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ACOUSTIC CHARACTERISTICS OF PYROCLASTIC DENSITY CURRENTS

A THESIS PRESENTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
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RESILIENCE
TO NATURE'S
CHALLENGES

Kia manaweroa
– Ngā Ākina o
Te Ao Tūroa

National
Science
Challenges



Volcanic Risk Solutions

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Abstract

Pyroclastic Density Currents (PDCs) are a deadly and destructive aspect of volcanic eruptions; however, their study has been hampered by a lack of direct observations and measurements of their internal flow dynamics in the field. Although deposits, videos, and photos offer some insight into PDC behavior, there remains a need to interrogate their poorly constrained internal flow structure and dynamics. Owing to their destructive nature, field-based studies are challenging. Remote measurements through infrasound sensors have been proposed as a possible remedy to close this gap. However, there is a lack of understanding of how and where the infrasound signals recorded from PDCs are generated and what properties they are linked to. This thesis covers the use of large-scale analog experimental PDCs at the PELE facility (the Pyroclastic flow Eruption Large-scale Experiment) to constrain PDC infrasound signal generation. In addition, this thesis expands on the case study literature by revisiting the pressure signals recorded and observed by eyewitnesses from the May 18, 1980 lateral blast of Mount St. Helens.

Through the combination of case study data and three dedicated PDC infrasound experiments, three distinct pressure signals were identified. The first is the displacement of the atmosphere by the initial intrusion of the material into the ambient atmosphere and the transition of the material into a flow. This signal has previously been observed and interpreted as an intrusion displacement; however, the use of experimental PDCs allowed for the confirmation of this signal. This signal was scaled with the initial momentum of the flow within the experiments, with increasing acoustic power and decreasing dominant frequency with increasing momentum. Preliminary analysis

results suggest that this relationship holds in natural examples. On larger scales, such as the Mount St. Helens blast, this signal may even be a Lamb wave directed in the direction of the blast. There are currently insufficient datasets to develop a physical or empirical relationship for this behavior; however, this may be possible at volcanoes with a repeating source (e.g., a collapsing dome). The results also suggest that the use of pre-flow arrival signals generated by PDCs could differentiate between pyroclastic surge and pyroclastic flow end members.

The second type of pre-flow arrival signal is a dynamic pressure increase that occurs immediately before the arrival of the front flow. This signal suggests that the acceleration of the atmosphere ahead of a flow can produce a previously unrecognized dynamic pressure hazard due to the acceleration of the atmosphere up to the flow front velocity. Given the range of velocities associated with propagating PDCs, this has the potential to be a significant dynamic pressure before the arrival of the flow front.

Finally, the third type of signal generated by the propagating flow is driven by turbulence along the entire surface boundary with the atmosphere. While the initial signal front can be used to calculate propagation velocity of the flow front, subsequent signals may or may not be new flows, and could be reactions of the flow to underlying conditions like the passing of an energetic underflow.

These findings expand our knowledge of the recordable pressure signals produced by PDCs in the field. These findings need to be further validated and benchmarked in the field; in particular, the limited number of case studies needs to be addressed by increasing the deployments of infrasound arrays.

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Chapter 1

Introduction

1.1 Research Problem and Motivation

Pyroclastic density currents (PDCs) are hot, fast moving, multiphase flows of volcanic particles and gas (Sulpizio et al., 2014; Dufek et al., 2015). These ground hugging gravity currents propagate long distances through their density contrast with the atmosphere (Dufek, 2016). PDCs are conceptualized as a wide continuum of observed behavior described by their relative density from dilute flows (surge) to dense flows (pyroclastic flow) (Lube et al., 2020). Each individual event is capable of transiting between these end members. PDCs exert high dynamic pressures on the natural and built environment as they propagate, and this combined with their high temperature and inhalation of very fine ash contribute to their deadly impact. PDCs alone are responsible for almost a third of volcanic fatalities worldwide (Brown et al., 2017). Despite the significant hazard posed by PDCs, significant gaps remain in our understanding of their dynamics. This is largely due to their destructive nature and the difficulty in obtaining direct measurements of actively propagating flows. Field measurements are predominantly from deposits and post-event damage surveys (Guinn et al., 2022; Brown and D. M. Andrews, 2015; Lerner et al., 2022; Yamamoto et al., 1993; Mastrolorenzo et al., 2010; Jenkins et al., 2016, 2013; Cronin et al., 2013; Cooper, 2018; Cole et al., 2022; Benage et al., 2016; Abdurachman et al., 2000). To address this gap, the study of

PDCs also relies on the study of other analog gravity currents, numerical modeling, and scaled analog experiments (Dufek et al., 2015; Benage et al., 2016; Breard et al., 2016; Lube et al., 2014; Dufek, 2016; Neri et al., 2022; Roche et al., 2008). However, it is important to compare these results with groundtruthed datasets of natural PDCs. To further understand the interior dynamics of PDCs, several geophysical methods have been proposed (Biagioli et al., 2026; Watson et al., 2023; Bougouin et al., 2026; Brosch et al., 2022). Among these technologies, infrasound is increasingly being deployed as part of volcano monitoring networks.

Infrasound, or sound below the threshold of human hearing (20 Hz), is an emerging tool for early warning systems for a range of volcanic hazards, including eruption detection, characterization, and lahar detection (Thelen et al., 2024; Johnson et al., 2023b; Watson et al., 2022b; Sanderson et al., 2021; Johnson and Ronan, 2015; Bosa et al., 2021a). Low frequency sound can travel long distances with relatively little attenuation, making it possible to monitor volcanoes from relatively safe areas. Infrasound is generally classified as local (within 20 km), regional (20–250 km), and global (over 250 km), with volcano eruption detection carried out across all three ranges. Even though the field of infrasound dates back to the late 19th century with the 1883 eruption of Krakatau (Campus and Christie, 2009; Taisne et al., 2025; Blom and Bishop, 2024), detailed studies of volcanic infrasound are relatively new. The field of volcano infrasound has experienced rapid growth since the establishment of the International Monitoring System (IMS) network in 2001 (Campus and Christie, 2009; Christie and Campus, 2010). The majority of volcano infrasound studies focus on volcanic eruptions and their eruption plumes (Perttu et al., 2020b; Caplan-Auerbach et al., 2010; Fee and Matoza, 2013; Fee et al., 2010; Dabrowa et al., 2011; Watson, 2020; Taisne et al., 2019, 2025). As low-frequency acoustics propagate long-distances with minimal attenuation, infrasound is well-suited for observations of destructive volcanic phenomena like PDCs from a range of distances. Despite this potential, there are major knowledge gaps and a lack of systematic study into the signal generation source mechanisms of PDCs. Without proper context and understanding of the source characteristics of a signal, it

is difficult to tie any specific signal to a specific parameter or feature of the source. The seismic characteristics of PDCs have been studied for decades (Yamasato et al., 1993; Watson et al., 2023; Allstadt et al., 2018; Yamasato, 1997; Calder et al., 2022; Jolly et al., 2002; Luckett et al., 2002; De Angelis et al., 2007; Uhira et al., 1994; Zobin et al., 2009); however, seismic studies are only sensitive to the direct coupling of the flow with the solid Earth. With further understanding of the generation of acoustics, the combined study of seismic and acoustic signals would enable the determination of energy partitioning between the atmosphere and solid Earth during PDCs.

This thesis addresses these knowledge gaps; in particular, the need for direct field measurements and identification of PDC acoustic sources by examining the signals generated by PDCs within the atmosphere and their source mechanisms. Viewed through the lens of PDC research, further investigation into PDC acoustics represents a unique opportunity to obtain direct field measurements. From the volcano infrasound research perspective, signal discrimination is crucial for characterizing different aspects of eruptions.

The studies present in the literature for PDC infrasound are based on either a dataset from the early 1990s at Unzen volcano (Yamasato et al., 1993; Yamasato, 1997; Oshima and Maekawa, 2001), or a dataset collected from Montserrat’s Soufriere hills volcano in the 2000’s (Ripepe et al., 2009, 2010; Delle Donne et al., 2014). Both case studies focus on dome collapse events. The similarities and lack of data availability for these case studies highlight the need for new approaches and further investigation. For a more controlled and systematic approach, this thesis takes advantage of an established analog PDC experimental facility, the Pyroclastic flow Eruption Large-scale Experiment (PELE) at Massey University in Palmerston North, New Zealand, to conduct a series of experiments into PDC infrasound. The PELE facility (Lube et al., 2015), allows for the detection of acoustic signals and comparison to measurable characteristics of the experimental flows.

1.2 Research Questions and Objectives

The research questions addressed in this thesis were determined based on the aforementioned gaps in knowledge, including: the need for field measurements that can be tied to the physical properties or dynamics of natural PDCs, and the source mechanisms and characteristics of PDC acoustics.

One significant limitation within the published PDC literature is that the two case studies each represent only one type of PDC source mechanism, as both studies were based on dome collapse events (Yamasato et al., 1993; Ripepe et al., 2009). However, given the prevalence of PDCs and increasing use of infrasound, it was desirable to identify another field dataset that could broaden the perspective of natural PDC acoustics. This led to:

Objective 1: Determine the state of the field-based understanding of audible and infrasonic signal generation by and within PDCs using published case studies. Assess whether there is an example of a well-characterized PDC event with complementary infrasound data that could complement existing PDC-infrasound studies.

Within the objective, both well known and characterized PDC events, as well as volcanoes with known infrasound deployments, were combined to find a suitable candidate for an additional case study that differed from the published literature. The methods for selecting the case study are presented in Chapter 2, and the case study is presented in Chapter 3.

Understanding how a specific source interacts with the atmosphere requires a carefully designed study. The PELE facility at Massey University offered an environment where analog experimental PDCs could be produced and recorded multiple times without having to wait for events to occur naturally. This led to:

Objective 2: Design and conduct a series of PDC infrasound experiments. Investigate if, similar to other analog natural events, experimental PDCs generate infrasound signals arriving before the flow, and how these relate to constrainable physical characteristics of the PDC or PDC generation.

Although PDCs are known to produce a signal in the infrasound range in the field, it is important to establish the wavefield around them and any other signals that might be generated in order to isolate the signal of interest. The results of Objective 2 led to the identification of additional pressure and acoustic signals related to the generation of PDCs that can be recorded with pressure sensors. The experimental setup is detailed in Chapter 2 and the results are presented in Chapter 4.

Following on from Objective 2:

Objective 3: Characterize the source of infrasound generated by PDCs, with a focus on the moving signals reported in the literature.

One of the key observations in the literature on PDC infrasound is that the signal originates from a moving source. Here, I looked at this moving source and worked to identify where the acoustic signal is generated and how. These results are presented in Chapter 5.

This thesis focuses on the signals generated by the PDCs themselves and not the variety of ways they can be generated.

1.3 Thesis Outline and Structure

This thesis comprises seven chapters and three appendices. Following this introduction, there is a review of the topics, methods, and fields relevant to this work. This section covers the fields of acoustics and infrasound used to characterize the experimental PDCs, aspects of physical volcanology related to PDC geophysical observations, and analog PDC experiments. The section of the introduction on infrasound produced by PDCs, along with the associated research history, has been published in a book chapter (Taisne et al., 2025), but it is expanded upon here.

Chapter 2 details the methodology of this thesis. As the bulk of this thesis focuses on experiments conducted at the PELE experimental facility, these methods are presented first. This chapter covers the experimental specifications, sensors selected, their technical specifications, and the design choices in their installation. It also covers

the data quality pre-processing methods developed for this unique dataset. Finally, it details the selection of the case study of Mount St. Helens. Chapters 3 –5 present the primary research results. These chapters have been prepared as three manuscripts for submission to internal peer-reviewed journals.

Chapter 3 is a case study that expands on the published literature on infrasound from PDCs by analyzing an event of a much larger magnitude than those documented in previous studies. This chapter characterizes the pressure signals generated by the lateral blast of the May 18, 1980 eruption of Mount St. Helens, using both geophysical observations and eyewitness accounts. The results demonstrate that large-scale PDC events can generate pressure signals in the atmospheric gravity-wave frequency band, and, similar to the 2022 eruption of Hunga Volcano (which I previously studied (Matoza et al., 2022)) can also produce an atmospheric Lamb wave. This study provides a contrast from the dominance of dome-collapse events within the limited number of case studies in the literature. This contrast is essential in order to identify features that are limited to single event types vs. PDCs in general.

Chapter 4 presents a full-length article focused on the pressure signals produced by the intrusion of a PDC into ambient atmosphere, and a dynamic pressure signal generated by the approach of a PDC flow front. This study identifies two signals independent from the moving source signal of PDC infrasound, which is typically the focus of previous studies. These additional signals have the potential to add to early warning systems. The relationships between physical parameters of the experimental flows and these signals were also expanded with comparison to other gravity current events in the literature and the case study presented in Chapter 3.

Chapter 5 continues with the results from the PELE experiments, and focuses on the signals generated by the propagating flow. This manuscript identifies the source of the signal generation, relates it to properties of the flows, and makes key observations important for the use of infrasound for PDC physics and early warning systems. This chapter concludes with a discussion on the revised description of what infrasound is generated by PDCs and how it can be used to identify these events for monitoring.

The final chapter, Chapter 6 expands on the topics covered in chapters 3–5, relating them together and giving a broad overview of the improvements within the understanding of acoustics and pressure signals from PDCs with the completion of this work. This chapter also offers a framework and recommendations on how to continue this work within both the infrasound and PDC fields.

1.4 Infrasound and Acoustics

The generation, propagation, and study of waves in both the solid Earth and atmosphere are intimately linked, and understanding their similarities and differences is crucial for monitoring and studying volcanic processes from a geophysical perspective. Within the solid Earth, seismic waves are classified into two main types: body waves, which include Pressure (P) waves and Shear (S) waves; and surface waves, which include Rayleigh and Love waves (Lay and Wallace, 1995). In the atmosphere, waves occur over a broad range of scales, from planetary waves with wavelengths spanning thousands of kilometers to gravity waves ranging from meters to kilometers, down to low-frequency acoustic waves (infrasound) and higher-frequency sound waves. Many geophysical phenomena, particularly those occurring at the solid Earth–atmosphere interface, generate both seismic and atmospheric waves. Understanding the source characteristics of such phenomena requires understanding how energy is partitioned into the solid Earth (seismic energy) and atmosphere (acoustic energy).

1.4.1 Pressure Wave Theory

Mathematically, seismic P-waves and acoustic waves are equivalent, both representing longitudinal pressure waves. They are differentiated by their propagating medium: seismic P waves propagate through solids and are solutions to the full elastic wave equation (with compression and shear), whereas acoustic waves propagate through fluids where the shear modulus is zero and only compressional properties govern the wave propagation. Pressure waves have a particle motion consisting of compression

followed by dilation of the propagating medium. The particle motion is parallel to the direction of propagation, and the surrounding medium returns to its original state after the wave passes. In solids, propagation velocity depends on the bulk modulus, shear modulus, and density of the medium, whereas in fluids, the velocity is governed only by the bulk modulus and density (Lay and Wallace, 1995).

$$v_p = \sqrt{(C + 4/3\mu)/\rho} \quad (1.1)$$

The velocity of a p-wave in a solid v_p is given above where C is the bulk modulus (incompressible), μ is the shear modulus, and ρ is the density of the material. In the solid Earth, p-wave velocities are primarily influenced by both the bulk and shear modulus (Lay and Wallace, 1995).

In acoustics, pressure wave velocity is also called the acoustic velocity or speed of sound, and is given by:

$$c = \sqrt{C/\rho} \quad (1.2)$$

where acoustic velocity c is dependent on the coefficient of stiffness C (bulk modulus) and density ρ . The speed of sound is primarily dominated by the temperature and humidity of the atmosphere where

$$c = \sqrt{\gamma RT} \quad (1.3)$$

where γ is the ratio of specific heats, R is the gas constant, and T is the temperature in absolute pressure. In a standard atmosphere at sea level, the generalized speed of sound is approximately 340 m/s. Generally speaking, the speed of sound decreases with altitude and increases with increasing temperature and increasing humidity. There is a shorthand equation for the speed of sound where $c = 332 + 0.6 T$, where T is in degrees Celsius. (Hansen, 1951)

Atmospheric acoustic waves are categorized based on the frequency band, which

also can act as a divide in research fields. The major division in acoustic wave research is between that within the human range of hearing (20 Hz–20 kHz) and that outside it, where ultrasound is above human hearing and infrasound is below. Within the context of this thesis we will be primarily concerned with infrasound and sound, which for simplicity are both referred to as "acoustic waves" as there is no physical differentiation. Below the frequency range of infrasound, typically defined as 3.3 mHz–20 Hz in the lower atmosphere, are acoustic gravity waves. Acoustic waves can also apply a downward force on the solid Earth and are recorded by seismic stations, and ground motion can generate acoustic waves. These observations are generally referred to as seismo-acoustic waves Gossard and Hooke (1975).

Acoustic waves that propagate through the atmosphere between a source and sensor can follow several different ray paths. Owing to the change in the speed of sound in the atmosphere, the travel time over the distance from source to sensor is referred to as the celerity. Additionally, the celerity can be greater than the speed of sound if the medium is also moving (wind). Thus, it is important to consider the effects of the atmosphere on long range detections.

1.4.2 Acoustics

The study of the generation of acoustic waves in both the infrasound and audible range is underpinned by M. J. Lighthill's pioneering work on aeroacoustics, establishing the theoretical foundations for understanding how fluid motion generates sound (Lighthill, 1954, 1952). This work was further applied to volcanoes by Woulff and McGetchin (1976).

Within linear acoustic theory, even with the complexity of the source, outside the source bounds the source can be represented by a sum of equivalent sources provided that the source is compact compared with the wavelength λ . The most basic source is one that has uniform radiation in all directions, called a "point source" or "monopole" (Table 1.2, Figure 1.1). The acoustic pressure at time t and distance r for a monopole is given in Lighthill (1978) as:

$$p(t, r) = \frac{\dot{q}(t - r/c)}{4\pi r} \quad (1.4)$$

where $\dot{q}$ is the rate of change of the mass outflow or source strength, c is the speed of sound, and r is the source to receiver distance. A dipole is defined as two monopole sources of equivalent strengths with opposite phases separated by a small distance. A quadrupole is similarly a combination of two dipoles and is attributed to jet noise in earlier references (Woulff and McGetchin, 1976). Equation 1.4 also illustrates that in regards to amplitude (in Pascals), acoustic wave decay is proportional to the inverse of distance, whereas for intensity (in dB) the signal will decay as the inverse square of distance (inverse square law equation 1.5).

$$I \propto \frac{1}{r^2} \quad (1.5)$$

The intensity measurement in acoustics is typically in decibels (dB) and is defined as $I = 10 \log_{10}(P/P_0)$, where P is the measured pressure and P_0 is a reference pressure. Sound pressure level is also measured in dB and is $SPL = 20 \log_{10}(p_{rms}/p_{ref})$, where p_{rms} is the root mean square of the sound pressure and p_{ref} is a reference sound pressure of 20 μ Pa in air. Acoustic power Π_a (equation 1.6) and acoustic energy E_a are reported in Watts (power), and Joules (energy):

$$\Pi_a = \Omega \frac{1}{\rho_0 c} \Delta P^2 \quad (1.6)$$

where Ω is a attenuation term from Perttu et al. (2020b), ρ is the density of the atmosphere, c , is the speed of sound, and ΔP^2 is the data term:

$$\Delta P(t_i)^2 = \frac{1}{\tau} \int_{t_i - \tau}^{t_i} |p(t_i) - p_{air}|^2 dt \quad (1.7)$$

where t_1 and t_2 are the start and end times of the data vector, τ is the processing window (s), p is the data term, and p_{air} is the ambient pressure in the atmosphere.

Initial studies in the field of jet noise from volcanic sources envisioned a combination

of dipole and quadrupole sources, whereas current studies on jet noise have recognized their complexity and the importance of coherent structures within the turbulence. From the 1980's onward, jet noise studies have moved away from the acoustic theories of Lighthill (1952) entirely (Matoza et al., 2013a). Matoza et al. (2013a) applied these advances in jet noise to the case of a volcanic jet, where the acoustic power dependence on jet velocity closely approximated Lighthill's acoustic power relationship:

$$\Pi_a = \frac{\rho_o d^2 V^8}{c^5} \quad (1.8)$$

which has a V^8 dependence for small Mach numbers, where ρ_o is the ambient air density, d is a characteristic dimension of the flow, V is the jet velocity, and c is the ambient sound speed. However, it also shows a weak dependence on temperature, and for acoustic intensity there is also a dependence on angle θ from the jet axis. Matoza et al. (2013a) revised this equation:

$$\bar{I}(\theta) \propto \left(\frac{V_j}{c}\right)_{\theta}^n, \quad n_{\theta} = n\left(\theta, \frac{T_t}{T_0}\right) \quad (1.9)$$

where the n exponent is close to, but not exactly the same as the n in the previous equation 1.8 where $n = 8$. Previous to these advances in acoustic jet source theory, the generalized model of Woulff and McGetchin (1976) relating the acoustic power of a signal with the volcanic gas exit velocity led to several studies on the use of infrasound in plume height estimation and eruption source parameter calculation (Vergnolle and Caplan-Auerbach, 2006; Caplan-Auerbach et al., 2010; Perttu et al., 2020b; Ripepe et al., 2013; Johnson and Miller, 2014; Kim et al., 2015; Lamb et al., 2015; Yamada et al., 2017; De Angelis et al., 2019; Perttu et al., 2023; Ripepe et al., 2013; Iezzi et al., 2019). Although the advances in jet noise radiation for volcanic vents have implications for near field measurements, for operational estimations and long range detection the source is compact and can be approximated as a monopole. See Perttu et al. (2020b) for more discussion on the use of the Woulff and McGetchin (1976) methodology for eruption source parameters. In this publication, I discuss the tradeoff and assumptions

that are required to produce the measurements. In the methodology developed, the acoustic power is converted into an exit velocity, then into a mass flux, and finally uses empirical plume height relationships. This method prioritizes speed over absolute accuracy.

Another factor in the field of acoustics has to do with the transition between subsonic and supersonic signals. This is usually expressed with a Mach Number defined as:

$$M = \frac{u}{c} \quad (1.10)$$

where the Mach number M is the ratio between the local flow velocity u and the local speed of sound c (Equation 1.10). At Mach 1, the local flow velocity is traveling at the local speed of sound, at Mach >1 is supersonic, and at Mach <1 is subsonic, with a low Mach number being defined as $M < 0.3$ (Table 1.1). The most common application is to the field of aeronautics where flights are categorized by their Mach number. In the field of acoustics with subsonic sources, the assumption is that the signal generated from the start of the signal will arrive before the signal generated at the end of the signal; however, this assumption does not hold for supersonic and hypersonic sources. This was illustrated by infrasound recorded in Hawaii during a US hypersonic vehicle test in the 2010's, where the arrival of the end of the flight preceded the arrival of the signals from the beginning of the flight (Perttu and Williams, 2011). By definition, an acoustic wave travels at Mach 1, and a signal generated at t_1 will arrive before a signal generated at t_2 regardless of geometry where $t_2 > t_1$.

1.4.3 History of Infrasound

In August 1883 perturbations of barometers were noted globally, and eventually the source was identified as the cataclysmic eruption on August 27, 1883 of Krakatau volcano. The field of infrasound, and the subdiscipline of volcano infrasound began with the investigation into these pressure derivations and the reports of audibility up to

Table 1.1: Mach numbers, categories, and properties important for signal processing

Mach Number	Categorization	Properties
< 0.3	Low mach number	
< 1	Subsonic	Subsonic is assumed for most acoustic propagation and generation work
1	Sonic	
> 1	Supersonic	For a source moving over Mach 1 the relative timing for the start and end of the path may be reversed
> 5	Hypersonic	Expected that relative timing between start and end of signal arrivals is flipped

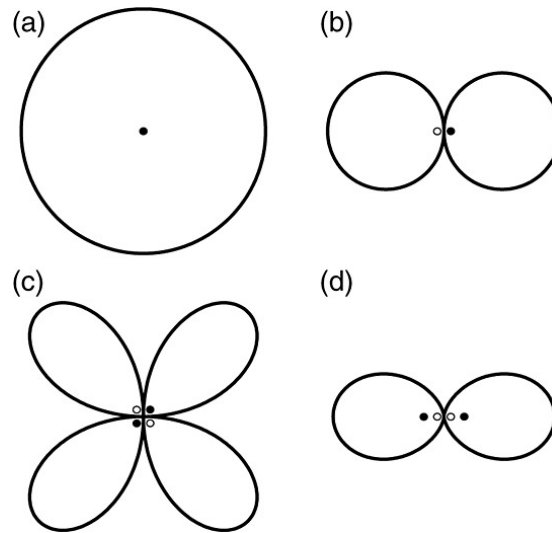


Figure 1.1: Acoustic radiation patterns for (A) a monopole and (B) a dipole. (C and D) Different views of a quadrupole. Figure from Matoza et al. (2013a)

Table 1.2: Acoustic radiation source types and their relation ship with different parameters from Woulff and McGetchin (1976).

Source type	Equation	Variables	Sources
Monopole	$p(t, r) = \frac{\dot{q}(t-r/c)}{4\pi r}$ $\Pi_a = K_m \frac{\pi R^2 \rho_{air} v^4}{c}$	$K_m = 1/16$ (circular flat orifice) to 1 (spherical source)	Point source, symmetrical radiation, time varying mass flux
Dipole	$\Pi_a = K_d \frac{\pi R^2 \rho_{air} v^4}{c}$	$K_d = 10^{-2}$ to 10^{-1}	Momentum change, directional source, fluid interaction with solid boundaries
Quadrupole	$\Pi_a = K_q \frac{\pi R^2 \rho_{air} v^4}{c}$	$K_q: 3 \times 10^{-5}$ to 10^{-4}	Noise due to jet turbulence

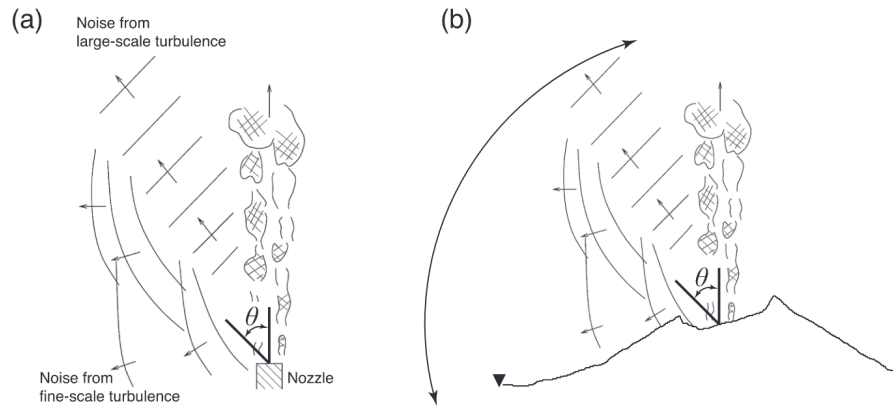


Figure 1.2: Jet noise radiation pattern showing the relative occurrence of sources and their differing amplitudes based on azimuth from the nozzle. Where a) is the model of jet noise from a nozzle in the lab, and b) is this model transferred to a volcanic model. Figure from Matoza et al. (2013a)

5,000 km from the volcano (Verbeek, 1885; Symons, 1888). Audible sound studies on volcanoes continued with the first reported audible range recordings from Frank Perret at Vesuvius in 1906 using moving-coil microphones. He continued to record audible signals at Etna, Stromboli, Kilauea, Sakuajima, Mount Pelee, Martinique, and Soufriere Hills (Perret, 1950) followed by recordings in Japan in 1950 of the Strombilian "detonations" at Oshima volcano by NHK Broadcasting Bureau of Japan (Snodgrass and Richards, 1956). However, recent work within the Global Volcanism Program (GVP) archive at the Smithsonian in Washington, DC, uncovered recordings of Hekla volcano in 1947 and 1970, along with Surtsey in 1964, by William "Bill" Melson, thought to be recorded by him and others (Venzke, Ed Feb. 21, 2025, Figure 1.4). The focus on volcano acoustics has dominantly shifted to lower frequencies with Lorenz et al. (2016) representing the only known study on just the audible range at the time of writing. Both the modern infrasound and acoustics of volcanoes fields are based on the fundamental work of Woulff and McGetchin (1976). Table 1.3 lists some of the earlier pioneering studies on volcanoes. Beginning in the late 1940's, the field of infrasound took a sharp turn towards conventional and nuclear weapons testing.

