallower.

The first dataset was collected between January 10 and February 16, 2025. To record ambient noise DAS data, we utilized a modern DAS interrogator unit (Treble, Terra15 LLC) with 1.6 m pulse width, 0.82 m spatial sampling, and 1 kHz time sampling rate. The nodes recorded data with the same time sampling. For the first four weeks, only the nodes and the well portion of the DAS cable were recording data; after that the surface cable was added to the acquisition geometry. During the experiment, the meteorological station at the site recorded multiple rain events on 15 different days. However, only two days received a substantial amount of rain (42 and 59 mm cumulatively on January 26 and February 11, respectively) while for the rest of the days the average total daily accumulation was under 4 mm. According to [Federal Meteorological Handbook \(2005\)](#), the latter are classified as light rain events with precipitation rates under 2.5 mm/hr. The rain event on January 26 is classified as moderate (2.5–7.5 mm/hr). The only heavy rain event (over 7.5 mm/hr) recorded during this experiment occurred on February 11. An additional set of DAS data on the surface portion of the cable was collected between April 30 and May 12, 2025 with the same acquisition settings. At this point, there was a substantial change in the ground and tree coverage at the site due to seasonal vegetation growth. There were 8 detected rainfall events during this period, 6 of which were light rains with the total accumulation under 4 mm per day.

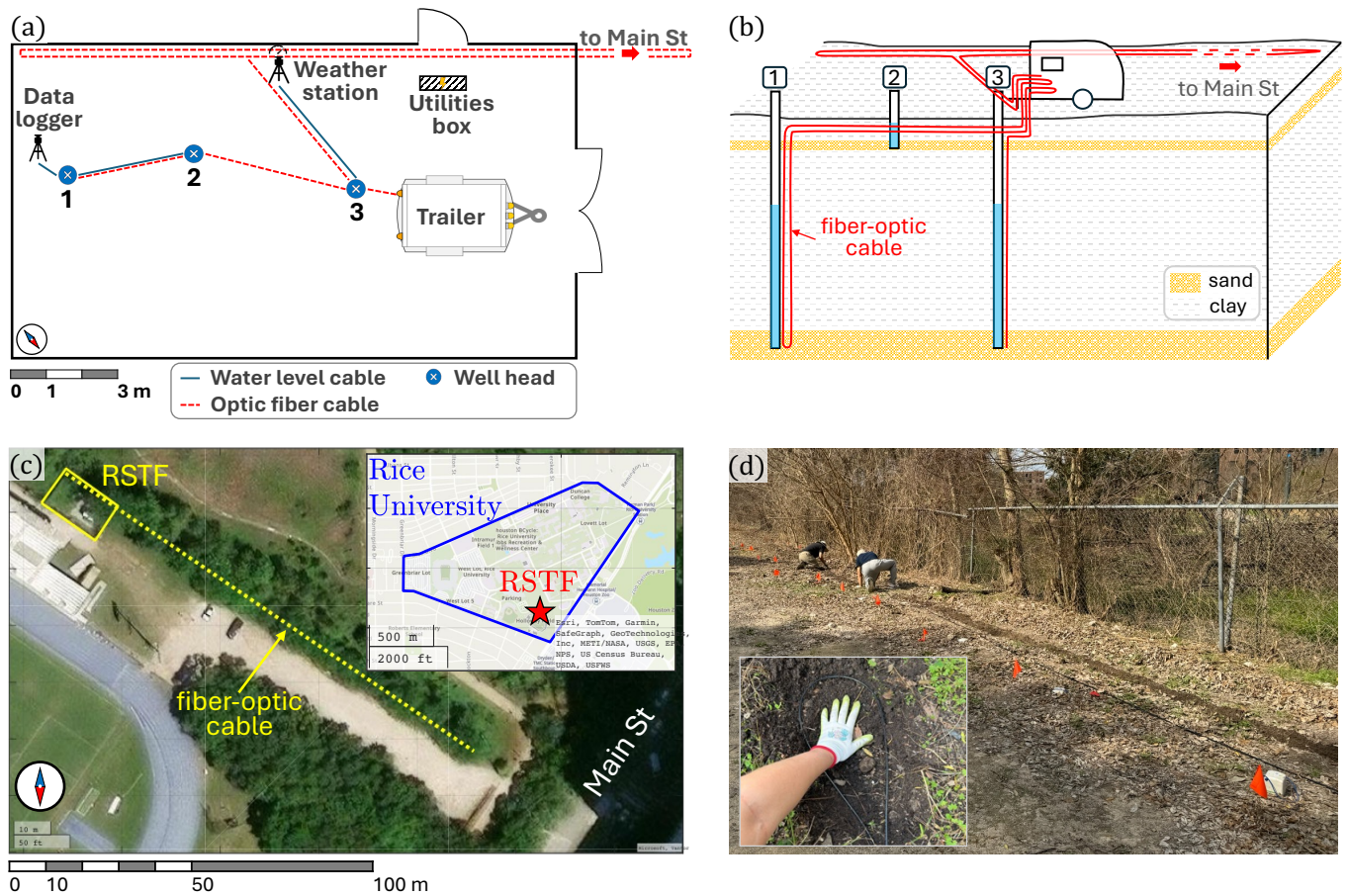


Figure 1 Experimental geometry at the Rice Subsurface Test Facility (RSTF). (a) Map and (b) schematic cross-section of the RSTF. (c) Aerial photograph with a schematic of the surface cable geometry and a map insert. (d) Photographs of the surface cable installation process and an insert view of the trench. Service layer credits for (c): Microsoft, Vantor. Service layer credits for the insert in (c): Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS

2.2 Houston Ambient Noise Array

Dark fiber refers to telecommunication cables that are not lit for data transfer; we repurposed such a dark fiber section to collect urban DAS data in this experiment similar to past studies (Ajo-Franklin et al., 2019). In this project we utilize the Houston Ambient Noise Array (HANA), the fiber component of which includes a dark fiber path that extends from the Rice University campus to the downtown section of Houston (Figure 2a). The southern end of the cable terminates in a building on Rice campus where the interrogator unit (IU) is housed. The cable crosses campus in a network of utility tunnels and surficial conduit before exiting campus and crossing the city, passing through Houston's Museum District, Midtown, and crossing Downtown before ending near Buffalo Bayou. The cable is buried in a conduit at a substantial depth below the surface and occasionally resurfaces in pull boxes (utility manholes) and surface utility boxes (Figures 2b-c). Surface utility boxes are above-ground enclosures that provide protected access to telecommunication and other utility infrastructure, housing cable terminations, splices, and associated equipment for maintenance and network distribution. The surface boxes usually have a metal frame and a cement base and are placed on sidewalks (Figure

2b). Pull boxes are underground access enclosures installed along fiber networks that provide access to fiber-optic cables for cable pulling, splicing, maintenance, and slack storage. The pull boxes are positioned on roads and sidewalks below the surface but at shallower depth than the actual cable (Figures 2b-c). At these pull-box locations, the fiber is housed without an external conduit. The total length of the cable we recorded on is 12 km, and the physical distance covered by the cable is about 7 km. The difference between the surface and optical cable lengths is due to slack cable (excess cable length intentionally retained to facilitate network maintenance) at the splicing locations and pull boxes that range between 30 and 300 m at each of numerous splicing points.

