DISTRIBUTED ACOUSTIC SENSING RESEARCH COORDINATION NETWORK (DAS RCN) FINAL REPORT

Name	Affiliation	Role
Herbert Wang	University of Wisconsin-Madison	PI
Scott Tyler	University of Nevada, Reno	Co-PI
Robert Woodward	EarthScope Consortium Inc.	Co-PI
Kasey Aderhold	EarthScope Consortium Inc.	Project Coordinator
Danica Roth	University of Colorado Boulder	Writing Team
Ethan Williams	University of Washington	
Léa Bouffaut	Cornell University	
Afonso Loureiro	ARDITI	
Jerry Carter	EarthScope Consortium Inc.	
Jess Johnson	University of East Anglia	
Voon Hui Lai	Australian National University	
Capstone Workshop Writing Group	(See Appendix A)	

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EXECUTIVE SUMMARY

This final report is largely a product of the Capstone Workshop held June 13-14, 2023 in Madison, WI. A small writing group (Appendix A) met for a day beyond the symposium portion of the Workshop to provide perspectives on challenges and opportunities. Several recurring issues were brought up throughout the award period – access to equipment and data management and storage. The report also recounts the initiation of the RCN and some pre- and syn-DAS science and technology developments.

The Distributed Acoustic Sensing (DAS) Research Coordination Network (RCN) was funded by the Earth Sciences Division (EAR) of the National Science Foundation (NSF). Its activities began in mid-2020, a year in which proposed in-person coordination activities operated largely online. These virtual meetings encouraged large-scale workshops and webinars. It expanded the reach of the RCN internationally. DAS technology adoption showed logistic growth from being a modest niche into a conventional tool over a range of research fields and applications (Figure 1).

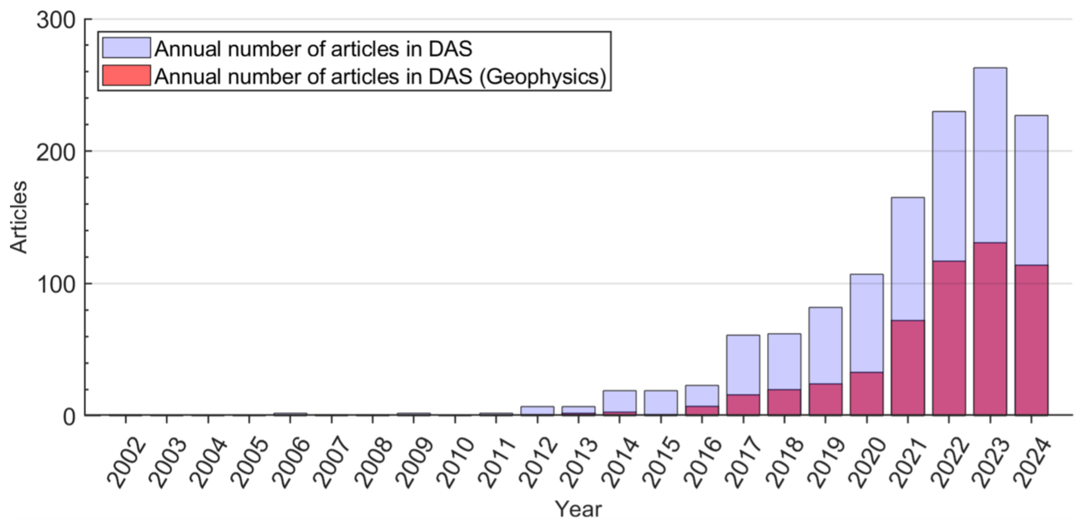

Figure 1. Bibliographic analysis showing logistic growth of DAS articles in all disciplines (blue) and in geophysics (red). The figure is slightly modified and updated by F. Cheng based on Cheng (2024).

The rapid adoption of DAS in the several years before the RCN was a large motivation for initiating it. Once underway, the Steering Committee quickly established a dozen Working Groups and organized RCN-wide workshops and webinars. Many members of the two governing groups were early adopters of the technology. However, the "entry fee" in terms of equipment and project costs was a barrier for many, especially non-seismologists. Early-career professors were among the leaders in DAS experiments because they used their start-up funds to purchase interrogators. Using start-up funds was a strong commitment to the potential of DAS.

At the heart of this report is a list of needs and opportunities from the perspective of the relatively broad and diverse DAS RCN participants. Issues of community equity and access are discussed side-by-side with science and technology opportunities. High priority is assigned to early-career researchers. We invite the DAS community and funding agencies to use this report as a "white paper" to realize the priorities, build connections to new disciplines, and address unanticipated opportunities in creative ways, such as providing funds to NSF awardees to support DAS field or analysis experiences to students and early-career researchers as a broader impact.

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1. Introduction

This report serves two purposes. First, it is a record of the DAS RCN's activities. Second, it is offered in the spirit of a "white paper" with recommendations and priorities for funding agencies and researchers. This introductory section provides a brief technical introduction to DAS, its origins, and its goals. Section 2 recounts the RCN's organization and sponsored events. It includes an account and list of archived webinars that retain value as entry points for researchers new to DAS. Section 3 is a snapshot of DAS research in the different Working Group topics during the RCN. Section 4 outlines a five-year timeframe for facilities data management, instrumentation, community building, and education/outreach that are needed to attain the bright future that DAS portends. Section 5 concludes with a succinct list of ten recommendations. A series of appendices provides detailed links and supporting material for the body of the report as well as visions of applications in Marine Biology and Geomorphology.

1.1 What is DAS?

Distributed Acoustic Sensing, or DAS, is a technology that records strain in the direction of a fiber-optic cable that is comparable in signal-to-noise ratio to measurements by single-component accelerometers or geophones (Arrowsmith et al., 2021). Its transformative potential arises from the fiber itself being the sensor allowing for measurements on the meter scale (Figure 2). The fiber can be tens of kilometers long and it can be located in a range of environments such as shallowly buried trenches, in boreholes, on the ocean bottom, in streams, on glaciers, and more. DAS inherently possesses properties of a large-N seismic array. Its principle of operation is that outgoing laser pulses are propagated in the near infrared (~1550 nm) where fused silica is optically transparent. Interferometric analysis of the phase difference of local variations of the Rayleigh backscattered signal over a short section of cable from two successive incident pulses generates a dynamic strain recording at a spatial resolution of a few meters. The phase response is linear in strain induced in the cable over the same amplitudes typically recorded by seismometers. Its frequency response is affected by cable construction and coupling to the ground. It is generally comparable to geophones in the one-to-100 Hz frequency range (Figure 3).

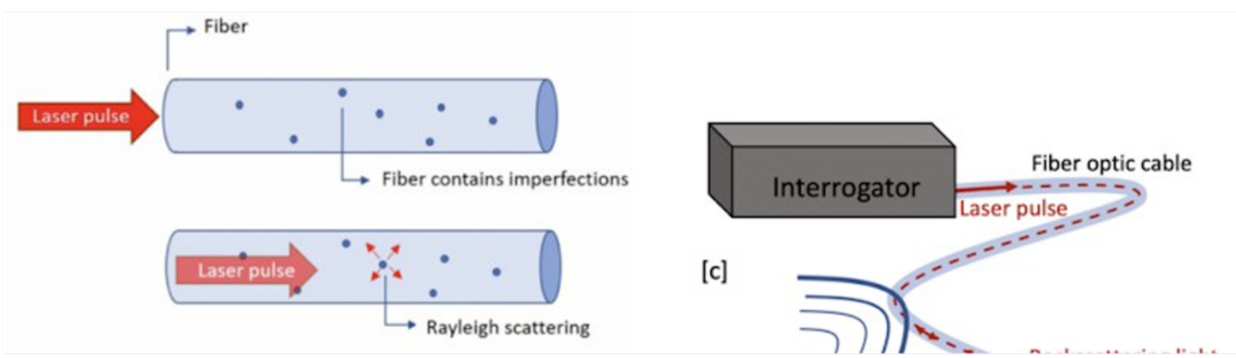

Figure 2. (a) Schematic drawing of the measuring principle of DAS. A laser pulse is sent into the cable from the interrogator, and due to naturally occurring inhomogeneities, Rayleigh scattering occurs (after Lindsey et al. 2019). About 0.01% of the outgoing light's energy is backscattered and returned to the interrogator. (b) Strain or strain-rate of each DAS channel, spaced by a small distance of a meter, is determined across a gauge length which works like a moving average across the fiber optic cable. (c) When strain occurs in the fiber optic cable due to acoustic waves, the signal of the backscattering light that reaches the interrogator

changes (adapted from Silixa, Ltd. (silixa.com). From these changes, the interrogator calculates the strain or strain-rate occurring in the cable for each DAS channel. The figure is not to scale. Adapted from NAP (2020). Reproduced from EGU Seismology ECS Team (2023).

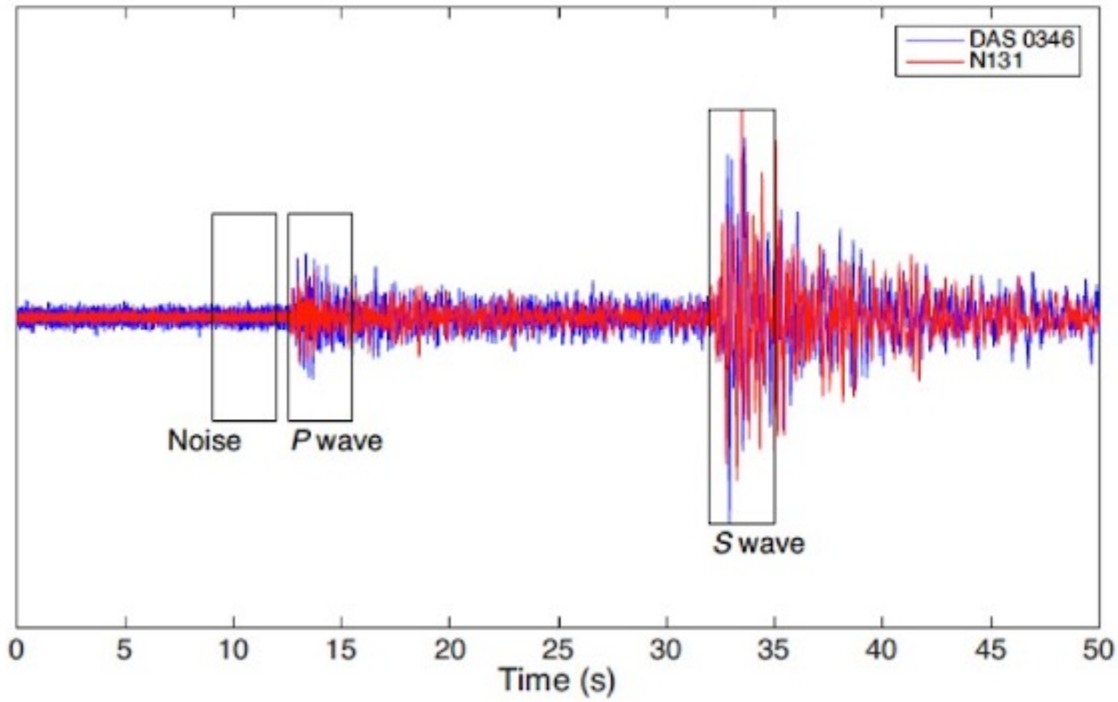

Figure 3. Example comparison of normalized DAS strain rate (blue) and geophone particle velocity (red) recorded on 2016 March 21 at Brady Hot Springs, NV of a magnitude 4.3 earthquake 150 km south-southeast. Reproduced from Wang et al. (2018).

1.2 RCN Origins

The PI was introduced to DAS at a pre-AGU CTEMPs workshop on the Stanford campus in 2012. Although its focus was Distributed Temperature Sensing (DTS), Mahmoud Farhadiroushan (Silixa) described DAS in passing. Detect a penny dropped from a meter height over telecom fiber near your house? It seemed unbelievably powerful. How did it work? Shortly afterwards, John Selker (Oregon State) and Michael Mondanos (Silixa) gave me the opportunity to observe DAS in action. Cable was laid in the Calapooia River and along the nearby forest road. A DAS interrogator sat in a trailer parked on the road recording Selker in waders clanking rocks under water as well as weight drops along the road. Many early demos were never published because follow up analysis was not completed or results were not conclusive. Others were delayed for several years because analysis was slow or the publication required numerous iterations due to skeptical reviewers unfamiliar with DAS technology. Nonetheless, these informal experiences and unsophisticated experiments were part of the diffusion of DAS into Earth science. As depicted in Figure 1, there was rapid growth of formal DAS articles in the peer-reviewed journals and conference proceedings between 2013 and 2018 to the point where full-day AGU DAS workshops in 2018 and 2019 drew 40-60 enthusiastic participants (see Appendix B for agendas). A partial indicator of the novelty of DAS in late 2018 was that the workshop summary appeared as an EOS article a few months later (Wang, et al., 2019). Many attendees were early adopters who gave presentations on their applications. Others had just started using DAS or were about to start. Applications covered a wide range of Earth sciences interests with experiments on glaciers, in mines, and over geothermal reservoirs. DAS vendors were a special group of attendees who had the deepest understanding of the technology and who had participated in many of the applications. Issues discussed during the 2018 and 2019 AGU workshops included access to instrumentation, and storage and analysis of tens of terabytes of data. These topics were revisited many times during the RCN award and continue to this day. Missing from these workshops were geophysicists and reservoir engineers from the oil and gas industry. There is now somewhat greater interaction between this energy community and the AGU community, e.g., DAS workshops at the annual symposium of the American Rock Mechanics Association (ARMA) and IMAGE (SEG/AAPG).

At the 2018 AGU meeting, the RCN PIs, which included Bob Detrick, then-President of IRIS, gathered with a few other colleagues to discuss submitting an RCN proposal. The process of writing and review is always lengthy but led eventually to an award beginning in mid-2020 as a collaboration between University of Wisconsin-Madison, University of Nevada-Reno's Centers for Transformative Environmental Monitoring Programs (CTEMPs), and EarthScope Consortium Inc. [then Incorporated Research Institutions for Seismology (IRIS)]. Additionally, the proposal formally included the names and bios of the Steering Committee (Appendix C).

1.3 RCN Goals

DAS applications in geosciences are numerous and growing, including opportunities for earthquake seismology, volcanic eruptions, ice movement and avalanches, continental and marine landslides, ocean noise, and groundwater hydrology (Lindsey and Martin, 2021). Opportunistic use of dark fiber along internet corridors and ambient noise provides exciting opportunities for seismic monitoring at the urban scale. DAS can complement and supplement conventional seismic sensors and arrays already used across a wide range of disciplines. We note finally that important commercial applications of DAS in oil and gas for Vertical Seismic Profiling (e.g., Mestayer et al., 2011) and hydraulic fracturing characterization (e.g., Jin and Roy, 2017) were not a focus of the RCN as its development and applications were robust in the oil and gas industry, in pipeline infrastructure monitoring, and in carbon sequestration and geothermal technology programs in the Department of Energy. We hope that more connections will be made in the future between these applications and research institutions.

As stated in the proposal, the DAS RCN had four main goals:

1. Identify applications of DAS and develop a network of potential DAS users.
2. Train a community of DAS users in the acquisition, handling and processing of DAS data.
3. Identify needed technical development (engineering and scientific).
4. Identify major challenges and next steps for supporting DAS science beyond the RCN.

