<u>DarkSeis: Seismic imaging of the urban subsurface using dark fibre</u>

Distributed Acoustic Sensing (DAS) seismic data is acquired by an interrogator unit (IU) attached to one end of a fibre-optic cable. The IU repeatedly fires a laser pulse along the cable and records the backscattered energy. The phase differences between the backscattered light from adjacent points along the cable are analysed. If strain has been applied to the fibre then the relative phases of the arrivals will change. As such, the IU records the spatial distribution of strain rate along the cable, turning standard fibre-optic cables into highly sensitive sensors capable of recording the seismic wavefield along the length of the cable with unprecedented spatial resolution.

Our towns and cities are criss-crossed with fibre-optic telecommunications cables (e.g., Figure 1). Over-engineering of fibre installation (in part for redundancy, and in part because subsequent improvements have reduced the required bandwidths) means that a significant proportion of installed fibre is unused. This so-called “dark fibre” therefore has the potential to be used for geophysical sensing, providing a readily-accessible means to acquire large volumes of seismic data in urban settings. Preliminary studies have shown that dark fibre networks have sufficient ground coupling to record passive seismic signals[1], and controlled-source seismic surveys have been acquired using DAS cables in subsea settings[2] (Figure 2). However, we are not aware of any published examples where dark fibre has been used for controlled-source seismic surveying in urban areas.

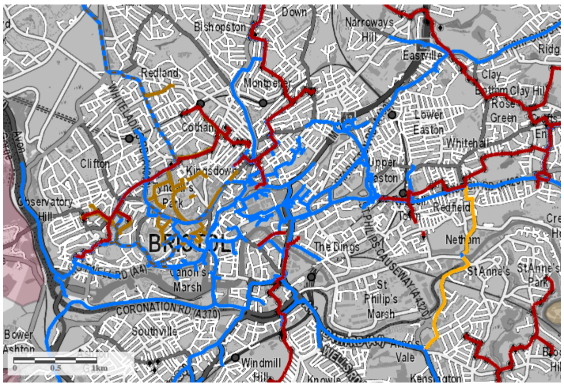

Figure 1: Routes of B-NET fibres in central Bristol (all coloured lines). B-NET is a 250 km-long fibre-optic network running across the centre of Bristol, owned by Bristol City Council, who are partners on this proposal.

The B-NET system, with a single, public owner that has a clear interest in using the subsurface for geothermal applications, represents an unprecedented and timely opportunity to acquire DAS seismic data with dark fibre in an urban setting.

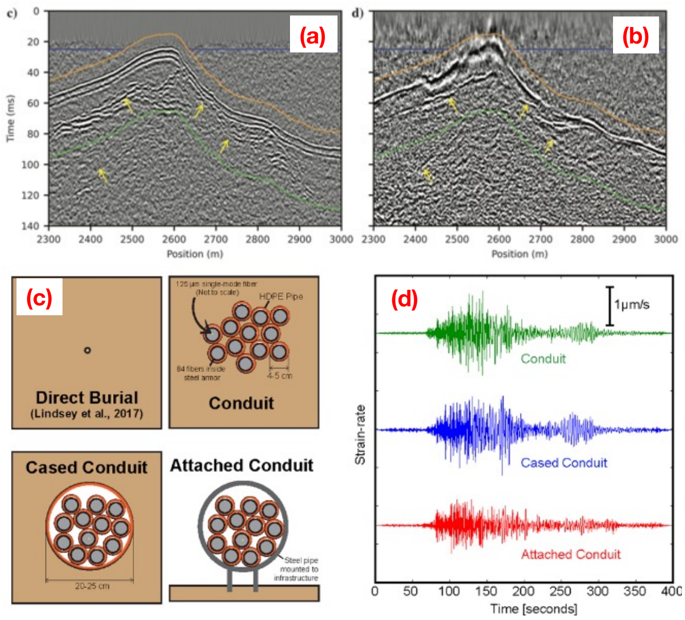

Figure 2: (a) and (b) show reflection seismic sections generated by (a) conventional hydrophones and (b) a subsea DAS cable[1]. (c) and (d) show the impact of different types of dark fibre conduit on the resulting seismic signals[2]. While direct burial of fibre is the optimum condition, various types subsurface of fibre installation provide useable seismic signals.

