Toward the Acoustic Detection of Two-Phase Flow Patterns and Helmholtz Resonators in Englacial Drainage Systems

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Abstract  Passive acoustic monitoring has revolutionized the characterization of industrial processes and the acoustic wavefield in various environments. However, cryospheric acoustic phenomena remain largely unknown, especially at medium and small scales. Furthermore, the englacial drainage system is poorly documented, even though it is fundamental for understanding water routing through the glacier body. Here I present the first-of-its-kind in situ records of periodic or sustained acoustic signals generated by water drainage through crevasses at the calving front of a glacier, in this case a Greenlandic tidewater glacier. The generative mechanisms of gurgling and bubbling noise are explained as flow-induced sounds that are excited by intermittent air-water two-phase flow and Helmholtz resonance, respectively. This paper demonstrates that there is the tremendous potential to study near-surface glacier systems using acoustic methods and detect different flow patterns in englacial conduits from their acoustic signatures, both of which can significantly advance our understanding of glaciological processes.

Plain Language Summary  The glacier surface is full of various audible sounds. While early polar explorers have documented this noisy glacier environment, these qualitative observations have never been supported by measurements. For example, Nansen (1897), wrote, "I can hear reports from the glacier...whenever it turns cold–it writhes horribly, and crevice after crevice appears in the huge body; there is a noise like the discharge of guns, and the sky and the earth tremble so that I can feel the ground that I am lying on quake" while wintering in Franz Josef Land, and Baldwin (1896) described his crossing of Bowdoin Glacier, which is the subject of this study, as follows: "...shrieking sounds frightful enough, came ... to our ears, seeming to vibrate through ... our very bodies, spitefully shouting in our ears: Why, presumptuous man, hast thou set disturbing foot upon my chaste bosom?" Here I analyze the first acoustic records that were directly acquired on a glacier, in Greenland, which reveal previously unknown repetitive or continuous sound sources. It appears that different patterns in air-water interactions give rise to interesting acoustic phenomena, such as bubble resonance and unstable flow in cracks. Future glaciological investigations could consider using microphones to better understand englacial water drainage.

1. Introduction  The acoustic wavefield of the glacier surface is largely unknown. While infrasound observations (<20 Hz) of large-scale processes exist, they have all focused on high-magnitude processes, such as iceberg calving (Richardson et al., 2010), ice falls (Preiswerk et al., 2016), or noise due to the turbulent water flow of a meltwater stream (Podolskiy et al., 2017). Underwater noise observations have recently been made in areas close to glacier ice, revealing a broad range of phenomena related to bubble melt-out (Pettit et al., 2015), icebergs, calving (Glowacki & Deane, 2020; Köhler et al., 2019), ice-related cracking, impacts, and rubbing between ice floes (Ashokan et al., 2016). Audio signals from calving events and motion of the ice mélangé were also recorded with microphones in front of Jakobshavn Isbræ, Greenland, by Amundson et al. (2010). Furthermore, Gräff et al. (2019) conducted the only known study in which a high-frequency pressure sensor was placed directly into the water-filled cavity at the base of a glacier via a borehole. They confirmed the presence of sound and crack waves and used the resonant oscillations of the latter to estimate the dimensions of the basal water-filled patch. However, no such observations have been conducted on the glacier surface to date, even though such areas are full of acoustic signals that have been well documented...
since early polar explorers and field scientists (Baldwin, 1896; Nansen, 1897) first visited these dynamic, high-noise environments.

Careful attention to unusual sounds in cold regions, such as “firn quakes” in Antarctica (Denhartog, 1982), is both a safety and scientific matter. For example, the “whumpfing” sound of a collapsing weak-snow layer is one of the most important indicators of unstable snowpack, which avalanche practitioners and skiers never ignore, and a study of this phenomenon has led to significant advances in anticrack fracture theory (Heierli et al., 2008).