In a recent article in *Acoustics Today* titled "Listening for a Boom You Can't Hear", Philip Blom and Jordan Bishop discuss the post 1940's history of the field dealing with military applications (Blom and Bishop, 2024). This phase of infrasound research began with the Trinity test (the worlds first atomic bomb test), where 45 km away an overpressure of 780 Pa (> 150 dB) was recorded near San Antonio, Texas. This "nuclear age" of infrasound research focused on yield estimation and propagation of signals and was focused on monitoring the globe for nuclear tests. After 1963, when the Partial Test Ban Treaty (PTBT) was signed by the US, infrasound transitioned to a supplemental application used alongside seismic data to differentiate between deep and shallow sources. With the introduction of project Vela and rise of satellite-based remote sensing, and with the lack of other applications within the scientific community at the time, infrasound research diminished in the 1960's and 1970s, and the field remained dormant for several decades. Following the eruption of Mount St. Helens in 1980,

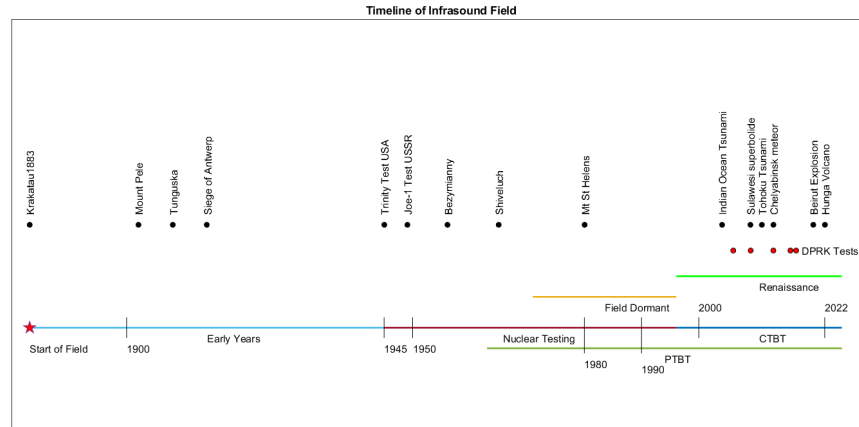


Figure 1.3: During the "dormant" phase, research continued but at a relatively reduced level.

the study of volcano infrasound underwent an increase in use. In the 1990's, Japan began using infrasound in volcano monitoring, and by the late 1990's with the signing of the Comprehensive Nuclear Test Ban Treaty and establishment of the International Monitoring System (IMS), infrasound research underwent a renaissance.

The history of infrasound provides important context to the state of the field and gaps within research. The majority of the research has focused on explosive sources. At the time I entered the field in 2006, researchers in infrasound generally came from a pure physics background, a marine acoustics background, or a seismic background. The field is still dominated by research from the national laboratories of several countries, but the use of infrasound in volcanology has increased dramatically in the last 20 years.

1.4.4 Application of Infrasound

Although the physics of infrasound does not significantly differ from that of acoustics, there are key differences when working with infrasound data. Infrasound is generally recorded on microbarometers or barometers. These sensors can be deployed as a single sensor, collocated with a seismic station (generally a three component broadband sensor), or as an array of sensors. The aperture and design of the array will depend on the frequency band of interest and constraints of the location. The distance between

the sensor and source is divided into local, regional, and global with variation on where the boundaries between them exist. In general, a local station is in the kilometers to tens of kilometers range, regional is in the hundreds of kilometers range (based on the extent of the shadow zones, which are usually ≥ 300 km), and global stations are in the thousands of kilometers range. Owing to the low attenuation and existence of wave guides in the atmosphere, low frequency infrasound can travel significant distances; therefore, infrasound is generally used as a remote detection method.

The most significant source of noise for an infrasound station is that of local wind noise. Thus, there has been significant research into minimizing wind noise with a variety of "Wind Noise Reduction Systems" (WNRS), which range from a bucket or hose to a large rosette of inlet ports. WNRS have traditionally suffered from not only lowering the amplitude of the wind noise but also decreasing signal amplitude. Therefore when working with historic datasets it is important to understand what WNRS was in use. Several of the designs were found to have resonances and have since fallen out of use.

Owing to the higher noise floor in infrasound data compared with that of seismic data, in which signals are generally identified through their amplitude relative to background (as highlighted in the use of Long Term Average/Sort Term Average [STA/LTA] detection methods), infrasound signals are generally identified via a combination of amplitude, spectral content, and, when available, array processing. For detailed discussion on the state of the art of these topics please see the *Infrasound Monitoring for Atmospheric Studies* book which has been put together by the leaders within the field. (Le Pichon et al., 2009a, 2019)

Based on the history of infrasound a large portion of the techniques and data handling comes from the field of seismology. However, there is one significant difference in the underlying assumptions between the two fields. In seismology the data recorded are a convolution of the source time function, instrument response, and path effects (filter) of the solid Earth. The source time function is a time series, the earth filter is constant, and the instrument response is a function of frequency (equation 1.11). Thus,

Table 1.3: Early infrasound and acoustic recordings cited in the literature

Volcano	Year	Frequency Range	Instrumentation	Publication
Krakatau	1883	Acoustic gravity waves	Barographs	Verbeek (1885); Strachey (1888); Symons (1888)
Mount Pelee, Martinique	1902	Infrasound	Barograph	Anderson et al. (2020)
Asamayama, Japan	1909	Infrasound	Barograph	Omori (1912)
Hekla Volcano	1947, 1970	Acoustic	Unknown	Global Volcanism Program collection
Bezymianny, Russia	1956	Infrasound	Barograph	Gorshkov (1960)
Surtsey	1964	Acoustic	Unknown	Global Volcanism Program collection
Mount Agung, Bali	1963	Infrasound	Microbarograph	Goerke et al. (1965)
Trident	1967	Infrasound	Microbarograph	Wilson and Forbes (1969)
Redoubt	1967	Infrasound	Microbarograph	Wilson and Forbes (1969)



Figure 1.4: Volcano sounds tapes from the Global Volcanism Program (GVP) from the collection of William "Bill" Melson. The tapes come with a note saying that all the recordings may not be his.

for a data series (time series) with a known instrument response and (theoretically) the same source to receiver pair, the path effects are constant and the difference between the signals is related to the source time function. However, with infrasound, the propagating medium is the atmosphere, which changes with time; therefore, two signals generated at the same source and recorded by the same sensor will not necessarily have the same path effects (Equation 1.12).

The data recorded at a seismic station D are a function of time, and are the result of the convolution of the source time function S , which is a function of time; the filter (in this case the path through the earth) F , which can be assumed to be constant; and the sensor response R , which is a function of frequency.

$$\text{Seismic} : D(t) = S(t) * F * R(f) \quad (1.11)$$

In infrasound, the data recorded D are a function of time and are the result of the convolution of the source time function S , which is a function of time, the filter

(in this case the path through the atmosphere), which is a function of time (owing to the changing nature of the atmosphere), and the response of the sensor R , which is a function of frequency.

$$\text{Infrasound} : D(t) = S(t) * F(t) * R(f) \quad (1.12)$$

In general, for signals with a source to sensor range of around 20 km there is an assumption that the decay of energy is dominated by the geometry (distance and topography); atmospheric conditions do not need to be taken into account (further discussed in (Perttu et al., 2020b)). However, the structure of the atmosphere can change drastically from day to night, and wind can also have a significant influence on the recordability of signals. Therefore, signals recorded at greater distances ideally have some aspect of atmospheric ray tracing involved.

1.5 Acoustic Characteristics of Mass Flow

Within the infrasound literature, PDCs are included within the grouping of signals from mass movements, which include rock falls, debris avalanches, snow avalanches, and volcanic lahars. A review paper on this topic by Allstadt et al. (2018) highlights that there is significantly more research on the seismic aspects of PDCs and on other mass movement acoustics compared with that of PDCs.

While the focus of this thesis is on the acoustics both within the infrasound range and audible range generated by PDCs, it is also important to understand the current research on these related signals. There are some key similarities between different mass movement signals in that they all tend to be emergent signals lacking a clear onset and can easily be confused with noise, like wind (Allstadt et al., 2018). This is particularly the case with single sensor installations. However, when array installations are used, owing to the coherence between sensors these signals can not only be differentiated from noise but also typically reveal a moving source. Although there is a prevalence of these types of signals within monitoring data, there remains a rich opportunity

to study these signals as the current infrasound literature is limited to a few case studies for each. Systematic study of these different classes of signals focused on their specific and unique characters would be of great benefit to monitoring efforts and signal identification. Mass movement signals can be both syn-eruptive and occur without an eruption, and different types of mass movement have vastly different hazard profiles. It is also important to be able to differentiate mass movement signals from eruption signals as increasingly infrasound is being used to estimate eruption source parameters (Perttu et al., 2020b; Caplan-Auerbach et al., 2010; Lamb et al., 2015). These publications detail the conversion of acoustic power recorded at a station into exit velocity based on the relationships in table 1.2. This can then be converted based on simple geometric relationships from a velocity to a volumetric flux, and with an assumption on the percentage of pyroclasts, this can be converted to a dense rock equivalent mass flux and used in the empirical plume relationships detailed in Mastin et al. (2009).

1.5.1 Rock Falls and Debris Avalanches

Rock falls and debris avalanches as a category covers a significant range in volume and composition. Rock falls are common within the datasets for monitored volcanoes but are poorly represented within the infrasound literature (Allstadt et al., 2018; Johnson and Ronan, 2015). Rock falls have an impulsive signal but can also exhibit complex waveforms that depend on both the source mechanism and medium onto which the rocks fall. The signal can include both a signal associated with the initial displacement of the material and that related to the impact of the material. The initial displacement signal is generally a lower frequency than the impact signal. Rock falls are the smallest volumetric type of mass movement types but are the most common (Allstadt et al., 2018).

1.5.2 Lahars

Lahars are a fluidized debris flow that can be generated with or without a coincident eruption. They are distinct from mudflows by occurring on a volcano. Infrasound can

be used operationally to identify these events since they can occur without precursory signals (Hürlimann et al., 2019; Sanderson et al., 2021). Lahars are generally a moving source, and this characteristic is used to differentiate them from other signals. Thus, installations designed to detect lahars are arrays with the ability to calculate the back azimuth of an incoming signal (Bosa et al., 2021b; Johnson and Palma, 2015). Lahars share other characteristics with mass flows in that they have an emergent signal, broadband frequency content, and a varying duration. Sanderson et al. (2021) described a pilot study for an infrasound-based lahar detection system for the Cascade Range in a study on Mt. Adams in Washington State. In this study, they state that they expect a lahar signal to be either emergent or impulsive depending on the generation mechanism, with most of the energy concentrated in the relatively higher frequencies of 1–10 Hz, with a varying back azimuth observed in the array processing, typical duration of tens of minutes to hours, and a reduced pressure at 1 km from source between 1–110 Pa dependent on the magnitude of the event. While not a lahar owing to the non-volcanic source, the recent studies of Belli et al. (2022) and Belli et al. (2025) suggest that the infrasound source of a lahar is likely to be turbulence-induced waves and splashes along the whole surface of the flow, which are enhanced at channel irregularities.

1.5.3 Snow Avalanches

Within the literature the mass movements used as an analog for PDCs are snow avalanches (Ancey, 2004; Gauer et al., 2008). Snow avalanches are much more common than PDCs, and relatively less destructive to the natural and built environment. Therefore, it is more practical to study snow avalanches than PDCs. On their own snow avalanches pose a hazard not only on volcanoes but also on other high latitude and high altitude snow covered areas and mountains. The infrasound source from snow avalanches is thought to be due to a single source and the displacement of the air by the moving flow (Marchetti et al., 2020; Watson et al., 2022a; Kogelnig et al., 2011; Johnson et al., 2021; Havens et al., 2014). These signals can be recorded at ranges up to tens to hundreds of kilometers from the source. Infrasound is also used operationally

for monitoring snow avalanches in both pilot projects and as a commercial product (Marchetti et al., 2021, 2015, 2020; Johnson et al., 2021).

1.5.4 Pyroclastic Density Currents - Seismic

In the recent review paper on mass movements, the seismic signals recorded from PDCs are described as having emergent onsets, typically with durations of a few minutes, broad frequency spectra, and a dominant frequency band energetically between 3 and 20 Hz. When measured at similar distances, they show a lower peak frequency than do lahars (Allstadt et al., 2018). It is also noted that the identification of the specific seismic signal of a PDC can be difficult since PDCs almost always occur as part of other eruption processes, and isolating the signal can be challenging. Their identification can therefore rely on the availability of detailed chronologies or other technologies. Typically, these signals begin with a lower frequency phase, with a variety of interpretations that depend on the volcano or type of event. This has been interpreted as gas escape, resonance of the conduit contributing to dome instability (Luckett et al., 2002), or the detachment and impact of the dome collapse (Uhira et al., 1994). Zobin et al. (2009) compared dome collapse and column collapse events and found that while this signal is present in both, the initiation of the signal between the two event types is different, with the dome collapse having an emergent onset and the column collapse having an impulsive signal related to the explosion.

1.5.5 Infrasound in Operational Monitoring

Infrasound is increasingly being used operationally for volcano monitoring around the globe. The first instance of infrasound being mentioned in a Global Volcanism Program weekly volcanic activity report was in 2012 for Cleveland volcano in Alaska (Program, a), in 2018 by PHIVOLCs in the Philippines (Program, c), and in Italy since 2021 (Program, b). In Switzerland, infrasound is used operationally for the detection of snow avalanches (Mayer et al., 2020), and an American start-up, Snowbound Solutions (<https://snowboundsolutions.com/>), operates several sites across North America.

Additionally, the United States Geological Survey (USGS) uses infrasound as one of the technologies that makes up its automated lahar detecting system (Thelen et al., 2024). Infrasound is increasingly common in volcano monitoring systems; however, its automation in event detection is still limited (Ripepe et al., 2018). In a previous position, I developed an operational tool for SE Asia to detect and characterize large volcanic plumes (Perttu et al., 2020b); however, this tool is currently only used within the academic environment and not in the public sector.

1.6 Pyroclastic Density Currents - Infrasound/Acoustics

1.6.1 Literature Review

The study of volcano acoustics began in 1883 with the eruption of Krakatau volcano in Indonesia. However, work on volcano acoustics outside of eruption/explosion signals did not begin until the early 1990s. Given the young history and recent renaissance of volcano infrasound and seismo-acoustics (Blom and Bishop, 2024), the limited number of studies in this field is understandable. Infrasound studies on PDCs are focused mainly on two volcanoes: Mount Unzen in Japan (Yamasato et al., 1993; Yamasato, 1997; Oshima and Maekawa, 2001) and Soufriere Hills Volcano in Montserrat (Ripepe et al., 2010, 2009; Delle Donne et al., 2014). One of the key findings of this literature review is the lack of studies outside these two case studies on infrasound from PDCs at other volcanoes. These studies focus on the location and tracking of signals, leading to the observation that for the most part (but not always) the signal originates near the front of the flow, the occurrence of a Doppler shift due to the moving source, and the impact of topography on the signal. Further review papers (Allstadt et al., 2018; Fee and Matoza, 2013) state that the signals are broadband and likely due to turbulent processes.

Within recent review papers, common themes from the PDC infrasound literature are highlighted and include the following descriptions of PDC infrasound:

1. Sustained broadband signals (Allstadt et al., 2018)

2. Moving source (requires more than one sensor) (Yamasato et al., 1993; Ripepe et al., 2009)
3. Can generate a Doppler shift in the recorded waveforms related to the velocity of the source (Yamasato, 1997)
4. Speculation from Ripepe et al. (2009) and Ripepe et al. (2010) that the size and intensity of the flow is inversely proportional to the dominant frequency of the signal based on observations at Soufriere Hills Volcano, Montserrat.
5. Common assumption that the signals of the flows themselves are generated by turbulence at the moving front of the flow, with signals generated by the displacement of the atmosphere and impact of material. (Yamasato, 1997; Ripepe et al., 2010)

The literature also notes that it can be difficult to identify surficial mass movement in infrasound based on signals' similarity to "wind" noise signals (Allstadt et al., 2018). The source theory presented for mass movement infrasound is based on a linear waveform assumption, where the distance between the source and sensors is large enough that the wave front can be considered linear. In this case, the source can be represented as a sum of smaller equivalent sources. Even so, the source mechanism for infrasound related to mass movement is not well understood (Allstadt et al., 2018). Volcanic sources of infrasound generally follow the work of Lighthill (1954) and Woulff and McGetchin (1976), and look at sources as being a monopole, dipole, or quadrupole. Matoza et al. (2013a) expanded on this by studying volcanic sources in the frame of jet noise acoustics.

The following is a discussion of the literature on PDC infrasound, organized by geographic study area. The literature is separated in space and time, with two major studies: one in Japan and one in Montserrat.

Japan

The earliest studies of PDC infrasound took place in Japan in the early 1990's. The first mention of infrasound being generated and recorded from a PDC is in Okada et al. (1990) during the Tokachi volcano eruptions between December 1988 to March 1989, but these signals are not explored in detail. Yamasato et al. (1993) published the first study specifically on the acoustics of pyroclastic flows at Unzen Volcano (in Japanese) using a combination of CCTV, seismic, and acoustic stations (low frequency microphones). The paper details how infrasound observations began at Unzen in June 1991 when the first microphone was installed, and beginning in April 1992 a total of four microphones were installed. The study also added an additional two infrasound sensors. The sensors were for the most part ACO 3348/7144 with a passband of 0.1–10 Hz with some additional Rion NA-17 with a response of 1–40 Hz. Both were sampled at 50 Hz and the phase and amplitude correction was determined with a parallel recording of the two sensors.

Yamasato et al. (1993) and Yamasato (1997) both examined events from 1992, with the later (in English) including additional signals from 1993. The results from these two studies will be discussed together. Several major initial observations of PDC infrasound came out of these studies, the first being that there is a clear moving source, and that the amplitudes of the events are sufficient to be recorded on the local network. The events in these studies were dome collapse events, and therefore the source was limited to the process of the dome collapsing, the material falling, and the generation and propagation of the flow. This eliminates the issue of separation of the PDC signal from another eruption related source.

Montserrat

Ripepe et al. (2009) and Ripepe et al. (2010), with the later expanding on the former, focused on moving infrasound sources present in PDCs that were detectable and trackable with an infrasound array at Soufriere Hills Volcano in Montserrat. The array was a four-element array located to the NW of the volcano, at 3.0 km from the summit,

with an array aperture of 200 m. Moving sources were used to calculate the direction and flow front velocity of the flows, and the results indicated an inverse relationship between the dominant frequency and size of the flow. This initial study was followed by Delle Donne et al. (2014), which combined the infrasound data at Soufriere Hills with seismic and thermal data. While this publication does not focus solely on the infrasound generated, it does note that the PDC source mechanism generates infrasound within the same frequency band as that of the explosive eruption infrasound. The results of the calculated flow front velocity from the thermal and infrasound data were consistent with each other; however, the infrasound appears to coincide with slope changes and topographic features, and one of the sources may be due to rapid changes in the flow front velocity. Finally, (Barfucci and Ripepe, 2018a) followed several PDC events that occurred within 45 min. The seismic and infrasound signals illustrate that the flows were coupled differently with the ground and atmosphere.

1.6.2 Pyroclastic Density Current Audible Acoustics

In addition to the literature on PDC infrasound, there is a history of observations regarding audible or lack of audible sound. Frank A. Perret, a significant figure in early 20th century Earth science, described PDCs as being able to "shapeshift and move with ominous silence", and as "PDCs look tumultuous, clamorous, terrifying, but they are deathly quiet" (Oppenheimer, 2023). After a visit in to Augustine Volcano, Alaska, in 1986, Maurice and Katia Krafft wrote (Global Volcanism Program, 1986)

" We were able to verify several of Frank Perret's important observations on pyroclastic flows (from Mt. Pelee in 1929-32). 1. The pyroclastic flows moved in silence, unheard even from very close range (50-200 m). This is in striking contrast to the loud rattle of rock avalanches high on the dome that preceded the pyroclastic flows. Sounds of the colliding blocks within the pyroclastic flow avalanche are apparently muffled by the elutriating fine ash. [...]".

These observations were reinforced by the survivors of the 25 June 1997 pyroclastic flows and surges from Soufriere Hills Volcano in Montserrat. Several survivors noted the lack of audible sound, and the importance of this property is highlighted by one survivor who stated:

”[...] I kept a watch for most of the day but it did not give any sound.

If I had heard some sound I would have moved away earlier.”

Loughlin et al. (2002) went on to state that many survivors noted that they were waiting for an audible warning and would have moved to safer areas if they had heard anything.

1.6.3 Application for Monitoring

The increased understanding of the infrasound generated by PDCs could aid in the development of early warning systems. This would require the ability to differentiate the signals from PDCs and other volcanic sources in near real time, with enough time to generate an actionable alert. Another use could be the differentiation of small events from larger events. However, a clear characteristic set of features would need to be identified, differentiating PDCs from other mass movement events and volcanic phenomena. Owing to the speed of PDCs and short time frame between the event and impact, this process would need to be completely automated. There would also need to be a low instance of false alerts. This is currently not possible with the current understanding and characterization of infrasound signals. Additionally, it is possible that infrasound could be used in addition to multiple other technologies in the alerting process.

1.7 Pyroclastic Density Currents

PDCs are multiphase flows that have been described with a variety of terminology over time. Different terms derive from different descriptive perspectives. This thesis focuses on the generation and propagation of these flows and will use terms related to

the density of the flow and the source mechanism. PDCs have been described based on their appearance, source, deposition, and other factors. For this thesis I will use the term 'pyroclastic density current' (or PDC) as an inclusive term encompassing the wide range of sources and properties of volcanic gravity currents. Within this umbrella term, a conceptual continuum is typically used to distinguish between the dilute and dense end members. The dilute end member is termed a "pyroclastic surge", while the dense end member is termed a "pyroclastic flow".

PDCs are gravity currents driven by the contrast between the density of the ambient atmosphere and that of the current itself. They are multiphase flows composed of two phases: a gas phase and a solid phase. The gas phase generally consists of entrained air from the surrounding atmosphere with some volcanic gasses, while the solid phase comprises volcanic material of varying size and composition, including pyroclasts (both ash and larger), lithics, and other entrained debris. The relative concentrations of the solid phase and gas phases determine the bulk density and behavior of the flows; these proportions vary in time and space within a single event. The density of the flow will also have an impact on the degree of coupling with the ground and atmosphere. This thesis does not focus on the source signals and is instead focused on the moving signals from the propagating PDC.

PDCs are highly mobile gravity currents that display wide variability in both runout distance and velocity. Runout distances span several orders of magnitudes and are generally considered to depend on the initial mass and discharge rate of the event (Cas and Wright, 1988; Bursik and Woods, 1996; Dufek and Bergantz, 2007a; Esposti Ongaro et al., 2008; Shimizu et al., 2019). Using a large dataset, Roche et al. (2021) demonstrated a relationship between runout distance and mass discharge rate. Reported flow velocities range from tens of meters per second, as observed at Soufriere Hills Volcano (Calder et al., 1999), to several hundreds of meters per second, as calculated for the Mount St. Helens lateral blast (Kieffer and Sturtevant, 1988). Although flow-front and overall propagation velocities are measured in the field, internal flow velocities remain poorly constrained. These internal dynamics likely also vary throughout an

event and are thought to be controlled by initial source conditions and interactions with topography.

The temperature of a PDC can vary widely, and although high temperatures are not required for PDC generation, they are a common and often deadly characteristic. Reported temperatures range from values close to ambient air (Moore, 1967) to near-magmatic temperatures of 800°C–900°C, such as those documented for the Katmai Valley of Ten Thousand Smokes deposit (Lovering, 1957). Similar to density and velocity, temperature evolves throughout a single event as the flow entrains air, exchanges heat with the environment, and undergoes internal mixing. Consequently, while a single PDC may have a characteristic temperature range, the thermal structure is rarely if ever homogeneous. "Cold" pyroclastic flows are generally associated with source mechanisms involving water (Cole et al., 2015).

The internal structure of a PDC can evolve throughout a single event, but typically a flow will consist of a dense basal region overlain by a more dilute ash-cloud layer (Figure 1.5). The ash-cloud region, which forms the upper fully turbulent portion of the flow, encompasses the head, body, and wake of the current. Beneath this the basal region may take the form of either a thin bed-load layer or a more energetic, dense underflow. When present, the dense underflow contains the majority of the flow's mass and exhibits the highest particle concentrations.

The sources that produce PDCs are diverse and have different hazard potential. During an eruption, the plume or portions of the plume can fail to become fully buoyant and can collapse down-slope generating a PDC. Additionally, as seen during the May 18 1980 eruption of Mount St. Helens, eruptions can also form lateral blasts. Collapses of lava domes can also occur during an eruption sequence or outside the time frame of explosive eruptions. Smaller scale phreatic and phreatomagmatic eruptions can also produce PDCs. Finally, renormalization of pyroclastic deposits can generate small scale PDCs. Each of these source mechanisms will also have a different geophysical signature.

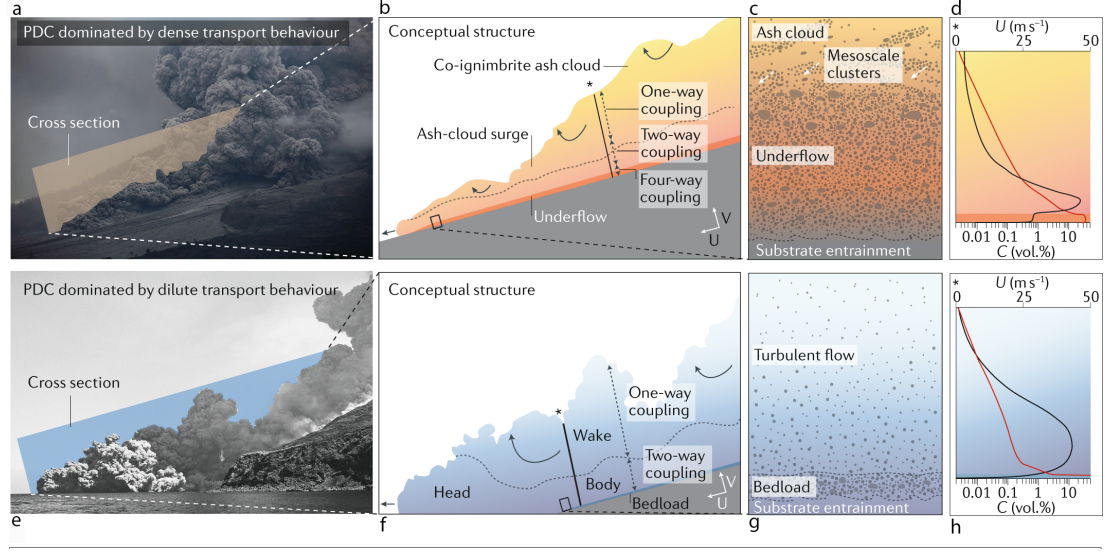


Figure 1.5: Modified from (Lube et al., 2020). Photos of pyroclastic density currents (PDCs) from A) Sinabung volcano in 2014, an example of a denser pyroclastic flow; and B) a pyroclastic surge from Stromboli volcano in 2019, an example of a more dilute surge-style PDC. Cross sectional conceptual models of the two internal flow structures for the B) concentrated and F) dilute PDCs. On the right in (C) and (D) and (G) and (H) are (C and G) conceptual models of the particle concentrations within the flows and (D and H) the patterns of velocity (black) and particle concentration (red).

1.7.1 PDC Field Measurements

Observations of PDCs in the field are typically limited to visual data, which is only capable of providing information about deposits and limited partial information on dynamics. However, recent studies have demonstrated the potential of radar to capture *in situ* measurements of PDCs. Scharff et al. (2019) and Syarifuddin et al. (2022) report the use of Doppler radar for measurements at Volcan de Colima and Sinabung volcano, respectively. Scharff et al. (2019) recorded several PDCs generated through the collapse of a 7-km high plume. The study captured multiple sections of the PDC along the slope of the volcano, providing apparent velocities and radar amplitudes that reflect the particle concentrations within the observed volume. Similarly, the Syarifuddin et al. (2022) study was able to provide measurements of apparent velocities and amplitude data related to particle density. Together, these radar-based studies demonstrate that radar has the ability to provide data from natural flows for comparison to models of

PDCs.

1.8 Experimental PDCs

Owing to the difficulty of obtaining field measurements, PDC field has also utilized analog experiments. There have been several large scale facilities and experimental setups to study the dynamics and physics of PDCs. The first such facility was located in Italy, and is described in Dellino et al. (2007). This facility used natural pyroclastic material within a 2.2 m cylindrical conduit, which expelled gas and material generating a two-phase mixture column that subsequently collapsed into an experimental flow. They were able to generate flow propagation up to 10 m distance from the source. However, there were limitations, as the facility was better scaled to dilute PDCs than it was to dense PDCs (Dellino et al., 2010a,b).

