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Abstract:

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Distributed Acoustic Sensing in a Greenlandic Outlet Glacier: Developing Machine Learning Approaches to Benefit Cryoseismic Data Analysis

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Abstract

The recognition of Distributed Acoustic Sensing (DAS) as a valuable tool for glaciological seismic applications is growing. However, besides the logistical challenges of installing fibre-optic cable, the volume of DAS data that can be collected in a field campaign poses computational challenges. In this paper, we show the potential of active-source DAS to image and characterise subglacial sediment, 20-30 m thick, beneath a fast-flowing Greenlandic outlet glacier, but highlight the difficulty of analysing a counterpart 3-day (9 TB) record of cryoseismicity. We describe experiments with data compression using the frequency-wavenumber (f-k) transform, that provides ~300-times improvement in the computational efficiency of the detection of cryoseismic events via a convolutional neural network. In combining active and passive-source and the machine learning framework, the potential of large DAS datasets can be unlocked for a range of future applications.

Introduction

Seismic methods are widely applied to explore the internal and basal properties of glaciers and ice sheets (Podolskiy and Walter, 2016). Although seismic phenomena can be recorded at high temporal resolution, the spatial resolution of a passive seismic dataset is often limited by the sparsity of the seismometer array. This is addressed, to some extent, by the use of nodal seismic technologies (Karplus and others, 2021), but the recent development of Distributed Acoustic Sensing (DAS) offers the potential for metre-scale sampling along survey profiles that are many kilometres in length. The principle of DAS is reported extensively in other papers (Hartog, 2017; Lindsey and Martin, 2021); here, it is sufficient to understand that DAS effectively converts a length of fibre-optic cable into a continuous string of pseudo-seismometers (Zhu and others, 2021). Consequently, seismic vibrations can in principle be recorded wherever fibre-optic cable can be deployed and sufficiently well coupled to the ground. Several glaciological DAS deployments have recently been reported, with examples including in the European Alps (Walter and others, 2020), Antarctica (Brisbourne and others, 2021; Hudson and others, 2021), Greenland (Booth and others, 2020) and Iceland (Fichtner and others, 2022), for both controlled-source and passive seismic applications.

Borehole DAS can be particularly valuable since fibre-optic cable is installed more simply and inexpensively than the equivalent number of conventional seismic sensors to provide the same sample density. Booth and others (2020) reported the first glaciological deployment of borehole DAS, at RESPONDER project site S30 (70.56793°N, 50.08697°W) on *Sermeq Kujalleq* (Store Glacier), a major marine-terminating outlet of the Greenland Ice Sheet (Figure 1a). Fibre-optic cable was installed in a 1043 m-long vertical borehole drilled to the glacier bed. A Silixa iDAS™ system was used to acquire active-source vertical seismic profiles (VSPs) at various offsets and azimuths around the borehole, and a 3-day record of passive seismicity.

The simplicity of the vertical borehole geometry allows englacial and subglacial seismic structure to be determined more robustly than from surface seismic deployments, and thus improve the detection of physical properties including englacial water and ice fabric. Booth and others (2020) used the direct wave in active-source VSPs to determine a high-resolution depth profile of compressional (P-) wave velocity (Figure 1b), detecting the transition from isotropic to anisotropic ice at 84% of Store Glacier's thickness. Basal temperate ice was detected in the lowermost 100 m, confirmed separately by distributed temperature sensing in the same cable (Law and others, 2021). Reflections in the VSPs (Figure 2a) were observed but did not appear to originate from the glacier bed, generated instead at a deeper horizon interpreted as the base of subglacial sediment. The time lag between a pair of direct and reflected waves implied a sediment thickness of 20 [-2, +17] m, assuming a sediment velocity of 1873 [-94, +1618] m/s (Hofstede and others, 2018).