Passive seismic observations have only recently expanded the glaciological toolbox by beginning to shed light on processes that are audibly familiar to mountaineers and glaciologists. For example, nocturnal thermal ice cracking in a Himalayan glacier has a distinct impact on ambient seismic noise, which can obscure transient seismic events (Podolskiy et al., 2018, 2019). Furthermore, an analysis of seismic moulin tremor, which was generated by surface meltwater falling into a cavity in the Greenland Ice Sheet, led to constraints on the geometry of the moulin using an open organ pipe model (Roeoesli et al., 2016). However, the sensitivity of seismic sensors is limited (usually below 0.1–1 kHz; Podolskiy & Walter, 2016), whereas the acoustic emissions of two-phase air-water flow in a moulin or crevasse, or bubble collapse may exceed audible frequencies (i.e., ultrasonic waves with frequencies greater than 20 kHz) (Al-lababidi et al., 2009; Deane, 2013).

Monitoring the englacial/subglacial drainage system and its temporal dynamics remains one of the most challenging tasks in glaciology due to the inherent difficulties in accessing these complex systems. Crevasses serve as the main pathways for delivering surface meltwater to the glacier bed, which may then affect the rate of basal motion (e.g., Chudley et al., 2019; Colgan et al., 2016). However, limited observations of the flow dynamics in such systems are available. Knowledge of the flow pattern in the conduit (e.g., crevasse or moulin) is crucial as it affects fluid friction, momentum loss, and mass flux estimates (Taitel et al., 1980). Furthermore, certain flow regimes may present a powerful acoustic source and therefore be undesirable due to severe vibrations and the risk of mechanical fatigue failure in engineered settings (Tonon et al., 2011).

As surface melting increases in Greenland and Antarctica, it is important to understand and forecast the evolution of englacial drainage systems, the associated changes in the surrounding ice, and the possible impacts of meltwater on future mass loss (e.g., Bell et al., 2018). Despite the enormous vertical scale of drainage systems (competing with the world’s tallest waterfalls; Chudley et al., 2019), direct observation of internal water flow patterns remain elusive and indirect methods have to be used. Moreover, no previous studies have explained what can be expected from an ablation zone soundscape, which is not only a topic of a broad interest in itself but may also be a useful resource for cryoseismic data interpretation (Podolskiy & Walter, 2016). As a step toward these goals, I propose to adapt a simple, but potentially promising acoustic monitoring approach. This method has been used in industry to detect flow patterns when direct visualization is impossible but has not been previously applied to glacier studies.

Here I present the first evidence of unexplained acoustic phenomena being generated by water drainage through a crevasse, in a study of a Greenlandic marine-terminating glacier. I compare this water drainage acoustic signal with those from a moulin and bubble bursts in a supraglacial pond and postulate that air-water interactions hold the key to the sound generation from these different flow regimes, which can be detected via passive acoustic monitoring, whereas the bubbles can be investigated as Helmholtz resonators. This study provides novel insights into the upper englacial drainage system, which (i) serve as a foundation for other potential applications, (ii) highlight the importance of obtaining such observations in the future, and (iii) bridge the disciplines of acoustics and glaciology to address research questions in glaciology.

2. Study Site and Data

Acoustic records were collected in July 2019 as part of a comprehensive geophysical campaign in the ablation area of Bowdoin Glacier (Kangerluarsuap Sermia in Greenlandic; Bjørk et al., 2015), Northwest Greenland (Figure 1a). This marine-terminating glacier is tide modulated, with an average ice flow velocity of about 1.5 m/day. It loses ice via iceberg calving and submarine melting into the fjord at its 3-km-wide calving front, where the ice thickness is about 260 m and the ice cliff is approximately 30 m high. Bowdoin Glacier and its fjord have been the focus of several recent campaigns (e.g., Kanna et al., 2018; Minowa et al., 2019; Podolskiy et al., 2016, 2017; Sugiyama et al., 2015), making this glacier an ideal target for an acoustic study. A unique feature of the glacier is the possibility to approach the calving front by walking directly on ice, which
allows observers the potential to acquire measurements in the most dynamic and heavily crevassed zone of the glacier.