Another facility at the Smithsonian Institute, USA, consists of an acrylic tank where a synthetic PDC is generated from heated talc powder, with a known discharge rate. This setup can be run with or without obstacles (Andrews and Manga, 2011). The material is heated between 30°C and 100°C, and is composed of 20 mm talc powder, which generates dilute particle gravity currents within the 6.5 x 1.8 x 0.6 m acrylic tank. The facility has been used for several studies (Andrews and Manga, 2011, 2012; Andrews, 2014); however, it is only able to produce dilute surge style PDCs and doesn't scale well because of low Reynolds number (Re).

The University of South Florida, USA, PyroCLAST facility is designed to investigate the dynamics of topography over spills of concentrated PDCs (Gueugneau et al., 2022). This setup utilizes subspherical borosilicate glass beads that are fluidized by airflow injected through a porous plate. It is designed to mimic sharp valley bends.

Finally, the facility used for this PhD thesis, the Pyroclastic flow Eruption Large-scale Experiment (PELE) facility, is hosted by Massey University. PELE is a large-scale experimental facility designed to study various features of PDCs and is described in detail in Chapter 2. All experimental facilities and experimental designs come with

unique challenges and issues. In this case, the facility is well established and issues like kinematic and dynamic scaling have been tested and validated (Lube et al., 2015). The major challenges for the design of experiments for this thesis were the budget available for the purchase of new instruments, and the design of the placement of these sensors. In the field, the sensors would be placed on the side of the channel; however, with the confined channel the acoustic wave field was unable to expand horizontally, leading to the choice to place the sensors in the unconfined direction: vertically, above the channel. The initial design was also influenced by initial acoustic sensor tests completed by colleagues at the University of Tokyo.

Chapter 2

Methods

This chapter describes the methods used in this thesis. Two complementary approaches were employed: (1) a case study of the 1980 eruption of Mount St. Helens and (2) controlled laboratory experiments. The experiments provided reproducible conditions under which to characterize the generation and properties of the pressure signals related to pyroclastic density currents. The case study provided a dataset beyond the published literature, and offered a larger, well-characterized example of a PDC to complement the case studies within the literature, both of which are based on dome collapse events. This chapter details the work completed using the PELE experimental facility. Additional data processing techniques employed for each research chapter are described within that chapter.

2.1 Mount St. Helens Case Study

In order to have sufficient field data for comparison with the experimental results, a larger pool of events need to be identified to progress from single event/volcano case studies to a more comprehensive understanding of the signal characteristics. Ideally this dataset would include events from a variety of volcanoes, with a variety of PDC magnitudes and source mechanisms. A search of the GVP and PDC literature was combined with personal knowledge of volcano networks where acoustics/infrasound are

available. As discussed, the majority of volcano infrasound is focused on the explosive source of the eruption, and therefore not all installations are ideal for a PDC study. To qualify as a potential case study, the event needed to have:

- A PDC event with direct observations and measured parameters
- Infrasound installed at the time of the event
- Infrasound sensors installed in a location where they could record PDC signals
- Ideally, an array configuration for differentiating signals
- Available waveform data

While there are potential events on multiple volcanoes, it quickly became apparent that data availability would be an issue. Volcanoes in Indonesia, while plentiful with a variety of PDC events, do not have open data; for example, signals have been recorded for events at Sinabung, but data access was not achieved. The studies at Soufriere Hills Volcano offered an intriguing option as the same events could be revisited and reprocessed in light of new findings. However, while access permissions were granted, the data files have not yet been shared owing to the age of the files and changing technologies for archiving data. Several volcanoes suffered from either the well described event not occurring when infrasound was deployed, or no significant described events occurring. However, it was found that while not local infrasound, and not an array, the pressure datasets for the May 18, 1980 eruption of Mount St. Helens offered an intriguing opportunity. Survivors of this event reported several eye witness accounts related to pressure phenomenon of the lateral blast, and both acoustic and seismo-acoustic signals are reported in the literature. The lateral blast is well described in the PDC literature (Eposti Ongaro et al., 2012; Brand et al., 2016; Eychenne et al., 2015; Ongaro et al., 2011) and represents a different order of magnitude in size, and a different source mechanism to the events within the current literature. Therefore this was selected as the case study for this thesis.

2.2 PELE

The bulk of this thesis is focused on a set of experiments specifically designed for the study of the acoustic wavefield produced by PDCs. These experiments were carried out at the Pyroclastic flow Eruption Large-scale Experiment (PELE) facility (Lube et al., 2015) named after Pelehonuamea (or 'Pele'), the Hawaiian deity associated with volcanoes. PELE is a large-scale analog experimental facility located at Massey University's Manawatu campus in Palmerston North, New Zealand. The facility is located within an old Boiler House (25 m long, 18 m wide, and 16 m high), and was constructed in 2013. PELE is designed to bridge the knowledge gap between PDC modeling, theory, and natural observations. Owing to the hazardous and destructive nature of natural PDCs, PELE provides an alternative method for direct observation. At the time of writing, PELE represents the largest scaled PDC experimental facility.

2.2.1 Experiments

To fulfill the first research objective, three experiments (InfraPDC1, InfraPDC2, and InfraPDC3) were designed and completed for this thesis. The design of these experiments was based on a doubling of the experimental mass (Table 2.1). These experiments are distinct from additional experiments conducted in parallel (Tsunami 1, Tsunami 2, Tsunami 3, and Tsunami 4) to study PDC and water interactions. Two previous proof-of-concept experiments were conducted in 2019 (Acoustic Test 1 and Acoustic Test 2).

The experiments were conducted in the following order: Tsunami setup test (15 Nov. 2022), InfraPDC1 (9 Feb. 2023), Tsunami 1 (13 May 2023), Tsunami 2 (11 Jun. 2023), InfraPDC2 (23 Jul. 2023), Tsunami 3 (18 Oct. 2023), Tsunami 4 (23 Nov. 2023), and InfraPDC3 (6 Mar. 2024). This order also reflects progressive improvements to the instrumentation design as lessons were learned from previous experiments. In this section, I will first discuss the overall design of the infrasound experiments, the instruments used, and the rationale for any changes.

Table 2.1: Infrasound experiments with the associated experimental parameters. * Material properties are detailed in 2.2.2

	Experiment 1 (InfraPDC1)	Experiment 2 (InfraPDC2)	Experiment 3 (InfraPDC3)
Date (MM/DD/YYYY)	02/09/2022	07/23/2023	03/06/2024
Design Mass (kg)	250	500	1100
Hopper Configuration	Small hopper with bars	Small hopper no bars	Large hopper no bars
Material	2B*	2B	2B
Temperature (°C)	100	14	100
Actual Mass (kg)	251	519	1116
Average Discharge (kg/s)	36.2	55.8	383.9
Discharge Time (s)	7.9	9.1	2.9
Ambient Air Temperature (°C)	17	9	10
Air Density	1.211042	1.230003	1.22722
Speed of Sound (m/s)	341	336	337.1

2.2.2 Design

The initial design of the infrasound experiments was based on lessons learned from the acoustic test experiments, which used a configuration similar to that of an infrasound array consisting of multiple triangular sub-arrays (Figure 2.1). However, attempts to perform traditional array processing with this setup were not successful (Ichihara, 2022). As such, the initial design was based on sampling the acoustic wavefield at multiple locations throughout the facility. The design for InfraPDC1 was based on the assumption that, since array processing had not been successful, the sensors should cover as much of the wavefield as possible.

The principles of sensor spacing are generally based on the desired frequency range. With a given array sensor spacing, if the frequency is too high (i.e., the wavelength is short compared with the spacing), spatial aliasing can occur and the signal may lose coherence between sensors. Conversely, for very low frequencies, it becomes more difficult to constrain parameters such as back-azimuth and apparent velocity.

The frequency of interest, based on the work of Brosch et al. (2021), was estimated

Table 2.2: Tsunami experiments with the associated experimental parameters

	Tsunami 1	Tsunami 2	Tsunami 3	Tsunami 4
Date (MM/D-D/YYYY)	05/13/2023	06/11/2023	10/18/2023	11/23/2023
Design Mass (kg)	250	500	1100	1000
Hopper Configuration	Small hopper with bars	Small hopper no bars	Large hopper no bars	Large hopper no bars
Material	2B	2B	2B	2B
Temperature (°C)	100	100	30	500
Actual Mass (kg)	249	569	1089	960
Average Discharge (kg/s)	25.3	50.3	237	82
Discharge Time (s)	9.3	10.6	4.5	8.52
Ambient Air Temperature (°C)	6.2	4.4	12.7	17
Air Density (kg/m ³)	1.2735	1.2717	1.2364	1.2096
Speed of Sound (m/s)	335	334	339	341

to be on the order of 1 Hz, which corresponds to an acoustic wavelength (λ) larger than any dimension of the building. There is a balance between the frequency of interest, the area available for sensors, the coherence between the sensors, and the sample rate. According to Garces (2013), "Taking $L/2 < \lambda < 12L$ as a practical array wavelength range leads to an array bandwidth of $c/(12L) < f < c(2/L)$." Using this as a nominal range calculator, then:

$$F_{min} = \frac{c}{12L} \quad (2.1)$$

$$F_{max} = \frac{2c}{L} \quad (2.2)$$

where L is the sensor spacing and c is the speed of sound in the building. Thus, for a signal of interest of 1 Hz, the corresponding sensor spacing can range from 0.7–4 km (Figure 2.2), a spacing commonly used in field deployments. Therefore, sensors installed within the facility should be able to resolve frequencies within this range. However, a

Table 2.3: Acoustic test experiments with the associated experimental parameters

	Acoustic Test 1	Acoustic Test 2
Date (MM/DD/YYYY)	01/13/2019	01/18/2019
Design Mass (kg)	300	120
Temperature (°C)	100	100
Average Discharge (kg/s)	17.1	13.6
Discharge Time (s)	15.7	7.7
Ambient Air Temperature (°C)	16	19
Air Density (kg/m ³)	1.223	1.2
Speed of sound (m/s)	341	343

planar wavefront assumption is only valid for far-field conditions where the source to sensor distance is much greater than the wavelength, whereas within the facility the wavefront is likely to exhibit curvature. In general, the curvature of a wavefront K is the inverse of the radius of curvature r :

$$K = 1/r \quad (2.3)$$

The original design was thought to be more than sufficient for signals on the order of 1 Hz and higher.

PELE Design

The PELE facility is comprised of a tower structure and confined channel housed within a building known as "The Boiler House" (Figure 2.3). The Boiler House is a former industrial building on the Massey University campus measuring 25 m long by 18 m wide, with a slanted roof reaching 16 m in height. The tower is a 13 m high structure that is used to lift the hopper to variable heights for discharge.

The hopper system consists of two hoppers, with the smaller one inside the larger one. The large hopper has an internal volume of 4.2 m^3 and can hold up to 4000 kg of material. The smaller hopper has an internal volume of 0.7 m^3 and can hold up to 600 kg of material. Both hoppers are equipped with internal heating systems capable of heating the material up to 400°C under standard conditions. Load cells are installed

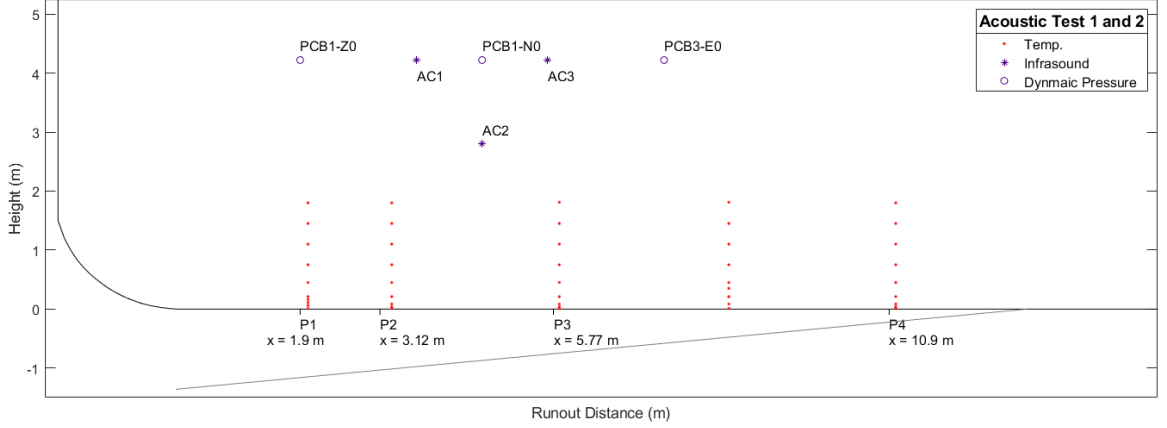


Figure 2.1: Design of Acoustic Test 1 and 2 sensor locations. Plotted are the locations of the timeseries sensors for dynamic pressure (purple circle), infrasound (asterisk), microphone (square), and temperature (red dot). Heights are measured in distance from the facility floor and locations taken from information provided by the University of Tokyo.

to monitor the weight of the hopper over time and track the discharge of material. Although the release height can vary, it is generally set to 7 m for the small hopper and 5.5 m for the large hopper. The material then drops through a shrouded vertical section where it can freely mix with the air in the Boiler House.

The PELE experimental facility has used a variety of materials in the past. For this experimental series, the material, called "2B", was an ash-rich material from the CE 232 Taupō ignimbrite (New Zealand). This material was collected from a site 17 km to the northeast of the vent (Corna et al., 2025a). The material is a poorly sorted mixture, is polymodal, and contains clasts from 2 to 16 mm (9 to -4ϕ) with a median particle diameter of $422.1 \mu\text{m}$ (1.2ϕ). After collection the material was dried for 1 week in an oven at 100°C .

The material exits the drop zone and enters the confined channel, which has an adjustable inclination that was set to 6° for these experiments. The channel is 1.8 m high on the observation side, enclosed by glass walls. The opposite wall is constructed from a combination of metal and small areas of wood up to approximately 1 m and

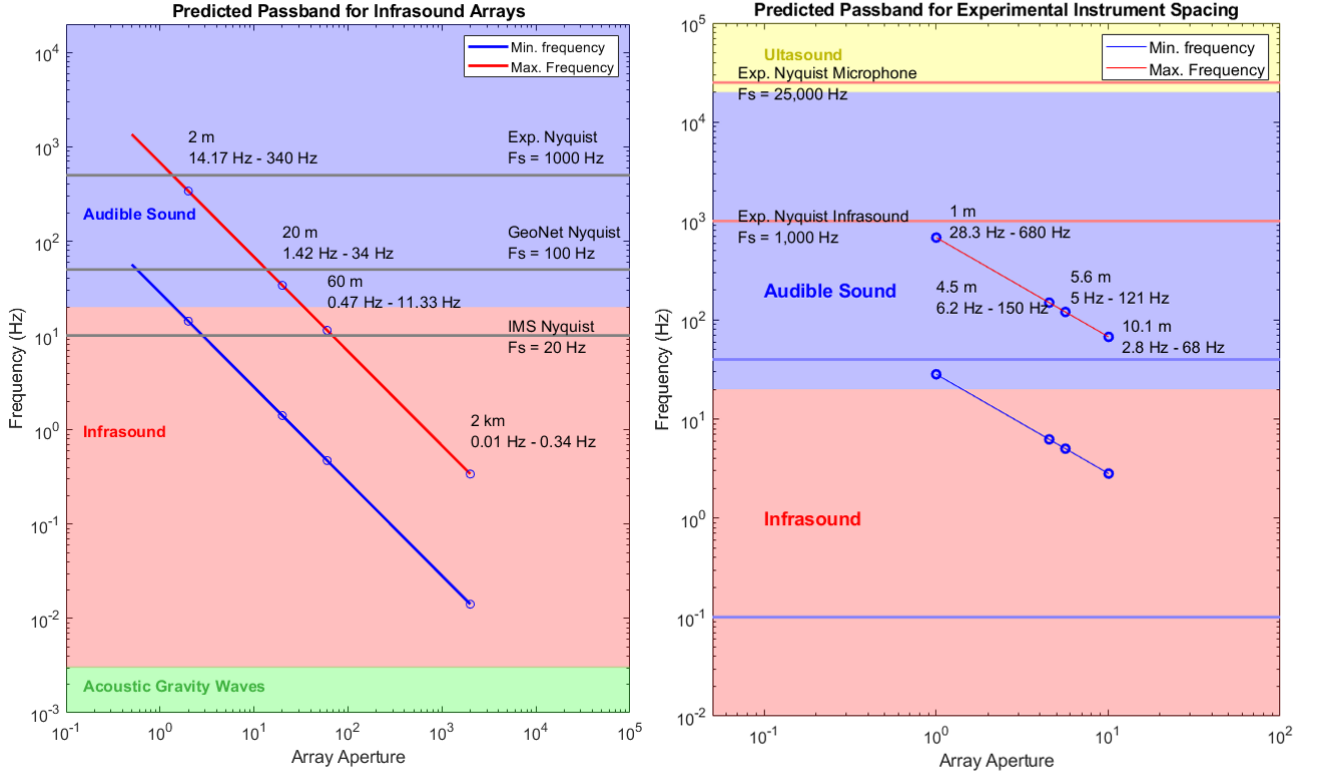


Figure 2.2: Theoretical passband for array processing with different length scales of sensor spacing. (left) Length scales common for different array spacings in meters combined with the Nyquist frequency from their sample rates showing the range of infrasound arrays in the field. (right) Sensor spacing for the infrasound experimental design used in InfraPDC1 calculated using equation 2.1 and 2.2

. Included are the Nyquist of different types of infrasound deployments, the International Monitoring System sampled at 20 Hz and designed for lower frequencies, and the GeoNet system installed on the volcanoes in New Zealand which is sampled at 200 Hz.

topped by fabric panels to the height of 1.8 m. The slope continues into a reinforced glass tank at the end of the sloping section. This tank, designed to hold water for the tsunami experiments, is 1.8 m high with glass on both sides, connected with beams connecting both sides on the top and bottom. This contrasts with the rest of the channel where the sides are only attached through the base. The channel maintains a 0.5 m width throughout. The tank also forms part of the horizontal outrun area, which extends outside the building and continues onto a flat concrete slab up to 35 m from the tower to a natural hill. The most significant change to previous experiments and the infrasound (InfraPDC) sequence was the addition of the reinforced glass tank at the end of the channel.

The reference grid for all measurements began at the end of the curved head of the confined channel (Figure 2.3), where a measuring tape was secured for repeated measurements. This measurement grid differed slightly from the setup in previous experiments. For the tsunami experimental sequence, the reference grid was defined as the start of the reinforced glass tank. The observation points were housed in protective greenhouses to shield the instruments from the airborne fine ash after an experiment. These greenhouses were named Pinatubo (the largest, closest to the drop zone), Sinabung (the middle), and Whakaari (covering the tank section) [Figure 2.3].

InfraPDC1

The international conference of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Scientific Assembly held in January 2023, meant that several international colleagues were already in New Zealand around the time planned for experiment InfraPDC1. We were able to take advantage of this overlap to install two additional infrasound sensors, two directed microphones, and two accelerometers brought with colleagues from the University of Tokyo.

For InfraPDC1 (Figure 2.4), three infrasound sensors were installed above the channel, located directly above established instrument profiles within the channel. Owing to the design of PELE, the horizontal sides of the channel are rigid structures that do

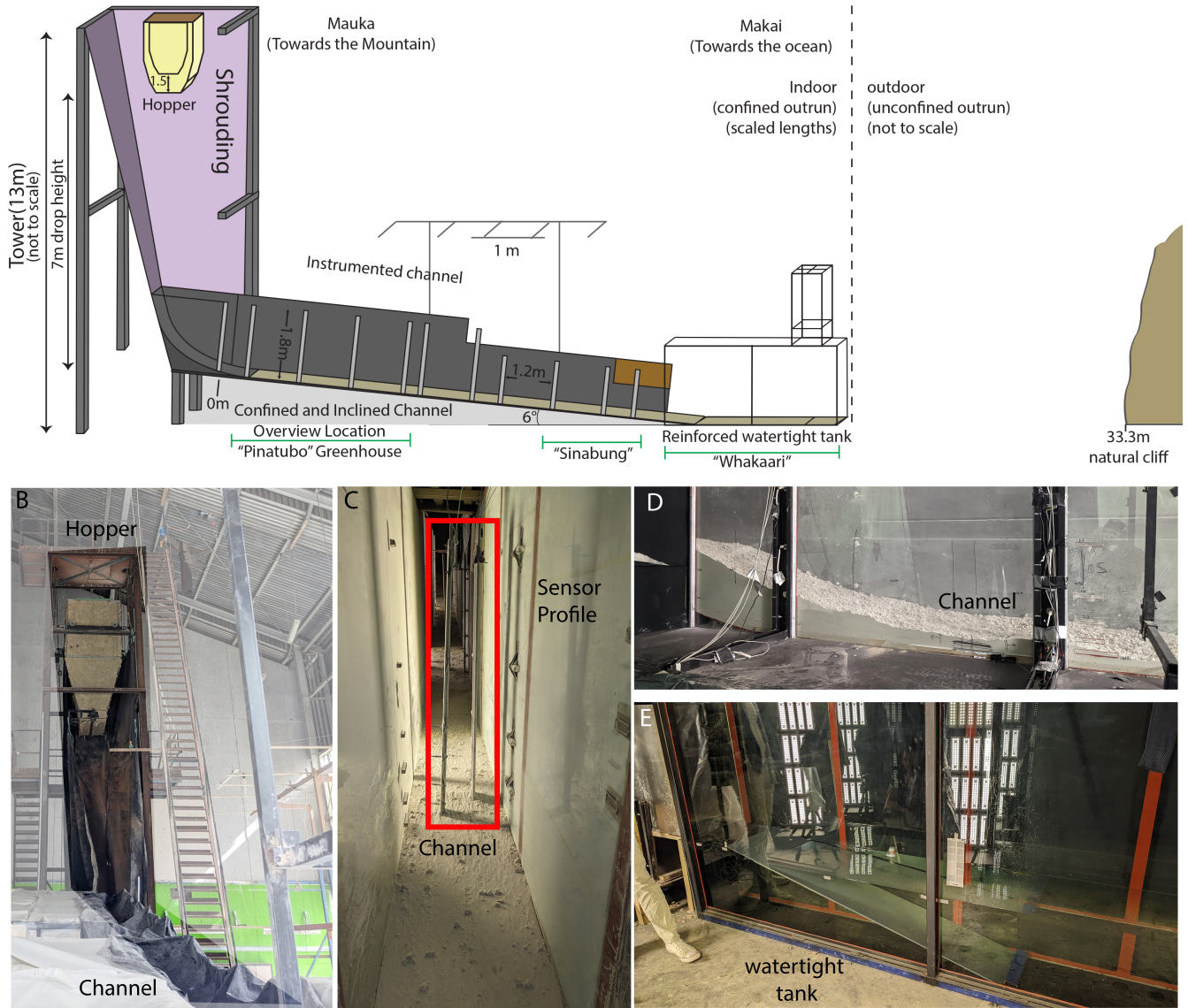


Figure 2.3: Schematic of the PELE facility showing the different aspects important for the experiments. A) Schematic of the experimental setup. On the left is the drop zone showing the tower and hopper with the smaller hopper installed in the larger hopper. In the center is the instrumented channel and coverage of each observation greenhouse. The reinforced tank with a structure for instrument attachment points is shown at the far right, with a transition from inside to outside and run-out to the natural cliff. B) Photo of the hopper with the channel in the foreground. C) Photo taken from inside the channel highlighting one of the instrument towers. D) Side view of the channel. E) Watertight tank during a tsunami setup.

now allow the acoustic signals to expand naturally; however, in the vertical there is an unconfined direction for radiation. An assumption was made that a signal generated by the flow would have some sort of spherical radiation pattern in regards to the horizontal and vertical. Owing to the limited number of sensors available for the experiments, a detailed examination of this assumption through study of the detailed radiation pattern was not possible. The fourth infrasound sensor was installed in the unconfined section of the run-out section, facing up the confined channel. The directed microphones were installed pointing down to the channel at two spaced locations along the channel. The accelerometers were installed on the main channel and the tank at the end of the channel. Locations were measured as relative to the channel floor not the building floor. The channel has a 6° slope, which is taken into account in the height measurements above channel floor (Table 2.4). Within the channel, set profiles had previously been established and were reoccupied. At these profiles, both dynamic pressure, pitot tubes, and thermocouples were installed at set heights established in previous PELE research ranging from 4 –170 cm from the channel floor. These locations and sensor heights can be seen in Table 2.8, Table 2.11, and Table 2.10

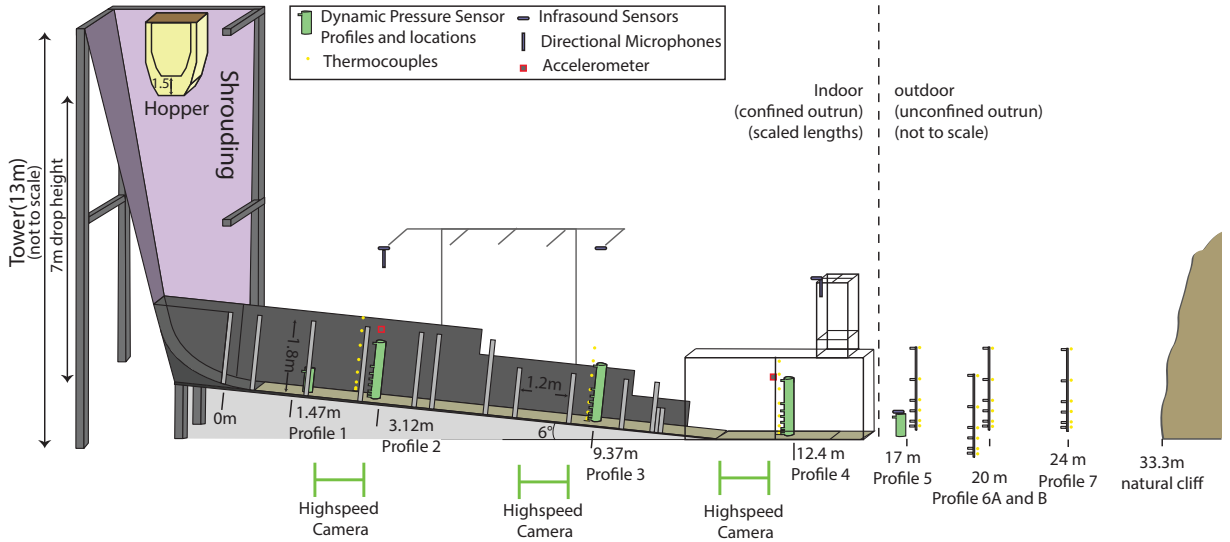


Figure 2.4: Design of the InfraPDC1 experiment with profiles and sensor locations. Dynamic pressure sensors, thermocouples, infrasound, microphone, and accelerometer locations are plotted along with the locations of high-speed cameras

In addition to the sensor timeseries data, visual and sample data were also collected. At the established profiles a system of samplers were installed at specified heights. These were both passive samplers (called "spoons" withing PELE) and filmed test tubes with an open end covered with a mesh (called "square tubes"). The square tubes were filmed with a GoPro camera for time-resolved filling information that could be used to calculate concentration and density through time within the flow. The passive samplers were collected after the experiment and the particle size distribution and total mass taken. Three high-speed camera locations were established, one in each greenhouse. For InfraPDC1, the Pinatubo and Whakaari greenhouses had the Basler cameras while the NAC (called the new NAC) was installed in Sinabung. Overview GoPro cameras were installed in the greenhouses and in the facility as well as outside in the unconfined run out area. A thermal camera captured the flow as it exited the building.

After the experiment, the design changes were considered to address the following questions:

- Where is the flow when the first signal is generated?
- Is there a radiation pattern responsible for the low signal-to-noise ratio in the infrasound?
- Is there a spot down channel with enough signal separation AND signal-to-noise for an ideal location?

The coherence between the sensors in Experiment 1 was insufficient to examine where in the flow a signal was generated, as this would have required closer spacing. However, a sufficient signal-to-noise ratio is also required for this type of analysis. A radiation pattern such as that in a jet (see Figure 1.2), where the highest amplitude is in the direction of flow and with a significant decrease in amplitude off axis, is also something to consider. Given these issues, the location of the infrasound and microphone sensors for subsequent experiments were places approximately 9 m down

slope, which satisfied the signal-to-noise based on distance as well as a separation between arrival times.