When the equivalent lags were measured for the full suite of reflected VSP arrivals, estimates of sediment thickness were mapped around the borehole up to a radial distance of 200 m away. This is possible because reflected energy measured at shallower borehole depth must reflect from a subsurface point at greater lateral offset (Figure 2b). Direct and reflected rays were traced through a 1-D velocity model, with deviations indicating a change in sediment thickness and/or velocity. Having no additional velocity constraint, we attributed all deviations to a thickness change, but our interpretation also neglects anisotropy and any local change in glacier thickness. Under these assumptions, preliminary estimates show sediment thickness varies between 20-30 m, with thinner sediment typically observed north of the borehole (Figure 2c).

Analysis of Passive DAS data via Machine Learning

The next stages of this research will refine this preliminary characterisation by enriching the availability of reflection data using cryoseismic events in the passive DAS record (Figure 3a) and by developing a more accurate event location algorithm (e.g., incorporating anisotropic propagation).

Furthermore, in their own right, detection and location of the crysoeismic events will give insight into local variations in the dynamics of the glacier. The challenge in undertaking this analysis comes from the large volume of passive data collected: although only 3 days long, the size of the passive DAS record exceeds 9 TB, having 1043 seismic channels sampled at 4000 Hz. Even navigating the full extent of this dataset is challenging, and manually identifying seismic events pushes current limits of feasibility. We are therefore developing machine learning tools to automate the detection of seismic events in the passive record, specifically using a convolutional neural network (CNN) trained to recognise cryoseismicity within a subset of the full data volume.

When implementing this approach, we found that even the CNN struggled for computational efficiency when applied on a standard-specification laptop. During training, 129 s was required for the CNN to process 30 s of passive data (just 0.01% of the full data volume). To boost computational efficiency, we therefore exploited the high density of spatial samples to convert the DAS data from the time-space domain to the frequency-wavenumber (f-k) domain; such a transformation would be pointless for passive data recorded with a conventional seismometer array as the spatial coverage would be too sparse. On making this conversion, the data volume in each window is reduced by ~340 times yet features representing the seismic arrivals are preserved (Figure 3b). Therefore, analysis of the same 30 s data windows in the f-k domain takes just 1.2 s, with 5.6 s required to initially implement the f-k transform. CNN training is therefore much more efficiently performed using the f-k transform: we are currently assessing its success using a validation dataset, but initial performance (to be described fully in a forthcoming paper) suggests that accuracy could exceed 90%.

Outlook

Interest is growing in new DAS deployments, but it is crucial that these happen alongside methodological developments to make data analysis practical. Our efficient compression of the passive seismic wavefield means that data analysis is tractable on standard CPUs, rather than GPUs or with specialist accelerators, permitting its use and further development on widely available hardware. The implementation of such algorithms could be vital for real-time monitoring of passive DAS deployments, triggering recording and/or transmission of data from a remote station on detecting cryoseismicity.

Further development of these tools can unlock the potential of passive DAS methods for a range of glaciological processes. By integrating observations from DAS and synchronous 3-component seismometer records, we can accurately locate and determine the focal mechanism of cryoseismicity, to improve our understanding of the dynamics of Store Glacier and the structure beneath it. DAS data are also amenable to ambient noise cross-correlation, and recent results (Tribaldos and Ajo-Franklin, 2021) highlight the connection between seismic velocity variations and changes in thermoelastic strain and hydrological dynamics.