The RCN welcomed participants from the research and technology communities representing a broad range of disciplines. The RCN tried to be a node connecting academia, national laboratories, industry, and government agencies. It intentionally promoted exchange with instrumentation developers and manufacturers, broadened its reach internationally, and addressed problems of community interest.

2. RCN Activities

2.1 Working Groups

The RCN Principal Investigators and steering committee members (Appendix C) began regular Zoom meetings a few months before the official start of the award. The first action was to form topical working groups (WGs) and identify group leads (Appendix D), The WGs were focused on research areas outlined in the proposal. Community members were encouraged to initiate and lead additional working groups as interests and RCN participation grew. An outstanding example of an added working group was Research and Development Test Sites led by Andreas Wuestefeld (NORSAR) in September 2020. This WG presented webinars featuring different test sites, including a video tour. Wuestefeld also proposed and led the highly successful Global DAS Month (see Section 2.2.3).

The following guidance was provided to working group leads with ample flexibility to fit their needs.

Key common contributions expected from all Working Groups:

- An annual Working Group (WG) "business" meeting (1-2 hours) to discuss activities in the past year and to plan for the future year.
- Submit an annual report on the Working Group activities (can be "minutes" from WG business meeting).
- Host 1-2 public virtual meetings/workshops/events per year, highlighting advances in DAS in the Working Group theme.
- Development living bibliography related to the Working Group theme.

Potential contributions from the Working Groups to be decided from the membership:

- Formal presentation(s) to the RCN on advances in the theme area (e.g., in monthly webinars)
- Develop meeting session proposals, either alone or in collaboration with other Working Groups to highlight advances/opportunities in the Working Group theme.
- WG webpage within the RCN with membership and contact, list of WG meetings, future meetings, products such as bibliographies, papers, preprints, tutorials, FAQs, meeting notices, brief reports on the state-of-the-art in different topical areas, "message" board of upcoming DAS installations/experiments, etc.

Although strict adherence to the guidelines was highly variable, most working groups were maintained throughout the RCN while others became inactive. Marine Geophysics continued to meet occasionally post award. Overall, it was an advantage to have focused groups within the RCN to address the wide range of research applications and diverse needs of the DAS community. Smaller online meetings of working groups allowed more participation and higher quality networking opportunities. Working Group leads were invited to attend RCN steering committee meeting to promote coordination.

2.2 RCN Events

The pandemic and subsequent travel restrictions required quick changes in approach. Core to realizing the RCN was developing an evolving set of in-person meetings, short-courses, workshops, webinars, and community forums. The complete list of events is documented in Appendix E. Web-based events can be streamed on EarthScope's YouTube channel. Many will stay current for a few years after the RCN. We highlight the opening workshop in August 2020 and the instrumentation showcase series as particularly useful for newcomers to DAS. In addition to RCN virtual events, we organized sessions at hybrid national meetings. We were finally able to hold two in-person events after nearly three years – a field experience at the Colorado School of Mines and the Capstone Workshop at the University of Wisconsin-Madison.

2.2.1 First DAS Virtual Workshop and Tutorial August 10, 12, 17, 2020

The RCN was kicked off in August 2020 with an ambitious and well-attended multi-day virtual short course and workshop led by Eileen Martin and Nate Lindsey (https://www.iris.edu/hq/event/2020_DAS_Workshop). The necessary pivot to virtual format allowed for a broader and international audience. Participation reached 270 people at its peak over the three, half-day sessions. Varied talk formats and topics related to collecting and using DAS data aimed at a broad audience, from new users to experienced researchers. The tutorial provided an opportunity to get experience with real DAS datasets. Synchronous presentations were complemented by asynchronous exercises. A Slack forum encouraged energetic discussions throughout the workshop and assisted participants in networking.

Pivoting to virtual events required significant planning from the teams that were still learning the Zoom platform and effective online meeting execution. But it also enabled a six-fold increase in participation. Presentations remain available on IRIS's and EarthScope's YouTube channels as an invaluable resource for newcomers to obtain a hands-on introduction to obtaining and analyzing major, publicly available DAS data sets such as FORGE (Pankow, 2022) and PoroTomo (Feigl et al., 2016) using the ObsPy Python toolbox. Recordings from this first workshop garnered views right away, perhaps due to time zone issues, but they also continued to be accessed well after the workshop. The significant, additional views encouraged us to continue to record and post events to allow later watching and a broader reach. At the conclusion of the RCN, the library now consists of about 100 archived events.

2.2.2 Hybrid National Meeting Events

Major virtual, hybrid, or in-person national meetings were another important opportunity to gather the community. These included a half-day DAS RCN event at the AGU Fall Meetings in 2020, 2021, and 2022. Two "Pod" meet ups were held in the poster area of the AGU Fall 2023 meeting. Special interest groups met at the 2021, 2022, and 2023 SAGE/GAGE Meetings, and sessions were proposed for SSA, AGU, and other meetings. The virtual Workshop and Tutorial generated more enthusiasm (100% Excellent or Very Good) than the virtual AGU meeting in December 2020 (~80%). The detailed survey results for these two events are provided in Appendix F. The survey included information on attendance demographics showing attributes such as discipline, career stage, etc.

2.2.3 Global DAS Month (February 2023)

The Global DAS Month campaign (Wuestefeld et al., 2023) was initiated by Andreas Wuestefeld of NORSAR who led the Research and Development Test Sites Working Group. Through that role, the Steering Committee and other Working Group Leads were brought into the plans at an early stage. In her role as Project Coordinator, Kasey Aderhold helped lead the effort by promoting it through the RCN. She became the third author following Wuestefeld and Zack Spica, who archived the data at his PubDAS site (Spica et al., 2023). In total, 32 institutions around the world participated. North America (9), Europe (19), Asia (5), and Australia (1) were all represented (Fig 4).

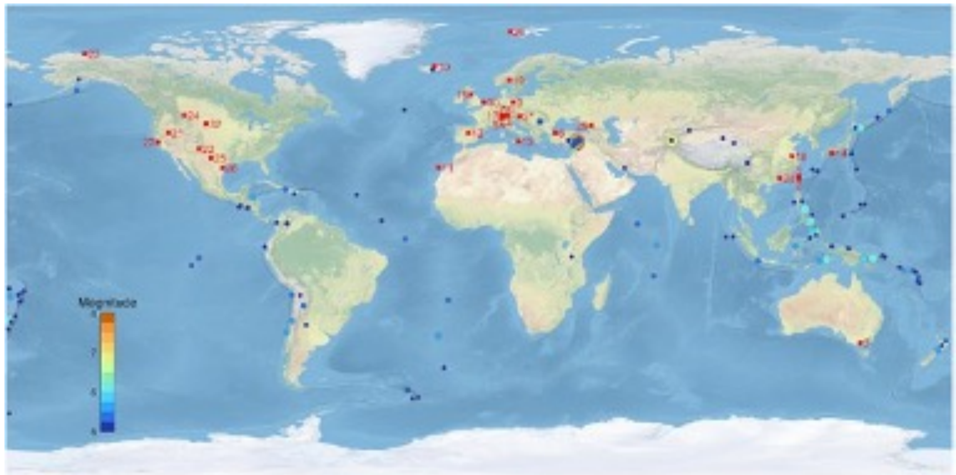

Figure 4. Map of the 32 systems contributing to the Global DAS Month of February 2023. Also shown are the locations of the 156 earthquakes with M ≥ 5 that occurred during February 2023, with size and color proportional to event magnitude. Reproduced from Wuestefeld et al., (2023).

2.2.4 In-Person Field Experience

Training early-career researchers in the practical aspects of DAS experiment planning, data acquisition, data analysis, and interpretation was an early priority. Jonathon Ajo-Franklin gave a humorous and insightful webinar presentation on “What I Learned” (see 2020 AGU DAS Workshop - Part 5 - User Experiences). However, there really is no substitute for experiencing practical aspects that are usually not presented in meaningful detail in scientific literature, e.g., “tap” testing for cable channel locations, managing clocks, choosing and installing cable, the meaning of gauge length, etc. The hands-on Distributed Acoustic Sensing (DAS) Field Experience was held May 30-June 1, 2023, at the Colorado School of Mines in Golden, Colorado where participants gathered for intensive work exploring this exciting technology and the observations it enables. Attendees represented a broad range of research focus, career stage, prior experience with DAS, and institutions. Participants were led through introductory material, a tour of the campus facilities including the Ken Larner GeoMaker Space, fiber splicing in the lab environment, deployment of a fiber with geophone array for comparison, tap tests, review of collected data, as well as exercises in experiment planning, data management, and data analysis with the DAS Data Analysis Ecosystem (DASDAE) software (Figures 5 and 6). Throughout the three-day program there was an emphasis on hands-on interaction and sharing real-world experience. The field course was a fitting bookend to the opening, 3-day virtual short course and workshop in August 2020. Thus, we compared the participant experience levels of the 2023 Field Experience RCN Workshop and the 2023 Hybrid Capstone Workshop (Appendix G) as we did for the 2020 virtual kickoff workshop and the 2020 hybrid AGU workshop. We note that Eileen Martin led both the first 2020 Virtual Workshop and Tutorial and the final 2023 Field Experience.

Figure 5. The participants and instructors of the 2023 DAS RCN Field Experience and DASDAE tutorial on the campus at the Colorado School of Mines. (Photo: Kasey Aderhold)

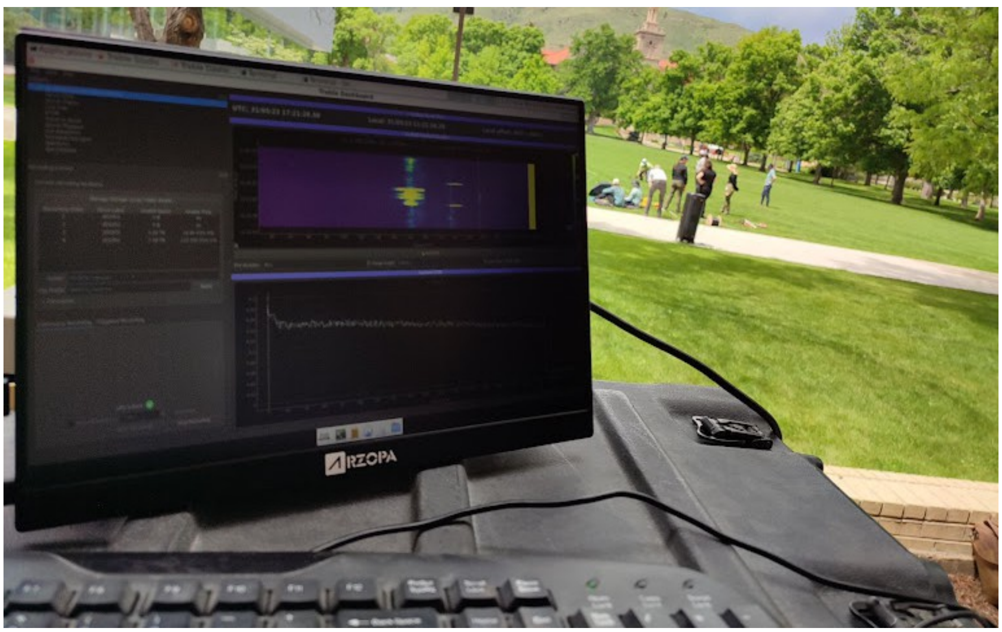

Figure 6. Live data from the installed fiber was displayed while Eileen Martin, course instructor and professor at Colorado School of Mines, leads the collection of sources via a hammer in the background. (Photo: Miguel Rodríguez- Domínguez)

2.2.5 Capstone Workshop

The final DAS RCN event was the Capstone Workshop held June 13-14, 2023 (see Appendix H for agenda), at the University of Wisconsin-Madison, which also included a virtual component for symposium presentations. This workshop brought together the DAS community and offered opportunities to present and discuss DAS science and technology during a 1.5-day program of oral presentations, posters, and ample time for much-needed in-person conversations. A writing team (Appendix A) met following the workshop to outline a vision of where DAS-enabled science should head and what is needed to get there.

2.3 Community Surveys

An active distribution email list that eventually included over 500 participants (Appendix I) was used to announce online Community Forums and conduct follow up surveys to identify priorities that could be addressed with available resources. A survey was made in 2022 to gauge the demands for instruments and services related to DAS. The survey summary is found on the IRIS website (https://www.iris.edu/hq/files/initiatives/das_rcn/Distributed_Acoustic_Sensing_Community_Resources_White_Paper.pdf) and survey results were presented to the community in a video also on the IRIS website (https://www.iris.edu/hq/files/initiatives/das_rcn/DAS-RCN-Call-Recording_2022_04_14.mp4). The survey received ~100 responses, with 60% of responses from early-career researchers in geophysics and seismology (the majority of DAS RCN mailing list subscribers at the time). Responses included representation from many sectors of Earth sciences including geomorphology, cryosphere, hydrology and volcanology. Ninety percent of the respondents indicated they are considering incorporating DAS into their research or teaching portfolios in the next five years. The DAS RCN survey demonstrated the large demand for DAS instruments across the Earth science community. Respondents were specifically asked if DAS were to be available in a "lending library" model such as CTEMPs or PASSCAL, at what frequency would you use these resources. To this question, ~60% responded at least once per year or more frequently. Respondents also indicated that training and support of experimental design and data processing and storage continue to be needed.

As a result of the RCN facilities survey, it was clear that community demand for DAS interrogators and supporting equipment was present across a wide range of the earth sciences and engineering. As the investment by NSF or others in a single, large pool of instruments was unlikely in the immediate future, CTEMPs was funded in 2023 to set up a DAS "Collaborative" with several existing NSF instrument centers and universities to leverage existing instrumentation and to maximize efficiency of instrument accessibility (see Section 4.3). This collaborative concept was designed to add significantly to the several existing and planned DAS instruments in the community by making available a lending pool of instruments managed by CTEMPs. The collaborative concept will eliminate the need, at least in the first few years of DAS community use, for a significant investment up front and will also allow the community to take advantage of instrument evolution in the future, given that DAS instruments are rapidly improving in resolution and performance. In addition to meeting user demand and maximizing instrument use, the collaboration provides financial support (either as pass through from CTEMPs or directly billed by the instrument owners) that can be used for regular instrument maintenance and upgrades.

CTEMPs, NHERI@UTexas, and EarthScope made it their intent to each have DAS interrogator units by early 2024, with NHERI's focus on high spatial resolution for geotechnical applications, EarthScope's focus on longer gauge length seismic monitoring, and CTEMPs focus on high to mid-range resolution. In addition, CTEMPs co-PIs Megan Wendroth (Oregon State) and Eileen Martin (Colorado School of Mines), and Matt Becker (Cal State-Long Beach) and Tieyuan Zhu (Penn State University) agreed to provide their instruments to the pool when not in use for their own research. The landscape of DAS instrumentation continues to adjust amidst demand and new applications, but the spirit of collaboration remains strong with new partnerships, shared resources, and multi-institutional research projects.