Table 2.4: Locations and types of sensor for the acoustic dataset for the InfraPDC experimental series

	Location Along Channel (m)	Height above channel (m)	Sensor
InfraPDC1			
Infrasound 1	3.045	3.22	ACO Type 7744N
Infrasound 2	8.605	4.14	PCB model 378A07
Infrasound 3	13.1	3.50	ACO Type 7744N
Infrasound 4	17	0.47	PCB model 378A07
Microphone 1	8.605	2.952	SONY ECM-674
Microphone 2	13.1	3.232	SONY ECM-674
InfraPDC2			
Infrasound 1	8.42	3.115	PCB model 378A07
Infrasound 2	9.42	3.220	PCB model 378A07
Microphone 1	8.42	2.847	SONY ECM-674
Microphone 2	9.42	2.852	SONY ECM-674
InfraPDC3			
Infrasound 1	8.42	3.115	PCB model 378A07
Infrasound 2	9.42	3.220	PCB model 378A07
Microphone 1	8.42	2.847	SONY ECM-674
Microphone 2	9.42	2.852	SONY ECM-674
Microphone 3	11.38	3.158	SONY ECM-674
Microphone 4	17	0.47	SONY ECM-674

Tsunami 1 and 2

The Tsunami experiments, which were a series of experiments that were run concurrently with the infrasound experiments, were also used to test configurations and address questions that arose during the infrasound experiments. The tsunami experiments were designed to study the interaction of the experimental flow with a tank of water. The tank consisted of the glass structure at the end of the channel, with a wood extension outside the Boiler House. For these experiments, the sensors were concentrated in this section at the end of the experimental channel. The sensors were also placed relative to the height of the water, and infrasound was added in order to test ideas of location and configuration and sensors. These experiments were used as

a way to add additional data to the three main experiments owing to the challenges of running additional experiments. The changes that were implemented for Tsunami 1 and 2 (Figure 2.5) were as follows:

- a camera was installed in the channel facing the drop zone for Tsunami 1;
- the number of infrasound sensors was reduced to two, which were installed at 13.1 m at different heights with one sensor installed within the confined channel;
- the PELE lab had not yet purchased their own microphones and no directed microphones were available.

The remainder of the experiments were designed and completed for a project related to the interaction of PDCs with water (Robert et al., 2026). These tests allowed comparison of signal arrival with video of the material entering the confined channel. Additionally, the potential for a radiation pattern examined but the results were inconclusive. With the increase in mass from Tsunami 1 to 2 there was an increase in the signal-to-noise ratio. With increased signal-to-noise, there was coherence that made inter-sensor calculations possible. It was deemed that a spacing of 1 m would give sufficient spacing for sample offsets but close enough for high cross correlation. While further spacing would give more offset between sensors, the sensor coherence was likely to drop off owing to multiple sources. These lessons were applied to the subsequent experiments.

InfraPDC2

For InfraPDC2 (Figure 2.6), given the results from both InfraPDC1, Tsunami 1, and Tsunami 2, it was decided to move the infrasound sensors closer to a 1 m spacing. Based on the consistency between the infrasound sensors and reduction to two sensors, it was decided to try and space the sensors at 1 m and to develop a method to determine the location of a signal. The locations of 8.4 m and 9.4 m were chosen based on the initial results from the research in presented in Chapter 4. This profile location was chosen

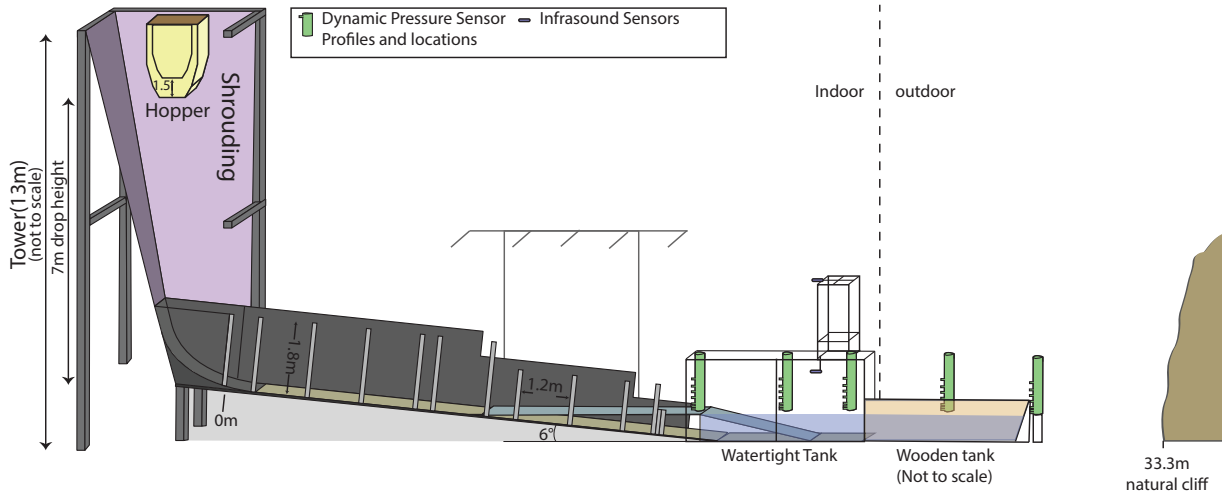


Figure 2.5: Design of Tsunami 1 and 2 with scaled sensor locations. This section is the watertight tank (see Figure 2.3). Plotted are the scaled locations for the dynamic pressure sensors (dot), infrasound sensors (asterisk), pitot tubes sensors (green circle), and thermocouple sensors (red dot). Heights are measured in distance from the channel floor in centimeters.

to correspond with a dynamic pressure and temperature profile, along with a high-speed camera observation point. The directional microphones were collocated with the infrasound pointing down into the channel. An additional profile was added in the first greenhouse to bring the number of profiles within the confined section of the channel to five. We also purchased the same directed microphones; however, we purchased audio recording that could be isolated from the power mains, and this recorded in relative amplitude instead of pressure (Pa).

The changes in configuration between InfraPDC1 and InfraPDC2 were as follows:

- reduction of infrasound from four to two sensors;
- PELE purchased two directed microphones and a logger;
- movement of the infrasound to 1 m spacing between 8.4 m and 9.4 m along the channel;
- removal of accelerometers owing to no access to sensors;

- directed microphone added to the infrasound sensors;
- addition of profiles between profiles 1 (1.5 m) and 3 (9.4 m), changing them to 1 (1.5 m), 2 (3.1 m), 3 (5.2 m), and 4 (9.4 m).

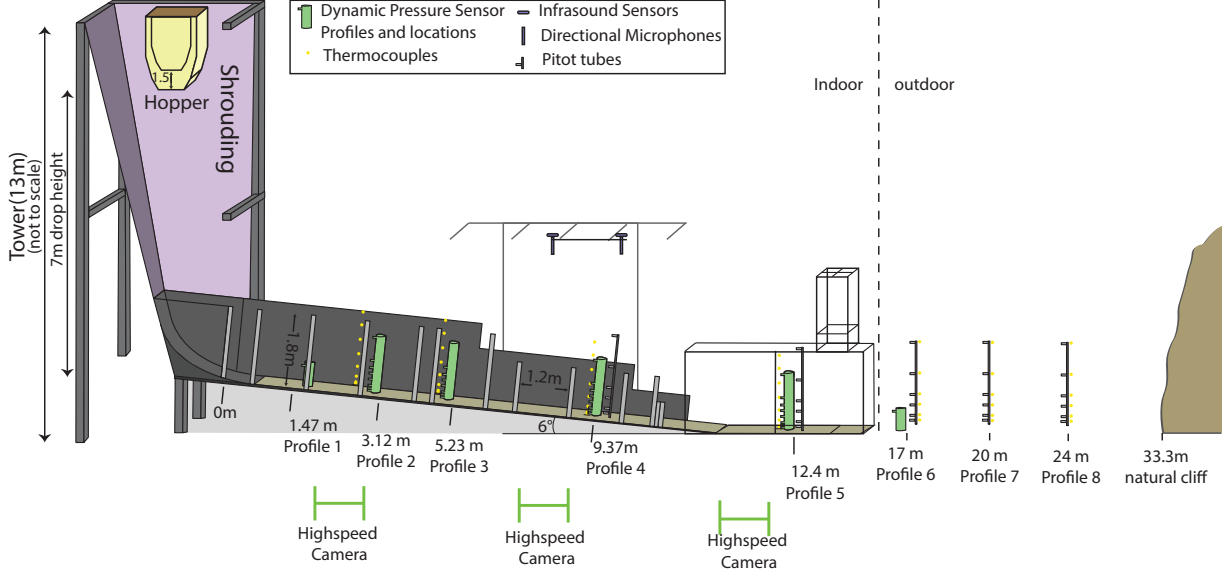


Figure 2.6: Design of the InfraPDC2 experiment with profiles and sensor locations. Dynamic pressure sensors, thermocouples, infrasound, and microphone locations are plotted along with the locations of the high-speed cameras.

Tsunami 3 and 4

Following a rapid post analysis of the data from InfraPDC2, it was decided that the infrasound and microphone sensors should remain in the same locations for Tsunami 3 and Tsunami 4 (Figure 2.7). This allowed for comparison among signals for all three signals.

InfraPDC3

The locations for the infrasound and microphone remained unchanged for InfraPDC3 (Figure 2.8). The location of Profile 2 was shifted back to 4 m. Additionally, two additional directed microphones were purchased and installed above the channel at 13 m and 17 m facing up the channel. A GoPro was installed within the channel to check

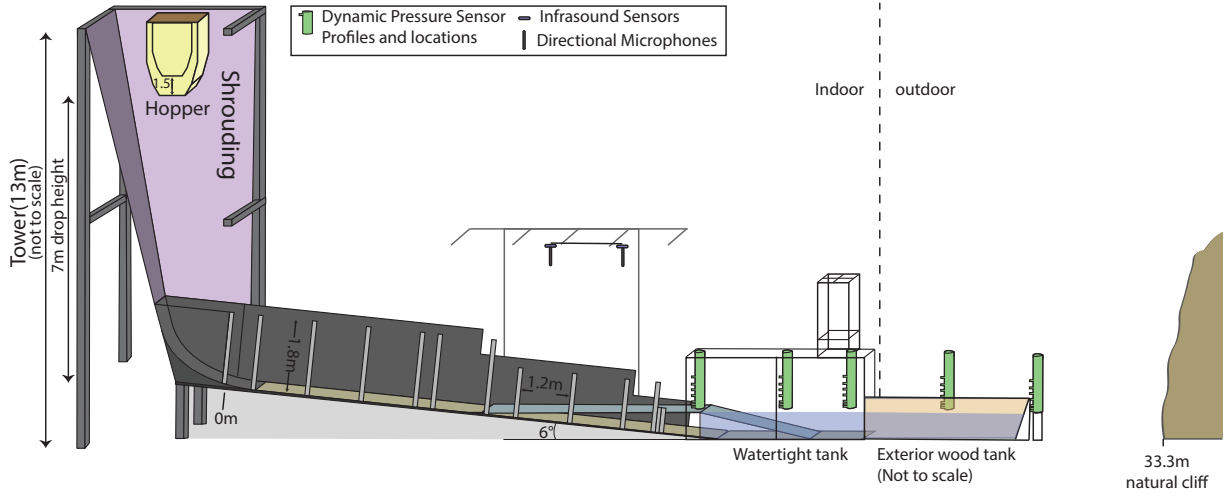


Figure 2.7: Design of the Tsunami 3 and 4 sensor locations. Plotted are the timeseries sensors for dynamic pressure (dot), infrasound (asterisk), microphone (square), pitot tubes (green circle), and temperature (red dot). Heights are measured in distance from the channel floor.

where the flow was located (see Chapter 4). Owing to ongoing issues with data quality, logging, and other factors, we decided not to install and use the pitot tubes for this experiment.

The changes for InfraPDC3 were:

- two additional directed microphones;
- Profile 2 shifted back by approximately 1 m;
- drop zone camera added;
- pitot tubes removed.

2.3 Instrumentation

2.3.1 Infrasound

Infrasound was recorded via two different configurations. For the first experiment, colleagues from the University of Tokyo installed their infrasound system alongside the

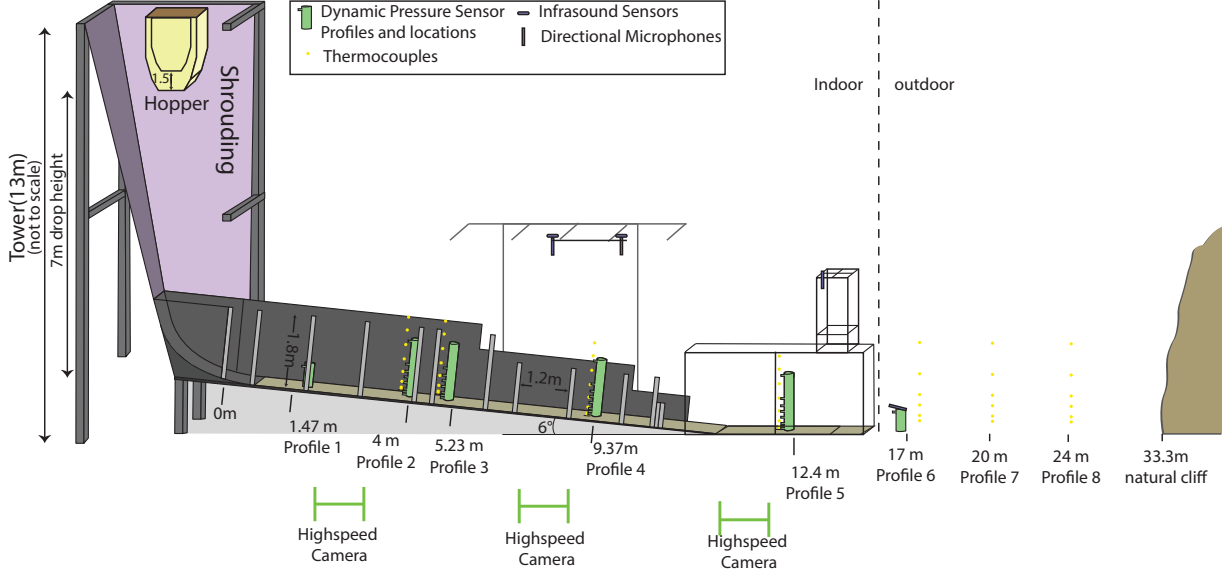


Figure 2.8: Design of the InfraPDC3 experiment with profiles and sensor locations. Dynamic pressure sensors, thermocouples, infrasound, and microphone locations are plotted along with the locations of the high-speed cameras.

system designed and installed by the PELE team. These sensors were installed external to the flow in order to record the ambient infrasound generated by the flow.

The majority of the infrasound data were recorded by the system designed and installed for the PELE lab. This system is recorded via a PicoCoulomB (PCB) Piezotronics ICP Infrasound Microphone system model 378A07 2.6 This sensor has a sensitivity of 5.8 mV/Pa, with a dynamic range of > 134 dB relative to $20 \mu\text{Pa}$ (Figure 2.9A). The sensors have an operating temperature of -40 to 80°C . The sensors have a recording range of 0.13 to 20,000 Hz at ± 2 dB, a lower limiting frequency of 0.1 HZ, and a flat response from 0.25 to 10,000 Hz (Figure 2.10). These sensors were recorded using the signal conditioner PCB Piezotronics Model 482C15 (Figure 2.9C). This had to be externally grounded within the facility. The waveforms were digitized with the National Instruments system at 1000 Hz yielding a Nyquist frequency of 500 Hz (see below in section 2.2.5).

The first experiment, InfraPDC1, includes data from colleagues at the University of Tokyo. This system was recorded with an ACO Type 7744N infrasound sensor 2.5. This is a preamplifier integrated microphone designed for measurements between 0.1

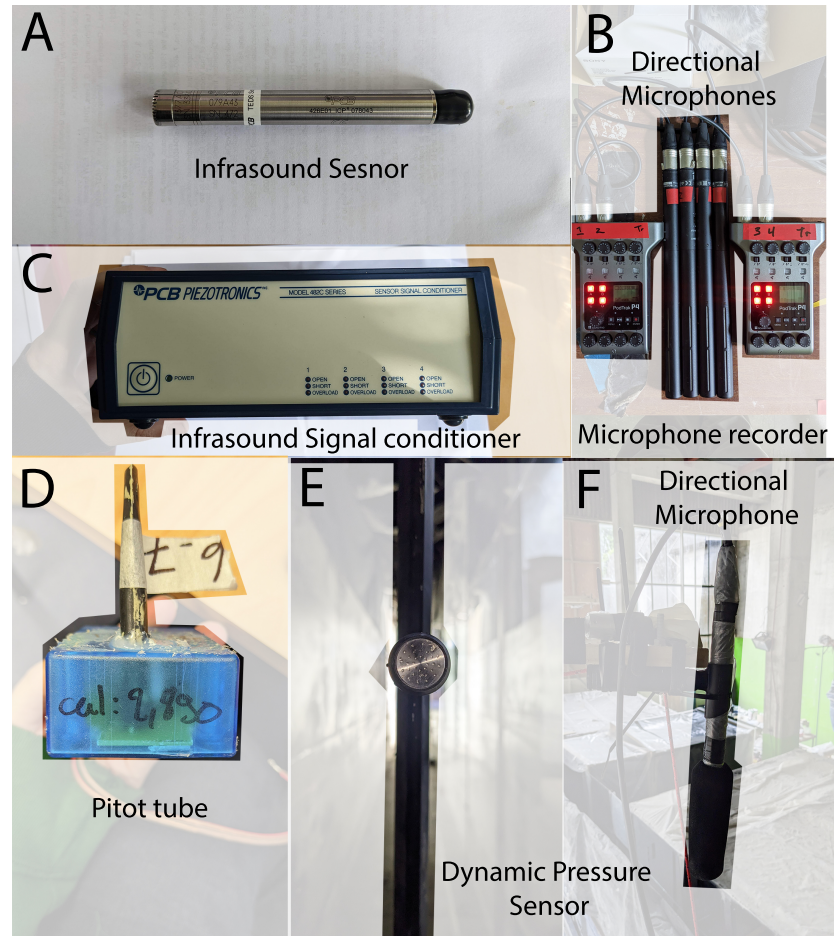


Figure 2.9: Photos of the pressure-related sensors used in the experiments. (A) PCB Piezotronics Model 378A07 infrasound sensor used with the (C) signal processor model 482C15. (B) Directional microphones along with the data recorder; (F) installed directional microphone. (D) Pitot tube installed in its housing; these sensors were made in house. (E) Face of a dynamic pressure sensor installation within the channel.

and 1000 Hz. Sensitivity for the sensors is reported as 8.9 and 6.8 mV/Pa for the specific sensors, with a maximum sound pressure level of ± 400 Pa, and it was designed as a field sensor for mobile volcano observations. This had to be externally grounded within the facility. The waveforms were digitized with the National Instruments system at 1000 Hz, yielding a Nyquist frequency of 500 Hz (see section 2.2.5).

Note that while these two instruments both reportedly have a flat response above 0.25 Hz, they have different low end responses. There are no response files available for either sensor.

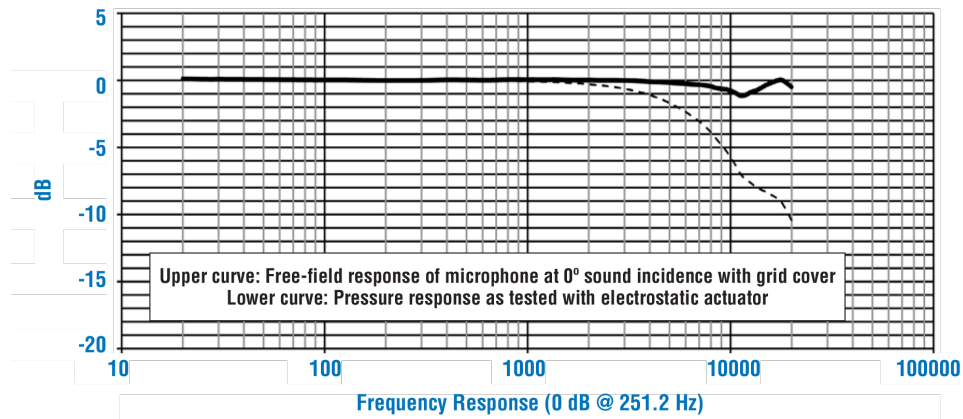


Figure 2.10: Nominal response of the PCB infrasound sensors from the literature published by the company.

Table 2.5: ACO infrasound sensor technical specifications. Nominal sensitivities from the manufacturer are listed along with the calibrated sensitivity.

Specification	Value (SI)
Sensitivity	25 $\pm$ 3 mV/Pa
Specific Sensor Sensitivity	8.9 and 6.8 mV/Pa
Frequency Range	0.1 to 1,000 ($\pm$ 3dB)
Maximum Pressure	$\pm$ 400 Pa
Operating Temperature	-20 °C to 50°C
Minimum Resolution	0.01 Pa

2.3.2 Microphones

Directed microphones used in the experiments were Sony ECM-674 directed microphones (Figure 2.9 B and F). The use of the microphones was initially validated by Dan Muramatsu at the Earthquake Research Institute in Japan. These sensors have strong directionality allowing for constraint on the direction of the incoming signal 2.11. This microphone has a sensitivity of 15.8 mV/Pa, the recording frequency range is reported between 40 to 20 kHz, with a flat response between 50 and 1000 Hz, and +5 dB to 5000 Hz, and +10 to 20,000 Hz. The sensors were installed with a windscreen. For InfraPDC1, they were recorded on a digitizer provided by the University of Tokyo at 50,000 Hz, and for the remaining experiments they were recorded with the Zoom PodTrak P4 portable multi-track recorder (Figure 2.9 B). The digitizer recorded output in Pascals, while the multi-track recorded was measured in relative amplitude.

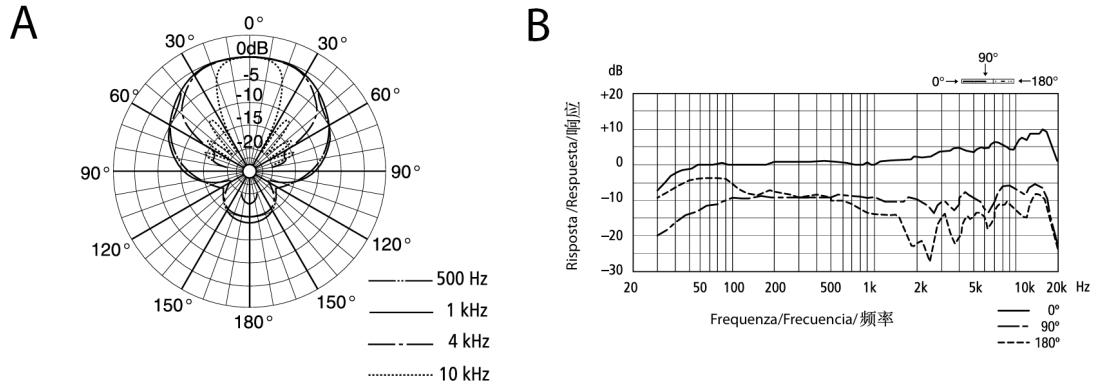


Figure 2.11: A) Directionality of the microphones provided by the University of Tokyo. B) Response curves for the microphones provided by the University of Tokyo.

2.3.3 Dynamic Pressure Sensors

The dynamic pressure sensors were a piezoelectric dynamic pressure sensor installed within the channel (Figure 2.9E). We used PCB Piezotronics ICP Dynamic Pressure Model 106B51, which is an Integrated Circuit Piezoelectric (ICP) Pressure sensor (<https://www.pcb.com/products?m=106b51>). This sensor has a sensitivity of 1000

mV/Pa, with a resolution of 0.345 Pa, maximum pressure step of 690 kPa, and maximum static pressure of 3448 kPa. The operating temperature ranges from -54 to 121°C. Model 106B51 is designed to have a rapid response time (microsecond) and resonant frequency above the sampling rate used in the experiments. Thus, no correction for frequency or delay in sensor response should be required. Individual calibration sheets are provided for each sensor, including the specific sensitivity values and frequency response. The majority of the PCB sensors were within a 4% range of the mean sensitivity (of 145.768 mV/kPa), with the exception of one sensor, which was 10% lower (Figure 2.12 A). The sensors were digitized using the National Instruments system (see section 2.2.5) at 1000 Hz, giving the data a Nyquist of 500 Hz.

There are two important considerations for these sensors. First, the output of these sensors shows a decay with repeated input over time until the signal is centered around zero; however, the peak-to-peak amplitude is maintained, as is the frequency (Figure 2.12 C). This should be taken into account during signal processing to recover input amplitude measurements through time. Second, while the quartz crystals within the sensors are not significantly impacted by thermal shocks, the case/housing around them is. Any thermal shock causes the case to expand, lessening the pre-load force on the crystal and causing a negative signal output (Figure 2.12 D).

Table 2.6: PCB Infrasound model 378A07 sensor technical specifications. Nominal sensitivities from the manufacturer are listed along with the calibrated sensitivity.

Specification	Value (SI)
Sensitivity (+/- 1.5 dB)	-44.7 dB re 1 V/Pa
Sensitivity	5.8 mV/Pa
Specific Sensor Sensitivity	0.148 and 0.147 mV/Pa
Frequency Range (+/- 2dB)	0.13 to 20,000 Hz
Frequency Range (+/- 1 dB)	0.25 to 10,000 Hz
Lower Limiting Frequency	< 0.1 Hz
Temperature Range (Operating)	-40 °C to 80 °C
Flat response	0.25 to 20000 Hz
Dynamic Range	> 134 dB relative to 20x10 ⁻⁶ Pa

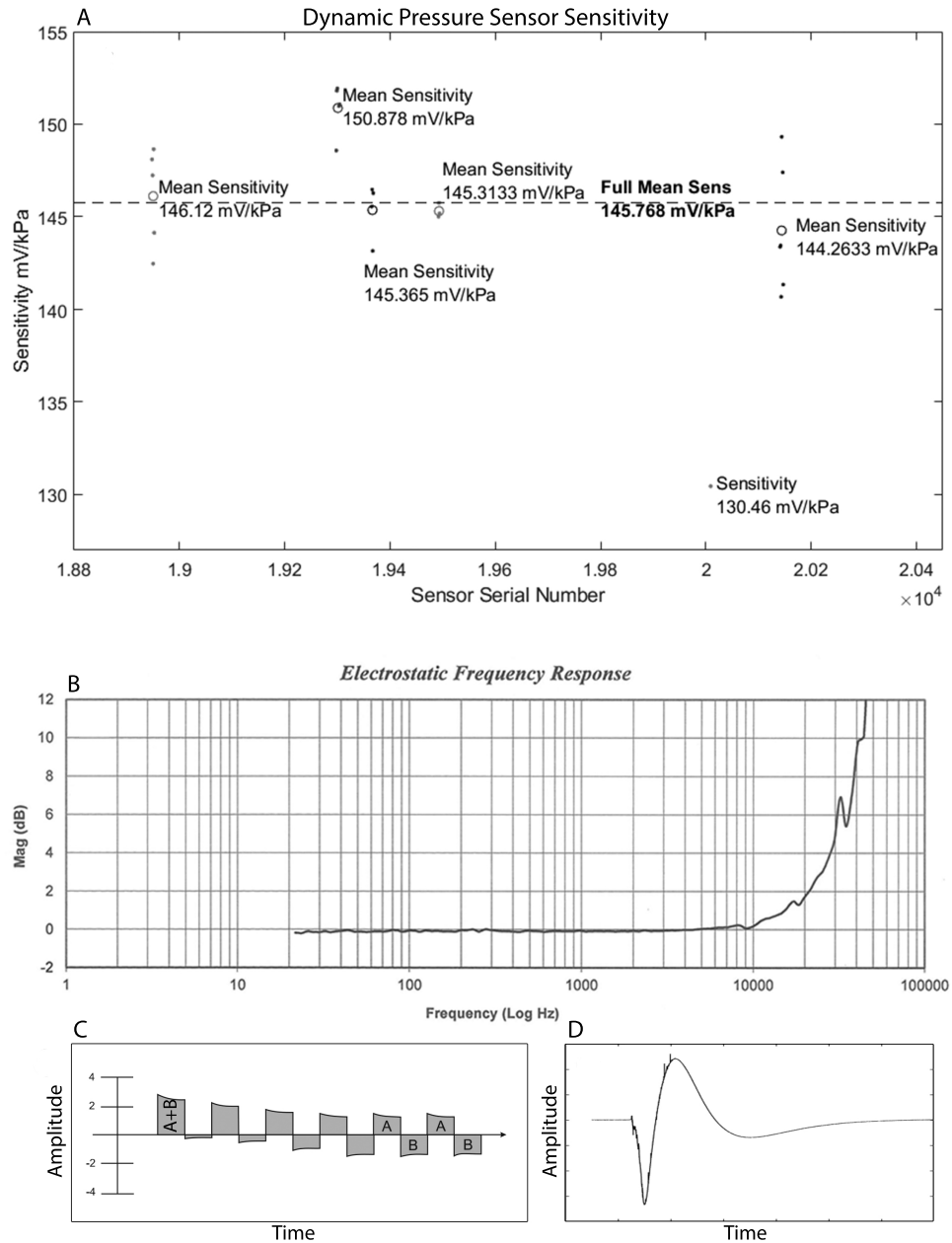


Figure 2.12: (A) Range of calibration values for the dynamic pressure sensors used in the PELE facility. (B) Example of the response of the sensors from the calibration sheets showing a flat response up to the Nyquist of 500 Hz. (C) Effect of a repeated signal of amplitude (A+B) applied to the sensor showing that while peak-to-peak is preserved through time, the sensor re-centers around zero. (D) Example of the sharp drop of the sensor output with an increase in temperature, also showing the sensor response with the associated rebound and long term recovery.