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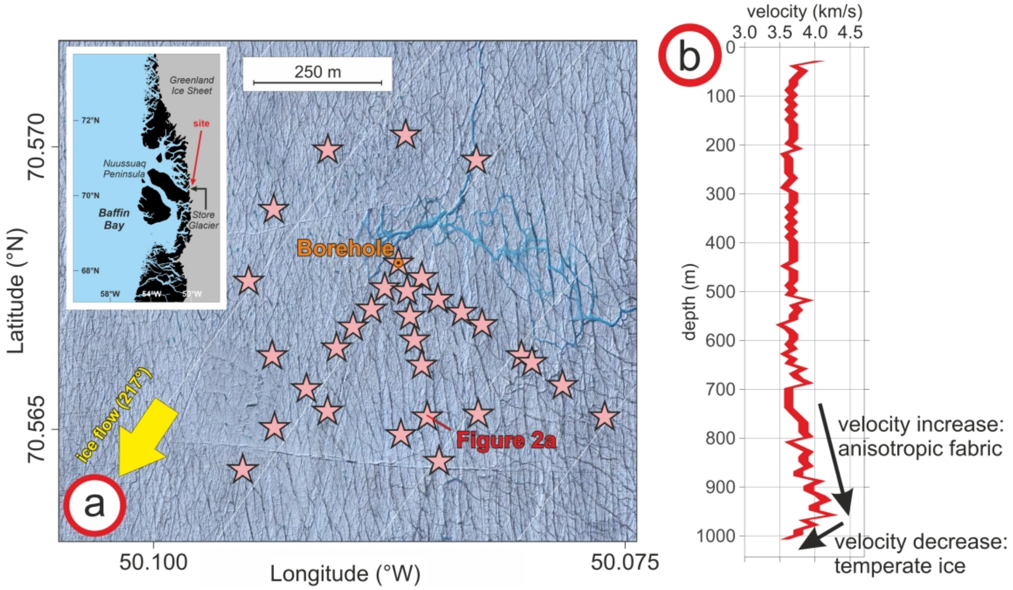
FIGURE CAPTIONS

Figure 1. a) Site S30 on Store Glacier. Active-source shots (stars) are located at various offsets and azimuths around a DAS-instrumented borehole. The offset VSP shown in Figure 2a uses the highlighted shotpoint. Inset panel: location in West Greenland. b) Vertical P-wave velocity trend, derived from zero-offset VSP data (Booth and others, 2020).

Figure 2. a) VSP record highlighting direct and reflected waves, and the lag time between them. b) Schematic VSP ray diagram for direct raypaths (blue) and subglacial reflections (red) from the base of a 30 m thick sediment layer. The lateral offset of the reflection point from the borehole increases the shallower the reflections are observed. c) Subglacial sediment thickness around the borehole, from analysis of lag times in VSP data.

Figure 3. A cryoseismic event recorded in the passive DAS acquisition, shown in a) time-space domain, together with a basal reflection (parallel to yellow-dashed line), and b) frequency-wavenumber (f-k) domain. The same information is expressed with fewer samples in the f-k domain.