The source mechanisms of sounds described below (also see supporting information for details) were studied by holding a recorder as close as possible to the acoustic source and acquiring 13- to 60-s-long smartphone videos with 16-bit audio using a built-in microelectromechanical system microphone that sampled at 44.1 kHz (iPhone 6S, A1586, iOS 12.4.3). Microelectromechanical system microphones similar to the one used in this study are currently recognized as possessing industry-standard measurement capabilities (flat frequency response between 50 and 18,000 Hz) (e.g., Faber, 2017; Kardous & Shaw, 2014; Picaut et al., 2019).}

According to direct observation by the author during this and three previous expeditions, the main audible sounds in the ablation area of the glacier were produced by iceberg calving (Podolskiy et al., 2017), crevasse opening (Podolskiy et al., 2016), the collapse of so-called ice blisters (10-m-long ice arches), meltwater streams, and black-legged kittiwakes and glaucous gulls that were attracted to the calving front by the subglacial meltwater plume (supporting information Video S1) (Nishizawa et al., 2019). A clearly audible and persistent periodic sound that emanated from a 0.5-m-wide glacier crevasse was heard on a calm day (7 July 2019) during the field campaign, approximately 600 m from the calving front. More obvious sources that were associated with well-developed moulins and bubbles (several centimeters in diameter) nucleating at a single crack beneath the supraglacial pond surface and bursting at the surface were also detected, approximately 130 m from the calving front (Figures 1b–1e). A discrete Fourier transform of the original

Figure 1. (a) Map of Bowdoin Glacier (lower) and its location in Greenland (upper). The red markers on Bowdoin Glacier show where the acoustic measurements were collected. The northing and easting coordinates (m) are in WGS 84 UTM Zone 19. The background map is a Copernicus Sentinel-2A satellite image taken on 27 July 2019. (b–e) Photographs of the three main acoustic sources. (b and c) Transverse crevasse emitting pulsating sounds (the width of the crevasse is less than 0.5 m; the glacier flows toward the left). Its position is marked with a “C” on the map. (d) Supraglacial pond (~1 m deep) with bubbles rising from a small crack that is draining the water. Its position is marked with a “P” on the map. (e) Well-developed glacial moulin (~1 m in diameter). Its position is marked with an “M” on the map.
Figure 2. Examples of the bandpass-filtered waveforms and corresponding spectrograms of the relative sound pressure variations in the three drainage systems. The spectrogram for the raw signal was generated using a 2048-point fast Fourier transform (FFT) with a 0.0454-s Hamming window and 90% overlap. (a) Acoustic signal from a crevasse. The relative pressures for the LF (upper; 20–2,500 Hz) and HF (middle; 3,000–6,000 Hz) bands, as well as the corresponding spectrogram (lower), are shown. The red curves correspond to the signal envelope (moving root-mean-square envelope with a 0.25-s sliding window). Note that the y-axis range shown for the 3,000–6,000 Hz band is an order of magnitude smaller than the range in the 20–2,500 Hz band. The inset plot shows the empirical cumulative distribution function (CDF) of the interevent intervals (IEIs) for each event type (sample sizes: $n_{HF}=45$, $n_{LF}=47$). (b and c) Acoustic signals due to (b) bubble bursts on the supraglacial pond surface (inset spectrogram is for an individual bubble event with a clearly upsweeping tonal signal) and (c) continuous moulin roar.

sound signals (supporting information Audios S1–S3) was performed using sliding windows (the parameters are provided in the corresponding figure captions) to explore the frequency spectra of these sounds.

3. Results
3.1. Pulsating Noise of a Crevasse
Two recurrent types of event are noted in the acoustic emissions from the crevasse in the low (0.02–2.5 kHz) and medium (3–6 kHz) frequency bands (Figure 2a). The primary type is a rumble-like sound pressure pulse with a low-frequency (LF) content below 2.5 kHz, which is labeled a LF event. Such pulsations last almost 1 s and are continuously repetitive, with a quasi-stable interevent interval of about 0.92 s between the peaks of a signal envelope (computed as the root-mean-square of the amplitude in a 0.25-s-long sliding window). The envelope can be seen as a proxy for the source’s energy oscillations. The secondary type is an impulsive event with a narrowband characteristic frequency between 3.0 and 4.5 kHz, hereafter labeled a high-frequency
Figure 3. (a) Power spectral density (PSD) of the observed signals compared with the “noise” intervals (i.e., interevent gaps with relatively quiet conditions). The spectra were smoothed via Konno-Ohmachi smoothing (smoothing factor of 50). The subpanels on the right show the normalized spectra for each drainage system. (b) Anticipated theoretical limits for Helmholtz resonators with variable dimensions. The dashed lines indicate the range of initial frequencies observed during the bubble bursts at the supraglacial pond (Figure 2b).