3. DAS Science and Technology (2013-2023)

3.1 Portfolio Review Committee on DAS Technology (2021)

Where DAS fits into a facility in the broader geophysical community over the next decade is addressed in this section. Like any science, the investigation of Earth processes that span multiple orders of magnitude in space and time can be significantly propelled by new technologies in one or more dimensions. New technologies often come with a steep cost, even as they reduce the cost of data gathering using previous methods. Whether tried-and-true or new, investing in facilities requires examination of technological developments combined with a crystal ball. NSF's Division of Earth Sciences (EAR) charged the Portfolio Review Committee (Arrowsmith et al., 2021) with examining EarthScope's SAGE-GAGE portfolio and projecting a ten-year future for consideration by EAR's Advisory Committee (AC-GEO). To deal with the range of sensors and the "unknowns" of technology development and adoption, the Portfolio Review Committee found it conceptually useful to represent priorities of different geophysical sensors in a Venn-like diagram (Figure 7). DAS was viewed as an exciting but still emerging technology. Therefore, it was given lower priority than the decades-long instrument base of seismometers. At the same time, DAS development was viewed as both "near frontier" technology, as well as "blue sky" or "far frontier" because it is still in early development and its impact not fully understood. And, by interpolation, it necessarily occupies the "intermediate frontier" space as well.

A glimpse of the "Far Frontier" is exploitation of transoceanic fiber by Marra et al. (2018) in which sub-seafloor earthquakes were located using femtosecond-stable laser interferometry. This application is a case of the meteorologist's noise being the geophysicist's signal. Follow-up improvement in earthquake localization by Marra in 2022 is described in Section 3.2 because it appeared after the work of the Portfolio Review Committee and during the RCN award period. Sub-seabed sensing assumes cooperation between EAR and OCE with regard to oceanic seismic sensing networks.

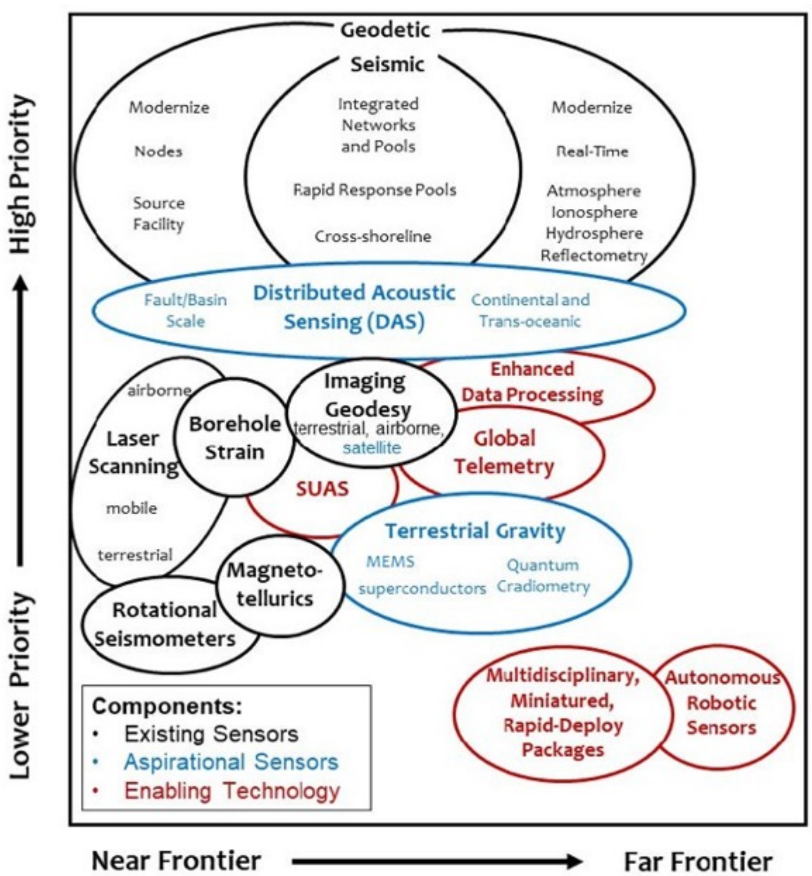

Figure 7. Geophysical sensors by frontier stage and priority for inclusion in a future geophysical facility. Created by W. Hammond for Portfolio Review report (Arrowsmith et al., 2021).

3.2 DAS Advancements During RCN Award (2020-2023)

It would be well beyond the scope of the DAS RCN Final Report to cite, let alone, describe advancements in technology and Earth-sciences applications between 2020 and 2023. Suffice it to say that many of the expectations for DAS described in the Portfolio Review have now appeared in print. One cross-cutting development across many of the Working Groups is the rapidly growing use of existing internet fiber for DAS applications (Lindsey et al., 2019, 2020; Rodríguez Tribaldos and Ajo-Franklin, 2021; Cheng et al., 2023). It can be very cost effect compared with for-purpose fiber as well as expand fiber-sensing activities to submarine fiber (Landrø et al., 2022; Bouffaut et al., 2022). Subsea applications include phenomena as diverse as ship and whale tracking.

Here, we highlight one or two representative papers that were compiled by Working Groups (Appendix J. These papers are not only excellent examples of recent progress in important topical areas of DAS science, but many are seminal. They provide a snapshot of RCN-wide advances during the RCN's activities.

Data Management. Two of the developments in DAS Data Management had roots in the RCN. 1) The newcomer to DAS is immediately faced with the challenge of software for reading, analyzing, and interpreting a DAS recording. The Distributed Acoustic Sensing Data Analysis Ecology (DASDAE) github repository (https://github.com/DASDAE/) comes to the rescue with Python code for managing those tasks (Martin et al, 2022). 2) Secondly, publicly available DAS data hosted by the Department of Energy's Geothermal Data Repository (GDR) (Taverna et al., 2023) and PubDAS at the University of Michigan (Spica et al., 2023) lead to a need to communicate metadata providing context of a big folder of two-dimensional arrays. These include, for example, gage length, file format, spatial coordinates of individual channels, etc. (Lai et al., 2024).

Energy Technologies and CO_2 Sequestration. The development of DAS was driven in the beginning by cementing fiber behind case for repeat Vertical Seismic Profiling (VSP) for reservoir management in the energy industry. In the period 2020-2023, DAS provided a step change in the ability to image the formation and propagation of hydraulic fractures (Liu et al., 2021). Today, low-frequency DAS has become standard industry practice for 4D imaging of stimulated fractures and microseismic events in hydrocarbon and geothermal reservoirs during hydraulic fracturing.

Earthquake and Array Seismology. Perhaps an underappreciated attribute of DAS is that it is a large seismic *array*, that is, it is the equivalent of many thousands of single-component all of which are synchronized in time -- no clocks required, at least to the extent that light travels to all points of the array in a negligibly short amount of time (Ichinose et al., 2022; Näsholm et al., 2022, Kennett, 2022). The major development that blossomed during the RCN time frame was accessing "dark (unlit) fiber" and opening vistas for large-scale deployments of global extent. Logistically, accessing dark fiber required cooperation with telecom cable owners. Technically, it can be problematic to interpret the uneven and unknown coupling of the fiber to the earth, especially when fiber is in conduit. On the other hand, deploying fiber is costly in terms of trenching and limited DAS to maybe ten kilometers or so. Furthermore, the presence of submarine cable for other purposes provided a window to the marine environment for applications anthropogenic and biological sensing (Sladen et al., 2019) and Earthquake Early Warning (Romanowicz et al., 2022).

Instrumentation. The number of DAS vendors increased from about half a dozen to several dozen during the RCN award. Most DAS systems are based on phase-Optical Time Domain Reflectometry (φ-OTDR), including chirped φ-OTDR (Fernando-Ruiz et al., 2019). Additionally, spatial resolution at centimeter-scale is available, particularly for engineering infrastructure monitoring using Optical Frequency Domain Reflectometry (OFDR) (Abedin et al., 2023).

Machine Learning. Machine, or deep learning exploded everywhere in the scientific community and beyond in the last decade. DAS with its large amounts of data was, and will continue to be, a prime candidate. One of the earliest applications was denoising DAS data (Trainor-Guitton et al., 2022); van den Ende et al., 2021). More recently, Zhu et al. (2023) have taken advantage of the two-dimensional, image-like form of coherent DAS data in picking earthquake arrivals with PhaseNet DAS as an extension of automated picking from a network of seismic stations.

Engineering and Urban Seismology. Traditional geotechnical engineering uses near-surface seismics to obtain foundation properties. Techniques like Multichannel Analysis of Surface Waves (MASW) would be conducted with a seismic source and a string of geophones. It turns out that one of the strongest near-surface signals recorded by DAS is surface waves generated by ambient noise, which can be exploited for a dispersion curve and inverted (Zhao et al., 2023; Rossi et al., 2022). Another novel application of DAS is traffic monitoring whose patterns are indicative of societal behavior such as during the COVID pandemic (Lindsey et al., 2020) or the Rose Parade in Pasadena (Wang et al., 2020).

Hydrology. As mentioned in the Introduction, an unpublished experiment by John Selker in the Calapooia River was aimed at problems of stream hydrology. This community sees great potential for hydrology research but also feels somewhat stymied by need for multidisciplinary collaborations. Nonetheless, early studies have begun to elucidate the nature of what can be learned using DAS (Roth et al., 2021).

Geomorphology. Loss of life from landslides is a major geohazard (Froude and Petley, 2018). The British Geological Survey has been researching the use of DAS and Distributed Strain Sensing (DSS) to monitor landslides (Ravet et al., 2021). DAS Priorities for Geomorphology are outlined in Appendix K.

Cryosphere. Avalanches are a significant hazard like landslides but in a glacial environment. Paitz et al. (2023) found consistent properties in a dozen DAS recordings of avalanches. In another alpine glacial study, Walter et al. (2020) recorded numerous stick-slip events using one kilometer of fiber-optic cable on the surface of a glacier that provided measurements of the ice and bed properties (see Appendix E for Walter's February 25, 2021 RCN presentation). As a third example, icequakes were recorded by DAS on an Antarctic ice stream to provide a new method for understanding the physics of icequakes and measuring the influence of ice fabric in the propagation of seismic waves (Hudson et al., 2021).

Volcanic and Seismic Hazard Monitoring. As with other natural hazards, DAS monitoring in volcanically active areas has used both fiber laid in trenches as well as telecom fiber (Klaasen et al., 2023, Nishimura et al., 2021; Jousset et al., 2024). Public awareness of DAS is being increased through outreach efforts such as real-time, live streaming of DAS images of the 2025 Grindavik, Iceland volcanic eruption, by Silixa, Ltd. and ETH-Zurich.

Marine Geophysics. The rapid community adoption of using telecom fiber was described briefly in the introduction to this section in terms of its crosscutting nature. A very comprehensive study by Landrø et al. (2022) using subsea cable showed applications from ship and whale tracking to earthquakes and storms. In addition, the subsea cable enabled subsurface imaging and it detected ocean currents (Spica et al. 2022). Novel applications to marine biology highlight the potential of DAS beyond physical science. Appendix L provides a roadmap to using DAS for a research agenda in marine biology and ocean conservancy.

Geotechnical. Characterizing fracture flow in crystalline rock is a challenging problem in hydrogeology and geothermal systems. The field setup of Becker et al. (2020) consisted of injection/pumping wells and observation wells. Periodic injection/pumping pulse durations varied between two and eighteen minutes. Low-frequency DAS strain response was then used to identify fluid stimulation between wells that were hydraulically connected by bedrock fractures.

Research and Development Test Sites. DAS arrays have the potential to be a contender for new research directions in array seismology for detecting earthquakes or to be a cost-effective method for monitoring industrial-scale hydrogen or carbon dioxide storage. The design of the NORFOX DAS array design paid close attention to optimizing the geometry. The result was a five-arm array with each curvilinear, tentacle-like arm approximately 1.7-kim long (NORSAR, 2023).

4. Challenges, Opportunities, and Priorities

This section is a narrative of challenges, opportunities, and facility needs, as perceived by the DAS RCN community after three years. The section offers background and supporting material for Section 5's top twelve recommendations. The section is organized into five action subtopics to strengthen the DAS community, create a data archive, support new applications of DAS, provide equitable access, and strengthen international engagement.

4.1 Strengthening the DAS Community

As DAS becomes mainstream, DAS results are more scattered at science and engineering meetings like AGU, SSA, SEG, EGU, ARMA, and IMAGE where it has increased from single abstracts to full sessions. In the belief that there is still a place for DAS researchers to communicate with each other with a focus on the technology, the DAS community would probably still benefit from DAS-centric interactions. Recent DAS community meeting events include IMAGE in Houston in September 2024 and SSA's Photonic Seismology Workshop in Vancouver October 7-10, 2024. These DAS-specific meetings provided a space for cross-disciplinary interactions centered around the use of this technology in which representatives of facilities and vendors were present. They also provide a needed space for recruitment of new DAS users, which will continue to be a priority. Although such meetings depend upon individuals to propose session topics, their future occurrences seem quite likely.

Along with events, an online forum would be valuable to continue the same kind of interactions but asynchronously. Maintaining a space that is up-to-date, accessible, and accurate will require dedicated resources. The priority should be for entry point information for new-to-DAS users. Unlike DAS-centric meeting sessions and workshops, it is much less certain that an interactive, online DAS community forum will materialize beyond EarthScope's continuing the DAS email list and events page.

Large-scale community experiments would be another strategy to reach a broader audience and provide access to technology, training, and data. Vendors could be solicited to participate. Existing materials from past events like the DAS RCN field experience can be re-used. At a smaller scale, funding for hands-on training experiences and/or REU internships could be included in proposals as part of a Broader Impacts plan. Although such meetings depend upon individual initiatives in the way meeting session topics are proffered, their future occurrences seem quite likely.

4.2 Creating Open, Sustained, and Standard Data Archive

The second priority of the DAS user community is a sustainable facility that accepts, archives, and distributes DAS data and metadata that are Findable, Accessible, Interoperable, and Reproducible (FAIR). To date, this has been an intractable issue for EarthScope and USGS. EarthScope personnel were active participants in the RCN, but policies have not been established for DAS data. The USGS has found itself constrained in its deployment of DAS because of its open-science data policy. The paradox is that federal and journal policies require “Open Access”, yet cannot provide it, nor can universities. While cloud services could, in principle, provide the storage, can the costs be justified?

Although cost is a factor, practicality looms even larger. Principal investigators who collect DAS data for a specific scientific purpose are not in a position to be burdened with the task of data stewardship, nor trapped between that requirement and the lack of outlets. Data stewardship requires specialized data management expertise for which PIs and the general user community are not typically prepared. Long-term government-funded data center facilities have been used for Distributed Temperature Sensing data (CTEMPs), seismological data (SAGE), geodetic data (GAGE), environmental data (NEON), etc. Only a government-funded, community-governed DAS data facility could provide storage, curation, and distribution services, which has many benefits for funding agencies and the scientific community compared with PI stewardship. The facility will need to establish policies on what and how much will be archived. For example, it could create a review system to accept data. The policies might include minimalist. Its metadata requirements could meet journal requirements for accepted published results, or it could provide storage periods of a year or two beyond publication before sunsetting the data for maximum effectiveness. In general, data archiving requirements need to be consistent with reasonable availability of adequate storage facility and conversations need to occur among the stakeholders, including the DAS user community. Important considerations for an archive are outlined below.

Data and Metadata Standards. Use of internationally accepted metadata content, data format, and derived data product standards increases the value of a DAS data facility. Standardization increases the amount of data that is available to researchers, reduces the time spent retrieving and manipulating data, and provides a solid base for open-source software tools. Broad community representation is essential to avoid standards that become obsolete rapidly or have high barriers to access and use. Tremendous progress has already been made by the Data Management Working Group of the RCN in developing a metadata standard (Lai et al., 2024); incidentally, publication costs were paid by the DAS RCN. Data formats have yet to be standardized for the academic community and the output formats of the various interrogators (typically one of many flavors of HDF5) are used. Establishing an internationally accepted, formally defined DAS data format and metadata standard will enhance the usability of DAS data in the way that seismic data standards established by the International Federation of Digital Seismograph Networks (FDSN) have made seismic data globally accessible and interoperable.