Two sets of data were collected using this fiber-optic cable. First, two weeks of ambient noise data were recorded in June and July 2025 using an IU similar to the one used for the RSTF experiment (Treble+, Terra15 Inc.) with a pulse width of 9.8 m, a spatial sampling of 4.9 m, and a sampling frequency of 1.6 kHz. In August 2025 we deployed a second type of IU (QuantX, Optasense Inc.) with a gauge length (GL) of 10 m, a spatial sampling of 1 m, and a frequency sampling of 5 kHz. In September the spatial sampling was increased to 5 m and the temporal sampling was reduced to 500 Hz. This

interrogator was set to continuously record data over the course of several months. To facilitate data interpretation for the entire cable, weather data were obtained from multiple stations in close vicinity to the cable using a publicly available database [Weather Underground](#) (Figure 2a). Over a dozen rain events ranging, from light to heavy rain and storms, were recorded and analyzed in each dataset.

2.3 Data Processing

To streamline comparison of the datasets recorded by different acquisition systems, first, all data are converted from their raw format to strain rate. For the data collected using Treble+ in its native integrated velocity format, this involved using a spatial differencing operator over the gauge length across all time samples. After initial testing and rain sensitivity analysis, data collected with QuantX IU was also downsampled to 250 Hz to improve computational efficiency while preserving the observed signal. To characterize the rain signature recorded by DAS, we calculate the power spectral density (PSD) of the strain rate for all datasets following the method of [Welch \(2003\)](#). This method estimates the power of recorded signals as a function of frequency, averaged over a specific time window. To maintain high temporal resolution, we used a 60-second computational window split into 5 segments with a 25% overlap. To compress PSD profiles, an additional smoothing in the frequency domain is applied. As a last step, a lateral smoothing over 5 min was applied to reduce noise and highlight temporal variations. The final periodogram volume for each dataset contains PSD as a function of frequency, spatial location along the cable, and calendar time.

To identify sections of the dark fiber cable with strong sensitivity to rain, we calculated the normalized average DAS energy for the entire cable for each recording system. First, a median of 1-minute periodograms over a 5-minute interval was calculated for a period before and during an intense rain event. We then computed mean periodogram energy for 80–250 Hz and 40–100 Hz windows for the Treble+ and QuantX data, respectively. While the precipitation noise appears to be broadband, the selected frequency band was driven by the dominant rain energy observed in the respective datasets, likely influenced by interrogator characteristics. Finally, the estimated mean energy during rain was normalized by its pre-rain equivalent to remove the variability in the background energy level. The spikes in the resulting normalized mean DAS energy correspond to the zone of increased sensitivity to precipitation events (Figures 2d).

3 Results

3.1 Rain signature on the shallow fiber-optic cable

To demonstrate the rain signature recorded by a shallow DAS cable, we first compare DAS recordings immediately before and during a significant rain event in the

time and frequency domains (Figure 3). Given the proximity of the deployed DAS cable to a busy street, the example gather before rain (Figure 3a) clearly shows surface waves generated by passing vehicles. These waves predominantly contain low-frequency energy (below 30 Hz) and dominate the recording frequency spectrum (Figure 3b). While the traffic pattern remains similar as the rain starts, DAS data shows an overall increase in noise levels across all channels and all recorded frequencies during the rain event (Figures 3c and 3d). Comparison of low-pass and high-pass filtered versions of the corresponding recording (split at 30 Hz, Figures 3e and 3f, respectively), demonstrates that rain generates high-energy broadband noise across all channels with dominant frequencies between 80 and 250 Hz (Figure 3d). However, its amplitude and the width of the spectrum vary along the cable. This suggests that fiber sensitivity to rain might be affected by external factors such as burial conditions, soil type, and ground cover, which we explore in this section.

Earlier studies have demonstrated that for traditional sensors the average magnitude of a seismic noise recorded during rainfall is proportional to the precipitation intensity ([Dean, 2017](#)). Our study demonstrates that this remains true for DAS data as well. Figure 4 shows the time-lapse of mean DAS spectrogram energy above 30 Hz recorded at several locations at RSTF and measured precipitation for the corresponding time periods. There were 22 different rain events recorded during the January–February and May experiments. However, most of them were light rains with cumulative precipitation not exceeding 4 mm per event and precipitation rate below 2.5 mm/hr. Regardless of the deployment conditions, these events did not boost the recorded DAS energy above the background noise level and are considered to be below the sensitivity threshold for this site. The only seeming exception is the rainfall event on February 15, 2025 that was detected by DAS regardless of its small magnitude. However, this rainfall measurement is biased low due to a clog in the rainfall gauge that was removed shortly after the event.

With increasing precipitation rate, mean DAS energy rises linearly at all locations, but the rate of this increase varies across the channels. Figure 5 shows mean DAS spectrogram energy above 30 Hz as a function of the precipitation rate for the same locations as in Figure 4. It should be noted that the vertical scale varies between the subplots to demonstrate the trend while preserving the actual amplitudes recorded by DAS. There are multiple factors contributing to the observed variability in DAS response. First, the surface fiber at RSTF was deployed in two ways, i.e., in a plastic tubing (the surface portion of the original cable in the boreholes, Figures 5a–c) and directly in contact with soil (the new surface cable, Figures 5e–g). In open spaces (i.e., when there is no obstruction from trees or other objects) a cable in direct contact with soil (Figures 5e–g) is more sensitive to rain than the same cable deployed in a conduit (Figures 5a–c) with the overall stronger amplitude and higher correlation (solid lines in 5) for the latter. Second, the soil at the site varies from soft dirt and gravel at the site to hard-packed rocky soil and sand piles out-