(HF) event (Figure 2a). These impulsive events are short (less than \(\sim 50 \text{ ms}\)) and an order of magnitude smaller in amplitude than the LF events. They overlap with the LF events and also repeat at regular rate, with an interevent interval similar to that of the LF events, but are remarkably stable (\(\sim 0.95 \text{ s}\)). The LF events gradually emerge and decay, whereas the HF events start with an impulsive onset followed by the coda (the polarity of the onset is unclear). The third type of identified event, which could be confirmed visually and was familiar for the untrained ear, is chaotic meltwater dripping on crevasse walls (\(>6 \text{ kHz}\)) (not shown).
No linear relation can be found between the types of event (e.g., HF impulses may occur either on a peak or trough of the LF pulse train; Figure 2a) due to the variance in the occurrence rates of the LF pulsations. Increases in the signal-to-noise ratio of both the LF and HF events after the acoustic recorder was placed closer to the crevasse mouth suggest that both superimposed signals originate from the crevasse (supporting information Figure S1).

3.2. Bubble Burst at a Supraglacial Pond and Moulin Roar

Bubble burst at the pond surface generally lasts less than 0.5 s. The rate of bubble nucleation is approximately 2.6 bubbles per second; however, it is quite irregular and may consist of different-sized bubble clouds. The most remarkable spectral feature of bubbling is a hockey-stick-like increase in frequency with time; that is, upsweeping tonal signal (Figure 2b). Video inspection indicates that a LF onset of the signal (0.1–0.5 kHz) is first produced, while the bubble is emerging at the surface, and then collapsing at higher frequencies (up to 2 kHz and above). A cracking noise at >6 kHz is also audible (not shown), reflecting the melt-out of small pressurized air bubbles from the ice.

The waterfall-like continuous roar of the moulin has the simplest acoustic characteristics, which are dominated by high-amplitude, apparently broadband noise (Figure 2c).

3.3. Spectral Properties

The spectral differences between the main sources are shown in Figure 3a; they are also compared with interevent time intervals (i.e., “noise”), if applicable. The most striking features of the LF pulsations are a well-defined peak at 0.67 kHz, a lack of energy along a horizontal “bandgap” that is centered at approximately 1.12 kHz, and a secondary peak around 1.3 kHz (Figure 3a). The acoustic bandgap indicates either excitation of only certain frequencies or some absorption of acoustic energy, which inhibits the propagation of sound waves (e.g., Roeoesli et al., 2016). The peak at 0.67 kHz remains visible during time intervals without LF and HF events.

The HF spectra exhibit a short-term increase in energy between 3.0 and 4.5 kHz (Figure 3a). A similarity with LF spectra is observed in the HF spectra, especially below 2 kHz, which is due to the superposition of acoustic energy (i.e., there is LF energy remaining from a continuing LF event). Bubble bursts also produce a transient, but longer, rise in spectral amplitudes up to 2 kHz (Figure 3), which is the only phenomenon here that can be explained through a well-established theory, as discussed in the next section. The interburst intervals were the quietest and could be seen as the background sound pressure levels for the study area.

The moulin sound spectra were uniquely wide and flat compared with the other acoustic sources. Meltwater falling into the moulin cavity produced significant LF noise (<0.5 kHz). The spectral amplitude of the moulin exhibited a slower decay with frequency than the normalized spectra of the inter-bubble interval (Figure 3a).