Open-Source Software Tools. Open-source software tools, such as DASDAE (https://github.com/DASDAE) and DASCore (https://github.com/DASDAE/dascore) can greatly advance the community especially when they take advantage of standard formats. Software should also be adaptable to future applications.

Open Data Sets. Open and standard data sets archived long-term at a distribution facility, or facilities, governed by a community of users allows for wider access. For example, the DOE’s

Geothermal Data Repository provides storage of 80 TB of DAS data for the PoroTomo experiment at Brady Hot Springs, NV (Feigl et al., 2016) and the currently active FORGE experiment near Roosevelt Hot Springs, UT (Pankow, 2022). Considerable funds are expended to collect these data. Making them openly available greatly expands and democratizes their use and can promote scientific discovery that might not occur otherwise. Original data should be accompanied by reduced data sets and/or derived products, providing both access and views of data that can be easily scanned to determine if further investigation is warranted for further analysis or interpretation.

Computational Resources. Computational resources close to the data, such as AWS or Google cloud services, are needed for processing and accessing data in place. This sidesteps the time-consuming step of moving data across the internet. To fully democratize the use of large DAS data sets, the facility must subsidize this activity to provide affordable data access as well as computational resources for processing that data. Within the wide scale move to the cloud for storage of geophysical data, specific DAS considerations have also been proposed (Ni et al., 2023).

4.3 Providing Equitable Access

4.3.1 DAS Interrogator Pool

The major barriers to entry for incorporating DAS into geophysical observations are access to a DAS interrogator and computational resources for managing and analyzing large volumes of data. Unlike geophones and broadband seismometers, DAS interrogators are *not* available through NSF facilities like PASSCAL. An extremely limited number have been purchased through NSF's Major Research Instrumentation Program (MRI). Commercially, DAS interrogators can be rented at monthly rates that typically are 5-10% of the purchase price. If acquisition continues to be by individuals and their institutions, transition to a more centralized approach might increase purchasing power as well as leveraging influence for instrumentation development in areas such as signal-to-noise, weight, power draw, alternative power, standard data formats, tools/software, etc. Community-based testing of interrogators by multiple vendors would aid individuals in making a selection best suited to their needs among the growing number of DAS interrogators on the market.

There are advantages of addressing the needs of a science community through a centralized facility, as demonstrated by the successes of long-term NSF facilities like SAGE and GAGE, CTEMPS, OBSIC, IODP, and NCAR. The usual five-year timeframe of facility renewals allows for stability while keeping a competitive edge sharp. Whether the human resources and infrastructure needed by the DAS community are housed in one or several facilities, we take this opportunity to describe what is needed. In the NSF Program Solicitation 23-623, "Competition for the Management of Operation and Maintenance of the National Geophysical Facility", capabilities for DAS were included as part of the portable seismic instrument pool and PI support, data management and access, and software support.

The RCN facilitated the initiation by CTEMPs to facilitate sharing "privately-owned" DAS interrogators that were purchased by early-career professors using their start-up packages. The DAS Instrument Collaborative operating principles and governing rules are provided in Appendix M.

4.3.2 Fiber Access

Access to dark fiber can be obtained through individual academic institutions, e.g., Stanford, Penn State, University of Wisconsin-Madison, University of Washington, and government-sponsored networks, e.g., ESNet, as well as commercially.

4.3.3 Training

Because DAS has a relatively high barrier to entry in both cost as well as computational and analytical tools, perhaps, not unexpectedly, the lead for research projects in these domains have been primarily by seismologists or domain scientists experienced in seismology. Examples include monitoring water-table fluctuations (Sobolevskaia et al., 2024) or alpine glacial processes (Walter et al., 2020). While there is much promise for DAS to contribute to understanding hydrologic or geomorphic processes, adoption has been slow but underway (Roth et al, 2021) (see Appendix K for the Geomorphology Working Group's experience). Nonetheless, a core value of the DAS RCN was to be accessible to all relevant NSF-GEO disciplines – seismology (of course), but also hydrology, geomorphology, polar research, ocean acoustics, and marine geophysics – as well as engineering, that is, DAS without bounds. DAS, however, is not a proven, or even on-the-radar, technology for observing earth processes across all its disciplines.

Multidisciplinary teams are likely to remain the case, but training is needed for non-DAS experts to reach a proficiency level that provides an understanding of DAS' strengths and weaknesses in different applications. Using DAS is similar to many scientific endeavors in which new and emerging technology become more user friendly with time, thus allowing non-experts to concentrate on their science. Already, DAS interrogators can be set up remotely over the internet using menu-driven dialogues. However, details of field installation of DAS cable and subsequent data management and analysis are often not included in published papers. The "tricks of the trade" are incredibly important to a researcher managing a DAS project for the first time. Without a doubt, the best way to learn DAS best practices is to participate in a DAS field course or experiment). Barring an actual field experience, we previously commended Jonathan Ajo-Franklin engaging "what I learned" covering such basics as "tap testing" and managing GPS or Network Time Protocol (NTP). Another resource for learning about the practical aspects of DAS is the RCN webinar series "Instrumentation Showcase" in which half a dozen DAS vendors described their products along with excellent background descriptions of DAS basics (see DAS RCN Webinar Series). Because many vendors offer their services for field installations and acquisition, their engineers are extremely seasoned practitioners, who have experience with multiple cable types of interrogators and who have faced many different field challenges from moles to frostbite and are aware (perhaps confidentially) of novel opportunities or sensitive/proprietary information not always shared in public spaces. Interacting with them can be of enormous benefit to a newcomer. Their participation in research is often reflected by co-authorship on publications.

In summary, training opportunities to learn state-of-the-art tools and processing to gain an entry point to DAS will continue to be a priority. In addition to practical aspects of deployment, potential topics for such offerings might include 1) Accessing big data and cloud computing, 2) Utilizing unique DAS sensing capabilities, such as high spatial resolution and synchronous timing among channels, 3) Showing DAS limitations and differences in comparison with standard seismometers, such as its strain sensing sensitivity with direction, and 4) Demonstrating how DAS might complement other instruments and techniques.

4.4 Addressing Critical Needs of New and Emerging Applications

4.4.1 DAS Instrument, Cable, and Coupling Characterization

The RCN community sees high value in research to characterize DAS in different environments with different techniques and for different applications. These are basic calibration needs that would benefit many areas of DAS geophysical applications. Suggested topics for this broad characterization of DAS for applications include:

- Quantifying characteristics of existing instrumentation and cables.
- Advancing observational capabilities through improvements in coupling, signal-to-noise, calibration, and validation.
- Comparing DAS interrogators from different vendors (see NHERI@UTexas Workshop on Hawaii Shared-Use Equipment Site (December 14, 2022 2-4pm ET | Virtual)).

4.4.2 New Processing Algorithms

Processing algorithms that utilize DAS' array attribute of coherence among channels can improve signal detection (Ichinose and Mellors, 2021; Ichinose et al., 2022) and denoising (van den Ende et al. 2021). Full-waveform modeling (Muir and Zhan, 2022) was used to characterize DAS instrument response and coupling at Brady Hot Springs where a nodal array was co-located. All these studies used the PoroTomo data set and further explorations into different DAS arrays are needed. Being able to estimate signal parameters and infer source characteristics from uniaxial strain will also be an important contribution for many applications. Although individual channels can look like seismograms, DAS requires a different perspective than that of conventional seismic instruments (Kennett, 2022).

4.4.3 Emerging DAS Technologies and Applications

The RCN community must also stay abreast of near- and far-frontier geophysical sensing methods (Figure 7). Future DAS and other fiber-optic sensing technologies are present today in various stages of development. The RCN-sponsored Fall 2022 AGU Special Session on “Novel Methods of Vibration Sensing on Fiber-Optic Cable” received 20 abstracts and an audience that topped 100 attendees showed exciting future possibilities for seismic monitoring, such as a “homebrew” microwave-frequency, forward-transmission “DAS-like” system for earthquake monitoring on internet cable (Bogris et al, 2022), transoceanic sensing of earthquakes using metrology-grade, stable lasers (Marra et al., 2018, 2022), and earthquake detection using information available on internet transponders on submarine cable using State of Polarization (SoP) (Zhan et al., 2021). The October 2024 SSA Photonic Seismology Workshop drew 150 registrants, which again demonstrated continuing strong community interest and involvement in these developments. Participation by telecom developers and DAS instrument vendors led to exciting interactions. In addition, the geophysical DAS community and funding agencies need to maintain cross-disciplinary interactions with developments in fiber-optic sensing in other disciplines like electrical engineering, computer sciences, and even the biomedical and biology communities. In a nutshell, funding is needed to ensure continued Earth sciences awareness and access to photonic sensing technology wherever it is in development.

Because of new forward-transmission interferometry sensing technologies over tens to thousands of kilometers, another promising area for further research is obtaining localized information from long-distance averages. For example, Noe et al. (2023) showed that curvature of the fiber path enabled them to obtain earthquake source parameters from phase interferometry over the 123-km distance between Bern and Basel from full-waveform inverse modeling.

Going outside seismology, electro-magnetically sensitive coatings on fiber can create strain that is sensed using DAS or DSS (Dejneika et al., 2024), opening the way to using fiber for EM sensing in boreholes. In summary, funding agencies should include a priority for emerging fields. As described above, some inroads have already been made in some of the areas below, but there is need for these kinds of science-motivated technological advancements, e.g., earthquake early warning.

New developments already on the horizon include:

- Utilizing gauge lengths less than one meter (already available at less than five centimeters) for infrastructure monitoring and flow characterization such as ocean turbulence and mixing) and for recording whales and other marine life.
- Extending total range by going through repeaters in subsea long-haul cables or including DAS in SMART cables at repeaters (https://www.smartcables.org/).
- Achieving long-period SNR and sensitivity that bridge the gap between seismology and geodesy.
- Increasing high-frequency SNR and sensitivity for acoustic studies.
- Studying value added of co-deploying DAS with broadband seismometers and other geophysical sensors.
- Developing ability to telemeter limited DAS data that might, for example, be based on triggering algorithms for events of interest.
- Determining how measurements of forward-transmission phase or State-of-Polarization on submarine cables can be used for earthquake and ocean-wave monitoring.

4.5 Supporting International Engagement

DAS has been solidly embraced by the global seismological community as a transformative technology. Global DAS Month was an outstanding example (see Section 2.2.3). International participation has been embedded in the RCN. Several initial members of the DAS Steering Committee were based in Europe or China. There are many benefits of international collaboration with respect to DAS technology and applications, just as there are for virtually every discipline in science and technology. No commercial DAS company originated in the U.S. Aside from sharing of opportunities and challenges, international cooperation for DAS specifically includes access to subsea cables, data, and establishing global standards. Because DAS has significant surveillance applications on land and in the oceans, it might run into conflicts with national security and border issues. For example, when operating in the coastal waters, it is always advisable to inform the U.S. Navy.

5. Recommendations

We conclude with a set of twelve recommendations that address the challenges, opportunities, and priorities described in the preceding section.

1. Support regular interactions for the DAS community, both with DAS dedicated in-person/hybrid/virtual events as well as asynchronous online forums. Prioritize student and early career participation and needs.

2. Establish paid internships and funded student research opportunities using DAS instrumentation and/or data.

3. Support a community data archive with the resources to 1) establish and maintain international standards for DAS data and metadata, and to 2) provide data storage and

access in proximity to the computational resources needed to conduct scientific analysis and discovery.

4. Develop data access tools and codes for basic preparation and analysis. Provide training with in-person instruction at meetings of opportunities as well as recorded tutorials available online.

5. Support a formal instrumentation pool for lending interrogators and other DAS equipment. Provide hands-on training with the equipment and guidance on experiment planning, equipment handling, and shipping.

6. Facilitate technical interchange between users and vendors, particularly in collecting specifications and desired instrumentation advances from the user community and distilling use trends for vendors.

7. Establish seed funding or advocate for additional funding for principal investigators to allow uses and applications of DAS to be explored in new and emerging fields.

8. Provide best-practices documents, including basic entry information on using DAS as well as more advanced aspects like establishing data sharing agreements with fiber owners. Ensure information is posted publicly and updates can be submitted for review as advances are made.

9. Advocate for and facilitate planning of large-scale community projects in DAS, e.g. Antarctic Subsea Cable.

10. Participate in planning of large-scale community projects in geophysics and provide information on potential use of DAS, e.g. earthquake early warning, SZ4D, RuFZO.

11. Encourage vendors to provide tools to convert their internal formats into a standardized data format.

12. Establish a framework to facilitate international collaborations on DAS projects.

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Appendix A: Capstone Workshop Writing Group

Name	Affiliation
Herb Wang	University of Wisconsin- Madison
Scott Tyler	University of Nevada, Reno
Robert Woodward	EarthScope Consortium Inc.
Kasey Aderhold	EarthScope Consortium Inc.
Danica Roth	Colorado School of Mines
Ethan Williams	University of Washington
Léa Bouffaut	Cornell University
Afonso Loureiro	ARDITI
Jerry Carter	EarthScope Consortium Inc.
Xiaohang Ji	Pennsylvania State University
Brad Lipovsky	University of Washington
Dante Fratta	University of Wisconsin-Madison
Yingping Li	BlueSkyDas LLC

Appendix B: AGU DAS Workshop Agendas (2018, 2019)

AGU DAS Workshop, Sunday, December 9, 2018, Grand Hyatt, Wilson and Roosevelt Rooms, Washington, D.C.