The primary objective of this work is to assess the seismic imaging capabilities that can be achieved using dark fibre networks in urban areas, using both controlled-source and passive seismic methods. By providing guidance and optimisation for acquisition and subsequent data processing workflows, we aim to deliver a novel, viable seismic acquisition toolkit that will be utilised by a range of end-user applications as described below. The transformational nature of this research is the potential to perform wide area, high resolution, cost effective seismic imaging of urban areas that is simply not possible using conventional seismic (i.e., geophone-based) methods.

Motivation: Characterisation of the subsurface below our towns and cities is necessary for a range of geo-energy, geotechnical and hazard applications. For example, since heat cannot easily be transported over large distances, geothermal heating projects must be sited near to end-users in urban and industrial settings. However, without geophysical imaging the lack of subsurface data is a major obstacle to geothermal investment. Geotechnical data is needed to quantify the likelihood of hazards such as subsidence, ground heave, landslips, and the amount of shaking that could be generated during earthquakes. Mapping of the properties of the shallow urban subsurface is also necessary to constrain groundwater and drainage behaviours (vital for understanding urban flooding potential), and to design sustainable drainage systems (SuDS). Seismic imaging can also identify subsurface hazards such as active tectonic faults, unmapped abandoned mine workings, and subsurface voids that could develop into sinkholes.

Reflection seismic surveys, which typically image from 100s to 1000s of metres depth, are needed to map the positions of geological formations and structures such as faults in the subsurface. More detailed seismic observations such variations in seismic velocities, impedances, or V_P/V_S ratios can be used to constrain rock and fluid properties. Seismic imaging of the near-surface (i.e., the upper 10s of metres) uses refracted arrivals and surface waves to constrain key geotechnical properties such as depths to bedrock, rock strengths and stiffnesses, and V_{S30} values.

However, geophysical imaging beneath our towns and cities using conventional methods (i.e., geophones) is challenging. In urban settings there is limited surface access to deploy sensors, and noise levels are high. As a result, there is a significant lack of subsurface data in urban areas. Hence, there is a clear need for novel seismic imaging methods suitable for urban settings. These methods must be able to deal with the twin challenges of (i) deployment of extensive sensor arrays in urban areas, and (ii) high levels of background noise. Our research program will address this need by (i) developing the use of seismic acquisition using DAS with dark fibre networks, and (ii) developing novel machine learning methods to denoise DAS datasets.

DAS Acquisition Advantages: The presence of fibre-optic cables across most urban areas, to which DAS IUs can be easily connected, presents an immediate advantage in terms of deployment when compared with the need to deploy large numbers of geophones across an urban survey area. DAS acquisition also offers a number of additional benefits. The gauge-length, which refers to the distance over which each DAS strain measurement is taken, is a key parameter for DAS acquisition: gauge lengths can be as low as 50 cm (there is a trade-off where larger gauge lengths increase signal strength but reduce the spatial resolution). Measurement frequency is determined by the length of time taken for the light pulse to traverse the cable and is typically of the order of 10 kHz or more. Hence, in addition to the ease of deployment in an urban setting, a major attraction of DAS for seismic acquisition is the spatial and temporal resolution, with the massive channel count and dense spatial sampling giving complete capture of the seismic wavefield (as a comparison, geophones might be placed at 10s to 100s of metres spacing, and typically record at <1 kHz).

For geophone-based seismic surveys, there is a trade-off between resolution and coverage. Shallow imaging requires tight geophone spacing and will incorporate analysis of refracted phases and surface waves, however the tight sensor spacing required often limits the resulting lateral coverage. Surveys imaging deeper levels use wider sensor spacings and focus on reflected arrivals. The wider sensor spacing leaves "blind spots" where the shallower subsurface is not imaged. In contrast, the spatial resolution of DAS recording, which is controlled by the channel spacing and gauge length of the interrogator, is highly flexible, meaning that DAS offers the potential for a "seismic zoom"[3], simultaneously imaging both the shallow and deeper subsurface with a single survey. Meanwhile, the lateral spread of dark fibre networks (Figure 1) means that high resolution measurements can be obtained over a wide area. As such, DAS offers the potential to acquire seismic data with a resolution and extent that is simply not possible in urban areas using conventional methods.

