PORTABLE REAL-TIME VOLCANO INFRASOUND AUDITORY DISPLAY DEVICES

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ABSTRACT

Active open-vent volcanoes produce intense infrasound airwaves, and volcanoes with prominent craters can create strongly resonant signals, which are inaudible to humans, and often peak around 1 Hz. Study of volcano infrasound is used to model eruption dynamics, the structure of volcanic craters, and can be used as a component of volcano monitoring infrastructure. We have developed a portable on-site real-time sonification device that emits an audible sound in response to an infrasonic airwave. This device can be used near an active volcano both as a real-time educational aid and as an accessible tool for monitoring the state of volcano activity. This paper presents this device with its hardware and software implementation, its parameter mapping sonification algorithm, recommendations for its use in the field, and strategies for future improvements.

1. INTRODUCTION

1.1. Volcano Infrasound

Volcano monitoring may incorporate signal collection from seismic, deformation, thermal, gas sensing, and infrasound recordings. Infrasound is inaudible sound below 20 Hz and is a particularly useful tool when a volcano is open-vent (degassing) or erupting [1, 2]. Due to the high-amplitude infrasound sources and low intrinsic attenuation of infrasound propagation, infrasonic microphones are often deployed many kilometers from an active vent. Recorded waveforms are usually examined visually to identify explosions or other types of activity, including steady degassing or mudflows, rock falls, and other gravity-driven flows. Infrasound is a particularly effective tool to track activity when the volcano might be obscured at night or during inclement weather [3].

Infrasound recording has also been used to effectively monitor resonant sounds produced by a volcanic crater, which has important implications as a forecasting tool [4]. As an example, in the case of Volcán Villarrica in Chile, a rising lava lake preceded a paroxysmal eruption on 3 March 2015 and the attendant changing infrasound frequencies were monitored remotely [5]. Villarrica has now returned to its background state of a stable lava lake boiling deep within the summit crater.

1.2. Motivation

It is common for volcanologists to create audifications from recordings of both infrasonic sound and seismological activity produced by volcanoes [6]. Typically, this is performed by listening to the data at time-dilation rates of 100 to 500 times the recording rate, which would convert a typical 1 Hz volcanic tone to an audible signal ranging from 100 to 500 Hz. This technique, which is also widely used for making audible signals from earthquake seismograms, is effective for identifying subtle changes in signal character, which are not always immediately evident thorough visual inspection of waveforms. This type of audification, which is used offline and accelerates review of the geophysical record, is not possible in real-time and while on-site at a volcano.

For this project we are motivated by a desire to demonstrate infrasonic phenomena present at volcanoes to people who are within proximity to the infrasonic sound. We have created a process monitoring auditory display device that employs parameter mapping sonification to create an audible sound that corresponds to the low frequency characteristics of the on-site infrasound. Our goal is to create a low-cost portable system of real-time sonification that audibly displays important infrasonic features and fluctuations to the user in the field.

By creating an audible sound that has correspondences to the live infrasonic sound, a user can readily become aware of the otherwise inaudible infrasonic phenomena. Sound here is used over a visual representation of the infrasonic signal as it does not require translation into a different sensory modality. The sound from our device reinforces the user's understanding of the sonic nature of the infrasonic airwave. In addition, the audible sound allows listeners to experience any time-dependent changes as they happen, allowing listeners a more immediate understanding of the infrasonic phenomena [7].

2. SONIFICATION METHOD

Due to the real-time requirement of our application, time-dilation audification techniques are not possible. Instead we have devised a parameter mapping sonification algorithm that demonstrates to the user specific features of the infrasonic sound present. In particular, we wish to show that the infrasound has a pitched nature created from its origin in the resonant chamber of the volcano vent, and that the specific time varying nature of the infrasonic signal can be monitored.

Our real-time DSP algorithm uses frequency modulation (FM) of the live volcano infrasound (modulator) with a user adjustable sinusoidal carrier. Frequency modulation has been used as a sound synthesis method in sonification projects, typically for its efficiency in producing complex waveforms [8]. In our case, the modulator frequency is not high enough to create audible sidebands and the modulator is simply used to create a slowly varying audible change to a user-selectable carrier frequency. This modulation is shown in equation (1).

$$y(t) = sin(2\pi t f_c + I_m x(t)), \tag{1}$$

where $x(t)$ is the volcano's infrasonic signal, $y(t)$ is the modulated signal, f_c is the carrier frequency set by the user, and I_m is the index of modulation set as an amplitude scalar by the user.

In order to silence the carrier sound when no infrasound is present, $y(t)$ is then filtered with a second order stopband filter centered at the carrier frequency. This filter is shown in Figure 1, where $z(t)$ is the resultant audible sound.