Time	Presenter	Institution	Title
8:00 – 9:30	**DAS Principles, Instrumentation, and Advances**		
	Herb Wang	U. of Wisconsin-Madison	Introduction to Workshop
	Mahmoud Farhadiroushan (20 mins.)	Silixa	Principles and Recent Advances in Distributed Acoustic Sensing
	Thomas Coleman	Silixa	Installation Considerations for Downhole and Surface Geophysics
	Rob Mellors	Lawrence Livermore National Laboratory	Simulating Distributed Fiber Optic Sensing in the Subsurface: Potential for Improvements
	Martin Karrenbach (20 mins.)	OptaSense	OptaSense Update
	Athena Chalari	Silixa	Silixa: Fiber Optic Distributed Sensors and Applications
9:30-10:00	**Case Studies I**		
	Veronica Rodriguez	Lawrence Berkeley National Laboratory	DAS for Intermediate-scale Near-surface Imaging Using Seismic Ambient Noise.
	Will Ray	Oak Ridge National Laboratory	Industrial Monitoring with DAS
	Dante Fratta	U. of Wisonsin-Madison	Traffic Monitoring with DAS
10:00-10:15	**Break**		
10:15-10:45	**Case Studies II**		
	Eileen Martin	Virginia Tech	Stanford Telecomm Array
	Rob Abbott	Sandia National Laboratories	Borehole DAS recordings of the DAG-1 chemical explosion
	Bane Sullivan	Colorado School of Mines	DAS Array on Colorado School of Mines Campus
10:45-11:30	**Breakout Groups 1) Instrumentation 2) Applications**	Jonathan Ajo-Franklin (Instrument recorder); Biondo Biondi (Case Studies recorder) Speakers stay in their topic group. Non-speakers rotate after 20 minutes between groups	Prepare list of future developments in next 2 years.
11:30-12:00	**Breakout Group Reports**	Jonathan Ajo-Franklin Biondo Biondi	
12:00-13:00	**Lunch**		
13:00-13:40	**DAS Instrument Response and Data Management**		

	Nate Lindsey	UC-Berkeley	How broadband is DAS? An empirical evaluation of instrument response using teleseismic surface waves
	Aleksei Titov	Colorado School of Mines	Understanding low-frequency and production DAS measurements via laboratory tests
	Matt Becker	Cal State Long Beach	Hydrologic Applications of Low-frequency DAS
	Chad Trabant	IRIS	Data Management at IRIS
13:40-14:00	**Earthquake Seismology**		
	Chunquan Yu	Caltech	The potential of DAS in teleseismic studies: insights from the Goldstone experiment
	Zefeng Li	Caltech	Earthquake detection with DAS arrays
14:00-14:40	**Hydrocarbon, Geothermal, and CO2 Reservoir Applications**		
	Doug Miller	MIT	Borehole DAS Results at Brady Hot Springs
	Martin Karrenbach	OptaSense	Hydrocarbon reservoir monitoring
	Mark Kelley	Battelle	CO2 Sequestration Monitoring
	Gary Binder	Colorado School of Mines	Time-lapse seismic monitoring of individual hydraulic frac stages using a downhole DAS array
14:40-15:00	**Break**		
15:00-15:45	**Breakout Groups 1) Instrumentation 2) Applications**	Jonathan Ajo-Franklin (Instrument recorder); Biondo Biondi (Case Studies recorder) Non-speakers rotate after 20 minutes between breakout groups	Prepare list of future developments in next 2 years.
15:45-16:15	**Breakout Group Reports**	Jonathan Ajo-Franklin Biondo Biondi	
16:15-17:00	**Future of DAS within the AGU Community** Herb Wang, Biondo Biondi, Jonathan Ajo-Franklin, Bob Detrick (panelists)	Committee of the Whole	Discuss future needs of AGU DAS community.

AGU DAS Workshop, Sunday, December 8, 2019, Grand Hyatt, Sunset Room, San Francisco

Distributed Acoustic Sensing (DAS) offers unique opportunities for acoustic sensing of the environment and is becoming more established in the seismic community and others because of its transformative potential. The workshop will provide an overview of the technology and its principles. Presenters include vendors whose equipment is being used by earth scientists. The technology overview will be followed a discussion of data processing and tools available, along with presentations by various teams illustrating applications that include near-surface characterization, infrastructure monitoring, earthquake seismology, hydrology, and geothermal reservoir and carbon sequestration monitoring.

The learning objective is to provide attendees a practical understanding of the potential and limitations of DAS when they consider using the technology for their application.

0700 – 0800: Continental Breakfast

0800 – 0830: Principles of DAS (Michael Mondanos, Martin Karrenbach)

0830 – 0930: Data Processing and Data Management

Field to Client (Thomas Coleman, Athena Chalari, Jerry Carter)

Archiving DAS Data (Nicole Taverna)

0930 – 1000: DAS Techniques

Ambient Noise (Patrick Paitz)

Machine Learning (Bob Clapp)

1000 – 1030: Break

10:30 – 11:15 DAS Case Histories

Infrastructure (e.g., traffic, rail, pipeline, road, industrial processes, etc.) (Dante Fratta)

Cryosphere (Andreas Fichtner)

Borehole guided waves (Ariel Lellouch)

1115 – 1200: Hydrology and Low-Frequency Applications (Matt Becker, Veronica Rodriguez) and Geothermal and Carbon Sequestration Applications (Julia Correa)

1200 – 1300: Lunch

1300 – 1400: Earthquake Seismology using Dark Fiber (Zhongwen Zhan) and Undersea DAS (Nate Lindsey, Anthony Sladen, Zhongwen Zhan)

1400 – 1430: Break

1430 – 1500: What is DAS Measuring? (Rob Mellors) and Source Physics Experiment (Rob Abbott)

1500 – 1515: Open Mike (5 min each) (Bin Luo, …)

1515 – 1600: Vendor Presentations and Demos

1600 – Adjourn

Organizers: Herb Wang (hfwang@wisc.edu, U. of Wisconsin-Madison), Robert Detrick (detrick@iris.edu, IRIS), Robert Woodward (woodward@iris.edu, IRIS), Scott Tyler (styler@unr.edu, U. of Nevada-Reno).

Appendix C: Steering Committee

Name	Affiliation	Role
Herb Wang	University of Wisconsin-Madison	PI
Scott Tyler	University of Nevada, Reno	Co-PI
Robert Woodward	EarthScope Consortium Inc.	Co-PI
Kasey Aderhold	EarthScope Consortium Inc.	Project Coordinator
Jonathan Ajo-Franklin	Rice University	Committee Member
Matt Becker	California State University, Long Beach	Committee Member
Dante Fratta	University of Wisconsin-Madison	Committee Member
Mark Hausner	Desert Research Institute	Committee Member
Zuyuan He	Shanghai Jiao Tong University	Committee Member
Charlotte Krawczyk	GFZ-Potsdam	Committee Member
Yingping Li	BlueSkyDas	Committee Member
Nate Lindsey	FiberSense	Committee Member
Eileen Martin	Colorado School of Mines	Committee Member
Whitney Trainor-Guitton	Colorado School of Mines / Zanskar Geothermal & Minerals	Committee Member
Zhongwen Zhan	Caltech	Committee Member
Lucas Zoet	University of Wisconsin-Madison	Committee Member
Danica Roth	Colorado School of Mines	Committee Member

Appendix D: Working Group Leads

Working Group Topic	Names and Affiliations
Data Management	Robert Mellors (UCSD), Jerry Carter (EarthScope)
Energy Technologies and CO2 Monitoring	Aleksei Titov (Fervo Energy), Marie Macquet (Carbon Management Canada), Ariel Lellouch (Stanford/Tel Aviv University), Julia Correa (LBL)
Earthquake and Array Seismology	Cliff Thurber (University of Wisconsin-Madison), Ray Willemann (AFRL)
Instrumentation	Kasey Aderhold (EarthScope), Zuyuan He (Shanghai Jiao Tong University), Yingping Li (BlueSky)
Machine Learning	Eileen Martin (Colorado School of Mines), Whitney Trainor-Guitton (Colorado School of Mines/Zanskar Geothermal & Minerals)
Engineering and Urban Seismology*	Dante Fratta (University of Wisconsin-Madison), Biondo Biondi (Stanford)
Hydrology	Mark Hausner (DRI), Scott Tyler (University of Nevada, Reno)
Geomorphology	Danica Roth (Colorado School of Mines), Claire Masteller (WUSTL)
Cryosphere	Luke Zoet (University of Wisconsin-Madison), Brad Lipovsky (University of Washington)
Volcanic and Seismic Hazard Monitoring	Lotte Krawczyk (GFZ Potsdam)
Marine Geophysics	Hannah Glover (Oregon State University), Meagan Wengrove (Oregon State University), Madison Smith (WHOI), Nate Lindsey (Stanford/Fibersense)
Geotechnical	Matt Becker (Cal State-Long Beach)
Early-Career DAS Network (Pigtails)	Nate Lindsey (FiberSense)
Research and Development Test Sites	Andreas Wuestefeld (NORSAR)

*Engineering and Urban Seismology were separate working groups and combined in March 2022.

Appendix E: DAS RCN And Community Events

Fiber Optic Seismology for Earthquake Hazards Research, Monitoring and Early Warning - USGS John Wesley Powell Center for Analysis and Synthesis (Ongoing)

Photonic Seismology: Lighting the Way Forward (October 8-11, 2024 | Vancouver, B.C., Canada)

Distributed Fiber-Optic Sensing: Advances in Applications and ML-based Techniques Workshop at 2023 IMAGE (September 1, 2023 | Houston, TX, USA)

DAS RCN Webinar Marine Geology/Geophysics WG - Exploring the use of Distributed Acoustic Sensing (DAS) for Ocean Acoustic Monitoring - Shima Abadi (August 31, 2023 | Virtual)

Advances in earthquake and explosion monitoring using Distributed Acoustic Sensing Symposium at 2023 IUGG (July 11- 20, 2023 | Berlin, Germany)

DAS RCN Webinar Marine Geology/Geophysics WG - Using DAS to observe nearshore waves and processes - Hannah Glover and Marcela Ifju (June 29, 2023 | Virtual)

ARMA Workshop on Distributed Fiber Optic Sensing for Geomechanical Applications (June 25, 2023 | Atlanta, Georgia, USA)

DAS RCN Workshop (June 13-14, 2023 | Madison, Wisconsin, USA)

DAS Field Experience and DASDAE Tutorial (May 30-June 1, 2023 | Golden, Colorado, USA)

DAS RCN Webinar Marine Geology/Geophysics WG - Detection of tsunami waves and ocean temperature anomalies with DAS - Carlos Becerril and Julián Pelaez (May 25, 2023 | Virtual)

DAS Workshop at 2023 SSA Meeting (April 17, 2023 | San Juan, Puerto Rico) DAS RCN Global Monitoring Month (February 1-28, 2023 | Globally)

DAS RCN Community Forum - Global DAS Day - Andreas Wuestefeld, Kit Chambers, Daniel Bowden, Lena Urmantseva, Fabian Lindner, Agatha Podrasky and David Podrasky, Andy Nowacki, Alan Baird (February 14, 2023 | Virtual) NHERI@UTexas Workshop on Hawaii Shared-Use Equipment Site (December 14, 2022 | Virtual)

Observing Wave Field Gradients in Seismology – Applications, Instrumentation and Theory Session at 2022 AGU Fall Meeting (December 12, 2022 | Chicago, Illinois, USA)

Novel Methods of Vibration Sensing on Subsea, Fiber-Optic Cable Session at 2022 AGU Fall Meeting (December 12, 2022 | Chicago, Illinois, USA)

DAS RCN Workshop on Managing Distributed Acoustic Sensing Data at 2022 AGU Fall Meeting (December 11, 2022 | Chicago, Illinois, USA)

2nd EAGE Workshop on Fiber Optic Sensing for Energy Applications (December 5-7, 2022 | Kuala Lumpur, Malaysia) DAS RCN Community Forum - Global DAS Month and PubDAS - Andreas Wuestefeld, Ƶack Spica (slides), Rob Mellors (December 2, 2022 | Virtual)

DAS RCN Webinar Series - Engineering and Urban Seismology WG - Siyuan Yuan, Jingxiao Liu, Joseph Vantassel (November 3, 2022 | Virtual)

DAS RCN Webinar Series - Instrumentation WG - Instrumentation Showcase - Part 5 - Agatha Podrasky (October 19, 2022 | Virtual)

Global EQ DAS Data Campaign Coordination Meeting (September 28, 2022 | Virtual)

DAS RCN Webinar Series - Instrumentation WG - Instrumentation Showcase - Part 4 - Oleg Valishin and Vincent Lanticq (September 21, 2022 | Virtual)

Distributed Fiber-Optic Sensing in Applied Geophysics Workshop at IMAGE 2022 (September 1, 2022 | Houston, Texas, USA)

DAS RCN Webinar Series - Instrumentation WG - Instrumentation Showcase - Part 3 - Dan Danskin and Jakob Haldorsen (July 20, 2022 | Virtual)

ARMA Workshop on Distributed Fiber Optic Sensing in Geomechanical Applications (June 26, 2022 | Santa Fe, New Mexico, USA)

Toward Gigatonnes CO2 Storage — Grand Geophysical Challenge (June 26-30, 2022 | Stanford, California, USA and Virtual)

Distributed Fiber Optics For Formation Evaluation at 2022 SPWLA (June 11-15, 2022 | Stavanger, Norway)

DAS RCN Webinar Series - Instrumentation WG - Instrumentation Showcase - Part 2 - Andreas Ellmauthaler and Andres Chavarria (June 15, 2022 | Virtual)

Visioning a DAS Facility to Advance SAGE-GAGE Science SIG at 2022 SAGE/GAGE Workshop (June 15, 2022 | Pittsburgh, Pennsylvania, USA)

Advances in Fiber-Optic Technologies for Geophysical Applications at 2022 EGU (May 24, 2022 | Vienna, Austria and Virtual)

DAS RCN Webinar Series - Instrumentation WG - Instrumentation Showcase - Part 1 - David Hill and Ricardo Arias (May 18, 2022 | Virtual)

Environmental Seismology and Distributed Acoustic Sensing Clinic at 2022 CSDMS (May 17-19, 2022 | Boulder, Colorado, USA)

Fiber Optic Seismology: Understanding Earth Structure and Dynamics with Distributed Sensors at 2022 SSA (April 21, 2022 | Bellevue, Washington, USA)

DAS RCN Community Forum - Community Resources/Facilities (April 14, 2022 11am ET | Virtual)

EAGE Workshop on Distributed Fibre Optics Sensing at Geotech (April 4-6, 2022 | London, England and Virtual)

DAS RCN Webinar Series - Marine Geophysics WG - Léa Bouffaut, Ethan Williams, William Wilcock, Han Xiao, Pierre Martz, Mikael Mazur - Seafloor Fiber Optic Sensing (March 30, 2022 | Virtual)

DAS RCN Community Forum - Future of the RCN (February 10, 2022 | Virtual)

Distributed Acoustic Sensing in Earth Sciences: From Novice to Cutting Edge at 2021 AGU Fall Meeting (December 12, 2021 | New Orleans, Louisiana, USA)

DAS Workshop - NHERI@UTexas - Infrastructure & Imaging (October 21-22, 2021 | Baton Rouge, Louisiana, USA and Virtual)

Distributed Fiber-Optic Sensing in Applied Geophysics at SEG Annual Meeting (September 30, 2021 and October 1, 2021| Denver, Colorado, USA)

Distributed Acoustic Sensing: Scientific Frontiers and Community Needs Workshop at 2021 GAGE/SAGE Workshop (August 13, 2021 | Virtual)

DAS RCN Webinar Series - Data Management WG - DAS Data Wrangling (July 28, 2021 | Virtual)

2021 Antarctic Subsea Cable Workshop: High-Speed Connectivity Needs to Advance US Antarctic Science (June 29 - July 1, 2021 | Virtual)

Fiber Optic Distributed Temperature, Acoustic, and Strain Sensing for Geomechanics at 55th US Rock Mechanics and Geomechanics Symposium (ARMA) (June 20-23, 2021 | Houston, Texas, USA)

DAS RCN Webinar Series - Machine Learning WG - Whitney Trainor-Guitton, Martijn van den Ende, Eileen Martin, Fantine Huot - Machine Learning for DAS Data Analysis (June 17, 2021 | Virtual)

DAS RCN Geomorphology Working Group: Earth and Planetary Surface Processes Community Forum (June 9, 2021 | Virtual)

AGU EPSP Connects Panel "Surface processes applications of environmental seismology and distributed acoustic sensing (DAS) Q&A" (May 26, 2021 | Virtual)

DAS RCN Webinar Series - Engineering WG - Meghan Quinn and Peter Hubbard - DAS and Engineering (May 19, 2021 | Virtual)

DAS RCN Webinar Series - Marine Geophysics WG - Itzhak Lior - Distributed Acoustic Sensing at the Ocean-Bottom (April 29, 2021 | Virtual)

Advances in Fibre-Optic Technologies for Geophysical Applications at 2021 EGU (19-30 April, 2021 | Virtual) Fiber-optic Seismology at 2021 SSA (April 18-23, 2021 | Virtual)

Recent Development in Ultra-dense Seismic Arrays with Nodes and Distributed Acoustic Sensing at 2021 SSA (April 18- 23, 2021 | Virtual)

DAS RCN Webinar Series - Energy Technologies and CO2 Monitoring WG - Don Lawton, Jan Dettmer, and David Eaton - Applications of Distributed Acoustic Sensing (DAS) for monitoring and verifying geological storage of CO2 (March 24, 2021 | Virtual)

EAGE (2nd Annual) Workshop on Distributed Fibre Optic Sensing (March 1-3, 2021 | The Hague, The Netherlands)

DAS RCN Webinar Series - Cryosphere WG - Fabian Walter - Distributed Acoustic Sensing in the Cryosphere (February 25, 2021 | Virtual)

Advances in Distributed Sensing for Geophysics Workshop at 2021 SEG-AGU (February 8-10, 2021 | Houston, Texas, USA)

Call-for-Papers - SEG/AAPG Interpretation Special Section on Distributed Acoustic Sensing (Manuscripts due February 1, 2021 | November 1, 2021)

Call-for-Papers - EGU Solid Earth Special Issue on Fibre-Optic Sensing in Earth Sciences (Manuscripts due December 31, 2020)

DAS Workshop at 2020 AGU Fall Meeting (December 1, 2020 | Virtual) [https://www.youtube.com/watch?v=U7tke4yInHY].