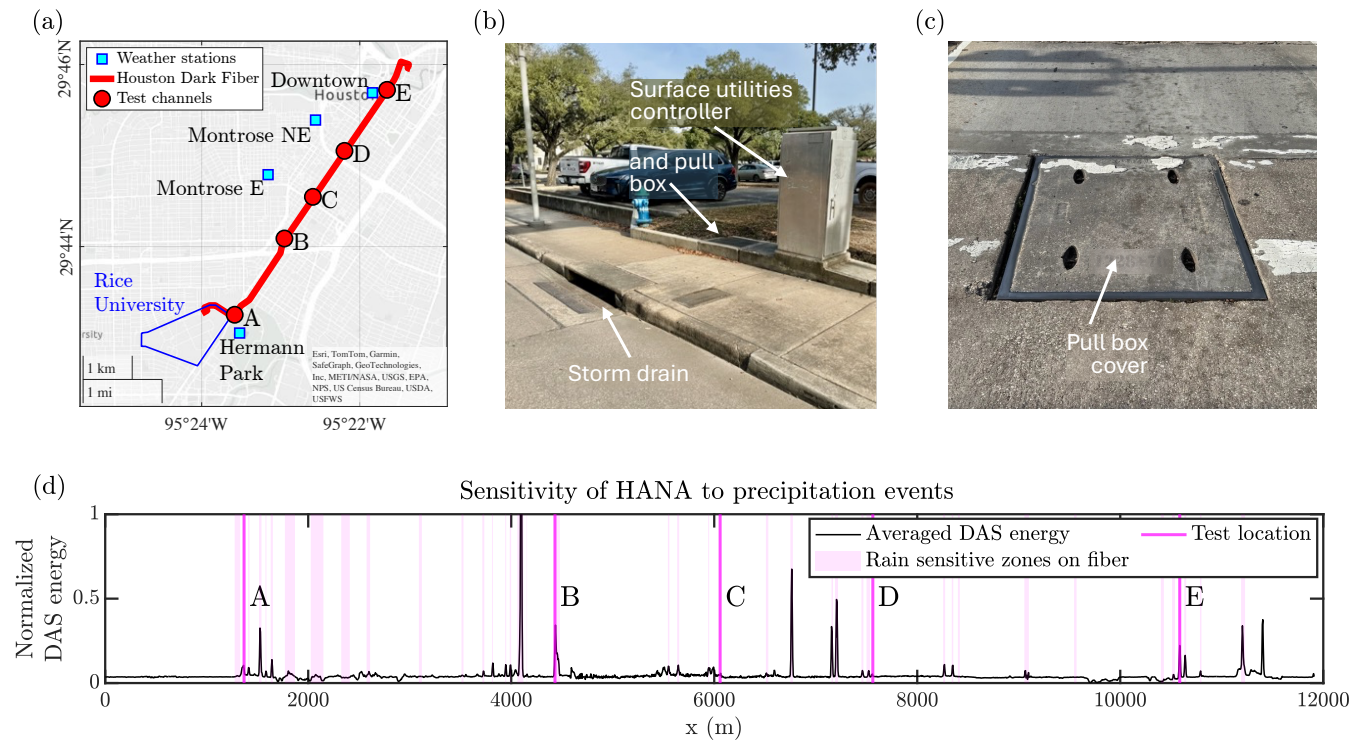


Figure 2 Houston Ambient Noise Array (HANA) description. (a) Map of approximate dark fiber cable path, test locations, and reference weather stations. (b) Photograph of an example surface utilities controller box and an adjustment pull box. (c) Photograph of an example standalone underground pull box. (d) Rain sensitivity curve (black) of the HANA data for a specific rain event recorded by Treble+ and detected rain-sensitive zones (light-magenta polygons). Magenta lines indicate example test locations analyzed in the study. Service layer credits for (a): Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc., METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS

side of the RSTF perimeter. In terms of absolute magnitudes, for a cable in direct contact with soil, softer sediments (Figures 5e, f) facilitate stronger seismic signals than hard-packed soils (Figure 5g). This can be a consequence of varying coupling and intrinsic soil attenuation. Lastly, we should note that the cable in close vicinity to the instrument trailer shows some false positive seismic anomalies (e.g., on January 14, 2025, 4a-c) that weaken further away from the trailer. We believe that these anomalies are caused by mechanical and electrical noises generated by the instrument trailer. For that reason the entire portion of the cable under the gravel pad was excluded from the analysis.

Ground coverage also affects the amount of seismic energy generated by raindrops. Figure 6 shows DAS energy recorded at two distinct locations. The first location has a regular turf surface with no additional vegetation (Figures 6a and 6b), and the second location has a dense tree line with no leaves in winter (Figure 6c) and full foliage in Spring (Figure 6d). In the absence of trees or any other obstructions to rain, the recorded seismic energy increases proportionally to rain rate. Hence, a stronger rain event in May with the maximum precipitation rate of 17 mm/hr (Figure 6b) generates more seismic energy than a weaker event in February (maximum 9 mm/hr, Figure 6a) as recorded in an open space location. However, when the cable is deployed under the tree line, the correlation between seismic and rain energy changes with seasons. In the absence of foliage, the seismic energy detected by the cable under a

tree line (Figure 6c) is similar to the turf location. In spring, while the DAS amplitudes still rise in response to rain, the absolute increase in energy drops significantly (Figure 6d). Even though the precipitation rate during the spring event is almost twice as high as during the winter event, the recorded seismic amplitudes are similar during both events. The same trend is observed for other events at this location (Figure 5f) with the overall drop in rain-generated seismic energy due to tree coverage, while other open-space locations show no seasonal change (Figures 5e) and a less dense tree line leads to a lower rate of seasonal energy drop (Figures 5g). The presence of vegetation also leads to a small dip in correlation between the precipitation rate and DAS amplitudes. For the locations F and G with dense tree lines and substantial seasonal drop in amplitudes, the correlation reduces from 0.78 in wintertime to 0.7 and 0.6 in spring, respectively. This suggests that the spring foliage partially attenuates the energy produced by raindrop impacts, hence decreasing the correlation between precipitation and seismic amplitudes.

The last factor affecting DAS sensitivity to rain is the depth of the cable. We have demonstrated that raindrops generate broadband noise with the dominant frequencies between 80 and 250 Hz. However, such high frequencies typically quickly attenuate with depth. To confirm this, we provide a comparison of DAS data recorded over time by the wellbore cable at different depths (Figure 7). At just 0.5 m below the surface (Figure 7b) DAS amplitudes decrease 2.5 times when compared