Passive seismic interferometric imaging requires acquisition over longer time periods. Again, in an urban setting this can be challenging as conventional sensors (and their associated power sources, GPS timing equipment, etc.) must be left in place, at risk of damage or other mishap, for long periods. In contrast, DAS acquisition uses a single IU which can be placed in a secure location, acquiring data on already-buried dark fibre networks that cross the area of interest. Again, the dense spatial sampling across a broad area will allow the generation of high-quality interferometric images that can supplement controlled-source seismic imaging.

DAS Acquisition Challenges: Despite its many advantages, the nature of DAS acquisition presents several challenges for successful seismic imaging. DAS IUs record the strain rate along the axis of the cable. For horizontal cables, this means that horizontal motions are recorded, and so DAS cables are primarily sensitive to S-waves and surface waves, rather than P-waves which are recorded by conventional vertical component geophones (see Figure 3). Hence, novel methods for acquisition and processing are required, for example by making better use of recorded S-waves and surface waves. There is a clear need to investigate the type of source to optimise controlled-source acquisition (e.g., the choice of S-wave or P-wave source, impulse source or vibroseis).

Noise levels in urban settings will be high, and may include both coherent and incoherent sources of noise. Instrumental noise levels from DAS IUs are often higher than geophones. Dark fibres will not have been installed with ground coupling as an objective, so reduced coupling may reduce the recorded signal strength[1]. Hence, we expect signal-to-noise ratios to be lower for DAS acquisition in comparison to conventional survey methods, and so advanced processing methods to remove noise and boost signal strength will be required.

Our research program is designed to address these challenges while leveraging the advantages offered by DAS seismic acquisition in urban areas. The research program is split into a series of interlocking work packages, as described below.

WP1: Acquisition Design – Existing Dataset and Modelling: To facilitate the design of our planned acquisition, the first stage of our project will be to develop full-waveform synthetic models for DAS seismic. These models will be benchmarked using an existing controlled-source seismic DAS dataset acquired by the project team. In September 2021 we acquired a DAS seismic dataset at the Field Research Station (FRS), Alberta, a CCS testbed where CO_2 is injected at a depth of c. 300 m[4]. Sensing at the FRS was provided by a 5 km loop of fibre, and we shot seismic surveys using a mini-vibroseis and an internal combustion impulse source (ICIS), using both P- and S-wave source types. Although this is a rural site with purpose-installed fibre, many aspects of the DAS system used for acquisition at FRS are similar to those expected for dark fibre in urban settings. To date, only minimal levels of processing have been applied to the FRS DAS dataset. We will begin this project by processing the FRS dataset, with a particular focus on identifying and characterising the different recorded arrivals (e.g., surface waves and near-surface refractions vs deeper body-wave reflections) produced by the different source and acquisition methods.

In combination with this analysis, we will generate full-waveform simulations to replicate the observed data. The objective here is to calibrate and benchmark a modelling strategy that is capable of faithfully replicating DAS observations. Having achieved this, we will then repurpose the modelling to simulate DAS acquisition using B-NET fibres in Bristol. By doing so, we will be able to investigate the impacts of different source and acquisition parameterisation on the resulting data quality prior to field deployment. Figure 3 shows a generic and simple example of this process, where we have simulated geophone and DAS acquisition with vertical and lateral impulse sources (though a generic subsurface model in this case). From this we can characterise the different reflected seismic arrivals. In this case, we might infer that a vertical source recorded with DAS will not provide usable P-wave reflections, though P-to-S conversions may be visible at larger offsets, while a lateral source, with stacked positive and negative source polarities, produces visible S-wave reflections. However, these preliminary models have not been benchmarked, highlighting the need to generate model results that are benchmarked with the observations made at the FRS site. This must be done before we can apply model results with confidence to the design and parameterisation of future acquisition campaigns using B-NET cables in the city of Bristol.

During the first year of the project we will also engage with Bristol City Council (BCC) to produce a detailed field acquisition plan: mapping of suitable access points to the network at which DAS IU can be installed; identifying specific fibre bundles to which a DAS IU can be connected; identification of options for suitable housing of the IU; and options for sourcing power connection to the IU.