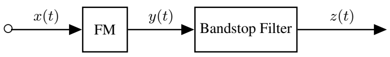

Figure 1: Signal processing with bandstop filter.

The result is a sound that glissandos up and down in frequency with a period that matches the frequency of the volcano infrasound. When no infrasound is present, the sonification is silent as the modulating frequency is substantially removed by the filter. As discussed below, this method of sonification is efficient at creating an audible sound that tracks the moment-to-moment changes in the volcano infrasound.

An offline demonstration of the algorithm, including modulation and notch filtering, is shown in Fig 2. Data collected from the Volcán Villarrica volcano with a stand-alone calibrated *infraBSU* microphone [9], recording at 100 Hz, was resampled to 44.1 kHz and then subjected to the DSP algorithm outlined above using 50 Hz carrier tone and a index of modulation of 20 followed by application of the bandpass filter. The original 4 minute long signal includes small spatter bursts (5 Hz peak frequency) from the lava lake at 50 s and 70 s, followed by an infrasonic tremor for the remaining duration. This tremor corresponds to the open-vent degassing of the lava lake with peak frequency around 1 Hz. The spectrogram of this raw signal shows almost all energy is below 20 Hz. The original source infrasound, having been processed by the algorithm, retains the envelope of the original data. The spectrogram shows that the signal is now audible. This sonified infrasound is available for review [10].

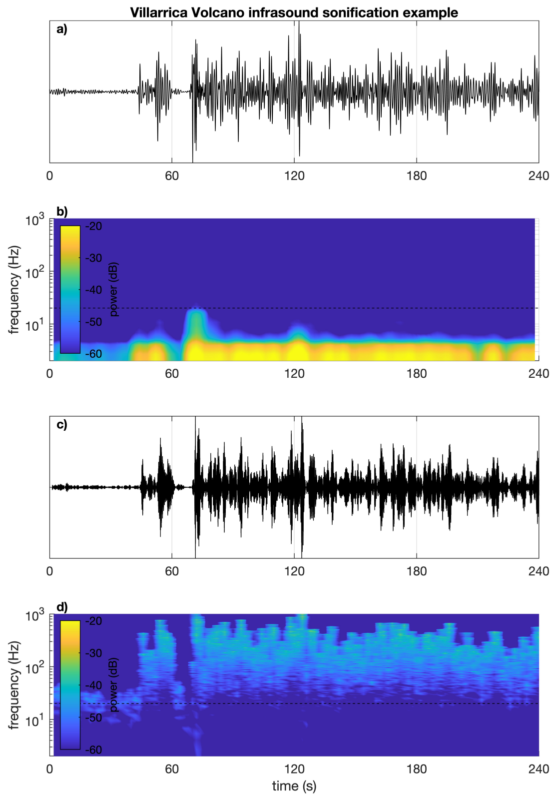

Figure 2: a) Infrasound collected at the Volcán Villarrica crater rim. b) Spectrogram calculated with 4 s windows and 2 s overlap. c) Processed infrasound using carrier frequency of 50 Hz and an index of modulation of 20. d) Corresponding spectrogram for panel c with 4 s windows and 2 s overlap. Spectrogram power is given in dB/Hz.

3. IMPLEMENTATION

3.1. Faust

The sonification algorithm was implemented in the Faust signal processing language [11]. Faust is a high level audio specific language that compiles into efficient C++ code for numerous hardware platforms. We chose this language because of its ability to compile code for our microcontroller as well as future hardware configurations we may investigate [12].

3.2. Hardware

The hardware of the device, here named the *VADD* (Volcano Auditory Display Device), is built around the Teensy 3.6 microprocessor and its audio breakout board as seen in Fig 3. The infrasonic signal is transduced by an electret microphone. We have previously found that an electret microphone can transduce infrasonic signals to a low of approximately 1 Hz. For our purposes, this is sufficient to capture the 1 to 2 Hz signals of volcanoes [13]. The Teensy audio breakout board features an audio pre-amplifier and a software controlled highpass filter which is disabled in our application.

A 2.5 Watt audio amplifier, the Adafruit PAM8302, is used to amplify the audio output of the Teensy. This amplifier, the Teensy, and the audio breakout board are all powered by a 5v USB battery that is enclosed in the device. A small loudspeaker, the Tang Band T1-1942SB, is built into the front of the case and functions as the only display for the device. This speaker was selected for its small size, durability, and relatively good low frequency capability.

Two knobs on the front of the device allow the user to set the base carrier frequency f_c and the depth of frequency modulation I_m. These controls use Teensy analog input pins to transfer their values to the modulation algorithm.