Table 2.7: Technical specifications for the PCB Piezotronics 106B51 ICP microphone relevant to experiments.

Specification	Value (SI)
Measurement Range	35 kPa
Sensitivity	145 mV/kPa
Resolution	0.34 Pa
Maximum Pressure (step)	690 kPa
Maximum Pressure (static)	3448 kPa
Resonant Frequency	> 40 kHz
Low Frequency Response	0.5 Hz
Frequency Range (flat)	0.5 to 2000 Hz
Temperature Range (operating)	-54 °C to + 121 °C
Maximum Flash Temperature	1,649 °C
Output Polarity	positive
Sensing Element (material)	Quartz
Housing (material)	17-4 Stainless Steel
Diaphragm (material)	316L Stainless Steel
Diameter (instrument face)	1.5 cm

2.3.4 Thermocouples

Internal and ambient temperatures within PELE are measured with TC Direct model number 410-345 Type K thermal sensors. These sensors have a “very fast response” (TD Direct url: https://www.tcdirect.net.au/Default.aspx?level=2&department_id=180/55) with an operating range between -75 °C and 250 °C. These sensors were digitized using the National Instruments system (see section 2.2.5) at 72 Hz with a Nyquist of 36 Hz and sample spacing 0.014 s.

2.3.5 Data Logging System

Infrasound, dynamic pressure PCB, and thermocouples were digitized using National Instruments (NI) data loggers recorded with the FlexLogger program. The data were digitized at 1,000 Hz for all channels with the exception of the thermal data, which was sampled at 72 Hz, a limit set by the NI system. The FlexLogger program has several inputs for each sensor. These include a name for the sensor, which for the infrasound experiments followed previous conventions within the facility and was a combination

Table 2.8: Location of the dynamic pressure sensors within the channel by height (in centimeters) for the infrasound experiments. The locations of the profiles are set by the location of holes within the floor of the channel. The location and number of samples was limited by the available resources and number of sensors. There was some damage to the cables for these sensors during the Tsuanmi 4 "hot" experiment and this is reflected in the data quality of some sensors.

InfraPDC1					
Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	
45	4	4	4	45	
	15	15	15		
	30	30	30		
	45	45	45		
	75	75	75		
	120	120	120		
	170		160		
InfraPDC2					
Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
45	4	15	4	15	45
	15	30	15	30	
	30	45	30	45	
	45	75	45	75	
	75			75	
	120			120	
InfraPDC3					
Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
45	4	15	4	15	45
	15	30	15	30	
	30	45	30	45	
	45	75	45	75	
	75		75		
	120		120		

of the sensor type, profile number, and height within the channel (ex: PCB_P2.4_75). Additionally, the type of measurement (e.g., temperature vs. pressure), signal type (voltage), sensitivity, and hardware voltage range and type (-5/5V differential) were input and the system output the data to a csv file with sensitivity already applied to the data. This system takes a signal from the trigger box for synchronization between modules and other datasets, and with the release of the material. This system uses two types of data logging modules: 9213 for thermocouples with a logging limit of 75 Hz (according to the manufacturer, but found to be at 72 Hz), and 9205 for PCB and

Table 2.9: Thermocouple technical specifications for the sensors used in these experiments. Information as reported by the manufacturer.

Specification	Value (SI)
Operating Range	-75 °C to +250 °C
Size	0.08 mm diameter
Response Time	“Very fast response”
Type	“K” Nickel-Chromium vs. Nickel-Aluminium, IEC 60584-1

infrasound. These were then logged in the network of computers (Figure 2.13).

2.3.6 Pitot Tubes

Fluid flow velocity is measured in the makai (outdoor) section of the flow using pitot tubes (Figure 2.9 D). This type of instrument is established within the aviation industry. The sensor measures a static and dynamic pressure that can then be converted into fluid flow. These sensors were constructed in-house. However, in practice, owing to the fine grained particles within the flow, these sensors have become blocked in several experiments. Therefore, it was decided to only use these sensors outside, where the flow is unconfined and more dilute. These sensors have their own custom logging system written by the Engineering Department at Massey. Data are recorded on arduino boards, values are recorded in LabView, and data are output in a csv file. Data were digitized at 250 Hz, which was a hardware limit. This system also takes a signal from the trigger for synchronization. After extensive testing and trouble shooting, it was decided to not use this dataset for subsequent research owing to multiple issues. However, data from individual sensors may be useful in future research.

2.3.7 Accelerometers

Colleagues from the University of Tokyo also brought two TE connectivity 4030-002-120 accelerometers, which have an average sensitivity of 996 mV/g, acceleration range of $\pm 2g$, and frequency response of 0–200 Hz; they were installed and leveled on the

Table 2.10: Locations of the thermocouple sensors in terms of their height within the channel for each of the InfraPDC experiments. Each height is given in centimeters above the channel floor and was remeasured each experiment to account for the changes in the tube height based on flexure and amount of wire extended. A variable number of sensors were used based on the constraints of location (pre-existing holes) and sensor availability.

Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8
InfraPDC1						
6	19	8	4	4	4	4
18	43	15	15	15	15	15
43	72	45	30	30	30	30
73	108	75	45	45	45	45
107		110	75	75	75	75
141		145	120	120	120	
171		160				
InfraPDC2						
5	20	7	4	4	3	4
19	44	19	15	20	19	20
42	74	43	30	33	34	34
72	109	72	45	63	64	45
107	142	108	75	108	109	64
141	178					
176						
InfraPDC3						
4	6	5	4	15	15	15
8	23	21	15	30	30	30
20	47	46	30	45	45	45
46	77	75	45	75	75	75
75	112	110	75			
112						
180						

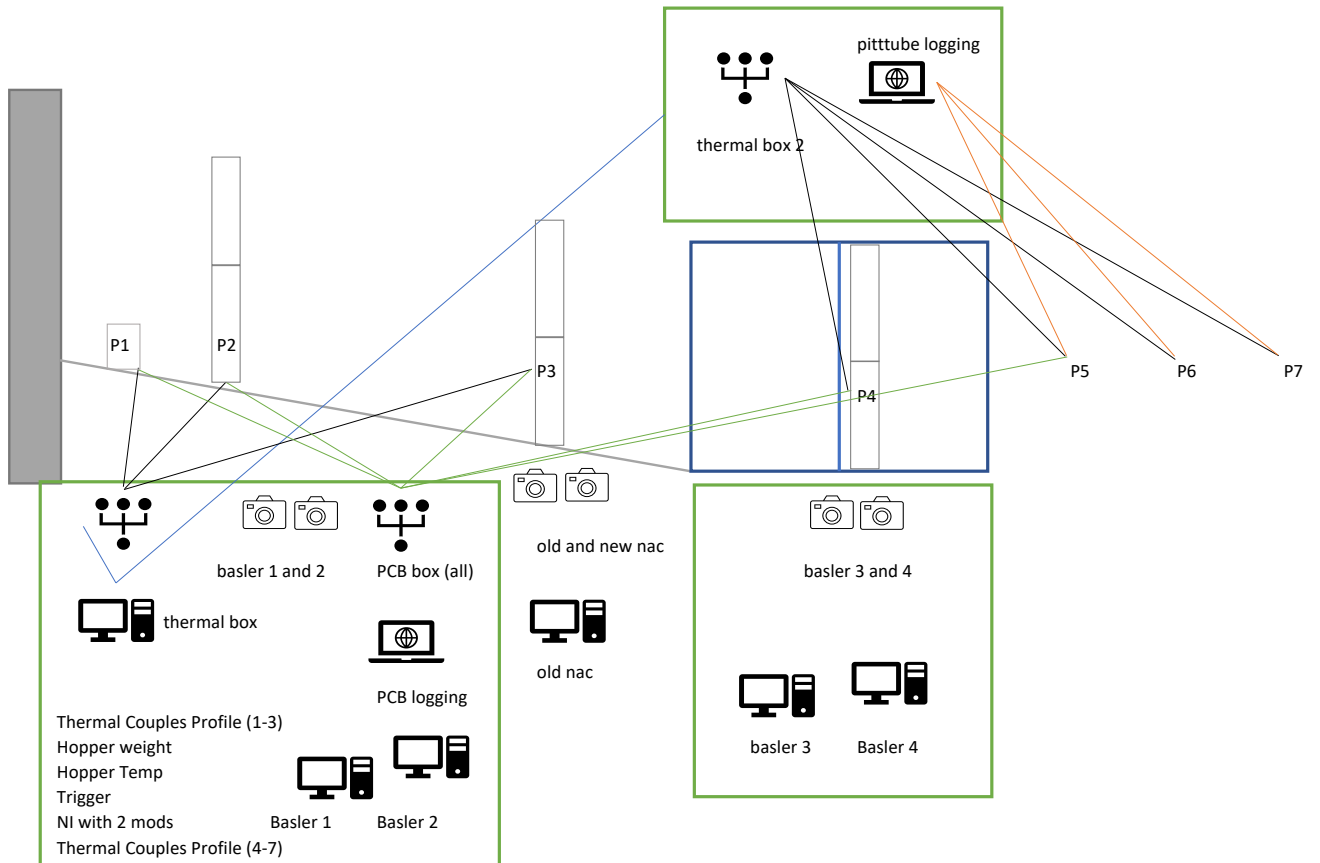


Figure 2.13: Schematic showing the PELE facility with the locations of the profiles (P1–8), computers, high-speed cameras, data logging boxes, and which profile goes to which system. Dynamic pressure sensor connections are plotted in green, thermal sensor cable connections are plotted in black, and pitot-tube connections are in orange. Infrasond sensors were added to this wiring setup with the dynamic pressure sensors. Locations are not to scale but relative to the actual locations within the Boiler House.

Table 2.11: Locations of pitot tube sensors for experiments InfraPDC1 and 2. Heights are given in centimeters above the ground and are fixed by the configuration of the 3D printed housings. The Tsunami 4 "hot" experiment damaged these sensors beyond repair for infrasound experiment 3.

Profile 4	Profile 5	Profile 6	Profile 7	Profile 8
InfraPDC1				
		8	8	8
		15	15	15
		30	30	30
		45	45	45
		75	75	75
		120	120	120
InfraPDC2				
4	4	4	3	4
15	15	20	19	20
30	30	33	34	34
45	45	63	64	64
75	75	108	109	
120	120			

channel at both the main channel and tank sections. These instruments were installed in order to further understand the vibrations of the structures during the experiment.

2.3.8 High-Speed Cameras

Internal flow dynamics, including velocities, were measured using high-speed cameras and particle image velocimetry (PIV). There were a total of six high-speed cameras, four Basler acA2000-340km, one NAC HotShot 1280, and one NAC Memrecam HX-7 ST-839. These cameras were installed as pairs to cover the entire view. Data from these cameras were used for visual analysis and PIV to understand the internal dynamics. PIV velocity results were combined with time-resolved sampling to calculate particle volume concentration within the flow at different locations and heights. All high-speed cameras were sampled at 500 fps and the length of the video was dependent on the specifics of each camera. The Baster cameras and NAC HotShot recorded to their own dedicated computer. The NAC Memrecam recorded internally. LEDs were placed within the field of view and triggered from the same system as that used to synchronize

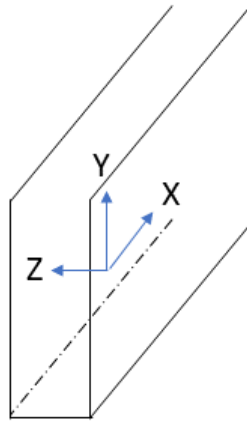


Figure 2.14: Accelerometers were installed on the wall of the channel with Y as the vertical component, X the horizontal component, with positive downslope, and Z the channel width component.

the waveform data.

2.3.9 GoPro

In addition to the high-speed cameras, there was a network of up to 19 GoPros that ranged from Hero3 to Hero8. These were used to map the flow front location through time, film the total extent of the flow through time, and film the time-resolved samplers. These were run at 60 fps, and several locations throughout the Boiler House had dedicated GoPros with known distortion. Other locations with a system of marks within the view were used as a scale owing to known video distortion for GoPros. LEDs were placed within the view of each camera for synchronization with the trigger.

2.3.10 Data Quality Assessment

Although every effort was made during the lead-up to the experiments, some data quality issues were expected. After each experiment, the first data processing set was to assess which channels recorded usable data and which had issues. A variety of different issues were found to occur during this experimental series:

Table 2.12: Data quality matrix for experimental series. Note that there was an issue with the recording system for InfraPDC2 for the thermocouple data and there are no pitot tubes for InfraPDC3.

	Good	Needs Processing	Bad	Total
InfraPDC1				
Dynamic Pressure	21		1	22
Temperature	35	4	2	41
Infrasound	4			4
Acc	2			2
Microphone	2			2
Pitot Tubes	9	3	6	18
High-Speed Cameras	4		2	6
InfraPDC2				
Dynamic Pressure	21		1	22
Temperature	9	1	29	39
Infrasound	2			2
Microphone	2			2
Pitot Tubes	5		21	26
High-Speed Cameras	5			5
InfraPDC3				
Dynamic Pressure	20		2	22
Temperature	29	4	2	35
Infrasound	2			2
Microphone	4			4
High-Speed Cameras	4		1	5

1. electronic noise due to the grounding loop (50 Hz noise with overtones and semi-tones);
2. bit noise due to a miss-wired channel, dead instrument, or broken cable;
3. voltage leakage from a trigger signal into the data channel;
4. sensor malfunction or other unexplained noise.

A data quality matrix was compiled for each experiment to denote which channels were good (green), required extra processing to be usable (yellow), or bad (red). After each experiment, efforts were made to identify and correct the issues.

Table 2.13: PCB dynamic pressure sensor physical properties for thermal shock

Part of Sensor	Material	Thermal Conductivity	source
Sensing Element	Quartz		
Housing Material	17-4 Stainless Steel	17.9 (W/m-K) at 149 °C 19.5 (W/m-K) at 260 °C 22.5 (W/m-K) at 460 °C 22.6 (W/m-K) at 482 °C	TechSteel Website
Diaphragm	316L Stainless Steel	14.0 - 15.9 (W/m-K)	

2.3.11 Temperature Correction Dynamic Pressure

The dynamic pressure sensors (PCB 106B51 ICP pressure sensor) were subjected to temperature changes within the experimental flows. Thus, it was important to understand the sensor response to these changes in temperature. Owing to the lack of mitigating methods taken into account when installing these sensors and the complications known in identifying the response of the sensors to thermal shocks, a method was developed to reduce the impact of the thermal shock on each sensor.

The first step was to identify where the temperature effect from the flow dominated the signal. There were several types of temperature impacts on the data:

1. high-impact, single high-temperature change, thermal trend;
2. low temperature, single temperature change;
3. complicated and fluctuating temperature change;
4. temperature change response exceeds sensor counts range.

The following methodology worked best on type 1 and type 2 responses:

1. Determine the time when the flow reaches the sensor either through the change in the time series, the change in temperature as recorded on the temperature sensors, or preferably from the high-speed camera;
2. Smooth the PCB data over 100 samples and check corners with the raw data;
3. Subtract the smoothed data from the raw data;

4. Cut the data to pre-flow and flow data at the time determined in step 1;
5. The flow data are then used to calculate a peak-to-peak amplitude over 10 samples with an overlap of 50
6. Combine the two datasets (uncorrected data before the flow and corrected peak-to-peak data during the flow).

2.3.12 Electronic Noise Identification and Removal

There is a known grounding issue within the Boiler House, and in addition there are high voltage lines within the building. Several peaks consistent with the New Zealand electrical grid are visible in the data starting at 50 Hz. A notch filter with a 2 Hz width was designed for 50, 100, 150, and 200 Hz and applied to all data with high noise. When possible, additional grounding was applied (although this had mixed results), and when possible, sensors were powered from batteries. Figure 2.15 illustrates the results of this method; the strong 50 Hz peak was removed without significantly impacting the overall signal.

2.4 Data Access

Waveform data for the experiments have been uploaded to a data repository, and any other associated experimental data are available upon request. <https://dataverse.harvard.edu/dataverse/APerttuThesis> with dataset DOI: <https://doi.org/10.7910/DVN/QAX1RU>. This repository contains the data files for the infrasound experiment sensors.

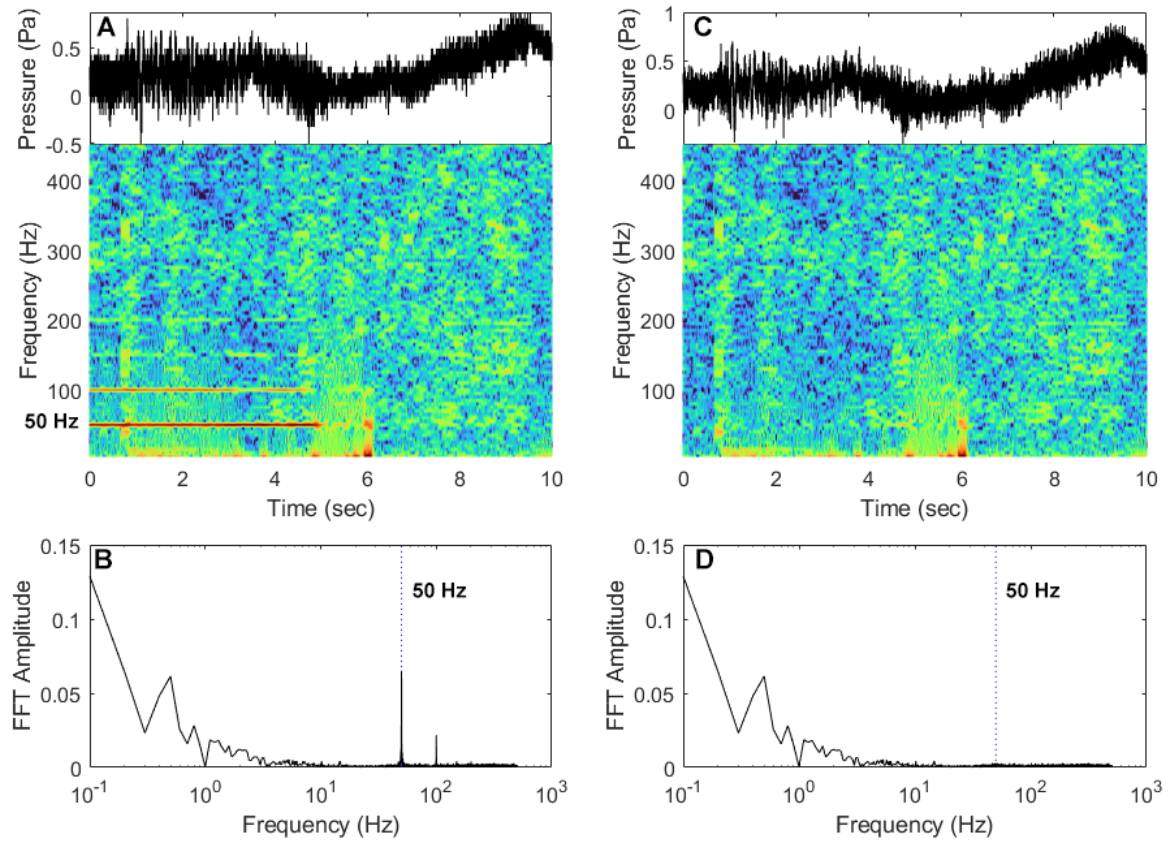


Figure 2.15: (A) Waveform and associated spectrogram for an infrasound sensor for InfraPDC1 showing variable electronic noise at 50, 100, 150, and 200 Hz. (B) FFT showing the strong peak at 50 Hz from the electronic noise. (C) The same dataset waveform and spectrogram pair showing that the removal of the electronic noise did not significantly impact the data. (D) FFT for the noise reduced data showing the removal of the 50 and 100 Hz peaks.

Chapter 3

Reanalysis of Atmospheric Pressure Wave and Lamb Wave Generation from the May 18, 1980 Mount St. Helens Eruption

3.1 Abstract

The May 18, 1980 eruption of Mount St. Helens is notable for its well-observed onset, beginning with a large landslide, catastrophic lateral blast, significant regional impact, and atmospheric pressure waves that were recorded locally and globally. Insights from this eruption are particularly relevant in light of the 2021–2022 eruption of Hunga Volcano, Kingdom of Tonga, which generated a large-scale atmospheric Lamb wave. In this study, we compiled and reanalyzed all known pressure signals recorded globally, along with seismo-acoustic observations and eyewitness accounts of the Mount St. Helens eruption signal. Given the results from this analysis, we reinterpret the archival datasets for this eruption as an atmospheric Lamb wave, the same type of acoustic gravity wave generated at Hunga in 2022. This interpretation is supported by the

mismatch between the observations and ray tracing analysis, along with the smaller-than-expected shadow zone. Eyewitness reports further constrain the directionality of the signal. These findings highlight the value of integrating historical records and instrumented observations within the context of ongoing scientific advancements.

3.2 Introduction

The 2022 eruption of Hunga volcano (also called Hunga-Tonga Hunga-Ha’apai in the literature) renewed interest in historic eruptions that produced acoustic gravity waves (AGWs). The instrumented historical record contains only a limited number of events, particularly since the transition to continuous digital recording. Researchers refer to acoustic gravity waves as ultra-long-period (ULP) infrasound (Fee and Matoza, 2013; Ripepe et al., 2010) or very-long-period (VLP) signals (Garces et al., 2013). These atmospheric waves have periods ranging from 50 to 230 s (0.004 to 0.02 Hz). Pre-digital eruption datasets include additional events that expand this sparse dataset, most prominently for the 1883 eruption of Krakatau, which researchers frequently use as a comparison for the Hunga eruption (Matoza et al., 2022). These two events represent the largest recorded signals within the instrumented record.

On May 18, 1980, *Lawetlat’la* / Mount St. Helens erupted into a clear morning in southwest Washington state, USA, in what at the time was the most closely observed eruption of its type. A unique sequence of photographs, taken by Gary Rosenquist and Keith Ronnholm 17.5 km to the northeast of the volcano, enabled researchers to reconstruct a detailed chronology of the first few minutes of subaerial events (Voight, 1981). The first few minutes of the eruption encompassed a large landslide on the north side of the volcano, a lateral blast northward, and the establishment of a Plinian eruption column. The eruption generated a globally observable acoustic gravity wave; at the time, it was only comparable to Krakatau’s 1883 eruption and to atmospheric nuclear explosions (Båth, 1982; Ritsema, 1980). Despite their global significance, researchers have rarely revisited these pressure signals since the late 1980s, excepting one study

(Johnson and Malone, 2007) on seismo-acoustic signals recorded on the local seismic network. Given the renewed interest in these infrequent large explosion signals, re-examining the Mount St. Helens dataset represents a valuable case study on acoustic gravity waves generated by volcanic eruptions.

Significant advances have occurred in aero-acoustics, atmospheric ray tracing, attenuation modeling, and the study of acoustic gravity waves from volcanoes since these initial studies (e.g., digitized datasets, increased computer power, theoretical advances, improved meteorological models and data, and developments in ray tracing and waveform propagation models), which allow for refined interpretations of modern and archival datasets. This study revisited the historic Mount St. Helens dataset, collecting all available data preserved from various sources, and applied modern and new methods to quantify and interpret the pressure waves generated during the initial phase of this eruption. We combined barometric, microbarograph, seismic, and eyewitness/earwitness accounts within the context of recent advances. As globally recorded acoustic gravity waves from volcanoes are rare in the literature, it was important to archive, preserve, and reanalyze the archive data, and to address fundamental questions about these valuable pressure signatures, including which aspects of eruptions can generate them.

3.3 Methods and Data

Global barometers, microbarometers, and seismic stations recorded the pressure signals from the 18 May, 1980 climactic eruption. Eyewitnesses near the volcano felt and heard these signals, and earwitnesses throughout the region heard them. The following sections categorize the available data by recording method, describe the data quality and limitations, and provide results for each dataset.

Table 3.1: Geophysical observations listing number of stations, number of available amplitudes, and timing of observations

Sensor Type	Number of Stations	Amplitude Observations	Timing Observations	Sources and/or References
Barograph	58	21	37	Banister (1984); Dewey (1985); Fairfield (1980); Reed (1987, 1980a), NOAA Archive
Seismometer	36	1	36	Båth (1982); Donn and Balachabdran (1981); Johnson and Malone (2007), paper records
Microbarometer	26	25	22	Bolt and Tanimoto (1981); Donn and Balachabdran (1981); Liu et al. (1982); Reed (1987); Delclose et al. (1990)

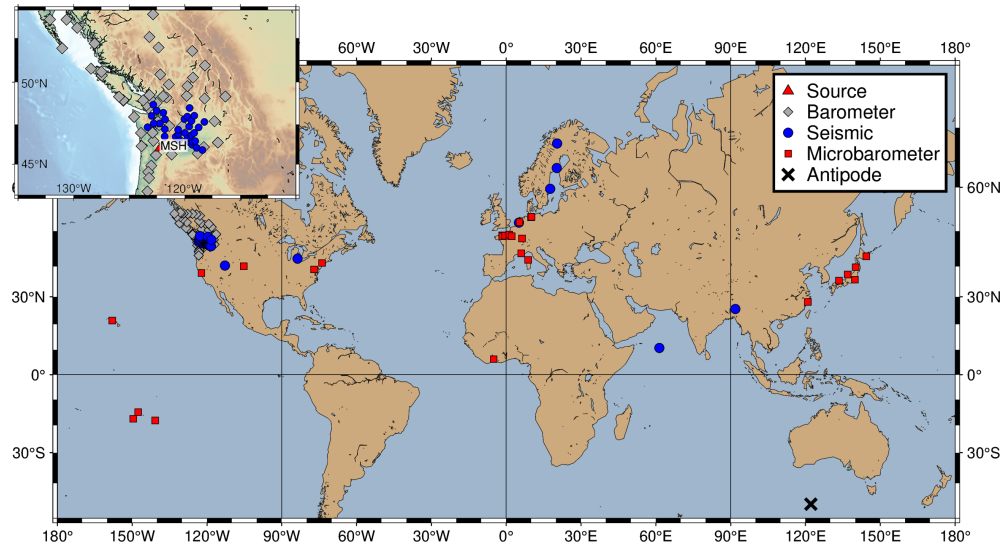


Figure 3.1: Global distribution of the seismic, barometer, and microbarometer stations used in this study, relative to the source (Mount St. Helens) and antipode (south of Australia). The global distribution includes all stations from the literature and this study, which focused on the Pacific Northwest of the United States (see inset map for details).

3.3.1 Barometers and Microbarometers

Barometers, which measure atmospheric pressure, and microbarometers, which measure relative changes in pressure recorded pressure signals produced by the 1980 Mount St. Helens eruption in the Pacific Northwest region, nationally, and globally. The technologies available at the time, the passage of time, and different preservation methods and priorities have resulted in data that vary in quality and availability. Some original data and scanned original records remain available through institutional archives, while others are preserved only as secondary records within the published literature. Table A.1 lists all individual stations with observations from the literature. Data from barometers and microbarometers are not available as digitized waveforms and are archived at various resolutions depending on the original recording and preservation method. Figure 3.1 shows the global distribution of all sensor locations.

Weather station barographs from the United States, originally operated by the National Weather Service (NWS) and Federal Aviation Administration (FAA) in Washington, Idaho, and Oregon, are now archived by the National Oceanic and Atmospheric Administration (NOAA). However, due to archival policy, not all daily records for all stations are preserved. In Canada, the Pacific Region Atmospheric Environment Service of Canada, now the Canadian Department of Environment and Natural Resources, originally recorded measurements. This department was contacted, but barograph charts on microfilm for 1980 are not present in the British Columbia archives (Bramwell, 2025).

Data from several individual microbarometer stations, generally relative pressure stations designed to record smaller pressure oscillations from other global locations and sources, are also reported in the literature. These include Berkeley (California), Boulder (Colorado), Washington DC and Palisades (New York) in the United States (Bolt and Tanimoto, 1981); Hamburg and Buchholz in Germany (Donn and Balachabdran, 1981); French Polynesia (France) and Ivory Coast (Delclose et al., 1990); Eastern China (Liu, 1985); and five individual microbarograph records from Japan (Liu et al., 1982). At the time of writing, the original station records have not been located and the data remain available only through the published literature.