WP2: Dark Fibre Acquisition using B-NET: Our ability to access to the B-NET system provides a unique and extremely timely opportunity to acquire DAS data on a dark fibre network that runs across a wide portion of a major UK city. The B-NET fibre-optic telecommunications network covers 250 km under the city of Bristol (Figure 1). B-NET is owned by BCC, who are serving as partners on this project. The acquisition of controlled-source and passive seismic datasets from an extensive dark fibre network in a UK city setting represents a major contribution of our proposed research. Our initial focus for acquisition will be along the Colliters Way route in southwest Bristol. This site is underlain by historic 19th Century mine workings which may be of geotechnical significance for housing developments that are anticipated along this route, as well as representing a potential target for shallow, low-enthalpy geothermal resources. In addition, this area is underlain by Carboniferous Limestones that have been recognised as a potential deeper geothermal resource (being the aquifer from which the Hotwells hot springs, c. 4 km to the north, are thought to originate). Further sites for dark fibre acquisition may be identified in liaison with BCC during the feasibility work (WP1), or after initial acquisition at Colliters Way. Acquisition at multiple sites will allow a comprehensive evaluation of DAS performance that is not specific to a single location.

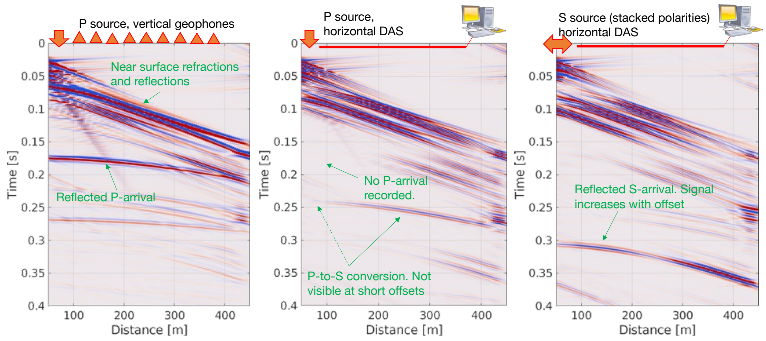

Figure 3: Synthetic seismic gathers modelled using a full-waveform simulation. We compare a conventional survey (vertical impulse, vertical geophones, left), a vertical source recorded using DAS (middle), and a lateral impulse (S-wave source) recorded with DAS (right). Comparison of these gathers show the different body-wave reflected phases that might be expected to be recorded.

Our acquisition program will be informed by the modelling work described in WP1. We will acquire data using different source types, including ICIS and mini-vibroseis, generating both P- and S-waves, and recording with a range of fibre configurations and IU setups (e.g., gauge lengths, channel spacings) to investigate the impacts of these choices with respect to the resulting imaging. In addition to the DAS acquisition, we will acquire the same seismic surveys using geophones to provide a point of comparison between DAS and conventional geophysical acquisition (we also acquired the controlled-source surveys at the FRS with a geophone array, allowing a similar comparison).

Having acquired controlled-source surveys at each site, we will then leave the IU system recording passive seismic data over several weeks. This will allow us to compare the controlled-source imaging performance with the imaging that can be generated using passive imaging methods, as well as providing data with which the background noise can be characterised for machine learning methods (see WP3). Whereas the controlled source surveys will be focussed on specific sites, we will acquire passive data across a broader area, looking to take advantage of the coverage of the B-NET cables to produce laterally-extensive subsurface images.

All acquired datasets will be archived with the National Geoscience Data Centre (NGDC). We note that neither this database nor the internationally-agglomerated PubDAS resource[5] contain any examples of controlled-source DAS seismic data acquired using dark fibre in urban settings. This absence demonstrates the novelty of our proposed research. In making the data we acquire publicly available, we anticipate providing an extremely valuable resource for researchers and commercial geophysical companies, both in the UK and globally, working in this field.

WP3: Noise Removal with Machine Learning: We anticipate that one of the largest challenges for DAS seismic in urban settings is the effective removal of noise. Background noise levels in urban settings will be high, and lower ground coupling (in comparison to geophones) along the fibre may reduce the recorded signal strength[1]. We will begin this WP with conventional noise removal methods (multi-dimensional filtering, stacking, etc.), looking to leverage the high spatial and temporal sampling offered by DAS data to improve the performance of these methods.

The focus of this WP is to develop the use of Machine Learning (ML) methods to denoise DAS seismic data. ML represents a powerful alternative for noise removal[6]. Data representations are learned directly from the data, so no prior assumptions about the background noise are required. ML models have the capacity to perform highly complex filtering and feature extraction in a single pass, giving fast processing times (necessary for the handling of the large datasets generated by DAS).