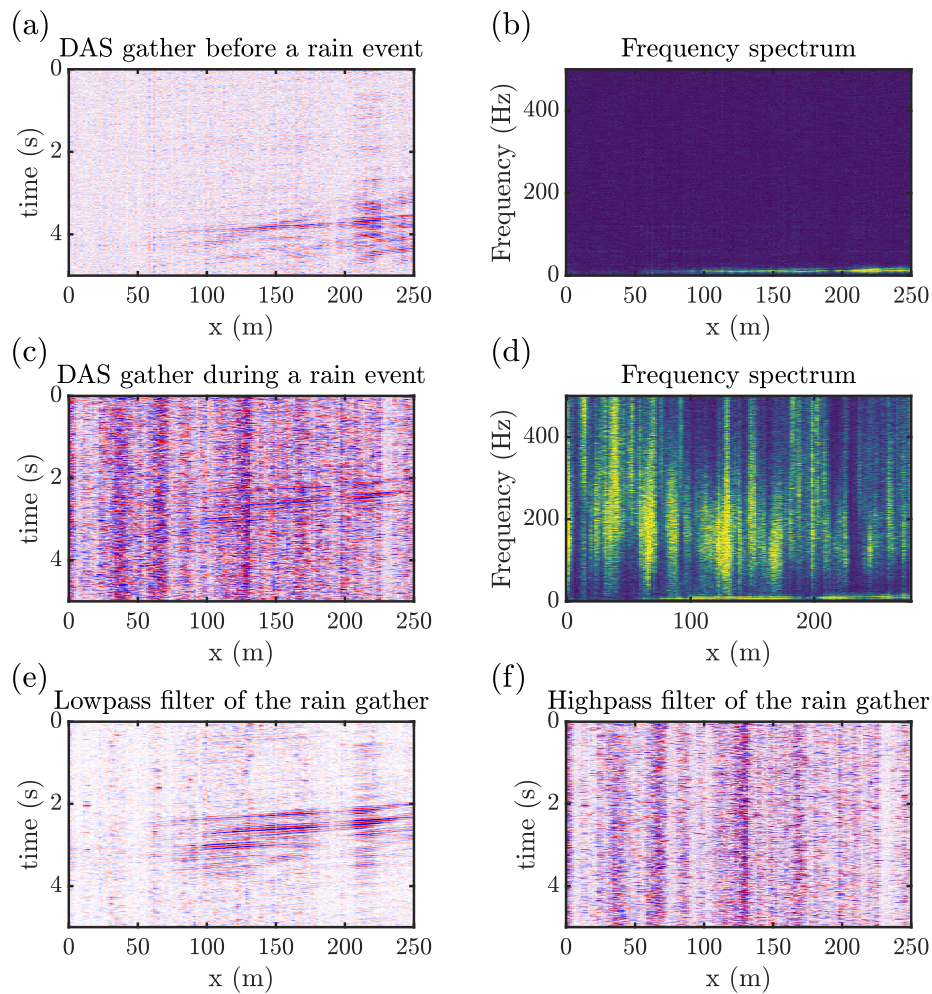


Figure 3 (a) Example DAS gather and (b) corresponding frequency spectrum recorded under dry conditions. (c) DAS gather and (d) its frequency spectrum recorded during a rain event. Comparison of (e) low-pass and (f) high-pass filtered versions of the rain-affected gather.

to the amplitudes recorded at the surface (Figure 7a) and at 1.5 m (Figure 7c) the rain-generated seismic energy is no longer detected by DAS. While these numbers will vary depending on the sediment (or cement) type and the type of encasing, the maximum viable fiber deployment depth for rain monitoring will likely remain within the first few meters.

3.2 Rain signature on a dark fiber array

Dark telecom fiber data analysis is intrinsically more complicated in comparison to the data collected in a controlled fit-for-purpose deployment due to complexities associated with changing and not always known geometry, fiber type, and installation environment. In contrast to the RSTF dataset, where precipitation induced significant broadband noise across the entire cable, the HANA data exhibited no spatially consistent variations in either time or frequency domains. To identify local zones sensitive to rain, we analyzed normalized mean DAS energy over the entire cable for the two recording systems. Figure 2d shows an example sensitivity curve for one of the rain events recorded by the Treble+ system. Multiple locations along the cable show increased energy levels during rain events. Close in-

spection of individual periodograms at these locations reveals that while these cable segments are sensitive to precipitation, their signal-to-noise ratios vary significantly. Here we focus on several locations in different parts of the cable that have substantial rain sensitivity on both recording systems (Figure 2). Locations B and D are within the slack zones at splicing locations with the cable slack resting in surficial pull boxes. Locations A and E are outside of the slack zone but next to man-holes covering fiber-optic junction boxes. Location C is a control point that corresponds to a non-sensitive zone with an average ambient noise levels.

Figure 8 shows temporal periodograms at the test locations covering one heavy rainfall recorded by each system. The recorded precipitation rate at the closest weather station(s) is also displayed in white and magenta lines. There is a rapid increase in recorded DAS energy across all frequencies at the onset of each rainfall event. The bandwidth of the rain-induced signal is constrained by the Nyquist frequency of the recording system (125 Hz for QuantX and 825 Hz Treble+), suggesting that the physical rain noise is inherently broadband. However, lower precipitation rates usually tend to generate more energy at lower frequencies. Therefore in additional analysis we set the working frequency