Barometer and microbarometer measurements reported in the literature include amplitude, period, duration, arrival time, and waveforms extracted from published figures. Banister (1984); Reed (1987, 1980a,b) reported barograph amplitude measurements without arrival times. Bolt and Tanimoto (1981); Delclose et al. (1990); Donn and Balachabdran (1981); Liu (1985); Mikumo and Bolt (1985) provided amplitude and time observations as well as selected microbarometer waveforms. B  th (1982); Dewey (1985) reported barometer timing information and Fairfield (1980) provided additional barometer waveforms.

Where possible, additional amplitude and arrival time measurements were obtained from original NOAA scans and reproduced figures from the literature. Each measurement carries an inherent uncertainty. Amplitudes were measured manually, with slight

differences in reported values across studies reflecting some degree of human error. Additionally, resolution error arises from the thickness of the pen, time resolution of the measurements, and scanning resolution. Timing measurements were taken from the paper records, which have an uncertainty due to the pens' write speed on the paper. The scanned NOAA barometer records have a resolution of 8 pixels/h hour. The original barograph records have a resolution of 2.7 mm/h and 2.5 inches/1.00 inHg (1.9mm/Pa) (Reed, 1987, 1980a,b). According to Banister (1984), the time interval required for these barographs to reach two thirds of their final value for a step pressure is 3-4 s, but this "sluggish" system has a reduced effect for longer period transients. Additionally, some US barographs were recorded in purple ink and did not copy clearly (Reed, 1980a). The Berkeley microbarometer station operated at a 6 mm/min, with a sensitivity of 1 mm /0.009 mbar (1.1 mm/Pa) (Bolt and Tanimoto, 1981). Despite these resolution limitations, a total of 58 barometers, 13 microbarometers, and 36 seismic stations provided usable measurements (figures 3.1, 3.2, and 3.3, Table 3.1, Table A.1, Table A.2)

3.3.2 Seismic Data

Seismo-acoustic signals from the eruption are reported in the literature, including data recorded within the US and globally (B  th, 1982; Johnson and Malone, 2007; Kanamori et al., 1984; Kanamori and Given, 1983; Liu et al., 1982). Johnson and Malone (2007) conducted the primary study focused on the seismo-acoustic coupled phases (e.g., Novoselov et al. (2020)) of the May 18, 1980 eruption, examining the local seismic network installed during the event. This network recorded a combination of continuous and triggered data. Researchers originally digitized these records as seismic helicorders and subsequently digitized them and made them available within Earthscope/IRIS in various stages (Malone, 2020). Some timing errors remain, and amplitudes are reported in uncorrected instrument counts rather than physical units.

The local network at the time, installed and maintained by the University of Washington (network code UW) consisted primarily of short-period seismometers, with the

exception the Longmire station (LON), a digital long-period seismic station (Kanamori et al., 1984). Additional seismic stations from Europe (Båth, 1982) and Japan (Liu et al., 1982) were also available. Given transmission complexities and a lack of calibrated amplitudes, researchers have focused primarily on timing information from the seismo-acoustic data, with only one seismo-acoustic-derived amplitude at the LON station (Kanamori and Given, 1983).

We obtained two paper records: one a hobby station in Vancouver, British Columbia, Canada, operated in the home of a University of British Columbia geophysics seismic technician (Cassidy, 2025), and the other a copy of the LON station long period signal. From these additional paper records, we picked arrival times to supplement the results reported in the seismic data literature (figures 3.1, 3.2, and 3.3, Table 3.1, Table A.1, Table A.1).

3.3.3 Waveform Calculations

To augment the measurements reported in the published literature, we include additional observations extracted from the available data (the scanned images of paper records and the original records required careful considerations). For some stations, scans of the original data records are available within archives; however, for some stations only figures reproduced from other publications are available (Appendix A). For these published figures, the quality of the reported parameter and timing scales varied. Where possible, we calculated new estimates of arrival time and amplitude, particularly for barometer stations that lacked previously reported arrival times. The majority of barometer data for Washington and Oregon came from (Reed, 1987), where the barographs were plotted to illustrate signal morphology across the region. Consequently, these records were not suitable for obtaining timing estimates.

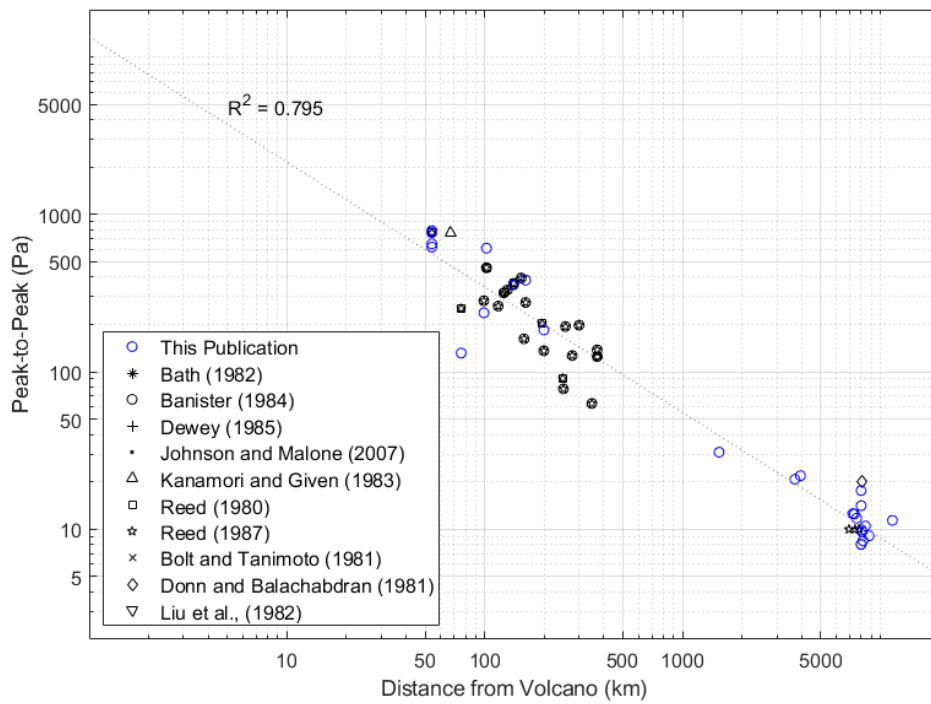


Figure 3.2: Amplitude results from barometer and microbarometer datasets reported in the literature and this publication. Results are plotted as the peak-to-peak pressure vs. distance from the volcano, and symbols represent the publication. Results plotted in blue are calculations from this publication from the various sources. A log-log fit was calculated to estimate the source amplitude.

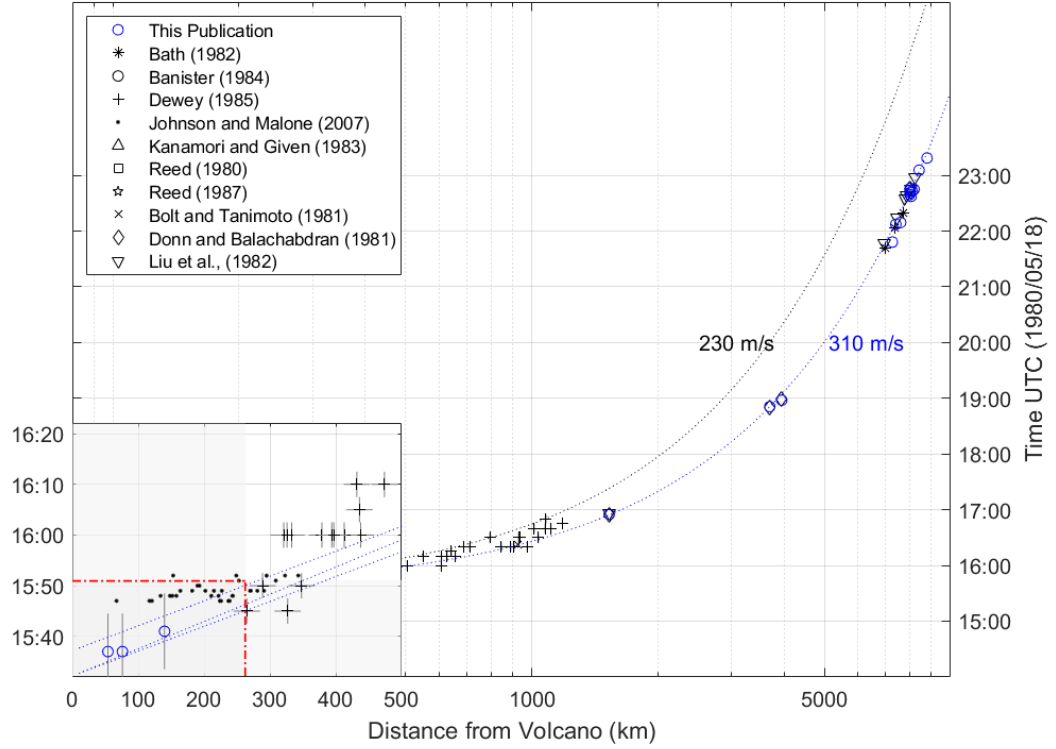


Figure 3.3: Arrival time vs. distance plot for the seismo-acoustic arrivals, barometer, and microbarometer datasets from the literature and this publication. Symbols for publications are identical to the ones used in Figure 3.2. Within the inset, which illustrates more local arrivals, the arrivals within the red dashed box are too early and too close according to the atmospheric ray tracing model for acoustic arrivals. The travel time curves plotted in blue correspond to acoustic arrivals with a celerity of 310–340 m/s from the start of the sequence (earthquake at 15:32:11) and 340 m/s from the start of the Plinian phase of the eruption. For the longer-range detections, the celerity at the first bounce range of around 230 m/s is plotted along with the 310 m/s for a Lamb wave starting from the Ms 5.2 start time at 15:32:11. The data conform to the Lamb wave velocity at large distances.

3.3.4 Eyewitnesses and Earwitnesses

Survivors

Eyewitnesses and survivors of the eruption reported a variety of pressure-related phenomena, including feeling a pressure increase, ear popping, and other related sensations. They also described variable wind directions before the arrival of the lateral blast and different audible sounds. Two primary publications document these eyewitness accounts: the original Rosenbaum and Waitt (1981), published in the Geological Survey Professional Paper 1250, and the updated and expanded book by Waitt (2014). For both publications, we reviewed each entry, identified accounts that mention pressure, wind, sound, ear popping, body squeezing, or visible waves (Table 3.3, Table A.3), and estimated a map position for each report (Figure 3.4).

Audibility Survey

The Oregon Museum of Science and Industry (OMSI) conducted a region-wide survey of observations by the general public who heard the eruption, placing advertisements in local newspapers within 300 km of the volcano (Fairfield, 1980). The original dataset is no longer available from OMSI (Benne, 2024). However, both Fairfield (1980) and Dewey (1985) provide details on the locations and general descriptions of the reported sounds. Here, results were grouped by the relative reported amplitudes: audible, loud, and very loud. The dataset shows a clear zone of silence around the volcano, with the nearest observation occurring 100 km from the source. The zone of maximum reported intensity lies between 250 and 300 km, and the farthest reported distance reaches 930 km.

Quantifying Eyewitness Accounts

To quantify the eyewitness data, we first identified the range of human perception for different frequencies and pressures. The human audible range for humans is generally cited as 20–20,000 Hz, constraining the frequency range for acoustic signals. Limits on

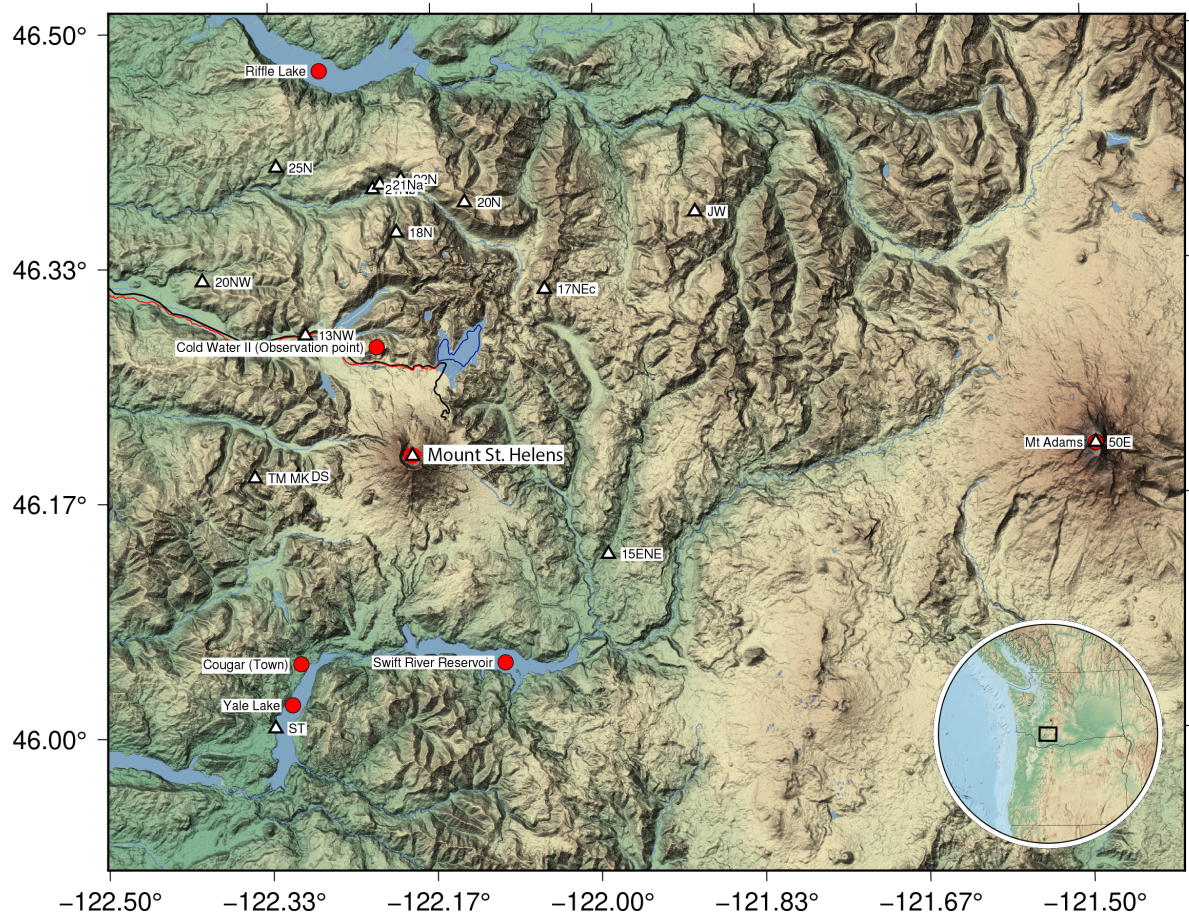


Figure 3.4: Eyewitness location map, with the eyewitness code numbers from Rosenbaum and Waitt (1981), as well as the codes assigned in Table 3.3. Additional key locations have been labeled and the Spirit Lake Highway (before the eruption) is plotted in black.

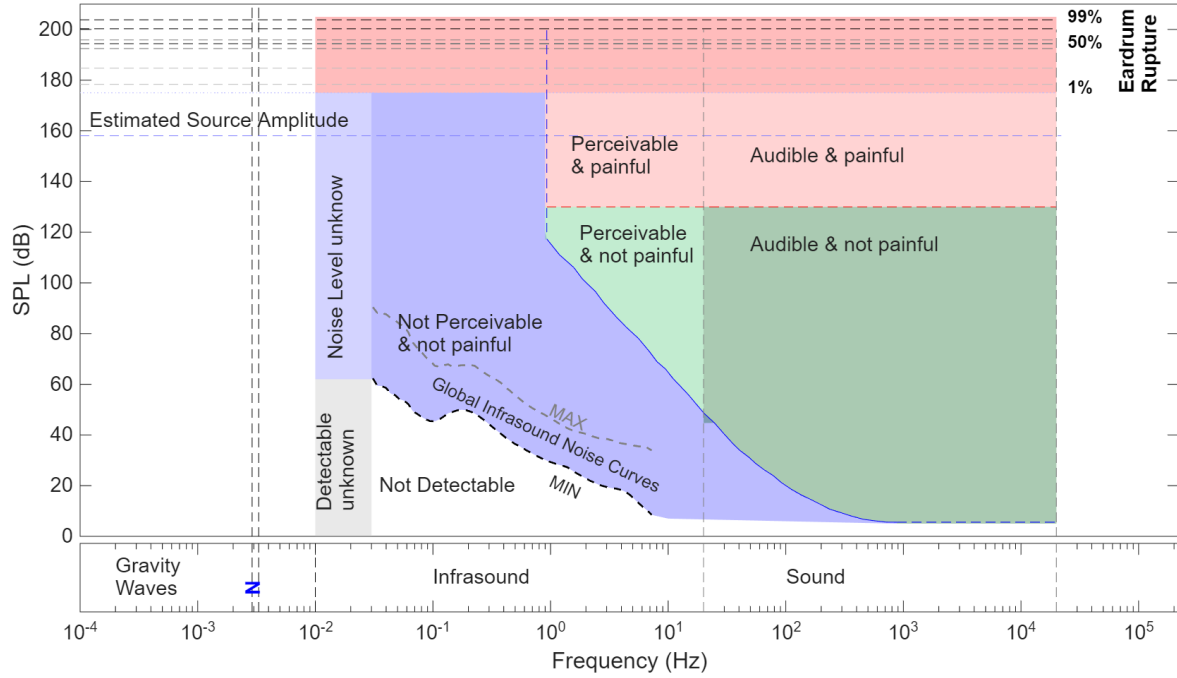


Figure 3.5: Frequency vs. sound pressure level (SPL) plot of perceivable acoustics and barotrauma limits. Sections are split into audible and non-audible, painful and not painful, and use an infrasound–sound threshold of 20 Hz. The full spectrum is not well understood. The global infrasound noise curve minimum and maximum are plotted and used for the limits for detectability in the infrasound range. Also plotted is the estimated source amplitude from Banister (1984) (in blue). The ranges of eardrum rupture thresholds, which have a range of measurements likely based on the variation of human anatomy, are noted on the left hand axis. There are no reports of eardrum rupture in the eyewitness accounts, with observations plotting below the 1% line, but closer to the transition to painful on the low end.

audibility and barotrauma also constrain the amplitude (Figure 3.5). While infrasound (< 20 Hz) generally cannot be “heard” at some amplitudes, it can be “perceived.” By combining these limits with research on barotrauma, we established quantitative constraints for acoustic and pressure signals reported by eyewitnesses.

For this study, we classified observations into the following categories: audible, not audible, perceivable, not perceivable, painful, and eardrum barotrauma. The impacts of overpressure shocks are well studied in the context of conventional explosions (Committee on Gulf War and Health, 2014; NOAA Office of Response and Restoration, 2025; Zipf and Cashdollar, 1983; Hirsch, 1966) and underwater sports and work. Banister (1984) compared their peak overpressure (1600 Pa) to the equivalent water depth of

0.2 m, and concluded that such overpressure could cause ear popping.

These values were combined with known thresholds of hearing, pain, and perception to constrain frequency and decibel (dB) range of a signal. For example, during the 1883 eruption of Krakatau, Indonesia, the Royal Mail Ship *Norham Castle*, located approximately 64 km north of the volcano in the Sunda Strait, reported that half of its crew suffered ruptured eardrums (Symons, 1888; Verbeek, 1885). Literature estimates suggest that amplitudes of 17–105 kPa are required to rupture eardrums in 1%–50% of the population, providing a rare quantitative constraint on the overpressure during this eruption. The results of the literature review on barotrauma are summarized in Figure 3.5 and guided interpretation, context, and constraints for the eyewitness accounts. The relative order of events was taken into consideration within the narratives; however, as noted by (Arstila, 2012), the perception of time during these sorts of events cannot be relied upon, and therefore self reported times were not considered.

3.4 Ray Tracing

Acoustic and infrasonic waves generated at the surface propagate through the stratified atmosphere, where the effective sound speed varies with altitude, and winds strongly influence their paths. Rays typically refract upward, and under favorable conditions, rays can be ducted within atmospheric layers, allowing them to travel long distances with relatively little attenuation. This upward refraction also creates a shadow zone where arrivals are absent until the rays return to the surface at the first bounce point. Ray-tracing methods are widely used to model these propagation paths, providing estimates of travel times, turning heights, ducting conditions, and transmission loss at local, regional, and remote distances.

Dewey (1985); Johnson and Malone (2007); Liu et al. (1982); Mikumo and Bolt (1985); Reed (1987) applied ray tracing using a variety of methods available at the time. To harness improvements in the ray tracing methodology and attenuation modeling of pressure signals, we conducted a new ray tracing and attenuation modeling for this

Table 3.2: Ray tracing results for the cardinal directions noting the wave guides that formed (Th., thermospheric wave guide; St., stratospheric wave guide).

Propagation Direction	Source Height (m ASL)	Wave Guides	First Bounce (km)	Celerity (m/s)	Transmission Loss
North	2500	Th.	268	224	-66 dB
North	4000	St., Th.	266	223	-54 dB
East	2500	Th.	293	231	-82 dB
East	4000	Th.	291	231	-79 dB
South	2500	Th.	288	234	-48 dB
South	4000	St., Th.	287	234	-56 dB
West	2500	St., Th.	281	232	-59 dB
West	4000	St., Th.	272	230	-54 dB

event. We used the *infraGA/GeoAc* tool (<https://github.com/LANL-Seismoacoustics/infraGA/>) to model propagation (Blom, 2019). *InfraGA* is a tool to model the propagation of infrasound within the limits of geometric acoustics over different coordinate systems, and allows for range dependence in the atmosphere and realistic terrain.

For this updated modeling, we used an average ground-2-space (G2S) model (Drob et al., 2003, 2010; Drob, 2019) for the MSH region. The National Center for Physical Acoustics (NCPA) generates the G2S model from 0 to 150 km ASL, which combines the National Oceanic and Atmospheric Administration’s (NOAA) Global Forecast System (GFS) model for troposphere, MERRA2 data for the middle atmosphere, and mass spectrometer incoherent scatter radar (MSIS-00) semi-empirical and Horizontal Wind Models for the mesosphere-thermosphere (Drob et al., 2015; NOAA National Centers for Environmental Prediction, (NCEP), 2015; Picone et al., 2002; Rienecker et al., 2008; Bosilovich et al., 2015). To create a mean profile, we averaged G2S models for the region every 6 h from May 15 to May 21 for the years 2014–2024 (Hetzer et al., 2019). These profiles (plotted with their averages in Figure 3.6) were then compared to the available measurements and observations on May 18, 1980 (Reed, 1980a; Dewey, 1985). There was significant agreement between the observed meteorological observations and the model used for this processing, indicating that the conditions at the time of the eruption did not differ significantly from the conditions within the model. The modeled rays

were computed using take-off angles from -30° to 50° in 2° increments, with topography included and two source elevations: 2500 m ASL corresponded to the lateral blast and 4000 m ASL was approximately 1 km above the summit. Rays were propagated along the four cardinal directions (0° , 90° , 180° , 270°).

3.5 Results

In this study we remeasured amplitudes for five microbarographs and seven barographs, and timing for five microbarographs and four barometers. We then combined these results with data available from the literature.

An initial comparison of amplitudes from all literature sources identified a significant outlier for the Berkeley microbarometer. Bolt and Tanimoto (1981) reported an amplitude of 3.5 mbar (350 Pa), approximately an order of magnitude higher than most other reported values. Hence, we reanalyzed the data using the available information on scale and resolution. This reanalysis confirmed that the timing information was correct but revealed a factor of ten error in the reported overpressure. The recalculated amplitude agrees with the value reported from a personal communication cited in Banister (1984). This recalculation relied on the literature record, which is reproduced on a square grid background. Assuming the same square grid applies to both timing and amplitude, the 1 mm deflection corresponds to a pressure variation of 0.009 mbar, yielding a remeasured overpressure of 32.4 Pa and peak-to-peak amplitude of 58.4 Pa, consistent with other stations in the dataset.

When combining dissimilar waveform data, we addressed several important considerations. Different data streams were sampled with different rates and, therefore, had different frequency resolving capabilities. For example, barometer arrival times typically exhibit lower time precision compared with that of nearby seismic stations owing to different sampling rates. All arrival and amplitude information appear in Table A.2, including both literature values and the results calculated herein. The combined results are presented in Figure 3.2 and Figure 3.3.

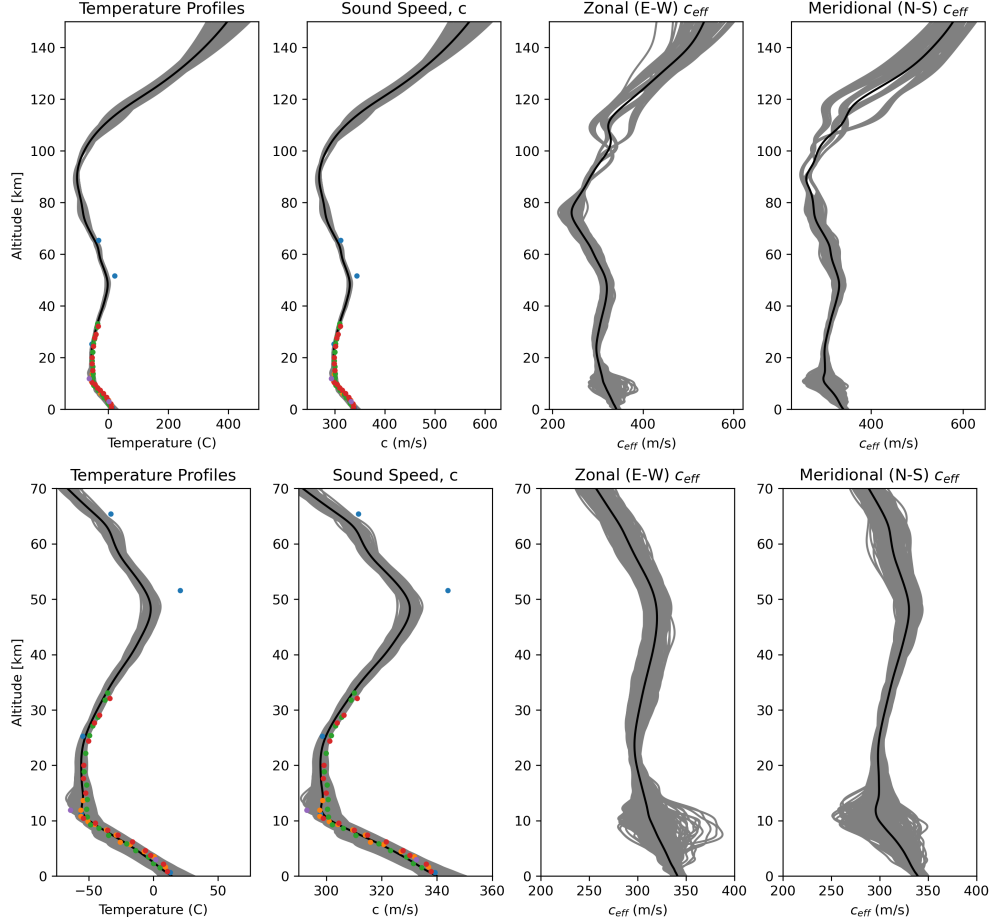


Figure 3.6: Average temperature, sound speed, and effective sound speed from 15 to 21 May in the 2014–2024 NCPA G2S dataset, with 0–150 km plotted on the top row and 0–70 km plotted below, with the average used in the ray tracing highlighted as a black line. Reported sound speed and temperature data were from Dewey (1985) and Reed (1980a). Weather stations from Portland (Oregon) and Toledo (Washington), and weather balloons from Salem (Oregon), Vernon (British Columbia), Port Hardy (British Columbia), and the International Civil Aviation Organization Standard Atmosphere (blue) are plotted on the model outputs and show good agreement with the average values.