“Traditional” supervised learning ML approaches (e.g., Noise2Clean[6], N2C) use pairs of noisy and clean images to estimate the optimal parameters of a convolutional neural network (CNN) for noise removal. However, for seismic applications obtaining these image pairs is challenging. No "noise-free" seismic data can be acquired in the field. Synthetic data can be generated (see WP1), to which noise drawn from a pre-defined model (e.g., Gaussian white noise) is added. However, even the most detailed synthetic data will not be a perfect representation of the actual signal, and simple noise models will not adequately represent real noise from field acquisition. We will address the background noise issue by recording extensive volumes of continuous passive data (see WP2), and create noisy images by adding synthetic data to a large number of different instances of real noise. The extensive modelling work performed in WP1 will provide the necessary inputs to allow a robust testing of the conventional ML approach to denoising to be compared with novel ML approaches.

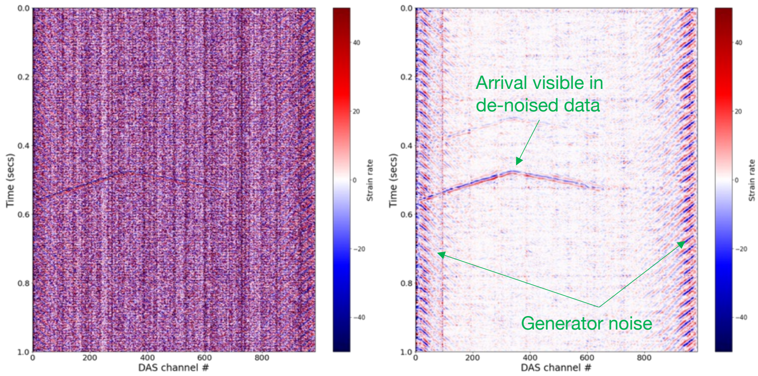

Figure 4: Example of an ML algorithm to denoise DAS data, in this case an ice-quake recorded on a glacier. We applied a Noise2Noise[6] approach using an "out-and-back" cable geometry.

Recent advances in image processing are addressing the challenge when noise-free "target" images are unavailable. One such example is a "fill-the-gap" (FTG) approach[7], whereby portions of the data containing the signal are masked, and a CNN is trained to fill in the data within the gap. Since the signal is coherent, a CNN will be able to interpolate coherent signals across the gap, while incoherent noise, which cannot be predicted within the masked portion, will be suppressed. The high spatial sampling of DAS data (in comparison with geophone acquisition) will facilitate the interpolation of coherent signals between channels, meaning that FTG methods will be ideally suited to this type of dataset. Another approach is to use pairs of noisy images that contain the same signal, but different instances of noise (e.g., Noise2Noise[6], N2N). This can be achieved by using data acquired simultaneously on adjacent fibres, for example. In this situation, the CNN maps between the coherent signals in each image, which are sufficiently similar, but is not able to map the random noise, and so this is suppressed. Figure 4 shows noise removal for a cryoseismic event that we have denoised in this manner.

The use of ML to denoise and process DAS seismic data is at a nascent stage, but we have recently demonstrated the potential that these methods hold (see Figure 4). The integration between this WP and our modelling (WP1) and field acquisition (WP2) are essential to drive further advances in this field. Advances and learnings from our development of ML methods will have implications for data acquisition: for example, what spatial resolution is required for effective use of FTG methods, what volumes of background noise are required for N2C methods, can we acquire data on adjacent strands of fibre to provide images with identical signal but different noise instances for N2N? Since our acquisition and processing programs are iterative, we can apply these learnings in subsequent phases of acquisition in order to optimise the performance of our ML denoising methods.

WP4: Imaging and Application: Having acquired and denoised the active-source DAS seismic data, the final stage of our research is to develop useful subsurface images. A key focus of this WP will be to investigate the potential offered by DAS for "seismic zoom"[3], whereby closely-spaced DAS channels are used to analyse refracted arrivals and surface waves to characterise the shallow subsurface in detail, while at the same time, using the same seismic gathers, body-wave reflections are analysed to image the deeper subsurface. Meanwhile, interferometric methods will be used to produce seismic images using passive data across the areas covered by B-NET cables.