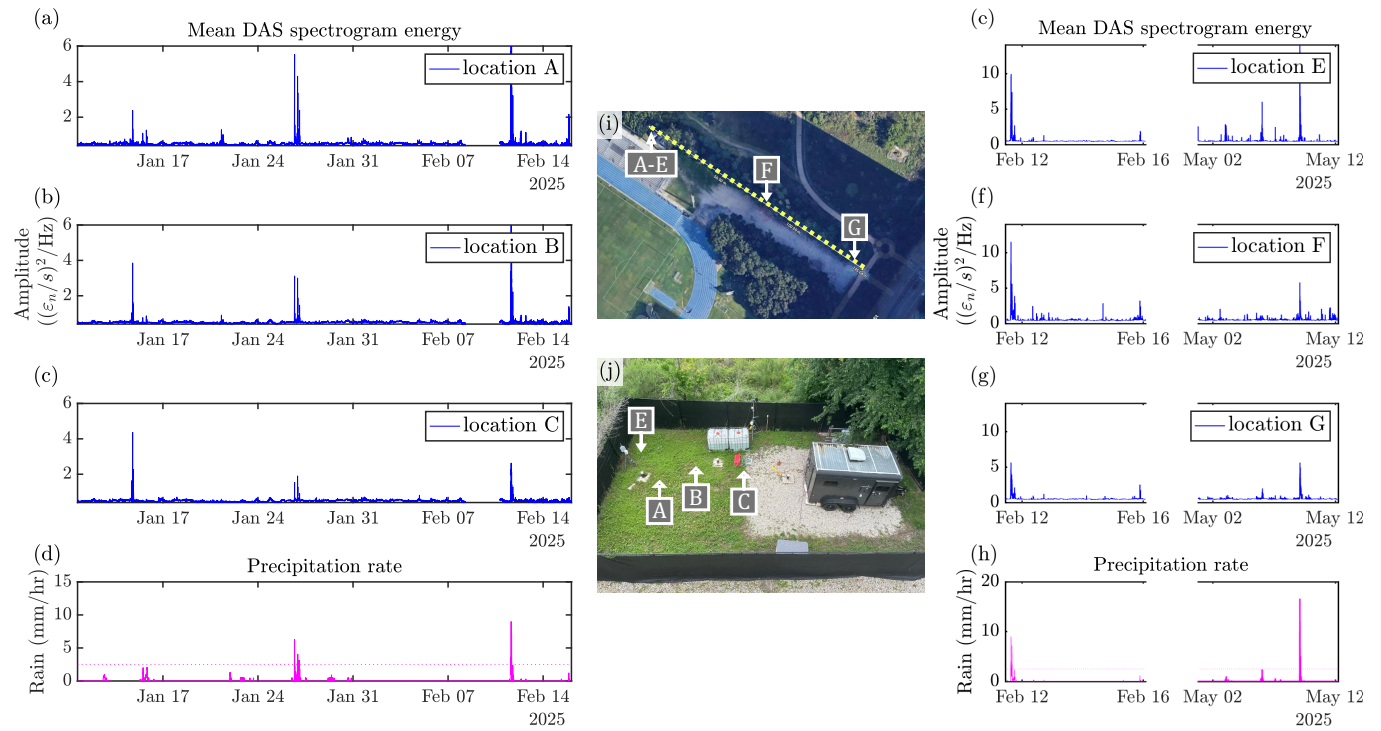


Figure 4 RSTF long-term DAS response. (a-c) and (e-g) show mean DAS spectrogram energy at the corresponding locations compared to (d, h) precipitation rates recorded at the local weather station. (i, j) show the aerial site photographs with labeled test locations.

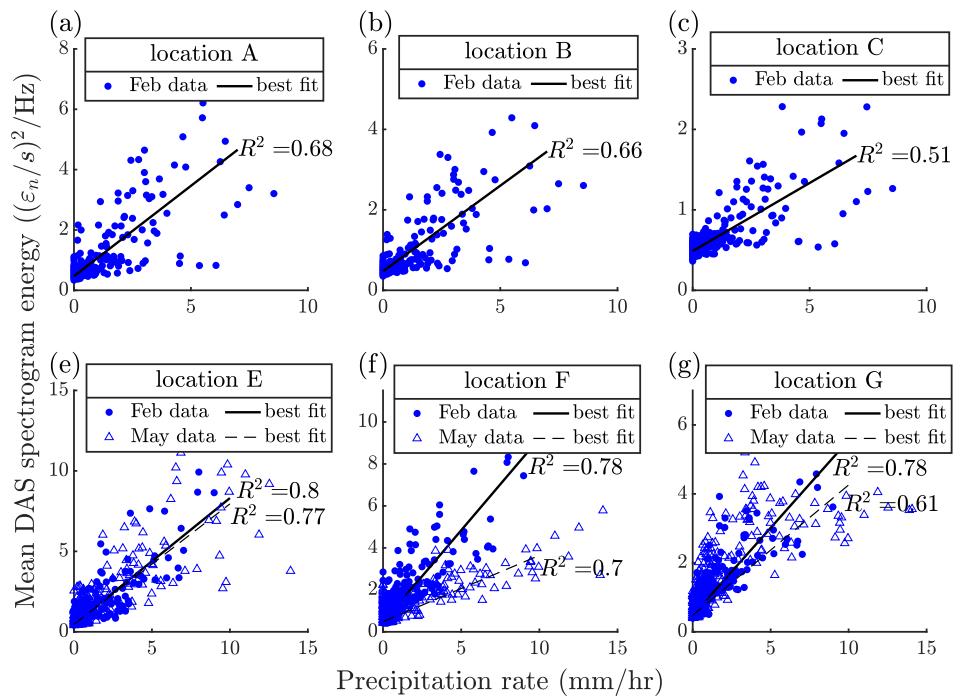


Figure 5 Cross-plots of precipitation rate versus normalized mean DAS spectrogram energy for selected test locations at RSTF. Data from the February experiment are denoted by solid blue circles with a solid black trend line, while the May dataset is represented by triangles with a dashed trend line.

range to 80-250 Hz for Treble+ and 40-100 Hz for QuantX, as noise at these frequencies dominate the spectrum during rainfall events. This also helps to eliminate the effect of low-frequency traffic and infrastructure noise that contaminates the rain signature. It should also be noted that this low-frequency background noise makes defining an average sensitivity threshold for the

HANA array challenging. Because the spectral content and intensity of this noise can vary considerably even over short distances, different sensitive zones along the same cable may exhibit substantially different detection thresholds.

Shen and Zhu (2023) previously reported delayed, low-frequency rain signals on a dark fiber array, which

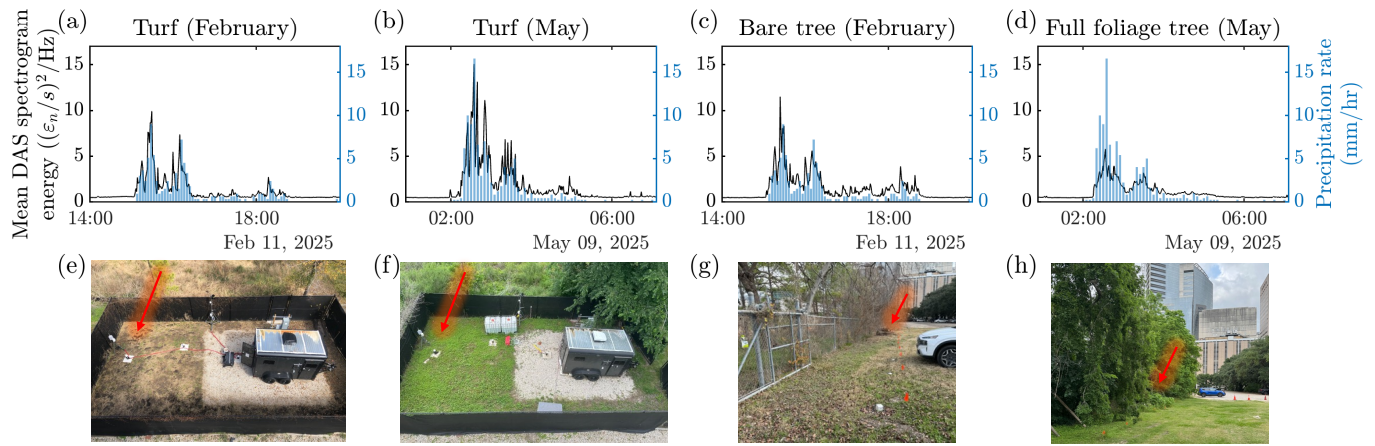


Figure 6 Impact of ground cover and seasonal vegetation on DAS rain sensitivity at RSTF. The top row shows mean DAS spectrogram energy (black lines) and precipitation rates (light-blue histograms). (a) February and (b) May data from a turf-covered location show consistent sensitivity, while data from a location situated under a tree line demonstrate a significant reduction in recorded seismic energy in May (d) compared to February (c). The bottom row (e-h) shows photographs documenting the surface conditions and canopy density for each corresponding dataset.