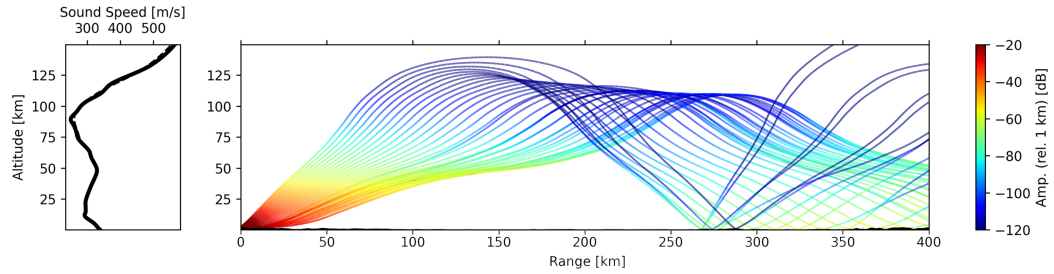
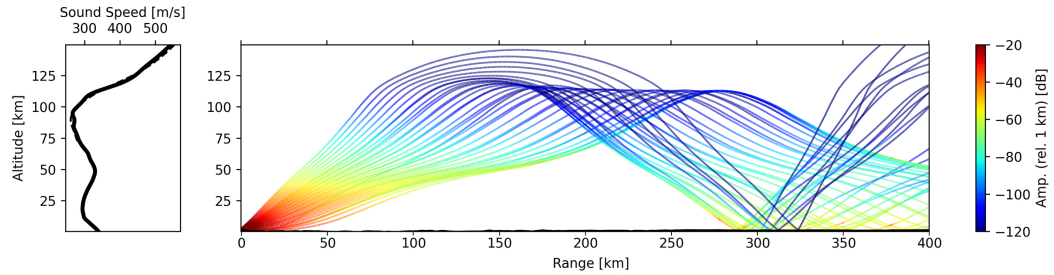
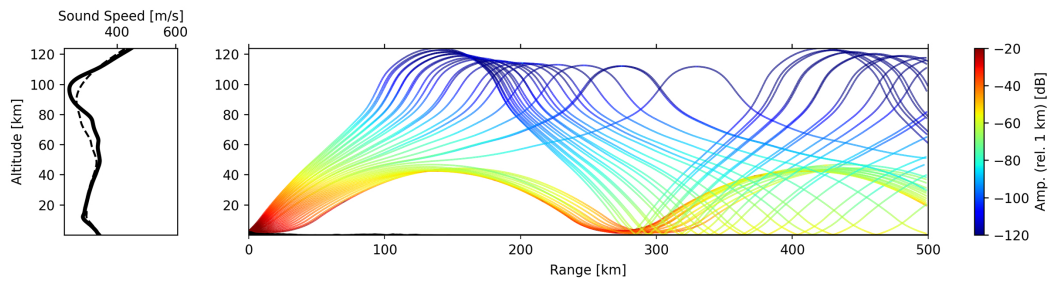
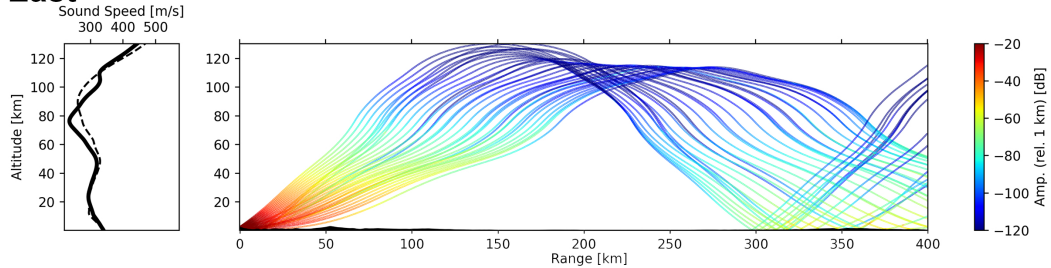
North**South****West****East**

Figure 3.7: Ray tracing results from InfraGA runs for the four cardinal directions. Rays plotted show the full complement of take-off angles and are initiated at the elevation of the landslide and lateral blast at 2400 m. All first bounces are expected to be further than 200 km and closer to 300 km distance from the source, with the least transmission loss at the first bounce to the west, and all rays.

Eyewitnesses described the sounds during the initial minutes as a rumble/roar [e.g., Jerry Wheeler (25 km N), Brian Cole (19 km N), Mike Moore (20 km N), Ty and Marinna Kearny (12 km W), V. Hodgson (27.4 N), and K. Rohnholm (27.4 N)], “like a freight/distant train” [Joe Findley (18 km E), and Wendell Johnson (27.4 km N)], as a “distant quarry blast” or cannon[(Steve Terril (25 km S), and G. and K. Palmer (24 km N)], and in some cases as a “low jet” / “like an F-4” [Buzz Smith (16 km N), and Brian Cole].

The remaining pressure-related observations can be grouped into the following categories: ear popping, body squeezing, pressure changes, and visible pressure waves. Some of the phrases describing the pressure increase include “an uneasy feeling, that grew, like an air pressure change” (“Buzz” Smith 16 km N; Waitt (2014)), “I felt a pressure as if someone were squeezing my body gently” (Mike Moore 20 km N; Waitt (2014)), and “A sudden pressure for half a minute made my ears pop a dozen times” (Brian Cole 19 km N Waitt (2014)). Several eyewitnesses also reported a visible wave described as “A thin bluish color ran out from the mountain in front of the big swelling gray cloud, like a horizontal wave you see on atomic bomb films.” (Wendell Johnson 27.4 km N; Waitt (2014)) and “A low-level shock wave ran out, a blurry little wave like heat rising from something hot. It passed by fast but I didn’t feel it” (J. Harvey inside moving vehicle 17 km N Waitt (2014)); from the top of Mt Adams 54 km to the east “One of the climbers reported seeing what seemed to be a shock wave, similar to that associated with a nuclear explosion traveling to the north 30 seconds or less after the start of the eruption” (Rosenbaum and Waitt (1981); interview with a 10 climbers led by J Christensen). We located these eyewitness accounts using a combination of the maps in Rosenbaum and Waitt (1981) and Waitt (2014), descriptions within the accounts, and a Google Earth file including historic logging road names and locations by Kelly Michaels (link in Acknowledgments).

Based on the barotrauma literature and eyewitness accounts, we can add some thresholds to the amplitude of the signals near the volcano. While the “squeezing” and “ear popping” were not described as “painful,” they are likely on the higher end

of the perceivable and not painful range, or on the lower end of the perceivable and painful range as human variability and variable perception has to be taken into account. Additionally, given the constraint of the measurement of the low frequency signal at Toledo (Washington) at approximately 350 Pa (145 dB), the amplitude at around 10–20 km from the volcano was greater than 350 Pa and below 17,000 Pa where eardrum damage is expected to begin.

In addition to the physical impacts, we analyzed the descriptive language used by the eyewitnesses for the sounds and feelings they reported to extract more information from the accounts. It is important to consider that the terms used are temporally and culturally specific to the time and place of the eyewitness accounts. For example, terms such as a *cannon* and *freight train* have distinct sound characterizations. Trains from different eras will have different acoustic characters. A cannon typically refers to a discrete impulsive signal with a lower frequency, whereas a freight train implies a more continuous, emergent sound. Similar considerations apply to descriptors such as *quarry blast* and *low jet*. Modifying words (e.g., *distant*) further constrain the relative amplitude of the reported signal. The location and occurrence of these reported sounds suggest that the “zone of silence” identified in the OMSI survey does not apply to the area immediately around the volcano where eyewitnesses observed a variety of signals.

Ray tracing analysis indicates that under all conditions, the first bounce occurred between 256 and 291 km from the source, with a celerity of 223–234 m/sec. None of the runs produced a tropospheric waveguide, although all generated thermosphere waveguides. For the lower source elevation, only the westward ray produced a stratospheric waveguide, whereas for the higher source, both northward and westward rays generated a stratospheric waveguide. Transmission loss was greatest in the eastward and southward directions (Table 3.2). In all cases, local direct arrivals did not extend beyond approximately 30 km from the summit (20 km to the north and west, 30–34 km to the south and east). This leaves a shadow zone between 30 and approximately 250 km around the volcano in all directions, which was not observed within the datasets.

3.6 Discussion

3.6.1 Established Timeline

The May 18, 1980 eruption began at 15:32:11 UTC with the gravitational failure of the north flank, where a cryptodome had been growing. The resulting landslide generated a seismic signal equivalent to a Ms 5.2 event (Kanamori et al., 1984). Despite the availability of photographs, video footage, eyewitness accounts, and geophysical data, the exact timing and sequence of events during the following few minutes remains an active topic of research and discussion, without consensus on the pre-Plinian events. The generally accepted sequence of events begins with the collapse of the north flank, which mobilized as a debris flow and liquefied into a lahar down the Toutle River. The landslide depressurized the cyprodome, triggering a lateral blast and small vertical plume. This sequence culminated in the establishment of a sustained Plinian eruption column.

Based on seismic observations (Endo et al., 1981; Kanamori et al., 1984; Kanamori and Given, 1983; Malone et al., 1981) and photographic documentation (Hoblitt, 2000; Voight, 1981), the events of the first five minutes are summarized as follows: 15:32:11, Ms 5.2 (mb 4.7) seismic event from landslide motion (Kanamori et al., 1984); 15:32:21, landslide becomes visually observable (Voight, 1981); 15:32:47, a small vertical plume forms (Voight, 1981); 15:32:56, the lateral blast initiates (Voight, 1981); 15:33:41, the second larger explosion cluster is recorded (Hoblitt, 2000); and 15:37:00, onset of the Plinian Phase (Voight, 1981).

Johnson and Malone (2007) identified five seismo-acoustic signals during this interval. The first occurred approximately 10 s after the landslide seismic signal (15:32:21 UTC) and was associated with landslide motion. However, their ray-path modeling indicates that this signal would be indistinguishable from a signal generated at 15:32:11. Furthermore, they stated that they were unable to identify a seismo-acoustic signal consistent with the timing of the lateral blast initiation based on ray tracing and travel time modeling. Three additional explosion signals followed at 15:34:05, 15:34:50,

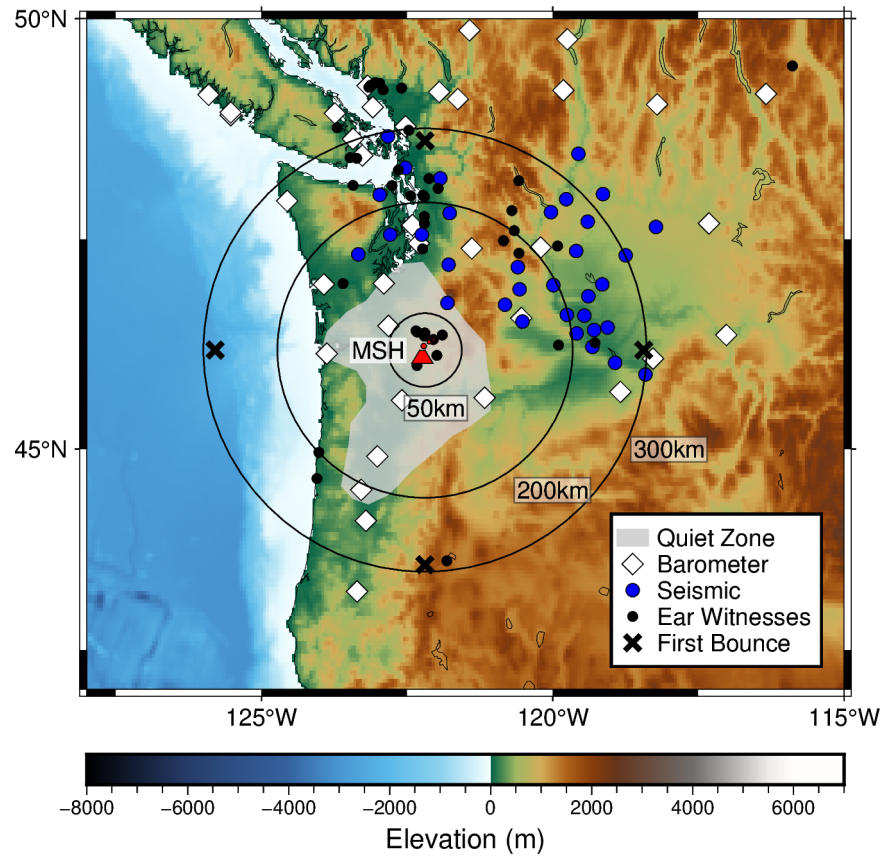


Figure 3.8: The locations of the expected first bounce from the modeled atmospheric ray tracing are plotted as black crosses with seismic station detections in blue, audibility reports in black, and barometer detections in white. There were detections on the barometers within the modeled shadow zone (ray tracing), and the reported quiet zone (audibility survey), along with detections and observations of sound from all datasets between the expected first bounce locations and the volcano.

and 15:35:20, and a final explosion signal from a more northern source occurred at 15:37:30. These seismic observations are based on short-period seismometers, which likely recorded higher-frequency energy associated with the passage of the large barometric disturbance rather than the lower frequency long period signal itself (on short period stations, broadband seismometers detected this signal globally). Additionally, this signal had a celerity of 310 m/s and would, therefore, not be consistent with ray tracing results.

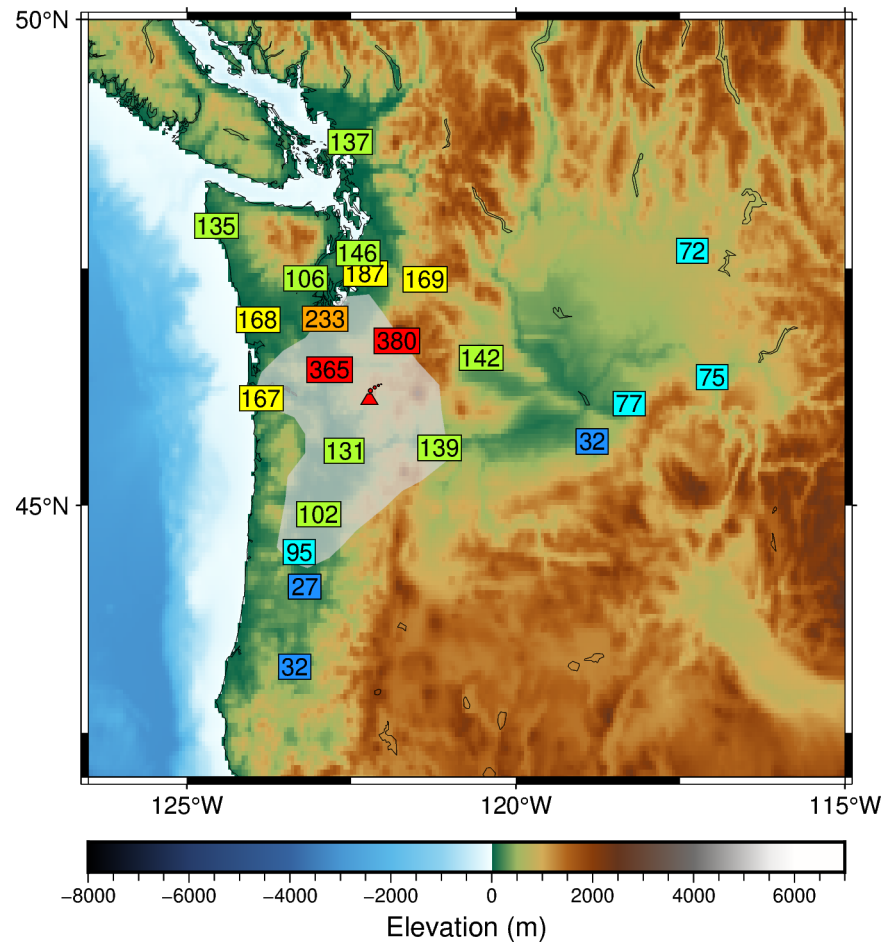


Figure 3.9: Contour map of overpressure amplitudes at available stations (in Pa); the shadow zone from the OMSI report is outlined in gray. The amplitudes are colored, with higher amplitudes to the north and west (with overpressures exceeding 100 Pa into Canada) and reduced amplitudes to the south and east.

3.6.2 Shock vs. Lamb Waves

Large volcanic eruptions generate atmospheric pressure signals spanning a wide frequency range, from gravity waves in the millihertz range to acoustic signals in the kilohertz range. Researchers have frequently compared volcanic eruption signals to those from nuclear and conventional explosions (Matoza et al., 2022). When an initial explosion expands faster than the local speed of sound in the surrounding medium, it produces a shock wave. Alternatively, if the source is below the local speed of sound, the eruption may generate infrasound and acoustic gravity waves. One type of acoustic gravity wave is the Lamb wave, a surface wave characterized by minimal attenuation as it propagates. Lamb waves travel along the ground, their amplitude primarily influenced by topography, and can be distinguished from other low-frequency signals by their characteristic velocity of approximately 310 m/s (Gossard and Hooke, 1975). In contrast, infrasound and acoustic waves propagate closer to 340 m/s at the surface and follow ray paths into the atmosphere where they attenuate based on the atmospheric conditions along the ray path. The January 2022 Hunga-Tonga Hunga-Ha’apai eruption produced an exceptional Lamb wave that circled the globe four times and could be detected for 6 days (Matoza et al., 2022), renewing scientific interest in these waves.

In the Mount St. Helens case, the pressure signals recorded by near field barometers resemble the classic “N-wave” typically associated with shockwaves. Several eyewitness accounts also described a visible “shock wave” or “mist” moving outward from the volcano. However, based on the available evidence, it is clear that these were not true shock waves. The barographs used at the time had relatively slow response times of centimeters per day paper speed (Banister, 1984). Furthermore, the Toledo barograph recorded an overpressure of 370 Pa, which is above the threshold for window rattling and breakage for a shock wave, yet there were no reports of such damage in the area (Reed, 1987). The signal was also inaudible, further arguing against a shock wave. If this signal had been a true shock wave, the eyewitnesses, who were likely familiar with the sound of a sonic boom, would have likely reported this phenomena a distinct “sonic boom”. The 2020 Beirut port explosion is one example of a classical shock wave

and was audible as far away as Cyprus at a distance of 200 km (Clifton, 2020; Kim and Pasyanos, 2022; El Sayed, 2020). In contrast, the Mount St. Helens blast was characterized by an expansion of the plumes and landslide with velocities well below the speed of sound (Voight, 1981).

The barometric signal reported in the literature included a dominant period ranging from 290 s in Utah (Donn and Balachabdran, 1981) to 390 s in Germany (Donn and Balachabdran, 1981; Liu et al., 1982; Reed, 1987), with most reported wave periods clustering near 300 or 360 s (Figure A.1). In terms of classification, audible sound falls within is 20–20,000 Hz, infrasound spans 0.01–20 Hz, and acoustic gravity waves range from the frequency of the Earth’s rotation to 0.01 Hz (Figure 3.5). The recorded signal, with a frequency between 2.5 and 3.4 mHz, clearly falls within the acoustic gravity wave band. Banister (1984) identified this signal as an acoustic gravity wave and modeled it with two different physical assumptions: one as the source of a wave radiating from an accelerated plane surface, and the second as a wave radiating from an expanding hemisphere. They concluded that when assuming an acoustic wave, neither model was in good agreement; instead, they preferred the expanding hemisphere model over the ballistic model, with a northward facing source.

Owing to the constraints of the barograph instrumentation available at the time, distant microbarograph stations provide higher timing resolution than did the nearby barometers. Given this distance, the difference between expected arrival times from different wave types (infrasound vs. Lamb wave) was greater. Pressure waves following the normal acoustic ray path (Figure 3.7) have an expected celerity of around 240 m/s. The Berkeley station, located 925 km south of the mountain, was equipped with a microbarometer with a higher temporal resolution. A clear arrival is plotted by Bolt and Tanimoto (1981), who reported an arrival time of approximately 50 min after the 15:32 UTC onset of the eruption sequence, with a celerity of 308 m/s. This celerity is consistent with Lamb wave propagation. At this distance, the difference between a Lamb wave traveling at approximately 310 m/s and an acoustic wave at 240 m/s is approximately 14 min and 30 seconds. This observation aligns with other reported

group velocities, which range from 302 m/s (Donn and Balachabdran, 1981) to 314 m/s (Båth, 1982) and 317 m/s (Reed, 1987), with a mean reported group velocity of 309 m/s (Table A.2).

The results of ray tracing and atmospheric modeling indicate a large shadow zone around the volcano, ranging from 265 to 291 km before the first return. Despite this predicted shadow zone, at least 17 stations within this range detected the pressure signal. The seismic network also recorded seismo-acoustic signals within this range, and multiple earwitnesses also reported hearing the eruption in this range (Figure 3.8). These observations suggest that a significant amount of energy transferred into the atmosphere but did not follow the expected acoustic ray path. Even with updated modeling, taking into account topography and a wide range of take-off angles, the observed pattern of detection cannot be explained through acoustic propagation. The recorded amplitudes, both in overpressure and peak-to-peak pressure, form a contour that extends significantly to the north, a pattern that cannot be explained by the atmospheric modeling. In fact, modeling predicts the strongest arrivals to the west, and at the time of the eruption the weather around the volcano was described as "clear and still" by David Johnson at Coldwater II (Waitt, 2014). This suggests a stronger initial source geometry to the north with an asymmetric source as opposed to a symmetrically radiating source.

Given the frequency content, celerity, group velocity, and absence of a shadow zone or agreement with modeled ray tracing, the results indicate that this signal is consistent with a Lamb wave with a northward-tilted source (Figure 3.9). This is consistent with the northward propagating large landslide and lateral blast portion of the initial stage of the eruption. The existence of a Lamb wave was noted by Liu et al. (1982) on the basis of observations of ionospheric disturbances and pressure waves at global distances, but they did not make an interpretation of the source. Both previous and current ray tracing and atmospheric attenuation modeling indicate an upward bending of rays and a shadow zone, which is inconsistent with the observations. A surface propagating Lamb wave explains the absence of a shadow zone, the apparent velocity and celerity, the

amplitude asymmetry, and the observed attenuation. Although some studies suggest that the signal recorded at the Berkeley station reflects two sources 6 min apart (Bolt and Tanimoto, 1981), this signal is consistent with the evolution of the Lamb wave with time and distance, as illustrated in Matoza et al. (2022). The timing information of the proximal stations remains insufficient to distinguish between the landslide or lateral blast, as both occurred within 30 s and could have generated acoustic gravity waves, although given the lack of evidence for landslide-induced Lamb waves in the literature, the lateral blast is the preferred source model.

Nonlinear Frequency Generation of Audible Signals

A surface propagating Lamb wave can explain the arrivals of the gravity wave signals within the expected shadow zone; however, this would not explain the higher frequency and audible signals within this zone. The Lamb wave generated by the HTHH eruption in 2022 was also accompanied by acoustic observations in places like Alaska, where propagation modeling could not explain their presence (Matoza et al., 2022). In this case, the acoustic arrivals were attributed to nonlinearity processes that generated higher frequencies along the Lamb wave path. Although we do not address those processes in detail, further research on the propagation and range of signals recorded within the expected shadow zone would contribute to HTHH eruption studies, especially given the data gap for that eruption within its expected shadow zone owing to its location.

Visible “Shocks”

Volcanologists first recorded visible “shocks” during Frank A. Perret’s observations at Vesuvius in 1906 (Perret, 1950), and later studied them at Ngauruhoe volcano in New Zealand (Nairn, 1976). With improvements in visual data recording, scientists have increasingly reported these visible waves (Johnson et al., 2023a; Taddeucci et al., 2014). These features are also referred to as condensation clouds because they are thought to develop owing to rapid dynamic pressure oscillations related to temperature and

dew point that modulate vapor condensation (Nairn, 1976). Condensation clouds can develop through several sources, including but not limited to: volcanic plumes, nuclear and conventional explosions, and supersonic aircraft. Birk (2017) states that “the passage of a strong shock wave in moist atmosphere usually produces a condensation cloud that is briefly visible to the human eye”, and further states that “if the air is laden with moisture it is possible that the temperature can drop below the dew point [...] and which may lead to the nucleation of liquid droplets in the air that appear as a fog”. Atmospheric conditions on the morning of 18 May 1980 can be used to test whether the passage of a large pressure wave could explain the eyewitness reports of a “shock wave” or “misty cloud”. Relative humidity represents the ratio of the partial pressure water vapor in the atmosphere to the saturation vapor pressure at a given temperature. The dew point marks the temperature at which the saturation vapor pressure equals the partial pressure, leading to condensation.

Using the available meteorological observations and temperature measurements recorded prior to the eruption at the “Coldwater II” observation point, we estimate that the rarefaction required to cool the atmosphere to dew point was between 1 and 4 kPa (see Appendix A). Given that the rarefaction of the signal directly to the west at Toledo WA exceeded 300 Pa, and the signals had a higher amplitude to the north, vapor condensation at this observation point is plausible. Eyewitnesses reported that the cloud was traveling north, ahead of the blast cloud, implying limited spread in other directions. Similar phenomena have been documented in other recent events, including the Beirut explosion (Goldstein, 2020) and in a widely circulated video of an explosion from the Tavurvur cone at Rabaul (Swearingen, 2015). These clouds, formed by condensation during the passing of strong pressure pulses, are known as Wilson Clouds (Waltz, 1978). Volcanologist Clive Oppenheimer provided a comparable description: “Then I spotted a diffuse white mist expand very rapidly outwards and downwards. I didn’t know what to make of it, and it momentarily terrified me. But I recalled Perret’s description of ‘flashing arcs’ that he had seen accompanying explosions, and realised it was a shockwave” (Oppenheimer, 2023).

3.6.3 Historic Data Preservation

Large, low-probability, high-impact volcanic eruptions pose significant hazards. However, owing to their infrequent occurrence, only a small number have been captured within the instrumented record. Preserving records from these events, though costly, remains essential for advancing volcanological research and hazard assessment. The field of volcanology advances one eruption at a time, and new analytical methods can be applied to past events to gain additional insight. Efforts to re-digitize analog records, such as those by Malone (2020), are therefore critical. This publication contributes to those efforts by providing a digital archive of all observations identified in the literature (see Data Availability). The 2022 eruption of Hunga-Tonga Hunga-Ha’apai (HTHH) highlighted the scarcity of globally observed volcanic atmospheric acoustic gravity waves and motivated the comparison of the HTHH eruption signal (Matoza et al., 2022) with the 1883 Krakatau signal.

The dataset compiled herein includes the following:

- signals from papers where the original waveforms no longer exist;
- digitized scans of surviving records;
- figures from papers where the underlying data tables are unavailable but could be extracted;
- resolution errors associated with these datasets, including paper speed and scan resolution;
- a comprehensive table of all extracted amplitude measurements and arrival times for the Lamb wave.

This dataset is intended to serve as a reference source for other researchers studying not only the May 18, 1980 eruption of Mount St. Helens, but also acoustic gravity waves and further comparative studies of volcanic events.

3.6.4 Eyewitness Accounts

Although eyewitness accounts are generally qualitative and lack precision of instrumented observations, they can still provide valuable constraints. Narrative descriptions and specific language choices allow researchers to infer key characteristics of the event, especially when instrumentation is unavailable, as is often the case for historic eruptions. It is also important to remember that visual and auditory impressions are typically better retained than a sense of absolute time. Consequently, relative timing is often inferred from spacing within the narrative, since eyewitness timing estimates are frequently inaccurate (Waite, 2014). These accounts must also be interpreted within the cultural and temporal context in which they were recorded. For example, the audible reports for the 1883 Krakatau eruption reference cannons (Symons, 1888), whereas descriptions of the 1980 Mount St. Helens eruption often invoke trains, jets, and other modern noise sources. Understanding such cultural references is essential for interpretation, as demonstrated in the translation of eyewitness accounts of the 2018 Anak Krakatau sector collapse, where eyewitnesses used a local instant coffee brand as a color descriptor (Perttu et al., 2020a).

Within the eyewitness dataset, at least eight accounts specifically mention a pressure change or pressure increase. The perceived intensity of this pressure change was likely influenced by the relatively slow rise time of the signal, which may have allowed for ear-popping rather than barotrauma. Barotrauma thresholds are generally derived from more classic shock waves with much steeper rise times, such as those generated from conventional explosions. These pressure-change observations are clustered to the north of the volcano, consistent with the direction of the lateral blast (Figure 3.10). The majority of the sound observations from within 30 km of the volcano are also concentrated to the north. Interestingly, the OMSI dataset (Fairfield, 1980) records that the loudest reported sounds were from distances near where the first acoustic bounce is expected based on ray theory.

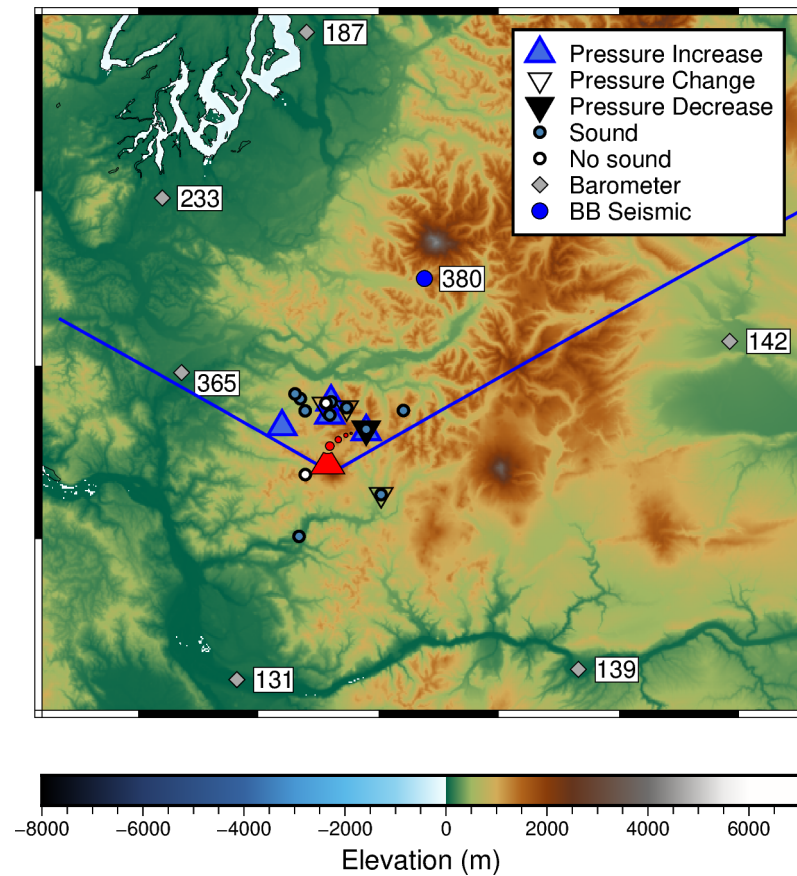


Figure 3.10: Locations of several eye and ear witnesses, along with measured overpressures relative to the volcano source from barometers (gray diamonds) and a broadband seismometer (BB seismic). Reports of audible sounds are not confined to the north of the volcano, whereas reports of perceivable pressure changes are concentrated there, consistent with the elevated observed overpressure. The maximum extent of the perceived pressure to the west and east is also plotted as a blue line.