Many of the imaging processes we anticipate using are relatively well established, but there is significant scope for improvement by leveraging the high spatial and temporal sampling offered by DAS. Further modifications to existing methods will also be required to account for the nature of DAS recordings, for example the fact that horizontal DAS cables will be most effective in detecting S-waves and converted waves, whereas they will not be sensitive to upcoming P-waves (Figure 3). The imaging from the DAS datasets will be compared with images produced from the geophone datasets acquired at the same sites in order to provide a direct comparison of imaging quality. At the FRS site, extensive subsurface characterisation has been carried out, against which DAS imaging will also be benchmarked. Data from the Coal Authority will be sought against which our observations at Colliters Way will be benchmarked.

DAS datasets – Significant benefit to the wider community: At present, few examples of publicly available DAS seismic data exist. The only examples of DAS seismic datasets in the NGDC are from the Skytrain Glacier and UKGEOS site (described in Track Record below), which have been acquired by this project's Investigator team (demonstrating both our firm commitment to UKRI's Open Research principles, and the leading position of the project team within this field). The PubDAS resource[5], which consists of 6 datasets mainly from the USA, also does not contain any active source DAS datasets from urban settings.

As such, there is a very limited number of publicly available DAS seismic datasets of any kind, and no examples whatsoever of active-source DAS seismic from urban settings, which could be used by scientists looking to develop novel methods to process and interpret DAS seismic data. The absence of publicly available datasets creates a major barrier to research in this nascent field. This barrier will be especially significant for less established and more junior researchers who might have excellent, novel ideas for processing DAS seismic data, but who lack the logistical resources and funding needed to acquire their own field DAS datasets.

A key outcome from this research is the public provision, via the NGDC, of active-source and passive DAS seismic datasets acquired using dark fibre in urban settings. All data will be posted within 1 year of acquisition. In doing this, we will actively encourage any researchers with an interest in DAS seismic to work with these datasets. In addition, all codes developed in the project will be made publicly available. We anticipate that the ML algorithms in particular will be of significant interest – by providing trained algorithms we anticipate that other researchers will be able to piggy-back on our efforts by, for example, further re-training ML algorithms for their specific applications.

Project Partners: To ensure the successful delivery of the project, we have secured partnerships with key stakeholders and relevant organisations. Most significantly, **Bristol City Council**, as owners of the B-NET system, have offered access to this fibre-optic network across the city to acquire dark fibre DAS data. BCC are actively exploring the potential for geothermal resources under the city, and have an interest in geotechnical implications of abandoned mines for new housing developments. As such they have a strong motivation to assist in the development of novel subsurface imaging tools.

We have secured partnerships with several additional companies: **Silixa** are a leading manufacturer of DAS interrogator systems and will provide advice and support on the use of their hardware. **TerraDat** are a geophysical surveying company who have extensive experience acquiring seismic data in a range of settings around the UK. TerraDat will support our active-source seismic acquisition, in particular the selection of appropriate active seismic sources. **Egdon** are currently developing geothermal projects in the UK, and **Atkins** are a global engineering and geotechnical consultancy – these partners represent potential end-users of the technology.

We have longstanding relationships with many of these partners, which reflects the ongoing benefits that these companies have realised through our interactions. We have a demonstrated record of producing research outcomes that have had impact with a broad range of stakeholders beyond the academic sphere. These partners will form an Advisory Board: through regular attendance at project meetings, our partners will be involved in the co-creation of research approaches and applications, as well as representing a route for research dissemination and impact. In order to disseminate the research outcomes, in Y3 of the project we will hold a DAS seismic workshop, to which we will invite a broad range of academic researchers and industry (in addition to our project partners) who are working with DAS for seismic acquisition. Given the levels of interest in this technology, there is a clear need for such meetings to foster collaboration between the academic and industrial communities, to encourage the use of these methods, and to identify potential novel applications.

References: **[1]** Ajo-Franklin et al., 2018, 10.1038/s41598-018-36675-8; **[2]** Taweesintananon et al., 2021, 10.1190/GEO 2020-0834.1; **[3]** Bakulin et al., 2020, 10.1190/tle39110808.1; **[4]** Butcher et al., 2022, 10.2139/ssrn.4286315; **[5]** Spica et al., 2023, 10.1785/0220220279; **[6]** Lehtinen et al., 2018, 10.48550/arXiv.1803.04189; **[7]** Van den Ende et al., 2021, 10.1109/TNNLS.2021.3132832.