The VADD is the first version of the device we created and we have found that it is robust in field use with a long battery life and

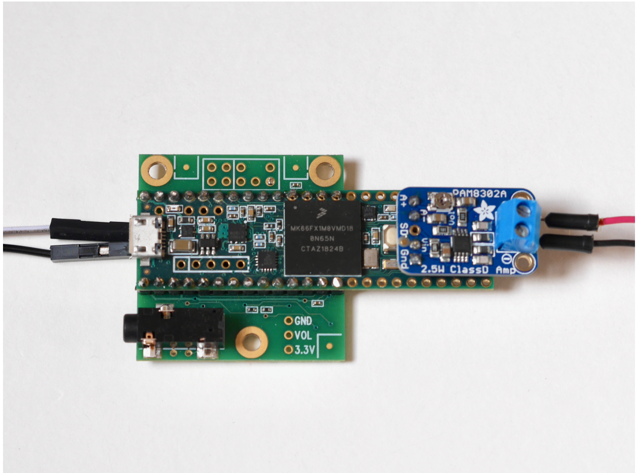

Figure 3: The Teensy 3.6, Audio breakout board, and audio amplifier assembly.

Figure 4: The VADD auditory display device.

sufficient sound volume.

4. FIELD USE

We have tested the VADD at three active volcanoes. In each case, we were able to successfully sonify the infrasonic sound from the volcano in real-time. In all three cases, the VADD was used as an educational device to teach about infrasound and in one case it was additionally used to assess infrasound characteristics.

The VADD was used at Yasur (Vanuatu), Masaya (Nicaragua), and Villarrica volcanoes to demonstrate to field participants and to the public (through documentary film) the inaudible, but intense sound wavefields that are continually emitted by volcanoes. As an example of its public outreach potential the VADD was demonstrated at Masaya Volcano as part of CBS's Good Morning America in March 2020 [14].

Most recently the VADD was used on a research trip to the Volcán Villarrica volcano near Pucon, Chile. The purpose of this trip was to deploy long-term infrasonic detectors at the volcano. Here the device was used to show infrasonic sounds presence to people who had lived their lives in volcanic infrasound without experiencing its presence directly. In addition, the VADD was successfully used to quickly assess locations for deployment of long-term infrasonic detectors for a research project.

Figure 5: The sonification device in use at Volcán Villarrica volcano, Chile, January 2020.

In all three cases, the device has been a useful tool for both demonstrating infrasound, and for making quick observations of the state of the volcano infrasound.

5. FUTURE DIRECTIONS

Future versions of the VADD are being considered and include changes to the hardware as well as to the sonification algorithm. A change of microprocessor will not require substantial rewriting of the DSP code because of the platform agnostic Faust language. The Teensy 4.1 could easily be substituted for our current Teensy 3.6 microcontroller. The Daisy Seed microcontroller could be employed as it can be a target for Faust code generation. However a change of microcontroller is not currently needed as the Teensy 3.6 microcontroller provides sufficient DSP processing power for our algorithm. A new generation of ESP32-based audio prototyping boards could be employed as the basis for a future iteration [15]. The ESP32-LyraT-Mini board in particular has a built-in electret microphone and audio amplifier, both of which would be ideal for our application. It is unknown whether this board incorporates a DC blocking circuit which would limit its use with our infrasound application.

Although the VADD is able to transduce infrasound with an electret microphone in the range of most volcano infrasound, a potential improvement exists to to record lower frequency infrasound using a differential pressure transducer, such as used by the infraBSU, which utilizes microelectromechanical systems (MEMS) [16]. MEMS-based infrasound sensors are able to record infrasound down to below 0.1 Hz with a flat frequency response [17].

We have found that the FM-based sonification algorithm achieves our specific goals of demonstrating the pitched nature of the infrasonic signal and monitoring the time-varying transients of the infrasonic signal. One potential change to the algorithm would be to employ pitch shifting of the infrasonic signal using the Hilbert transform before frequency modulation. This is the technique presented by Holdrich and Vogt as part of their "augmented audification" technique [18]. This method has the potential to allow the carrier signal to not be a synthesized sine wave, but a frequency shifted version of the signal itself. As Holdrich and Vogt point out, the frequency shifting process creates a very narrowband signal that may be perceptually indistinguishable from the synthesized sine tone we employ as the modulator.

Another potential change to the algorithm is to amplitude modulate the carrier signal with the infrasonic modulator signal. This could be performed simultaneously with the frequency modulation technique and could provide another path for perceiving the infrasonic phenomena.

Finally, we propose to distribute these devices to volcano visitors centers at active volcanoes for use by visitors. There are about 20 active volcanoes worldwide at any one time producing infrasound that is not perceived by humans. Kilauea Volcano (Hawaii), for instance, would be an ideal location to demonstrate the VADD's capabilities to the pubic. We have found that by hearing volcanic infrasound using the VADD, the natural phenomenon becomes both more tangible and easily understood.

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