4. Discussion

4.1. Fluid Oscillator as a Noise Mechanism

If the secondary peak at 1.3 kHz in LF spectra represents second harmonics that are excited at higher amplitudes, then a nearly even integer spacing with the fundamental mode (~2) should be seen as a function of the resonance of an open pipe with length $L = \frac{c^2}{2f}$, where $c$ is the sound speed in the air (331 m/s) and $f$ is the frequency. These assumptions yield $L = 25$ cm, which is difficult to interpret given the complex shape of the crevasse, but make dimensional sense for the length of the resonating section of a conduit. The most plausible explanation for the main LF sound generation mechanism in a crevasse is self-excited flow pulsation due to the instability of two-phase flow (air and water) in a vertical drainage conduit. Engineers and physicists have long studied noise and vibration sources in pipe and conduit networks (e.g., Blake, 2017; Naudascher & Rockwell, 2005), with two-phase gas-liquid flow known for its challenging complexity, which arises from an interaction between the phases. However, there are few data on the acoustic features and mechanisms of the flow-induced pulsating sounds identified here. Liu et al. (2015) have noted that a similar noise type is most likely to emerge in a vertical flow regime due to intermittent flow and is referred to as “gurgling noise.” The transition from stratified flow to a noise-generating flow pattern in a pipe depends on the gas/liquid flow rates and conduit geometry and may develop in a horizontal conduit due to the Kelvin-Helmholtz instability, but this transition usually takes place when the conduit becomes vertical. The air bubble, which has a radius almost equal to the radius of the conduit, must leave through the bottleneck against the downward flow in this configuration to compensate the overpressure from the water entering.
Figure 4. Idealized cartoons (not to scale) illustrating different flow patterns, and the separation between air and water in a glacier crack or conduit, each of which generates distinct acoustic signatures: (a) slug flow (i.e., crevasse), (b) unrestricted flow (i.e., moulin), and (c) bubble burst (i.e., supraglacial pond). The red “P+” indicates an increase in air pressure compared with the ambient atmospheric pressure “P.”

the unvented drain (Figure 4a). The gas pockets in this model, which are sometimes called “Taylor bubbles,” block the flow of meltwater, can open the conduit to the atmosphere, and generate audible sound pulsations when they are burst by water. This flow regime, which forms when the continuity of the liquid is repeatedly destroyed by Taylor bubbles and then restored after their collapse, is known as “slug” or “churn” flow (Taitel et al., 1980). Kolb et al. (1990) calls this flow regime the “pulsing regime.” These oscillatory dynamics imply that meltwater flow is composed of falling water-slug bodies, and inversely related to the relative sound pressure level. Significant air entrainment and the downward transport of bubbles via turbulent flow should occur for moulin roar at a given water flow rate, but the well-developed conduit provides sufficient space for the overall phase separation and therefore does not lead to the pulsing regime (Figure 4b).

The source of the secondary HF acoustic signals remains unknown. However, the similarity in the recurrence rates with LF pulses provides evidence that they are related through nonlinear processes in the hydraulic and/or solid response of the drainage periodic pressure fluctuations. Furthermore, it is possible that the HF source is shallower than the LF source; otherwise, it would be difficult to observe this acoustic signal due to absorption by the fluid around the bottleneck.

4.2. Bursting Bubbles as Helmholtz Resonators

The initiation of a bubble burst is recorded as a Helmholtz resonator by a microphone located above the supraglacial pond surface (Deane, 2013; Spiel, 1992). The corresponding upsweeping tonal sound can be conceptually explained as the resonance of a decreasing bubble volume during the escape of the trapped air through the growing upper opening, followed by the collapse of the bubble and a splash of spray (Figure 4c). Therefore, the signal can be used to constrain the bubble properties, with the bubble size being inversely proportional to the frequency in the beginning of the signal, and the duration of the Helmholtz oscillation can be an indicator of the film retraction time (Deane, 2013; Spiel, 1992).

The anticipated Helmholtz resonance frequency can be calculated for a bursting air bubble at 0 °C in fresh water, following equation (20) in Spiel (1992):

$$f = \frac{c}{4\pi} \sqrt{\frac{3\alpha}{kR^3}}$$

where $\alpha$ is the hole radius, $R$ is the equivalent spherical radius of the air bubble rising underwater, and $k$ is a dimensional parameter ($8/3\pi \leq k \leq 16/3\pi$). While $R$ and $\alpha$ are unknown, there is a dependency between the radii of the protruding cap at the surface and the equivalent bubble radius. Here the floating bubble is
assumed to have the shape of a hemisphere for the sake of simplicity and since an analytical solution for the shape of large bubbles floating on the water surface is lacking (e.g., Toba, 1959). Therefore, the aperture of the initial opening $a$ is equivalent to the spherical cap radius, where the latter is equal to the bubble's horizontal size, such that $a \approx \sqrt{2}R$ (see supporting information). For example, an air volume with an equivalent radius of 5 cm and a hole radius of around 6.3 cm corresponds to initial Helmholtz oscillations at $\sim$0.3 kHz (Figure 3b), which are close to the observed initial frequencies in the 0.1- to 0.5-kHz range (Figure 2b). However, while the size of the bubbles could not be measured from the images that were acquired at least $\sim$3 m from the water surface, the estimated order of magnitude is reasonable (Figure 1d). This implies that the volume flux of the air and corresponding volume of escaping water can be inverted. The air flux is also interesting because it points to the presence of internal air-filled voids and therefore to the low bulk density of ice. These implications generally align with other indications of low bulk densities (e.g., 700 kg/m$^3$) in the near-terminus, heavily crevassed environment (Colgan et al., 2016).