Track Record

Research Personnel: Our proposal brings together a multi-disciplinary team with a strong track record of delivering novel, high-quality research. Our project includes the following personnel:

Dr James Verdon (University of Bristol) is a Senior Lecturer in Applied Geophysics. His research is focussed on geophysical imaging and monitoring of industrial sites. In 2010 he was awarded the Keith Runcorn Prize for best doctoral thesis in geophysics for his work using geophysical methods to monitor carbon capture and storage. He has published over 60 articles in international peer-reviewed journals, being cited over 2,800 times. He is presently an Associate Editor for Geophysics specialising in borehole geophysics and passive seismic monitoring. He was a Co-I on the NERC FAST-MoDE grant (NE/R014531/1) developing the use of fibre-optic DAS arrays for monitoring of industrial sites and pioneering the use of machine learning to process DAS observations. He was a Co-I on two NERC UK Unconventional Hydrocarbon research grants (NE/R018162/1 and NE/R018006/1) using geophysical methods to assess the UK's shale gas resource and potential impacts associated with its extraction.

Dr Antony Butcher (University of Bristol) is the Geophysics Technical Specialist in the School of Earth Sciences. He has a PhD in Seismology, and from 2018 to 2022 was a Senior Research Associate, working primarily on seismic acquisition using DAS. Antony manages the extensive pool of geophysics field equipment held by the University. Before entering academia, Antony gained over 10 years of experience as a field geophysicist – he has acquired geophysical surveys at over 100 different field sites across the UK.

Professor Jonathan Chambers (British Geological Survey) is Head of the BGS Shallow Geohazards and Earth Observation Capability under the Multi-hazards and Resilience Challenge area. His research interests lie principally in the field of environmental and engineering geophysics, and he has published more than 80 papers in this field. He is an honorary professor with Bristol University, a NERC Individual Merit Promotion Scientist (IMP3), and previously a NERC knowledge exchange fellow for infrastructure monitoring, and co-editor-in-chief of the Journal of Applied Geophysics. The primary focus of his work in recent years has been the development of geophysical systems (PI for NE/P00914X/1, NE/M008479/1, NE/N012933/1, NE/M020622/1) for the long-term monitoring of safety critical infrastructure – for which he has won industry innovation awards. Recent research projects include the development of geotechnical asset monitoring (ACHILLES, Co-I, EP/R034575/1), investigating soil moisture dynamics in the context of conservation agriculture (CEPHaS, Co-I, NE/P02095X/1), geophysical methodologies for characterising soils in arctic conditions (SUN-SPEARS, Co-I, NE/T010568/1), and new technologies for monitoring of railway embankments (PRIME-Rail, PI, ECM_19105).

Dr Ben Dashwood (British Geological Survey) is an Engineering Geophysicist in the Multi-hazards and Resilience Challenge area, who leads the seismic acquisition capability at BGS. His work has included the use of "fibres of opportunity" in the railway environment, installation of a fibre-optic DAS array at the BGS Hollin Hill Landslide Observatory, and downhole DAS installations at the Sutton Bonnington CO_2 injection site in Nottinghamshire. Before joining the BGS, Ben worked for nine years in engineering consultancy, undertaking geophysical & geotechnical surveys across the UK & overseas.

Dr Sacha Lapins (University of Bristol) is a Research Fellow in the School of Earth Sciences. He gained his PhD in 2021 using machine learning to process seismic datasets. Sacha has been at the forefront of recent developments using artificial intelligence to denoise seismic datasets.

Professor Michael Kendall (University of Oxford) holds the Chair in Geophysics at Oxford. Mike's research interests cover most aspects of pure and applied seismology, including seismic theory with an emphasis on wave propagation in anisotropic media. He has coordinated seismic field deployments in regions as diverse as the Canadian Arctic (NE/D012317/1) and the Seychelles (NERC and Royal Society funding). He has recently deployed fibre optic cables as DAS arrays to monitor glacier stability in the Antarctic. He founded the Bristol University Microseismicity Project (BUMPS), an industry consortium interested in natural and induced seismicity in shallow reservoirs. He recently led Challenge 3 of the NERC funded (NE/R018006/1) Unconventional Hydrocarbons in the UK Energy System program, assessing the potential subsurface impacts of shale gas extraction. Mike is past President of the British Geophysical Association and past Vice-President (Geophysics) of the Royal Astronomical Society. In 2011 he was made a fellow of the American Geophysical Union and in 2019 he became a Fellow of the Royal Society.