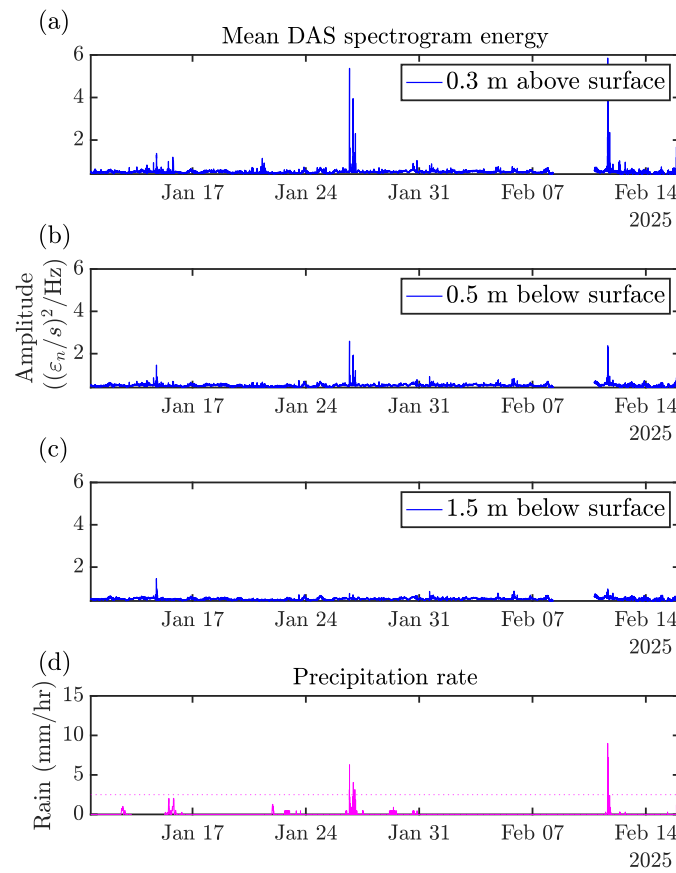


Figure 7 The effect of burial depth on rain-induced DAS response: mean DAS aptitudes at (a) 0.3 m above the surface and (b) 0.5 m and (c) 1.5 m below the surface compared to (d) precipitation rates recorded at the local weather station.

they interpreted as the acoustic signature of stormwater drainage flow. Higher frequency (up to 125 Hz) noise was attributed to rapid filling of the drainage system during heavy rain. In contrast, the lack of temporal lag and the presence of broadband energy distinguish our observations from the aforementioned drainage-related mechanisms. This spectral signature aligns with characteristics of the rain signal previously demonstrated at the RSTF. Consequently, we attribute the ob-

served noise to the direct impact of raindrops on man-hole covers or other utility infrastructure housing the fiber-optic cables. This interpretation is further corroborated by comparing cable segments near stormwater drains with those further away. Although the slack zones are situated adjacent to stormwater drains, a comparison between these sensitive segments and nearby non-slack segments, which lack proximal drainage infrastructure, reveals no clear difference in the onset

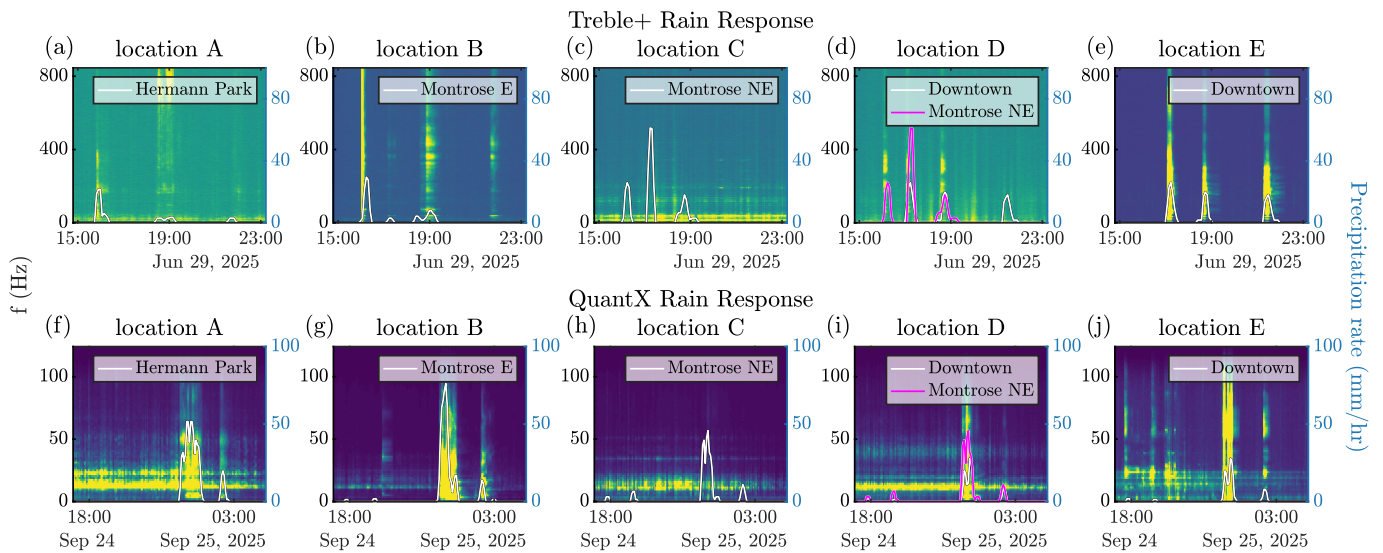


Figure 8 Example periodograms demonstrating HANA rain sensitivity at test locations. The top row shows data recorded during heavy rain in June by the Treble+ interrogator, and the bottom row shows a September event of a similar magnitude recorded by the QuantX interrogator. White and magenta lines show the recorded precipitation rate at the nearest weather station(s).

timing of DAS amplitude increases (Figure 10). These combined spatial and temporal observations suggest that the rain-induced DAS energy is coupled directly from surface impacts to the infrastructure-housed cable, rather than being secondary to internal stormwater flow.

The linear relationship between the intensity of rain and DAS amplitude also holds for the dark fiber data. Figure 9 presents cross-plots of precipitation rates versus normalized DAS amplitudes at the test locations across several rain events. At sensitive locations, correlation coefficients range from 0.31 to 0.78; while their values are comparable to the RSTF data, they remain slightly lower at the majority of the sites. This discrepancy is likely attributable to reduced accuracy in the precipitation data across both the time and amplitude domains. Specifically, the distance between the test locations and the reference weather stations ranges between 300 and 1,700 m, which introduces additional uncertainty regarding rain event onset and the localized volume of precipitation received. Furthermore, except for the Herman Park station, all reference weather stations are installed in a dense urban environment, where the proximity of buildings and other interfering factors can degrade measurement accuracy. Consequently, a lower correlation between DAS energy and rain intensity is expected in these urban settings compared to a more controlled environment.