Fiber Optic Sensing for Energy Applications in Asia Pacific at EAGE Workshop (November 9-11, 2020 | Virtual) DAS: Advances in Fiber Optic Sensing Over the Last Decade Workshop at 2020 SEG Workshop (October 15, 2020 | Virtual)

DAS Workshop - Part 5 - User Experiences (2020). IRIS Earthquake Science Presentations, YouTube, [https://www.youtube.com/watch?v=U7tke4yInHY].

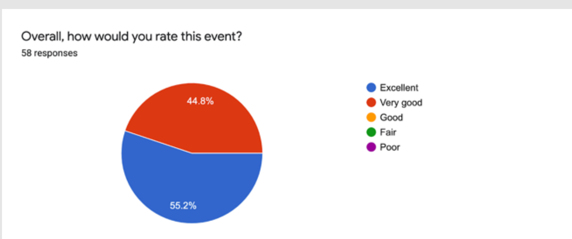
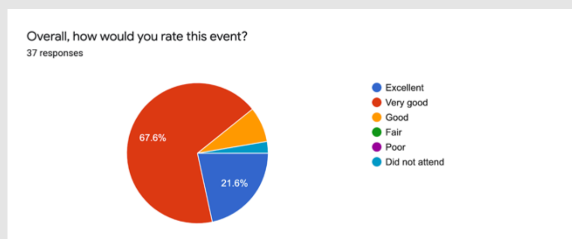
SPE Workshop: Fiber-Optic Sensing Applications for Well, Reservoir, and Asset Management (August 31-September 2, 2020 | San Diego, California, USA)

Distributed Acoustic Sensing Virtual Workshop and Tutorial (August 10, 12, 17, 2020 | Virtual) [https://www.youtube.com/playlist?list=PLvd8fqCFf8CVDFC9IEVAf0UuVXaBZRBPI].

Appendix F: Survey Results of 2020 Virtual Workshop and Tutorial vs. 2020 Virtual AGU Workshop

The 2020 AGU Workshop on Distributed Acoustic Sensing (DAS) Workshop was held December 1, 2020 from 1-7pm ET as part of the virtual 2020 AGU Fall Meeting. Sessions included varied talk formats and topics related to collecting and using DAS data as well as presentations from instrument vendors aimed at a broad audience, from new users to experienced researchers. Pre-registration ($100/participant paid to AGU) was ~200 persons, Actual participation reached 105 at its peak over the half-day session.

- Event website: https://www.iris.edu/hq/event/2020_agu_workshop_on_distributed_acoustic_sensing
- Recording playlist: https://www.youtube.com/playlist?list=PLvd8fqCFf8CXgn5m19f0zwcqIeuxmA38N
- Organizers: Scott Tyler (University of Nevada, Reno), Rachel Hatch (University of Nevada, Reno), Herbert Wang (University of Wisconsin-Madison), Kasey Aderhold (IRIS), Robert Woodward (IRIS)

<table>
<tr><th colspan="2">2020 Post-Event Survey Responses</th></tr>
<tr><th>Virtual Workshop and Tutorial - August 2020
~270 attendees at peak participation
58 Responses</th><th>AGU Workshop - December 2020
~105 attendees at peak participation
37 Responses</th></tr>
<tr><td>
</td><td>
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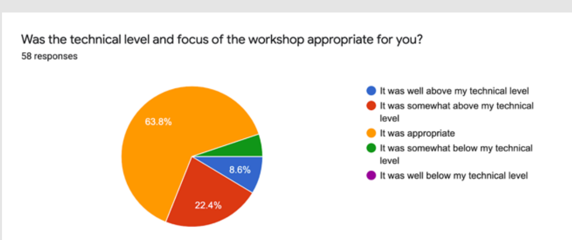
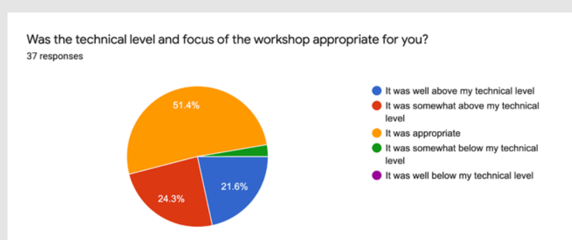
<tr><td>
</td><td>
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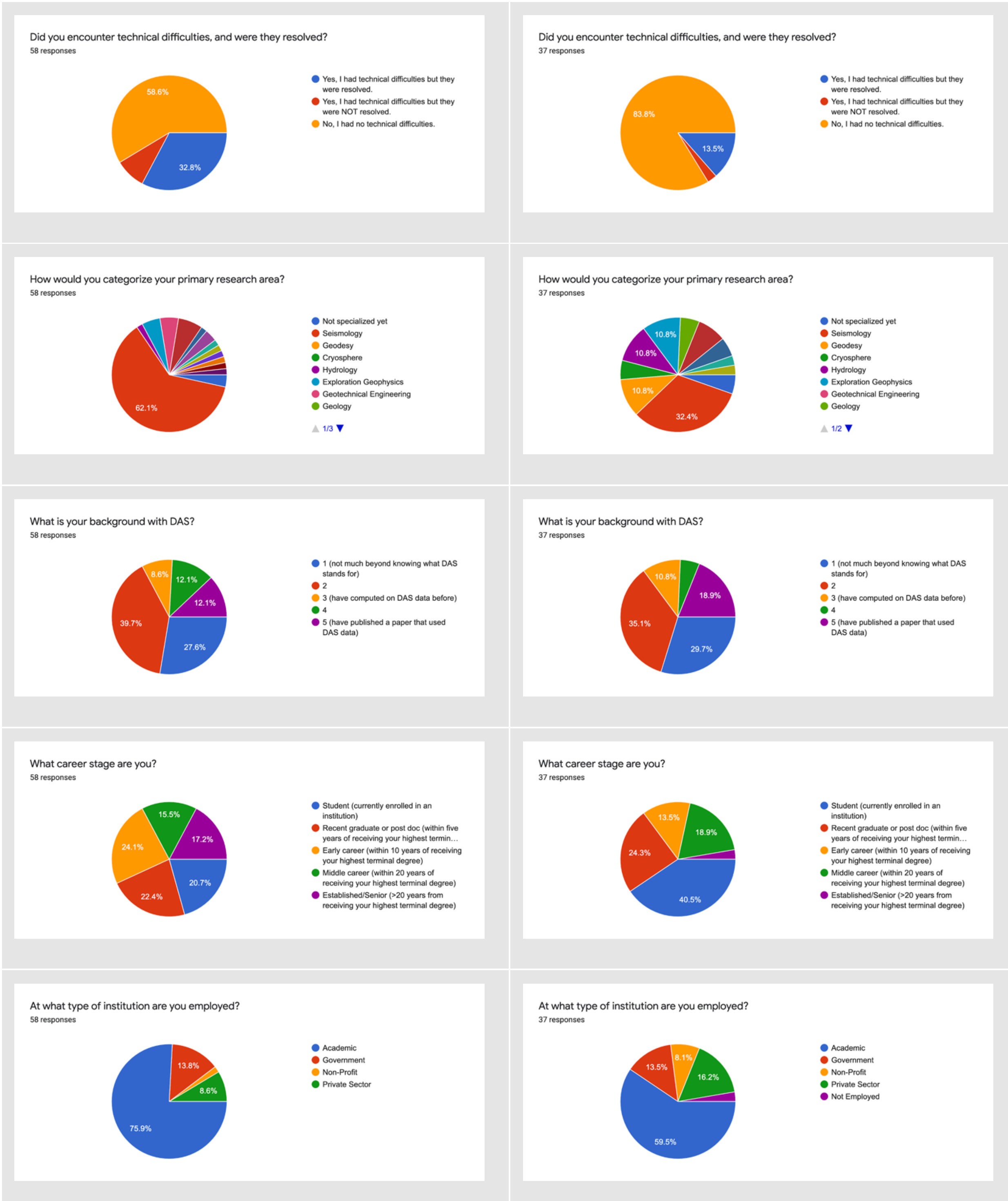
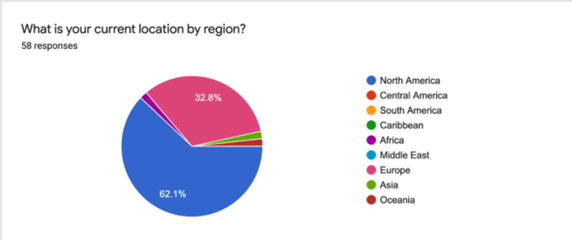
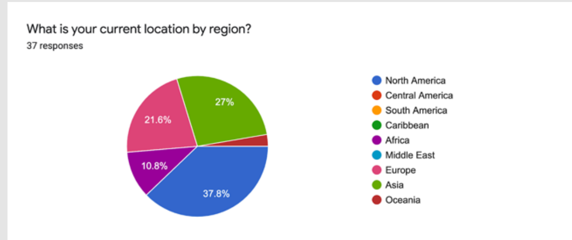
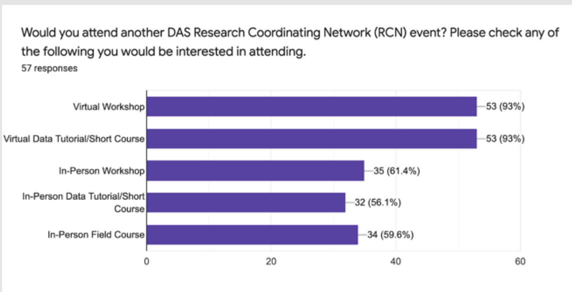
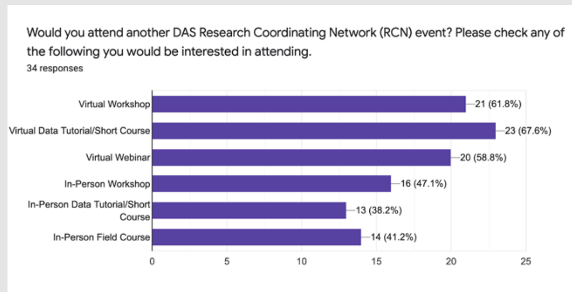


Did you encounter technical difficulties, and were they resolved?
58 responses
58.6%
32.8%
Yes, I had technical difficulties but they were resolved.
Yes, I had technical difficulties but they were NOT resolved.
No, I had no technical difficulties.
Did you encounter technical difficulties, and were they resolved?
37 responses
83.8%
13.5%
Yes, I had technical difficulties but they were resolved.
Yes, I had technical difficulties but they were NOT resolved.
No, I had no technical difficulties.
How would you categorize your primary research area?
58 responses
62.1%
Not specialized yet
Seismology
Geodesy
Cryosphere
Hydrology
Exploration Geophysics
Geotechnical Engineering
Geology
1/3
How would you categorize your primary research area?
37 responses
10.8%
10.8%
10.8%
32.4%
Not specialized yet
Seismology
Geodesy
Cryosphere
Hydrology
Exploration Geophysics
Geotechnical Engineering
Geology
1/2
What is your background with DAS?
58 responses
8.6%
12.1%
12.1%
39.7%
27.6%
1 (not much beyond knowing what DAS stands for)
2
3 (have computed on DAS data before)
4
5 (have published a paper that used DAS data)
What is your background with DAS?
37 responses
10.8%
18.9%
35.1%
29.7%
1 (not much beyond knowing what DAS stands for)
2
3 (have computed on DAS data before)
4
5 (have published a paper that used DAS data)
What career stage are you?
58 responses
15.5%
17.2%
24.1%
20.7%
22.4%
Student (currently enrolled in an institution)
Recent graduate or post doc (within five years of receiving your highest termin…
Early career (within 10 years of receiving your highest terminal degree)
Middle career (within 20 years of receiving your highest terminal degree)
Established/Senior (>20 years from receiving your highest terminal degree)
What career stage are you?
37 responses
13.5%
18.9%
24.3%
40.5%
Student (currently enrolled in an institution)
Recent graduate or post doc (within five years of receiving your highest termin…
Early career (within 10 years of receiving your highest terminal degree)
Middle career (within 20 years of receiving your highest terminal degree)
Established/Senior (>20 years from receiving your highest terminal degree)
At what type of institution are you employed?
58 responses
13.8%
8.6%
75.9%
Academic
Government
Non-Profit
Private Sector
At what type of institution are you employed?
37 responses
13.5%
8.1%
16.2%
59.5%
Academic
Government
Non-Profit
Private Sector
Not Employed









State up to three aspects of the workshop and/or tutorial which were most valuable to you: (select common answers)

- Hands on tutorials, working with real data/codes
- General overview of DAS
- Seeing different applications of DAS
- Networking - Having breakouts and Slack
- Variety in talk lengths and formats

State up to three aspects of the workshop and/or tutorial which were most valuable to you: (select common answers)

- Hearing from vendors, instrument manufacturers
- General overview of DAS
- Seeing different applications of DAS
- Getting to know the community and their work
- Remote access, allowing presenters to pre-record

State up to three aspects of the workshop which could be improved: (selection of common answers)

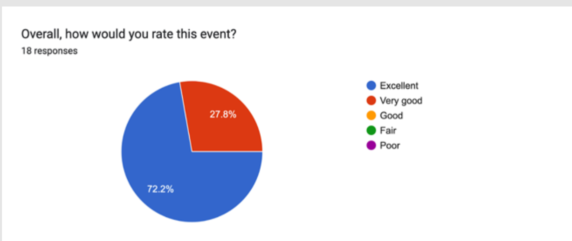
- Breakouts were good but still too short, more focus
- Time zone
- Lightning talks too “lightning”, pre-record next time
- Have tutorials and other work moved to offline
- Issue with data access (but fix was good)
- Better wrap up at the end of breakouts

State up to three aspects of the workshop which could be improved: (selection of common answers)

- More interaction with attendees, breakouts
- Time zone
- Timing/length of talks/Q&A - longer & more flexible
- Move DAS primer to be before the workshop
- Standard format for presenters, especially vendors
- More diversity in speakers

Appendix G: Survey Results of 2023 In-person Field Experience vs. 2023 Hybrid Capstone Workshop

The DAS RCN field experience was held May 30-June 1, 2023 in Golden, Colorado and the DAS RCN workshop was held June 13-14, 2023 in Madison, Wisconsin as well as virtually. See Section 1.3 for more details.