Professor Max Werner (University of Bristol) is Associate Professor of Geophysics and Natural Hazards at the University of Bristol. His research spans tectonic and human-induced earthquake seismology, recently focussing on seismic and geomechanical processes in subsurface geo-energy projects, as well as their hazards and risks on the surface and built infrastructure. Current research has focussed on the use of machine learning for seismic processing applications. He was co-I of the UK Unconventional Hydrocarbon Challenge 4 project EQUIPT4RISK (NE/R017956/1) and has advised the UK Oil and Gas Authority (OGA) and British Geological Survey on the seismic hazard and risk of hydraulic-fracturing induced seismicity. Max recently acquired the first active and passive borehole DAS seismic survey at the UKGEOS Glasgow site. Other current research focuses on the United Downs Geothermal Power Project (UK) and the deep geothermal project near Helsinki. Max is also a core scientist of the Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET), which provides NERC with national capability on earth observation and natural hazards. From 2010 to 2013, Max was a Harry H. Hess Fellow at Princeton University. He also serves on the Science Planning Committee of the Southern California Earthquake Center (SCEC).

DAS Acquisition – Expertise and Knowledge Generation: Successful delivery of our research is dependent on thorough and competent acquisition of DAS data in the field. We have extensive experience acquiring and processing controlled-source and passive seismic DAS datasets in challenging settings, as well as in acquiring both controlled-source and passive seismic data in general. We have pioneered the use of DAS for seismic imaging for a range of applications and have made fundamental contributions to this nascent science. Since 2020 we have authored 9 peer-reviewed publications on various applications of seismic DAS – these papers have been cited over 150 times. The examples listed below demonstrate that we are the forefront of research involving the use of DAS to acquire seismic data and are therefore ideally placed to deliver this project.

Hinkley Point C: Several of the project team (JV, MK, AB) led an industry-funded project at the UK's only nuclear construction site, where we used controlled-source and passive seismic methods to monitor rock slope stability during excavations. Our results enabled the constructor to make significant time and cost savings in their construction schedule. **FAST-MoDE:** JV and MK were Co-Is on the FAST-MoDE Project (NE/R014531/1): this grant was the first in the UK to develop the use of fibre-optic DAS arrays for passive seismic monitoring of industrial sites, and we pioneered the use of machine learning to rapidly process DAS observations. **Alberta FRS:** MK, AB and SL have been involved in the geophysical monitoring at the Alberta Field Research Station, a pilot-scale CO_2 injection project in Canada. MK and AB led a field campaign to acquire controlled-source seismic data at the site using DAS and geophone arrays, while SL has been involved in the development of machine learning methods to process and denoise this data. **Rutford Ice Stream, Antarctica:** In 2019 MK led the deployment of DAS cables to monitor ice flow on the Rutford Ice Stream and Skytrain Rise, Antarctica, using controlled-source and passive seismic methods. Subsequent processing of this data has been used to image the structure of the glacier and to detect cryoseismicity. SL has developed machine learning methods to denoise the Rutford DAS dataset. **UK Rail and Hollin Hill:** BD and JC have been involved with the installation of a fibre-optic monitoring array at the Hollin Hill Landslide Observatory (Yorks), and the use of "fibres of opportunity" to provide monitoring along railway networks owned by Network Rail. **UKGEOS:** The UKGEOS sites are designed to provide test beds for shallow geothermal heat production in urban/industrial settings. JC has led the design and implementation of geophysical monitoring systems deployed at the UKGEOS sites in Glasgow and Cheshire. In 2022 MW led the first acquisition of controlled-source and passive seismic at the UKGEOS Glasgow site using the permanent in-well DAS cables installed at the site. **Digimon:** From 2019, MK and AB were research contributors to the Digital Monitoring of CO_2 Storage (Digimon) project, funded by ACT-2. Their work on this project included feasibility studies for the use of DAS for seismic monitoring of offshore CCS.