4.3. Moulin Roar as a Waterfall
The moulin sound spectrum is indicative of waterfalls, which are acoustic sources that are dominated by LF noise. Previous studies have suggested that this LF noise is related to water impact (i.e., cavitation), water-to-solid impacts, and an increase in drop height (Watts et al., 2009). A preliminary interpretation of the highly stable, continuous roar of the moulin, lacking any obvious resonance, acoustic band gaps, and high-amplitude pulsations, can be an unrestricted draining process.

4.4. Acoustic Signatures of Flow Patterns
The presence of individual acoustic signatures in each considered noise sample (Figure 4) is consistent with previous experimental studies that were motivated by the fact that a flow pattern visualization is often impossible in many industrial processes. For example, there have been attempts to construct flow regime maps for different liquid and gas flow rates in pipes using their acoustic spectra (e.g., Diatschenko et al., 1994; Kolb et al., 1990). Specifically, Kolb et al. (1990) investigated the noise due to air-water downflow from a small outlet in a pressurized packed column and found that different flow regimes can be identified using their spectra. Even if direct comparisons between their study and the present study are not possible, it is interesting that they found sound pressure pulsations ($10^{-80}$ s$^{-1}$), which were generated by alternation of air- and water-rich slugs spanning the conduit width, and observed that interpulse time decreases when one of the flow rates increases.

5. Conclusion
In summary, two novel sources of distinct acoustic radiation were identified in the drainage systems of a calving glacier in Greenland: (1) repetitive ($\sim$1 s), self-excited flow pulsations that are attributed to two-phase flow instability in a crevasse and (2) bubble burst at the surface of a supraglacial pond, which can be seen as Helmholtz resonance. Both identified flow patterns highlight that the air phase plays a fundamental role in the acoustic emissions, which have not previously been considered as acoustic sources in glaciers. The existence of spectral differences and a clear periodicity suggests that passive acoustic monitoring has an unrecognized potential in extracting the mass flux and “fingerprinting” the flow regime in the englacial drainage system. Further experimental and theoretical studies are required to (i) determine the optimal acoustic detection setup, (ii) identify the limitations of this approach, as this approach might not be applicable in every glacial setting (e.g., insignificant surface melt, windy conditions, or multiple sources), and (iii) refine the feasibility of such an acoustic method in glaciology, particularly in relation to the potential evolution of the flow pattern in an englacial conduit (e.g., flow patterns may change down a conduit). The use of such a noninvasive method has previously been proposed for real-time machine condition, pipeline, nuclear power plant, and chemical engineering process monitoring (Al-lababidi et al., 2009; Boyd & Varley, 2001; Diatschenko et al., 1994; Hubbard & Dukler, 1966; Rondeau et al., 2019) but has yet to be adopted as a potentially powerful glaciological tool. Furthermore, the presence of such upsweeping acoustic events, especially for large bubbles, which ring at the sensitivity range of seismic instruments, can be confused with a dispersion and, therefore, needs to be considered to improve data interpretation. There are also an increasing number of seismic studies on supraglacial ponds and the initiation of hydrofracture in ice shelves and ice sheets, which could potentially observe such acoustic signals (Chudley et al., 2019; MacAyeal et al., 2019; Minowa et al., 2019).
It is therefore reasonable to suggest that the near-source acoustic characterization of glacial environments is likely to offer new insights into glaciological processes. Furthermore, the general rise in the number of studies on the environmental, biological, and anthropogenic noise in forests (Burivalova et al., 2019), cities (Picaud et al., 2019), and underwater environments (Risch & Parks, 2017) indicates that a more in-depth focus on the poorly understood cryospheric soundscape will be a step toward acquiring a more holistic view of the environmental noise field.

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