<table>
<tr><th colspan="2">2020 Post-Event Survey Responses</th></tr>
<tr><td>In-Person Field Experience - May/June 2023
32 attendees at peak participation
18 Responses</td><td>In-Person and Virtual Workshop - June 2023
~50 in-person/~50 virtual attendees at peak participation
24 Responses</td></tr>
<tr><td>


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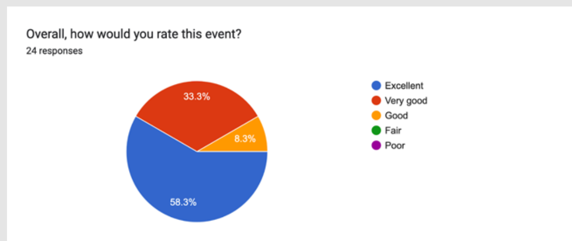

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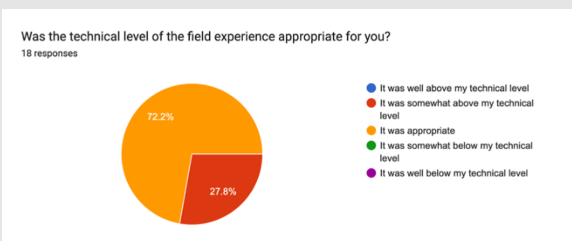

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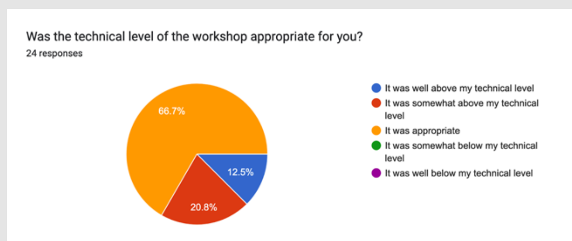

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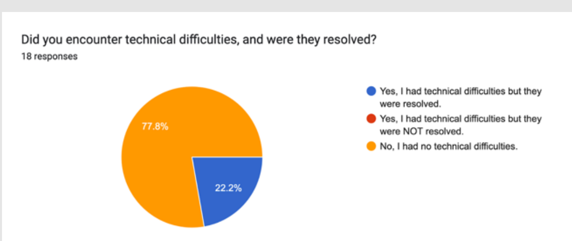

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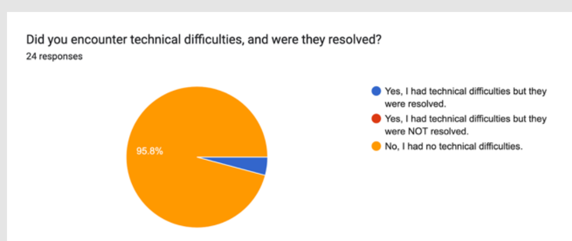

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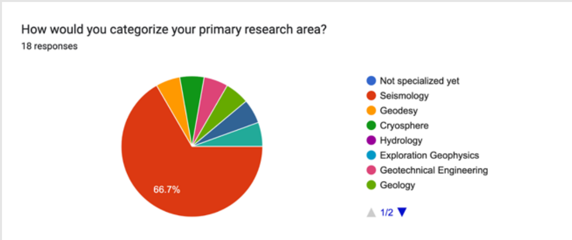
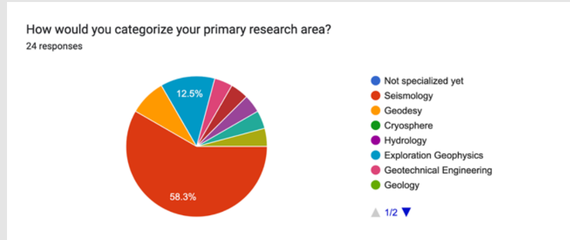
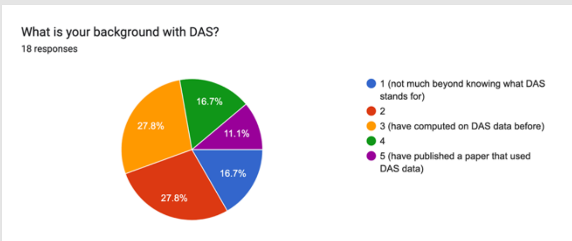
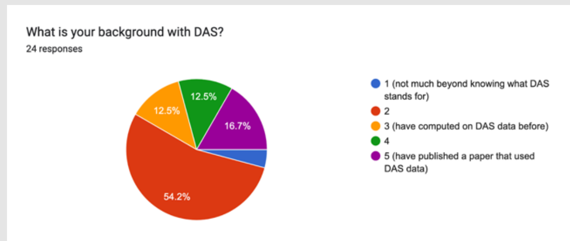
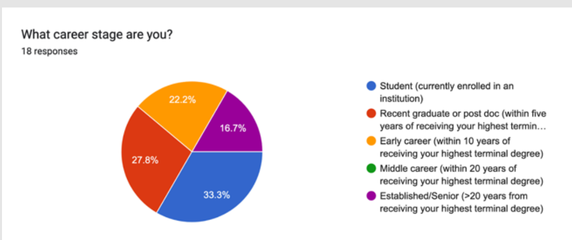
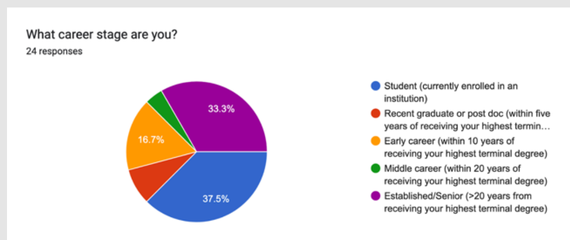

How would you categorize your primary research area?
18 responses
66.7%
Not specialized yet
Seismology
Geodesy
Cryosphere
Hydrology
Exploration Geophysics
Geotechnical Engineering
Geology
1/2

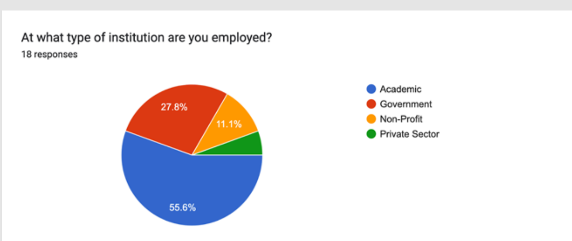

How would you categorize your primary research area?
24 responses
12.5%
58.3%
Not specialized yet
Seismology
Geodesy
Cryosphere
Hydrology
Exploration Geophysics
Geotechnical Engineering
Geology
1/2

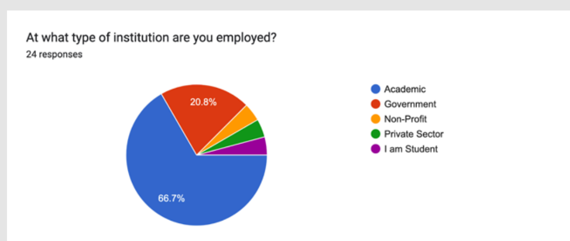

What is your background with DAS?
18 responses
16.7%
27.8%
11.1%
16.7%
27.8%
1 (not much beyond knowing what DAS stands for)
2
3 (have computed on DAS data before)
4
5 (have published a paper that used DAS data)

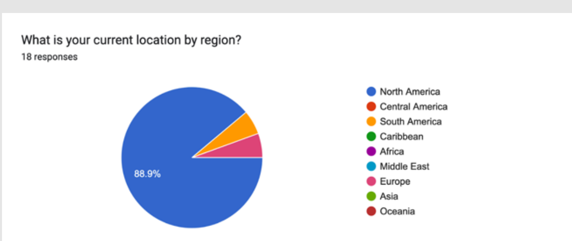

What is your background with DAS?
24 responses
12.5%
12.5%
16.7%
54.2%
1 (not much beyond knowing what DAS stands for)
2
3 (have computed on DAS data before)
4
5 (have published a paper that used DAS data)

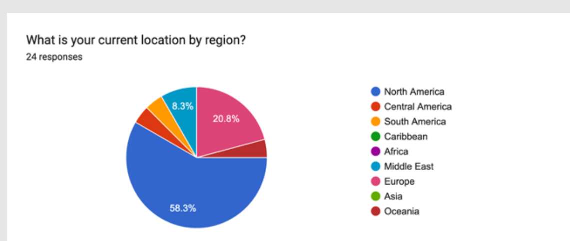

What career stage are you?
18 responses
22.2%
16.7%
27.8%
33.3%
Student (currently enrolled in an institution)
Recent graduate or post doc (within five years of receiving your highest termin…
Early career (within 10 years of receiving your highest terminal degree)
Middle career (within 20 years of receiving your highest terminal degree)
Established/Senior (>20 years from receiving your highest terminal degree)


What career stage are you?
24 responses
33.3%
16.7%
37.5%
Student (currently enrolled in an institution)
Recent graduate or post doc (within five years of receiving your highest termin…
Early career (within 10 years of receiving your highest terminal degree)
Middle career (within 20 years of receiving your highest terminal degree)
Established/Senior (>20 years from receiving your highest terminal degree)


At what type of institution are you employed?
18 responses
27.8%
11.1%
55.6%
Academic
Government
Non-Profit
Private Sector


At what type of institution are you employed?
24 responses
20.8%
66.7%
Academic
Government
Non-Profit
Private Sector
I am Student


What is your current location by region?
18 responses
88.9%
North America
Central America
South America
Caribbean
Africa
Middle East
Europe
Asia
Oceania


What is your current location by region?
24 responses
8.3%
20.8%
58.3%
North America
Central America
South America
Caribbean
Africa
Middle East
Europe
Asia
Oceania

Appendix H: 2023 DAS RCN Capstone Workshop Agenda

2023 DAS RCN WORKSHOP
JUNE 13-14, 2023
MADISON, WISCONSIN

June 13th, 2023 - Weeks Hall - Room 140 - 1215 W. Dayton St

8:00 - *Coffee/Registration*

8:30 - 8:45 - Introductions/Welcome - Herb Wang

8:45 - 9:15 - Comments from NSF, Q&A/Discussion - Eva Zanzerkia and Maggie Benoit

9:15 - 9:45 - Meeting the Challenges of DAS Data Archival & Dissemination - Jerry Carter

9:45 - 10:15 - DAS Instrumentation and Data Management for Real Time Geomechanics and Seismology - Andres Chavarria

10:15 - 10:30 - SeaFOAM: A permanent DAS deployment in Monterey Bay, California for monitoring and earthquake early warning - Richard Allen

10:30 - 11:15 - Break/Posters

11:15 - 11:30 - Eavesdropping at the speed of light: Distributed acoustic sensing of baleen whales - Léa Bouffaut

11:30 - 12:00 - Observational frontiers in physical oceanography enabled by fiber optic sensing - Ethan Williams

12:00 - 12:30 - Insights from the first in-river DAS deployment - Danica Roth

12:30 - 14:00 - *Lunch - on your own*

14:00 - 14:30 - Distributed Acoustic and Temperature Sensing in Permafrost Tundra in Utqiaġvik, Alaska for Long-term, In-situ Permafrost Monitoring Using Ambient Noise - Xiaohang Ji

14:30 - 15:00 - Cryosphere, Submarine, Urban, and Clean Energy Distributed Acoustic Sensing (DAS) projects at the University of Washington Fiber Lab - Brad Lipovsky

15:00 - 15:45 - Break/Posters

15:45 - 16:00 - 3C DAS array or Applications of borehole DAS Ambient noise - Yingping Li

16:00 - 16:15 - Microseismic monitoring of a geothermal reservoir using Fourier Neural Operators - Umair Waheed

16:15 - 16:30 - Examples of Dedicated and Dark Fiber DAS Applications in Civil Engineering Infrastructure - Dante Fratta

16:30 - 17:00 - Towards Earthquake Monitoring and Response with DAS: Recent Progress and Outstanding Challenges - Andrew Barbour

June 14th, 2023 - Weeks Hall - Room 140 - 1215 W. Dayton St

8:00 - *Coffee*

8:30 - 8:45 - Geomechanical strain measured by DAS - Matt Becker (recorded)

8:45 - 9:00 - Comparisons Between Array Derived Dynamic Strain Rate and Fiber-optic DAS Strain Rate - Gene Ichinose

9:00 - 9:15 - Observations of regional and teleseismic events at Sanford Underground Research Facility - Erin Cunningham

9:15 - 10:00 - Open Announcements/Discussion (Upcoming Research Projects, Future Directions)

10:00 - 10:30 - Break/Posters

10:30 - 11:30 - Panel Discussion - CTEMPS, EarthScope, and Community Resources - Scott Tyler, Bob Woodward

11:30 - 12:00 - Workshop Conclusion - Herb Wang

12:00 - 13:30 - *Lunch - on your own*

13:30 - 17:00 - Writing Team - Weeks Hall - Room A259 - 1215 W. Dayton St

18:30 - *Dinner*

June 15th, 2023

8:30 - 12:00 - Writing Team - Weeks Hall - Room A259 - 1215 W. Dayton St

12:00 - Conclude

Appendix I: DAS RCN E-mail Distribution List Numbers

Throughout the lifetime of the RCN, efforts were made to track participation both overall and by a variety of demographics including career stage, type of institution, research area, and physical location.

A mailing list was created and populated with the previous DAS Interest Group (DIG) subscribers (https://ds.iris.edu/message-center/topic/das/). This is a way for events, calls-for-papers, and other opportunities to be advertised to the DAS community and can continue to be used for other communications as the community grows. Subscriptions steadily increased with several large step increases occurring during the first two virtual workshops (August 2020 and December 2020) as well as smaller step increases during the first two webinars (February 2021 and March 2021).

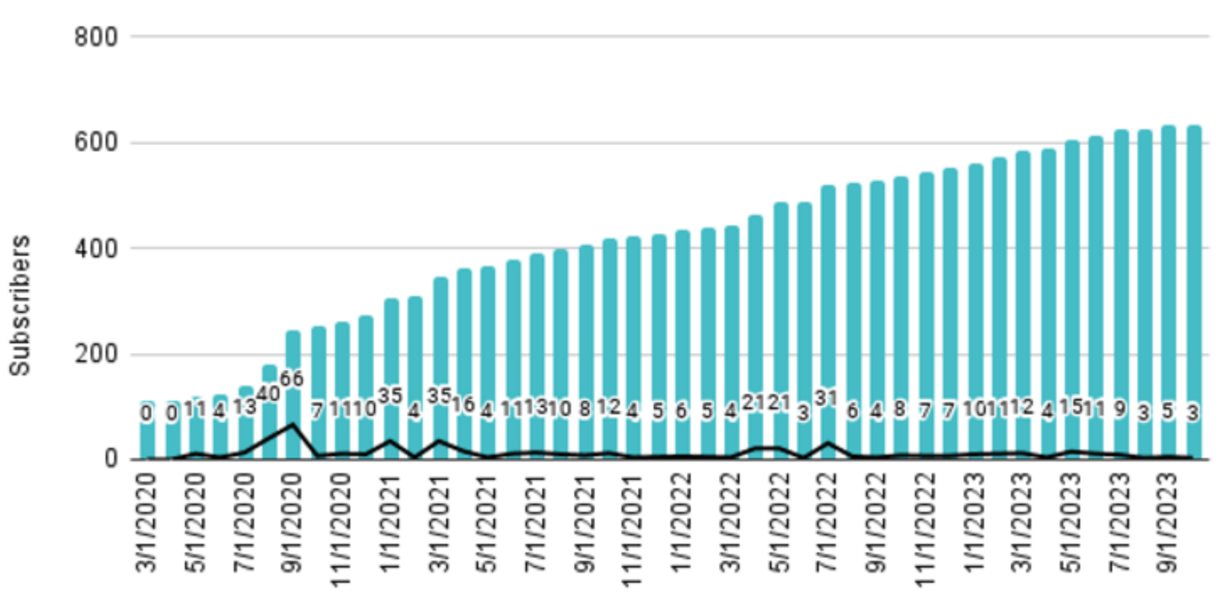


Figure H.1 Subscriptions to the DAS mailing list during the RCN. There were 635 subscribers to the DAS mailing list in September 2023. Blue bars show total number of subscribers and the annotated black line shows new subscribers added each month. Subscriptions leveled out to a modest but steady increase, signaling that we were still actively reaching a broader audience with each new event or opportunity being advertised. The mailing list is now maintained by EarthScope as a Google Group with over 1700 subscribers (https://groups.google.com/a/earthscope.org/g/das-community).