3.3 Discussion and Applications

The results presented in this study demonstrated the ability of DAS to record a direct rainfall signature, placing it within a broader body of hydrogeophysical studies that utilized inertial seismic sensors for similar purposes. Previous studies established that geophones and broadband seismometers can detect rain-generated high-frequency noise whose amplitudes scale with precipitation rate (Dean, 2017; Bakker et al., 2022; Rindra-

harisaona et al., 2022). Our observations from the RSTF experiment, where a shallow cable is directly coupled to the soil, show the same fundamental behavior: rain induces high-energy broadband noise, and its mean energy increases linearly with rain intensity. This agreement suggests that, in this setting, DAS records the same physical process as traditional sensors - ground movement generated by raindrop impacts. However, the geometry of these two measurement types is markedly different. While traditional seismic sensor networks are typically sparse due to logistical and financial constraints, DAS offers dense spatial sampling over kilometer-scale apertures at comparatively low cost and small environmental footprint. Diaz et al. (2023); Hua et al. (2023) demonstrated that dense nodal arrays can recover accurate spatial precipitation patterns with high spatiotemporal resolution. However, such deployments are not feasible in many settings and are difficult to maintain long-term. Our results suggest that DAS can provide comparable data with substantially lower deployment and maintenance costs by leveraging existing fiber infrastructure.

In an urban setting, dark fiber cables are also capable of detecting rain events. However, rain sensitivity in this environment is spatially localized with detectable signals primarily near infrastructure where the cable approaches the surface. This spatial phenomenon is consistent with the strong depth attenuation observed at the RSTF, where rain-induced high-frequency signals were no longer detectable at a depth of 1.5 m. Hence, for the purpose of rain monitoring a dark fiber cable can be treated as an array of surficial sensors embedded within a largely insensitive buried cable. Our findings in an urban setting also contrast with those of Shen and Zhu (2023), who observed lower frequency signals with temporal delays caused by water flow in drainage systems and higher frequency noise related to rapid filling of catch basins with storm water. On the con-

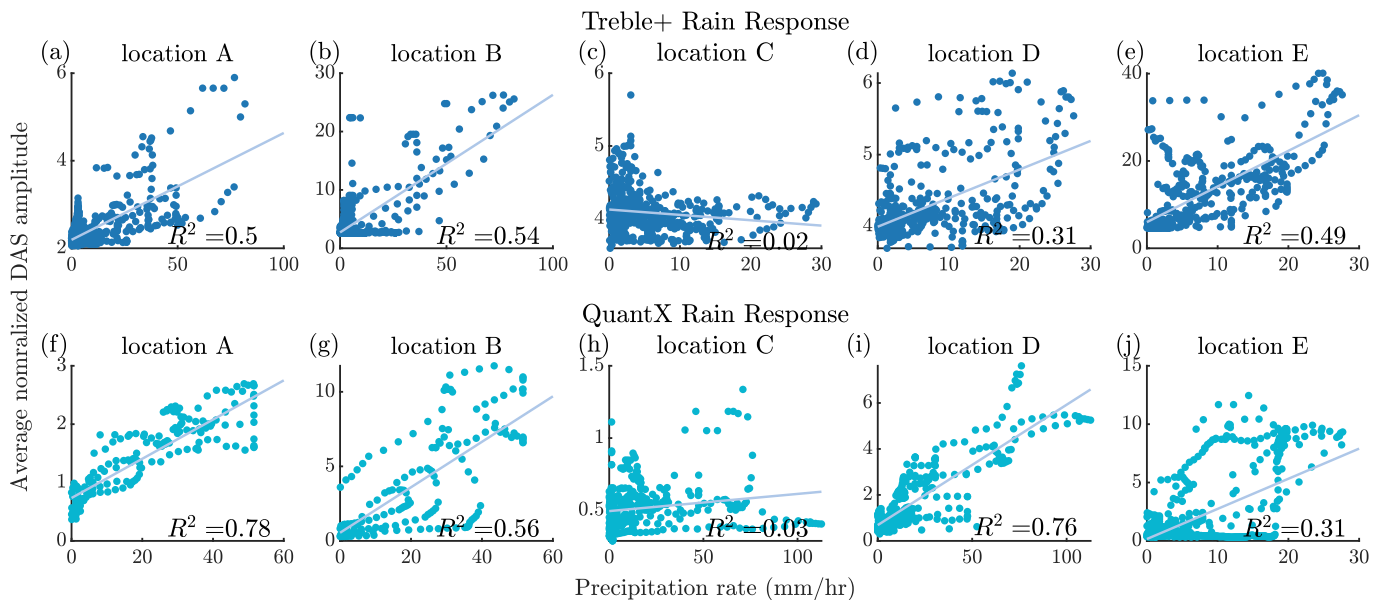


Figure 9 Cross-plots of precipitation rate versus normalized mean DAS spectrogram energy for selected test locations on HANA across multiple rain events. The top row shows data recorded by the Treble+ interrogator, and the bottom row represents the data recorded by the QuantX interrogator. The best-fit linear trend is represented by solid lines.

trary, we demonstrated broadband near-instantaneous response at rain-sensitive locations, which is consistent with direct raindrop impact. These differences are likely caused by variations in installation geometry and coupling, suggesting that DAS in an urban setting may record multiple rain-related processes, such as direct impacts, runoff, and drainage flow, depending on the cable environment.

Given the demonstrated ability of DAS to record direct rainfall signatures, there are several potentially transformative applications of DAS in hydrological monitoring and urban planning. While traditional rain gauges remain the most accurate source of precipitation data, the existing network of weather stations often has inadequate spatial coverage for local environmental risk assessment, and their installation in urban environments is often impractical due to limited space and accessibility issues. DAS in combination with dark fiber networks has the potential to fill critical gaps in precipitation data in these settings. Our study demonstrated that a fiber-optic cable can accurately detect the onset of rain and monitor its movement and strength variation across kilometers of a cable providing data with high spatiotemporal resolution. The automation of data processing can allow for real-time active storm development monitoring across a city or a rural area, which can contribute valuable information for inclement weather warning and management systems. With cables spanning tens to hundreds of kilometers, this information can provide a valuable insight into weather systems at an unprecedented scale and resolution.

Having said this, we also demonstrate a variety of challenges when utilizing these networks. Not all locations and installation environments are equally sensitive (or sensitive at all); this suggests that a key early effort when occupying networks for similar environmental sensing tasks is to map sensitivity to external measurands of interest, e.g., rainfall, wind, tempera-

ture, flood state. This is particularly crucial in cases like ours where detailed engineering information on the fiber path, conduit type, and burial depth is not available. A second challenge is the sensitivity of rainfall seismic response to vegetation conditions. While the fit-for-purpose installation at RSTF provided reasonable response linearity, the seasonality driven by ground cover and vegetation might make quantitative rainfall estimates more challenging. However, we should note that any non-maintained point measurement of rainfall (gauge, inertial sensor, etc.) will suffer from similar challenges. One potential solution for large networks would be to utilize satellite imagery, now available at a meter scale and daily cadence, for vegetation correction. In other words, like any other indirect measurement, DAS signal will require proper calibration for accurate quantitative interpretation.