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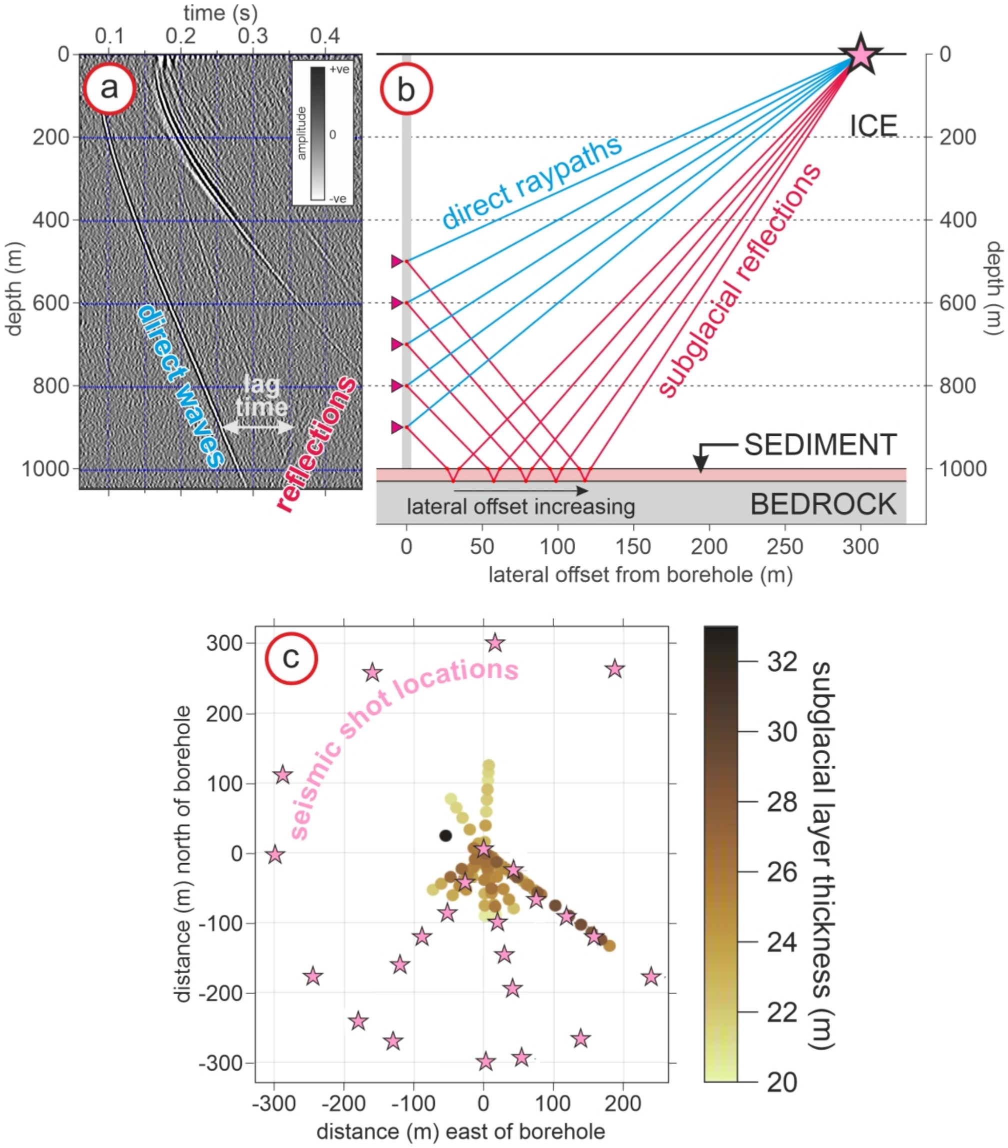

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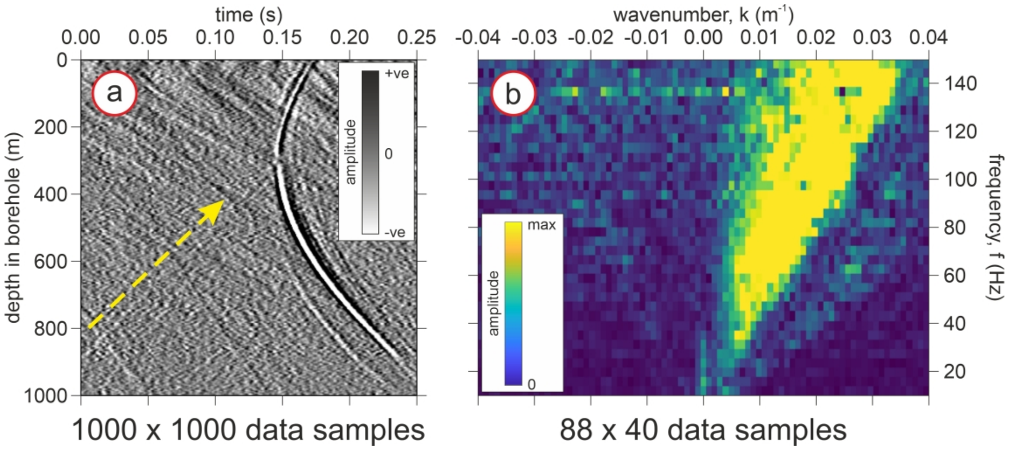

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