Appendix J: Representative Papers in Working Group Topics

Topic	Title	Reference
Data Management	Distributed Acoustic Sensing Data Analysis Ecosystem (DASDAE): Open- source Python Packages for Easier DAS Data Use	Martin et al. (2022) https://github.com/DASDAE/DASDAE
	Toward a Metadata Standard for Distributed Acoustic Sensing (DAS) Data Collection	Lai et al. (2022, 2024)
Energy Technologies and CO2 Monitoring	Fracture-Hit Detection Using LF-DAS Signals Measured during Multifracture Propagation in Unconventional Reservoirs	Liu et al. (2021)
Earthquake and Array Seismology	A Year-Long DAS Deployment in Monterey Bay, California.	Romanowicz et al. (2023)
	Comparisons between array derived dynamic strain rate (ADDS) and fiber-optic distributed acoustic sensing (DAS) strain rate.	Ichinose et al. (2022)
	Array signal processing on distributed acoustic sensing data: Directivity effects in slowness space.	Näsholm et al. (2022)
	The seismic wavefield as seen by distributed acoustic sensing arrays: local, regional and teleseismic sources	Kennett (2022)
Instrumentation	Scientific Applications of Distributed Acoustic Sensing: State-of-the-Art Review and Perspective	Gorshkov et al. (2022)
Machine Learning	Distributed sensing and machine learning hone seismic listening	Trainor-Guitton et al. (2022)
	A self-supervised deep learning approach for blind denoising and waveform coherence, enhancement in Distributed Acoustic Sensing data	van den Ende et al. (2021)

Engineering and Urban Seismology	On beamforming of DAS ambient noise recorded in an urban environment and Rayleigh-to-Love wave ratio estimation Assessment of Distributed Acoustic Sensing (DAS) performance for geotechnical applications, Engineering Geology	Zhao et al (2023) Rossi et al. (2022)
Hydrology	A river on fiber: spatially continuous fluvial monitoring with distributed acoustic sensing	Roth et al. (2024)
Geomorphology	Fiber Optic Sensing for Landslides Early Signs Monitoring and Consequences Assessment Distributed Sensing on a rapidly eroding coastal cliff	Ravet et al. (2021) Johnson et al. (2024)
Cryosphere	Distributed acoustic sensing of microseismic sources and wave propagation in glaciated terrain Observations of Ocean Surface Wave Attenuation in Sea Ice Using Seafloor Cables	Walter et al. (2020) Smith et al. (2023)
Volcanic and Seismic Hazard Monitoring	Subglacial volcano monitoring with fibre-optic sensing: Grímsvötn, Iceland Source location of volcanic earthquakes and subsurface characterization using fiber-optic cable and distributed acoustic sensing system Fiber optic sensing for volcano monitoring and imaging volcanic processes	Klaasen et al. (2023) Nishimura et al. (2021) Jousset et al. (2024)
Marine Geophysics	Sensing whales, storms, ships and earthquakes using an Arctic fibre optic cable Fiber-optic observations of internal waves and tides	Landrø et al. (2022) Williams et al. (2023)

	Subsurface imaging with ocean-bottom distributed acoustic sensing and water phases reverberations Eavesdropping at the speed of light: distributed acoustic sensing of baleen whales in the arctic	Spica et al. (2022) Bouffaut et al. (2022)
Geotechnical	Distributed Acoustic Sensing (DAS) as a Distributed Hydraulic Sensor in Fractured Bedrock	Becker et al. (2020)
Research and Development Test Sites	The Global DAS Campaign of February 2023	Wuestefeld et al. (2023)

Appendix K: Future DAS Priorities for Geomorphology

Danica Roth - Colorado School of Mines, droth@mines.edu

Community surveys, forums, and panel discussions conducted by the Geomorphology Working Group indicate that interest in DAS is widespread, but currently limited by several barriers to entry. Addressing discipline-specific needs and challenges summarized below will facilitate DAS applications in geomorphology.

Major current barriers to entry:

- Lack of awareness, existing user base, and proof of concept for DAS applications
- Lack of access to instruments
- Lack of background knowledge in collecting/accessing/processing/analyzing seismic or DAS data

Instrument/deployment/support needs and challenges specific to applications in geomorphology:

- Deployment and instrument access
    - Long deployments needed to capture stochastic processes (e.g., floods, landslides)
    - Remote deployments in locations without power
    - Dynamic environments expected to produce cable motion or complex cable coupling (e.g., rivers, landslides, debris flow channels)
    - Funding limitations relative to fields with more rapid DAS adoption (e.g., average NSF Geomorphology and Land-Use Dynamics grants significantly lower than Office of Polar Programs)
    - Open data requirements for common journals and funding sources limits access to some instruments
- Data storage and archiving
    - Validation and interpretation of environmental DAS data requires concurrent, co-located environmental variable datasets (requiring co-archival or cross-referencing with other archives)
    - Metadata currently not standardized or standards do not include relevant geomorphic/environmental information
    - Pre-processed, analysis-ready data products (e.g., analogous to topographic data products provided by UNAVCO or OpenTopography) would increase accessibility for multidisciplinary researchers
    - Reduced or derived data products may lose critical information for individual geomorphic processes and event cascades/triggers occurring over wide frequency ranges (<1 Hz - 10s of kHz)
- Training and support
    - Existing resources and services primarily developed for the seismology community; lack of background knowledge, jargon and programming fluency (e.g., python, command line, linux os) pose barriers for other disciplines

- Current resources primarily focused on student training; short-format training opportunities needed to recruit PIs
- Researchers without seismology backgrounds may require extra support for finding/downloading archived data, field campaign planning and collection, and data pre-processing
- More opportunities/venues needed for geomorphologists to form collaborations with interested geophysicists

Appendix L: Future DAS Priorities for Marine Biology and Ocean Conservation

Léa Bouffaut - K. Lisa Yang Center for Conservation Bioacoustics Cornell Lab of Ornithology, Cornell (NY), USA, lea.bouffaut@cornell.edu

L.1 Motivations

Currently, acoustic monitoring of marine life for conservation is limited by instrument scarcity, uneven sampling, and the lag between the beginning of recordings and final actionable results to communicate to stakeholders. The former is mainly driven by the intricacies of working at sea, including the costs associated with instrument deployment and recovery, while the latter results from the general difficulty of data transmission from sea to shore, considering the preservation of battery life, "heavy" acoustic data streams, and satellite transmission cost. One proposed solution has been the deployment of permanent cabled observatories providing power and directly streaming the data to shore. However, with the constraints of highly dynamic and rapidly shifting marine life and ecosystems, we need adaptable and robust technology to monitor marine life at relevant temporal and spatial scales.

L.2 Vision

DAS could become the go-to tool for real-time marine bioacoustics monitoring worldwide, providing the necessary flexibility at relevant spatial scales to study organisms from fish to whales and give a spatial dimension to soundscapes from coastal to oceanic regions. Following the model of satellite imagery, global DAS-enabled ocean monitoring should become an interdisciplinary platform, supporting a range of research fields and applications based on communal technology and analysis tools.

L.3 What is needed

- Advances in interrogation technology — The sampling frequency of DAS, using off-the-shelf interrogators, is currently limited by the physical length of the interrogated fiber between the connection point and the first repeater. For example, a 50 km-long fiber can be probed at 2 kHz, sufficient to monitor all baleen whales, some pinnipeds and likely fish. For marine conservation applications related to whales, it is crucial to enable their monitoring from shore to the continental shelf break, known to be a highly productive area. Unfortunately, these are often further than 50 km offshore, where hydrophone deployments are time and cost-intensive. Combining DAS possibilities of going beyond the first repeater while still interrogating at relatively high frequencies would be a game changer for the field. Additionally, while the availability of dark fibers is limited, several experiments have now shown the possibility of using DAS on lit fiber with little disturbances on the network, enabling broader spatial coverage in crucial areas where internet access is already limited (e.g., in the Arctic).

- Instrumentation performances— As a first step towards DAS-enabled marine bioacoustics monitoring, assessing DAS data quality and sensitivity for water-borne sources is crucial. It has direct implications for the species and ecosystems that can be monitored. It includes the need to:
  - Evaluate the best interrogation parameters (e.g. gauge length) for bioacoustics monitoring, e.g., to detect signals up to 1 kHz;
  - Evaluate the instrument response and sensitivity at the channel & array levels;

        - Evaluate the changes in data quality introduced by changes in fiber configurations (armor, live vs. dark fiber, trenching, seafloor, depth etc.);
        - Evaluate DAS detection range; and,
        - Compare DAS to traditional monitoring methods
    - Data processing and management — With its spatial coverage and resolution, it is no surprise that DAS collects vast amounts of data per day.
        - Aiming for DAS as a multidisciplinary platform, it is crucial first to develop methods to sort out relevant information and establish ground-truth dataset(s), allowing us to benefit from the advantages of machine learning, detect application-specific signals of interest, and become more efficient in data exploration. This step might also be crucial to passing Navy checks regarding water-borne sources. These methods and databases should be made publicly available with particular attention to software continuity
        - Archiving TBs/day of raw data is costly and has a non-negligible environmental impact. It is not sustainable in the long term, and methods and formats to archive only relevant data are a necessary direction.
    - Implementation & accessibility — A few steps can be taken to enable more widespread use of DAS technology, e.g.,
        - Reducing the cost of DAS instrumentation (which right now is prohibitive to buy) and/or increasing the amount of available pool of instruments to lease;
        - Reliable and ready to use DAS-data analysis and visualization packages or software

L.4 Bring and keep all stakeholders (e.g., telecom companies, federal agencies, researchers, and conservationists) in the loop as early as possible to enable higher-level discussions; determine equitable access to fibers, and ensure when objectives differ

L.5 Building capacity to develop the workforce by offering dedicated and suitable training across all concerned academic fields

Appendix M: CTEMPs "Private-Public" Collaborative DAS Facility Model

As a result of the RCN facilities survey, it was clear that community demand for DAS interrogators and supporting equipment was present across a wide range of the Earth sciences and engineering. As the investment by NSF or others in a single, large pool of instruments was unlikely in the immediate future, the Centers for Transformative Environmental Monitoring Programs (CTEMPs) developed and was funded (in 2023) to set up a DAS "Collaborative" with several existing NSF instrument centers and universities to leverage existing instrumentation and to maximize efficiency of instrument accessibility. This collaborative concept was designed to add the several existing and planned DAS instruments in the community to a list of available lending pool instruments managed by CTEMPs. The collaborative concept will eliminate the need, at least in the first few years of DAS community use, for a significant investment up front and will also allow the community to take advantage of instrument evolution in the future, given that DAS instruments are rapidly improving in resolution and performance. In addition to meeting user demand and maximizing instrument use, the collaboration provides financial support (either as pass through from CTEMPs or directly billed by the instrument owners) that can be used for regular instrument maintenance and upgrades.

The DAS Instrument Collaborative was initiated with the renewal of the CTEMPs facility in the summer of 2023. The initial focus of the Collaborative was on developing the existing Instrument Facilities (CTEMPs, EarthScope and NHERI) operating rules and ensuring the points of contact were clearly established. As a result of the coordination, the Collaborative is currently operating under the following principles and governing rules:

1. Collaborative university partners will be compensated for their instrument use. CTEMPs will handle user billing, with funds then transferred to the collaborating institution. Collaborative instrument facilities (IF) such as NHERI and EarthScope (and potentially university partners) who already have instrument lease experience and operations may choose to independently manage instrument support, leasing and shipping to streamline the process. In these cases. CTEMPs will refer DAS clients directly to the IF points of contact.

2. Collaborators will develop through their contracting units appropriate use contracts of damages to instruments as a result of user negligence if not already in place. CTEMPs will assist in developing these contracting documents where needed. Transit loss insurance can be arranged through CTEMPs (but paid by collaborators) for collaborators and be included in the instrument lease fee. Lease fee billing will be arranged in advance with each collaborator. Payment can be either direct to the collaborator's institution or from CTEMPs with subsequent remuneration to the collaborator.

3. Collaborators will provide a yearly estimate of expected instrument time available and unavailable. This will be for planning purposes only however, and collaborators will not be committed to this estimate.

4. Preference will be given to instruments operated by NSF instrument facilities where possible as these facilities will generally have more flexibility and in-house support for instrumentation. In the case of NHERI, prioritizing support for NSF projects is a contractual requirement. CTEMPs will work with collaborators on scheduling and shipping, and shipping costs can either be billed directly to CTEMPs or billed to collaborator's institutions and subsequently recovered.

5. Collaborators will agree to work with instrument users on instrument-specific issues and assist

in experiment design where it is specific to their instrument. CTEMPs staff will continue to serve as the initial point of contact and assist as needed. Publication arrangements are to be made between collaborators and users, however at a minimum, any publication must include an acknowledgement of instrument support from the collaborator and, if appropriate, CTEMPs.

CTEMPs announced its offering of DAS instrumentation to the community in August 2024, coincident with its summer 2024 DAS/DTS workshop that summer. In the Spring of 2025, CTEMPs, in collaboration with EarthScope and NHERI staff, hosted a DAS instrument comparison workshop with on-site participation from EarthScope, NHERI, and Silixa and loaner units from Aragon Photonics and Febus. Seven different DAS units were used, two different active sources (hammer blows and NEHRI's shaker truck) and a passive source (I80 traffic noise). This experiment aimed to (a) compare the performance of different DAS units when configured as close to one another as possible, (b) to determine how differences in cable type and coupling lead to differences in DAS signal amplitude and SNR, (c) to begin development of common standards for data processing, reporting, and sharing and archiving of DAS data, and (d) to begin developing best practices for installation and deployment of near-surface DAS systems. The team is still processing data and reconciling the data recorded by the different instruments, the experiment led to two AGU abstracts (led by CTEMPs postdoc Sara Sayaadi and EarthScope Intern Alison Kim) and has provided a basis for future collaborations between participants from multiple NSF-funded instrument centers.

Additionally, CTEMPs and EarthScope jointly proposed an AGU town hall for December 2025 centered around increasing awareness of NSF-funded instrument facilities. the primary goal of the town hall is the communication of opportunities to better support research efforts, the three facilities offering DAS and the recent joint-facility Reno experiment (CTEMPs, EarthScope, and NHERI) will be used as examples of how facilities can work together to provide benefits that reach across disciplinary lines.