We should also mention the expanding opportunities for similar sensing applications on lit fiber used for telecommunications. While our study had access to dedicated fiber, the recent availability of L-band DAS interrogators, e.g. [Brenne et al. \(2024\)](#); [Shi et al. \(2025\)](#), coupled to appropriate optical filters, has clearly demonstrated that high-quality DAS datasets can be acquired without interfering with telecommunications. Considering that fiber-optic networks are very common in urban environments and continue to grow with the development of technologies requiring this infrastructure (e.g., 5G and AI data centers), preexisting cables can successfully be used for monitoring in many cases. This substantially reduces costs and demanding logistics associated with the deployment and maintenance of a large number of traditional sensors, making it an attractive tool in various settings. Lastly, with proper calibration, DAS and dark fiber can be used to refine satellite-derived measurements in rural and ungauged regions where remote sensing is often the sole source of data. Looking forward, the implications of this re-

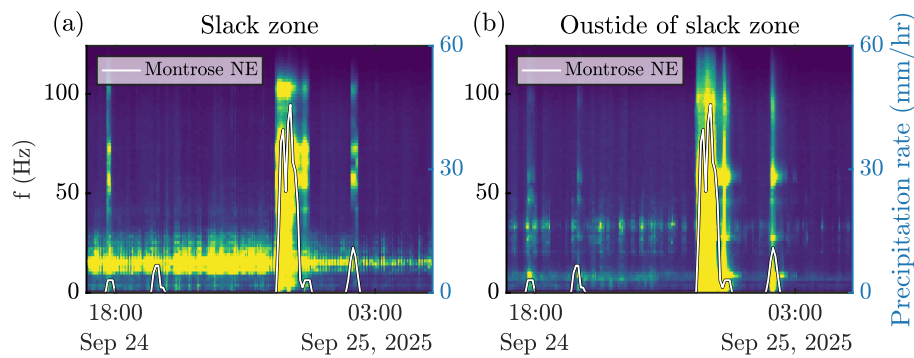


Figure 10 HANA example periodogram during a rain event close to location D: (a) in a slack and (b) outside of a slack zone (150 m away).

search suggest that even non-surface fiber, such as cables mounted on utility poles, could be repurposed for distributed rain sensing, further expanding the capacity for comprehensive rain mapping across vast urban and regional networks.

4 Conclusions

In this study we demonstrated that DAS can be utilized for direct observation of precipitation in different settings. In a controlled environment, the seismic signature of rain on DAS remains similar to the rain signal detected by traditional inertial seismic sensors. Precipitation noise has a broad frequency spectrum, and its amplitude increases linearly with intensifying rainfall rates. Given the strong attenuation of high frequencies with depth, the rain signature is not detectable when the fiber is buried more than a few meters underground. Furthermore, the signal intensity and quality are heavily dictated by installation conditions and the local environment. While cables in direct contact with soil are highly sensitive, those buried in conduits or shielded by dense seasonal foliage show a significant reduction in recorded energy. In an urban setting, we observe a similar rain-induced DAS response on dark fiber, albeit with a more limited spatial sensitivity and an overall noisier signature. Given the strong correlation between the onset of precipitation and the surge in DAS energy, we attribute the observed seismic response to the direct coupling of raindrop impact energy to the fiber, rather than to secondary water flow in storm drainage. This interpretation is further supported by the fact that the rain-sensitive locations along the dark fiber are situated within pull boxes, where the cable is not shielded by a conduit.

In comparison to conventional tools, DAS has a number of advantages that can make it an attractive tool for rainfall monitoring. First, using preexisting telecom cables substantially reduces installation and operation costs while increasing areal coverage with a low environmental footprint. With proper signal calibration, dark fiber cables can potentially be converted into a network of distributed rain gauges that will only be growing with time as the cost of internet-based sensing technologies decreases. Given its high spatiotemporal resolution, DAS data can provide an unprecedented

insight into storm development in real time. These data can be further used for flood risk and other hydrological modeling and inclement weather warning systems. However, the practical application of this technology in urban settings largely depends on the specific cable coupling. While we demonstrate a distinct signature of rainfall at locations where the cable almost reaches the surface, such as in manholes or pull boxes, the signal is typically lost in segments where the fiber is buried deeper in a conduit for protection. The overall fidelity of the data also remains limited by the interrogator unit's inherent noise floor, especially concerning its ability to resolve high-frequency signals. Despite these constraints, we conclude that under the right geometry and coupling conditions, DAS in combination with dark fiber networks has the potential to become a powerful tool for expanding rain mapping across urban settings and ungauged environments.

Acknowledgements

The authors would like to thank the Rice REAGLe field team, including Yuanyuan Ma, Qibin Shi, Fu Yin, Rosie Zhu, and Jaewoo Kim. We would like to thank the Rice IT Networking team, particularly Jason Glim, for assistance in accessing the dark fiber transect and establishing HANA. We would also like to give a special thanks to the Terra15 team for their continuous technical support, including Michael Roelens, Nader Issa, Alain Bartels, George Brawley, Simon Stobie, and others. Martin Karrenbach provided assistance with QuantX IU installation and configuration. Valeriia Sobolevskaia's research was partially funded by the Douglas and Martha Lou Broussard Fellowship (2024-2025). We also would like to thank Kevin Smith, Artem Goncharuk, and the team at X, The Moonshot Factory, for their analysis funds support and QuantX interrogator unit access. Lastly, the authors thank the anonymous reviewers for their constructive comments and suggestions, which helped improve the quality and clarity of this manuscript.

The epigraph from Emily Dickinson is the author's transcription from Dickinson's autograph manuscript (Dickinson, n.d.) and does not reproduce the text of any published edition.

Data and code availability

Due to size limitation and confidentiality agreements, only parts of the data presented in this paper are available for public access. All available data can be accessed at the following Dataverse repository: <https://doi.org/10.7910/DVN/8VZJNR> (Sobolevskaia, 2026). The following datasets are listed for RSTF: 1) a subset of raw DAS data from January 26 to January 27, 2025 covering multiple rainfall events and dry periods; 2) temporal periodograms for the entire period for select locations; 3) meteorological data for the entire duration of the experiment. The following datasets are listed for HANA: 1) a subset of raw DAS data recorded using Treble+ IU from 3 PM to 8 PM on June 29, 2025 covering a heavy rain event and dry periods before and after the event; 2) temporal periodograms for the Treble+ data for the entire period for select locations; 3) temporal periodograms for the QuantX IU data for the entire period for select locations (corresponding raw DAS data cannot be shared as per confidentiality agreement); 4) meteorological data for the entire duration of the experiment.

Competing interests

The authors have no competing interests.

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