3.6.5 Barotrauma

Current research on barotrauma (pressure induced injury to the human body) focuses on shock waves and other industrial applications like SCUBA. While the physiological impacts on the body from increased pressure are well characterized in the SCUBA diving literature, the impact of large pressure waves from volcanic eruptions remains less well understood. Given the longer rise time of the Lamb wave, eyewitnesses during the May 18, 1980 eruption may have been spared from barotrauma despite the overpressures involved. No survivors from the 1980 eruption reported eardrum rupture or related injuries, and by fitting a logarithmic scale to the peak-to-peak amplitudes the estimated source amplitude is below this threshold. However, all eyewitness accounts are from within a range where the amplitude of the signal is expected to be perceivable and potentially painful depending on the frequency content. By contrast, during the 1883 Krakatau eruption, a ship captain reported that more than 50% of his men suffered eardrum damage (Symons, 1888; Verbeek, 1885). Based on the estimated amplitude of the Krakatau Lamb wave relative to the Hunga Tonga-Hunga-Ha’apai signal in 2022, and considering the distance of the affected ship, it is plausible that some degree of eardrum damage could also have occurred in Tonga, although no reports are known. This potential hazard warrants consideration for future large-scale eruptions that release significant acoustic energy. While acoustic energy outputs often scale with other parameters (e.g., eruption size), it is not universally the case, and larger explosions and significant acoustic energy release can occur with a comparatively lower eruption mass (Connor et al., 2025).

3.7 Conclusions

This manuscript re-examines the pressure signals from the May 18, 1980 eruption of Mount St. Helens. The results suggest that the large pressure pulse observed globally was produced by the landslide, lateral blast, or a combination of both, and that this

signal propagated as an atmospheric Lamb wave. While instrumented observations exist for this eruption, comparison with eyewitness accounts demonstrates the potential for such qualitative reports to constrain pressure signals in eruptions where instrumentation is absent. Ray tracing and attenuation modeling are unable to explain the seismo-acoustic and acoustic arrivals within the expected “shadow zone”, or the smaller than expected “quiet zone”. The complex source likely generated a variety of pressure signals ranging from gravity waves through to acoustic signals, which further evolved with time. These findings illustrate the scientific value in revisiting historical eruption datasets, and the importance of preserving observational records. To support further research, we are providing a dataset of all available pressure data compiled during this project (<https://github.com/aperttu/MSHDataArchive>), enabling continued examination of this event to facilitate direct comparison with other globally significant eruptions (e.g., the 2022 Hunga-Tonga Hunga-Ha’apai and 1883 Krakatau eruptions).

Table 3.3: Eyewitness’ names, locations, distances, azimuths from the north slope source of the lateral blast, and interpretations of their report. The full table with full quotes and sources is included in the supplemental materials.

Names and Code	Approx Lat.	Approx Lon.	Distance (km)	Azimuth (deg)	Observation
L. McCully and J. Findley	46.128	-121.99	18	121	Pressure change (ears popping), sustained noise (freight train)
Continued on next page					

Table 3.3 – continued from previous page

Names and Code	Approx Lat.	Approx Lon.	Distance (km)	Azimuth (deg)	Observation
W. and L. Johnson	46.317	-122.052	16	44	Visible pressure wave (shock wave visible like a nuclear explosion), impulsive sound (thunder-clap), pressure change/increase
G. Rosenquist, J. and L. Harvey, and W. Dilly	46.317	-122.052	16	44	Visible pressure wave (like a shock wave), pressure change, sustained noise (rumble)
E. "Buzz" Smith	46.358	-122.203	16	358	Pressure change/increase (that forced people to the ground), uneasy feeling
Continued on next page					

Table 3.3 – continued from previous page

Names and Code	Approx Lat.	Approx Lon.	Distance (km)	Azimuth (deg)	Observation
B. Cole	46.379	-122.133	19	14	Pressure change (over 0.5 min, ears popped a dozen times), sustained noise (rumbling like a jet increasing in volume)
J. Scy- manky	46.324	-122.402	20	308	Potential pressure change (knocked down but not hit by anything)
D. Balch and B. Thomas	46.389	-122.227	20	353	Potential pressure change (sensed something un- usual)
M. and L. Moore	46.396	-122.198	20	359	Pressure change (ears popping), pressure increase (squeezed over body), sound (rumble)
Small Air- craft					No Sound
Continued on next page					

Table 3.3 – continued from previous page

Names and Code	Approx Lat.	Approx Lon.	Distance (km)	Azimuth (deg)	Observation
Mt. Adams climbers				81	Visible pressure wave (“shock wave”)
C. McNer- ney	46.286	-122.297	11	316	Visible pressure wave (white mist ahead of cloud)
G. and K. Palmer	46.405	-122.326	24	335	Sound (cannon and loud roaring noise), visible pressure front (wavefront across the lake surface)
A. Gould	46.420	-122.348	26	333	Sound (rumble), trees knocked down ahead of flow
B. Nelson and S. Ruff	46.392	-122.220	20	354	No sound
T, Mearney and M. Kerny	46.185	-122.350	12	255	Sound (low rum- bling)
Continued on next page					

Table 3.3 – continued from previous page

Names and Code	Approx Lat.	Approx Lon.	Distance (km)	Azimuth (deg)	Observation
D. Smith	46.186	-122.305	9	250	Visible pressure wave (ripples like shock waves), no sound
J. Wheeler	46.371	-121.897	29	52	Sound (rumbling)
S. Terril	46.007	-122.331	25	205	Sound (muffled like a distant quarry blast)

Chapter 4

Initial Acoustic Signature of Experimental Pyroclastic Density Currents: Implications for Flow Magnitude

This article has been prepared for submission to a journal and for U.S.G.S. internal review, which has been delayed due to the 2025 US government shutdown

4.1 Abstract

Infrasound has become an increasingly common component of volcano monitoring systems, offering real-time observations of the interaction between volcanic eruptions and the atmosphere. This offers a unique view of pyroclastic density currents (PDCs) in the field. PDCs are responsible for approximately one third of volcanic fatalities (Brown et al., 2017) and are destructive to both the natural and built environments. Despite this impact, their dynamics remain difficult to constrain. To further understand the interaction of PDCs with the atmosphere, a series of large-scale analog PDC experiments were instrumented with acoustic sensors. These experimental flows generated

three pressure signals prior to the arrival of the flow itself. The first signal generated by the displacement of the atmosphere by the intruding flow into the confined channel. The second signal was a series of pulses related to the formation of the PDC underflow region. It was generated when the multiphase mixture generated a pressure wave on impact with the ground when there was a separation between low and high Stokes number particles, leading to an acceleration of the interstitial air surrounding the inertial particles. Both signals were acoustic pressure waves generated by the initiation of the flow. The third signal was a dynamic pressure increase related to the acceleration of the displacement of the atmosphere away from the flow front. Scaling relationships from the experimental results show that the acoustic power and dominant frequency of the second signal, which were generated on impact, scale with the momentum of the falling pyroclastic and gas mixture feeding the experimental PDCs. Expanding this comparison to infrasound generated by natural multiphase flow events suggests that it may be possible to distinguish between pyroclastic surge and pyroclastic flow end member events based on their initial signals. This would provide a valuable tool for early warning systems.

4.2 Introduction

Pyroclastic density currents (PDC) are among the most dangerous volcanic phenomena and have resulted in more than 60,473 documented fatalities since 1500 CE (Brown et al., 2017; Auker et al., 2013; Charbonnier et al., 2025). PDCs are high temperatures (commonly more than 100°C and up to around 850°C) ground-hugging multiphase currents comprised of volcanic particles and gases; they reach velocities between 10 and 300 m/s with runout lengths from several hundreds of meters to more than 100 km (Sulpizio et al., 2014). They can cause significant mechanical damage with dynamic pressures from 10^{-1} to 10^2 kPa (Baxter et al., 2005; Jenkins et al., 2013; Valentine, 1998; Taniguchi and Suzuki-Kamata, 1993). A range of eruptive processes generate PDCs, including but not limited to gravitational collapses of lava domes, eruptive plumes and

jets, lateral blasts, and phreatic eruptions when the mixture of particles and gas fails to become positively buoyant (Dufek et al., 2015). Direct measurements of direct internal processes of PDCs during propagation are elusive.

There is general agreement that there is a continuous spectrum from dilute PDCs, also referred to as pyroclastic surges and blasts, through to concentrated PDCs, called pyroclastic flows. Dilute PDCs are volumetrically dominated by the gas phase and comprise a turbulent, density stratified ash-cloud surge region with a particle volume fraction of $<10^{-3}$ over a centimeter-to-decimeter-thick more concentrated bedload region (Brosch and Lube, 2020; Lube et al., 2020). The ash-cloud surge flow region dominates momentum transport (Breard et al., 2016; Lube et al., 2020). In contrast, concentrated flows contain a concentrated gravity driven basal flow region, the underflow, which can range from 10^0 to 10^2 meters thick and often contains a leading fully dilute turbulent ash-cloud region that overrides the underflow. The underflow region generally has a particle volume fraction greater than 3×10^{-1} . The underflow region behaves like dry granular to gas pore-pressure-modified granular flows, and particle stresses dominate flow behavior (Lube et al., 2020).

Transitions between dilute and concentrated gas-particle transport behaviors occur within a single flow (Lube et al., 2020). Strong vertical density stratification results from typically strong vertical gradients of volumetric concentration between the solid and gas phases. The volumetric solid phase concentration is represented as θ_v where the spectrum ranges from dilute ($\theta_v \gtrsim 10^{-4}$) to concentrated ($\theta_v \gtrsim 3 \times 10^1$), with an intermediate range where θ_v falls between 10^{-4} to 3×10^1 (Breard et al., 2016; Lube et al., 2020).

Owing to the complexity of flow dynamics and their destructiveness, researchers rely on a combination of field studies of deposits and damage (Breard et al., 2015; Gardner et al., 2018; Lube et al., 2007; Sulpizio et al., 2007), theoretical modeling (Burgisser and Bergantz, 2002; Bursik and Woods, 1996; Dade and Huppert, 1996), and numerical simulations to interrogate PDC flow and hazard behaviors. (Dufek and Bergantz, 2007b; Esposti Ongaro et al., 2012; Uhle et al., 2024). Researchers also

perform analog experiments (Breard and Lube, 2017; Dellino et al., 2007; Roche, 2012), which provide benchmarking for parameters that remain difficult to measure directly in the field.

Remote measurements of acoustic waves, including infrasound (below 20 Hz) and audible sound (20–20,000 Hz), offer a method of recording signals related to PDC internal dynamics from a safe distance (Allstadt et al., 2018; Jones et al., 2023; Lyons et al., 2024; Taisne et al., 2025; Watson et al., 2022b). Currently, the literature focuses on tracking flows using array processing (Delle Donne et al., 2014; Ripepe et al., 2010; Yamasato, 1997). No detailed examination has yet investigated the generation of these acoustic signals. Wohletz (1998) reports that one expected source of sound within PDC surges is particle impacts generating signals in the audible range and propagating through the surge and interacting with the ground. However, observers historically describe PDCs as “silent” in the audible range—Frank Perret at Mt. Pelee (1929–32), and Katia and Maurice Krafft at Augustine Volcano in (1986) reported that this silence is notable (Global Volcanism Program, 1986). Wohletz (1998) suggested that when the velocity relaxation wavelength is shorter than the characteristic wavelength of a topographic feature and Mach numbers are high, attenuation is largest. This theory implies that sound within the surge is dampened quickly, producing little to no audible sound.

At the same time, researchers have observed that PDCs generate measurable low-frequency pressure signals, recorded by infrasound sensors, which are a moving source that can be traced along known flow paths (Allstadt et al., 2018; Delle Donne et al., 2014; Oshima and Maekawa, 2001; Ripepe et al., 2009, 2010; Watson et al., 2022b; Yamasato, 1997; Yamasato et al., 1993). Although significant questions remain about the sources of all mass movement-generated infrasound, studies generally attribute acoustic signals to the rate of change of a mass outflow and model them as monopoles (Lighthill, 1954; Woulff and McGetchin, 1976). For PDCs specifically, researchers propose that turbulence at the flow head generates the signal, but studies have yet to test this hypothesis, representing a key gap in the research. In contrast, studies of other volcanic

mass movements such as lahars and avalanches demonstrate that infrasound research can support early warning system development (Allstadt et al., 2018; Havens et al., 2014; Johnson et al., 2023b, 2021; Johnson and Ronan, 2015; Marchetti et al., 2015, 2020, 2021; Sanderson et al., 2021; Watson et al., 2022a).

This study analyzed analog, large-scale experimental PDCs recorded using acoustic, infrasound, and dynamic pressure sensors. While most previous studies have focused on tracking PDCs with infrasound, this study examined the initial signals generated by the initial formation of PDCs. Researchers first described this type of signal for the gravitation collapse of a lava dome during the 1991 eruption at Mount Unzen, which generated several PDCs (Yamasato et al., 1993; Yamasato, 1997). This study tested the generation and occurrence of these signals in experimental PDCs ranging from dilute to concentrated. This research characterized the signals and evaluated their potential for monitoring applications by assessing their features and potential relationships with bulk flow properties.

4.2.1 Pyroclastic flow Eruption Large-scale Experiment (PELE)

We conducted this study at the Pyroclastic flow Eruption Large-scale Experiment (PELE) facility, a large-scale analog experimental facility, at Massey University in Palmerston North, New Zealand. PELE is a research facility designed for the safe study of PDCs and to provide quantitative results on their complex internal dynamics (Lube et al., 2015). The facility generates high energy gas-particle mixtures and covers a wide range of natural PDC transport and deposition regimes. PELE uses natural volcanic material and air to ensure natural stress coupling between solid and fluid phases, and allows quantitative comparisons to real-world deposits and flows. Experimental PDCs are generated by controlled gravitational collapse of variably diluted suspensions of natural pyroclasts and gas, which are discharged from an elevated hopper into an instrumented channel. This process is analogous to the collapse of an eruption column in nature. PELE generates high energy currents, and the resulting flows are fully turbulent, with typical velocities of 7–30 m/s, flow thicknesses of 2–4.5 m, and a full

runout of up to 35 m. This facility produces both experimental dilute surge PDCs with a thin basal regime, and higher concentration experimental pyroclastic flows with a dense basal underflow capped by an ash cloud.

Previous studies at PELE have examined the fundamental nature and internal flow structures of PDCs, their dynamics and mobility, hazards and destructiveness, as well as deposition and sediment transport (Breard et al., 2016, 2018; Breard and Lube, 2017; Brosch et al., 2021; Brosch and Lube, 2020; Lube et al., 2015, 2019, 2020). In this work, we expanded on prior experiments by incorporating pressure and acoustic sensors (see Appendix B for configuration and scaling details), to improve our understanding of infrasound as a potential field measurement tool and early warning system.

4.3 Methods

4.3.1 PELE Experimental Design

The design of the PELE facility allows independent adjustment of several initial conditions. The mass of the solid fraction ranges from 100 to 4150 kg, and by changing the hopper configuration, discharge rates range between 31 and 1591 kg/s. The drop height is adjustable and typically 5.5 or 7 m height. The temperature of the material varies from ambient to 500°C. While the facility has been modified over time, the configuration of PELE at the time of the study is shown in Figure 4.1. The natural material was loaded into the elevated hopper, heated, and released from a drop height of 7 m using a nested hopper system: a smaller hopper installed within a larger hopper that discharged material from 5.5 m into the instrumented channel. The confined channel extends 16.1 m indoors, with a width of 0.5 m and wall height of 1.8 m and then continues ~ 14 m outdoors on an unconfined concrete slab. The first 12.8 m of the channel has a 6° inclined slope. The final 3.6 m of the confined channel is housed within a reinforced tank. Instrumentation was placed along the channel centerline and cameras were positioned at designated observation points.

For this study, we conducted three dedicated experiments (experiments 1–3), each

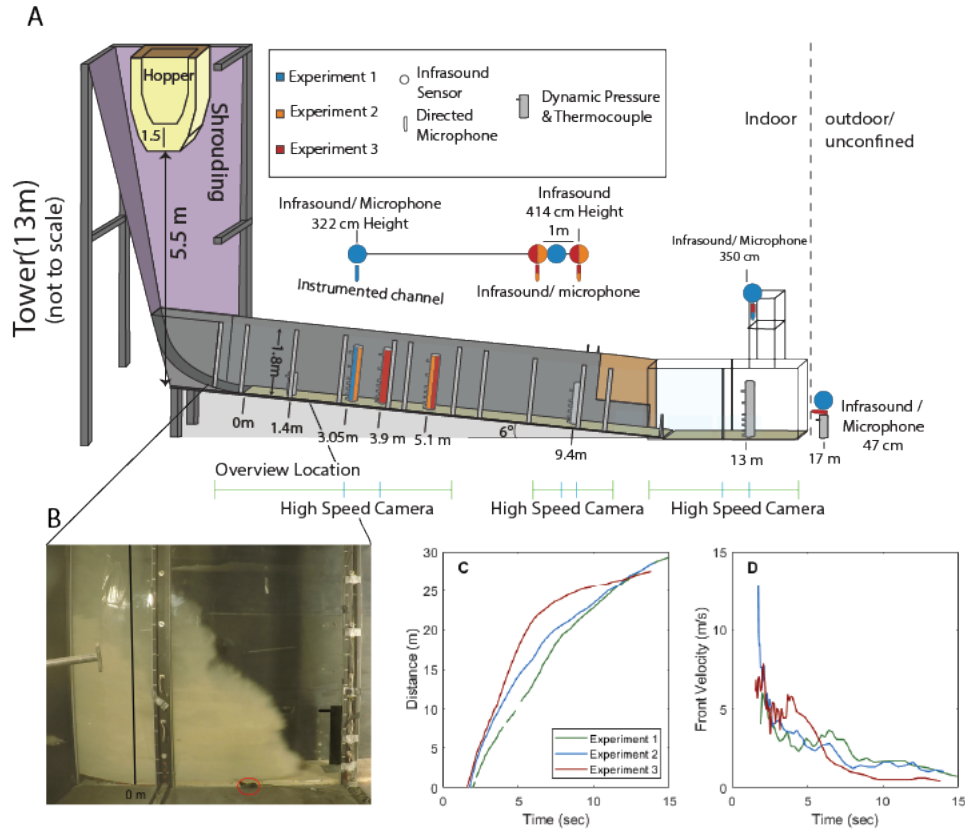


Figure 4.1: Overview of PELE experimental setup. (A) Diagram of the PELE experimental facility showing the relative locations of the drop zone, observation points, and sensors. The 0 point within the channel is also highlighted. The profiles within the channel are gray when used for all experiments, otherwise they are colored for which experiment was used. The infrasound sensors and microphones are likewise colored based on the location used for each experiment. Locations used in Experiment 1 are colored blue, those used in Experiment 2 are colored orange, and those used in Experiment 3 are colored red. Below the diagram of the channel are the locations of the overview observation points and high-speed camera locations. (B) GoPro image from the first observation point highlighting the 0 point within the channel and LED used to synchronize the visual data with the experimental data circled in red. On the far right of the photo, the dynamic pressure sensor profile is shown in black. (C) Temporal mapping of the flow through the channel from visual data for all three experiments. (D) Flow front mapping location converted into a flow front velocity through the channel.

doubling the mass of the previous run:

- **Experiment 1:** 250 kg, 100°C mixture temperature, surge
- **Experiment 2:** 500 kg, 30°C mixture temperature, small short underflow
- **Experiment 3:** 1100 kg, 100°C mixture temperature, dense pyroclastic flow (PF)- with long underflow

Additional experimental configuration information is given in Table 4.1. Previous PELE work showed that given the hopper discharge rates, and fall height, experiments ranging from 100–300 kg produce dilute surges, whereas larger masses generate dense underflows typical of experimental pyroclastic flows (Lube et al., 2015). When possible, we also analyzed relevant prior and concurrent experiments, with varying sensor coverage, channel conditions, and source materials. The most comparable are experiments 4–7, while experiments 8–9 used a different PELE configuration and different source material.

- **Experiment 4:** 250 kg, 100°C mixture temperature, surge type flow, into water
- **Experiment 5:** 500 kg, 100°C mixture temperature, small short underflow, into water
- **Experiment 6:** 1100 kg, 30°C mixture temperature, dense PF with long underflow, into water
- **Experiment 7:** 950 kg, 500°C mixture temperature, dense PF with long underflow, into water
- **Experiment 8:** 300 kg, 100°C mixture temperature, surge type flow
- **Experiment 9:** 120 kg, 100°C mixture temperature, surge type flow

Experiments 4–7 were designed for different objectives, with sensors concentrated in the distal channel and no proximal coverage. Experiments 4–7 had the same doubling of

Table 4.1: Experimental configuration for all experiments used in this manuscript

Exp. Num.	Mass (kg)	Hopper Temp. (°C)	Average Dis-charge	Duration (s)	Ambient Temp. (°C)	Air Den-sity	Speed of Sound	Fall Height (m)
1	258	100	36.2	7.94	17	1.211	341	7
2	524	30	55.79	9.1	9	1.230	336	7
3	1118	100	383.9	2.85	10	1.227	337.1	5.5
4	249	120	25.29	9.7	6.2	1.274	335	7
5	569	100	50.27	10.7	4.4	1.272	334	7
6	1089	30	238.8	4.4	12.7	1.236	339	5.5
7	963	500	81.7	10.7	17	1.210	341	5.5
8	300	120	17.1	15.7	16	1.223	341	7
9	120	120	13.6	7.7	19	1.200	343	7

mass (250, 500, 1100) and Experiment 7 represented a hot (500 °C) dense experimental pyroclastic flow. Experiments 8 and 9 were surge experiments conducted as initial tests of acoustic and infrasound recording at PELE. Additional experimental configuration information and details are presented in Appendix B.

4.3.2 Instrumentation

Each experiment employed pressure sensors, temperature sensors, and a visual recording system. The experimental setup included dynamic pressure sensors, microphones, infrasound microphones, thermocouples, four high-speed cameras (1000 fps), a dozen GoPro cameras (30–60 fps), and for Experiment 1, two accelerometers.

- **Dynamic pressure sensors:** The experiments employ Piezoelectric dynamic pressure sensors (PCB 106B51) with a flat response from 0.5 Hz to Nyquist (500 Hz), and a quartz crystal within a metal housing. The experimental installation was along the centerline at various heights for six to seven profile locations (see Appendix B). The sensors are designed for isotropic conditions and therefore exhibit a significant temperature response. The amplitude calibration validity was uncertain, since the manufacturer recommends that the sensors are re-calibrated annually and after exposure to high temperatures (maximum rated 121°C). The sensors were calibrated in 2021 and the experiments were completed 2023–2024,

with sensor exposure reaching temperatures up to 460°C. Additionally, the sensors may respond unpredictably to signals outside their expected application of high amplitude acoustic pressures and have a high noise floor. As a result, this study treated amplitude measurements as relative values only comparable within sensor type, and not indicative of absolute pressure. These sensors were sampled at 1000 Hz using a National Instruments system and Flexlogger program.

- **Infrasound sensors:** The experiments used two types of infrasound sensors, both sampled at 1000 Hz using a National Instruments system and Flexlogger program.

PCB 378A07: Two Piezotronics ICP infrasound microphones (PCB 378A07), sampled at 1000 Hz, with a flat response between 20 Hz to Nyquist frequency (500 Hz), ± 1 dB 0.25 Hz to Nyquist, and ± 2 dB 0.13 Hz to Nyquist, with a limiting lower frequency of >0.1 Hz and a sensitivity of 5.2 mV/Pa.

ACO 7744N: Two ACO (7744N) infrasound sensors, sampled at 1000 Hz with a flat response from 0.5 Hz to Nyquist, ± 3 dB from 0.1 Hz to 0.5 Hz, and a sensitivity of 8.9 and 6.8 mV/Pa.

- **Directed microphones:** The experiments used SONY (ECM-674), directed microphone, collocated with select infrasound sensors. These microphones have a flat response from 50 to 2 kHz, +5 dB from 2 to 10 kHz, and +10 dB from 10 to 20 kHz. The experiments used two digitizers: Experiment 1 recorded data on a DEWEsoft SIRIUS 8 channel digitizer sampled at 50 kHz, while experiments 2, 3, 6, and 7, recorded on a Zoom Podtrak P4 portable recorder sampled at 44.1 kHz. The Nyquist for Experiment 1 was 25 kHz, and 22 kHz for the others. The sensitivity of 15.8 mV/Pa was applied to Experiment 1, but for the other experiments, owing to the digitization method, the data were normalized.
- **Accelerometers** (Experiment 1 only): The experiments used TE Connectivity sensor model 4030 triaxial accelerometers, recording the data on a DEWEsoft

SIRIUS digitizer at a sample rate of 50 kHz. The Nyquist was 25 kHz, and the sensitivity was ~ 1 V/g.

- **Temperature sensors:** The experiments used TC Direct model number 410-345 Type K thermocouples, sampling data with a National Instruments system and FlexLogger program with a sample rate of 72 Hz.
- **Visual data:** The experiments used four high speed Basler cameras sampled at 1000 fps, along with various GoPro models sampled at 30–120 fps.

The experiments synchronized all systems using a voltage pulse that simultaneously illuminated an LED for camera timing. Herein, all times are in seconds relative to the trigger signal that released the material.

4.3.3 Flow Characterization

We characterized the experimental flows using visual datasets. Overview cameras (GoPro) were positioned along the channel and within the facility to capture both side views through the windows and overhead views of the confined channel. All cameras were synchronized with a triggered LED assigning time to each frame for each camera. The temporal location of the flow was tracked through the channel using the various cameras (Figure 4.1C). This was then used to calculate the bulk flow front velocity (Figure 4.1D).

The material drop and entrance into the channel were covered from two camera angles; however, these were not available for all experiments. For experiments with camera coverage of the drop zone and impact location, the location of the flow material was mapped by location and frame rate and converted to time, and this was used to calculate the fall velocity of the material (Figure 4.2).

Material release was characterized using both visual data and hopper load-cell measurements, which recorded hopper mass through time (Figure 4.2). Load-cell data were sampled using the National Instruments system, at 72 Hz (equipment limit). These

data were used to calculate discharge rates, both as an average and a function of time, and to determine cumulative mass release at specific time steps.

Fall velocity data from visual datasets and the load-cell data were combined to calculate the momentum of the material entering the confined channel for each experiment where:

$$P = mu \quad (4.1)$$

where momentum P (kg m/s) is the product of mass (m) and the velocity of the mixture at impact (u). When calculations for the specific experiment were not available, the closest experiment in conditions where the measurements of velocity was available was used as an analog.

4.3.4 Waveform Data Quality Control and Pre-processing

Upon completion of the experiments, quality-control analysis was conducted and the resulting waveform data were archived. Variable amplitude mains power noise represented the significant source of noise, reducing data quality and producing a low signal-to-noise in Experiment 1. Variable temperatures induced a thermal response in the piezoelectric sensors, which was due to expansion of the sensor housing.

In this study, whole waveform spectral analysis used the Fast Fourier Transform (FFT) to identify both the electronic noise and its spectral bandwidth. FFT analysis showed that the electrical grid noise had spectral peaks at 50 and 100 Hz, with overtones at 150 Hz. These peaks match the New Zealand national electrical grid frequency specification of 50 Hz $\pm$ 1.5 %, confirming that the signal originated from the system power source (Executive Council NZ, 2010). We applied a notch filter with a $\pm$ 1 Hz width around the spectral peaks at 50, 100, and 150 Hz to remove grid noise. Minor harmonic and semi-harmonic overtones also appeared on some sensors but did not significantly impact the data and were not filtered out.

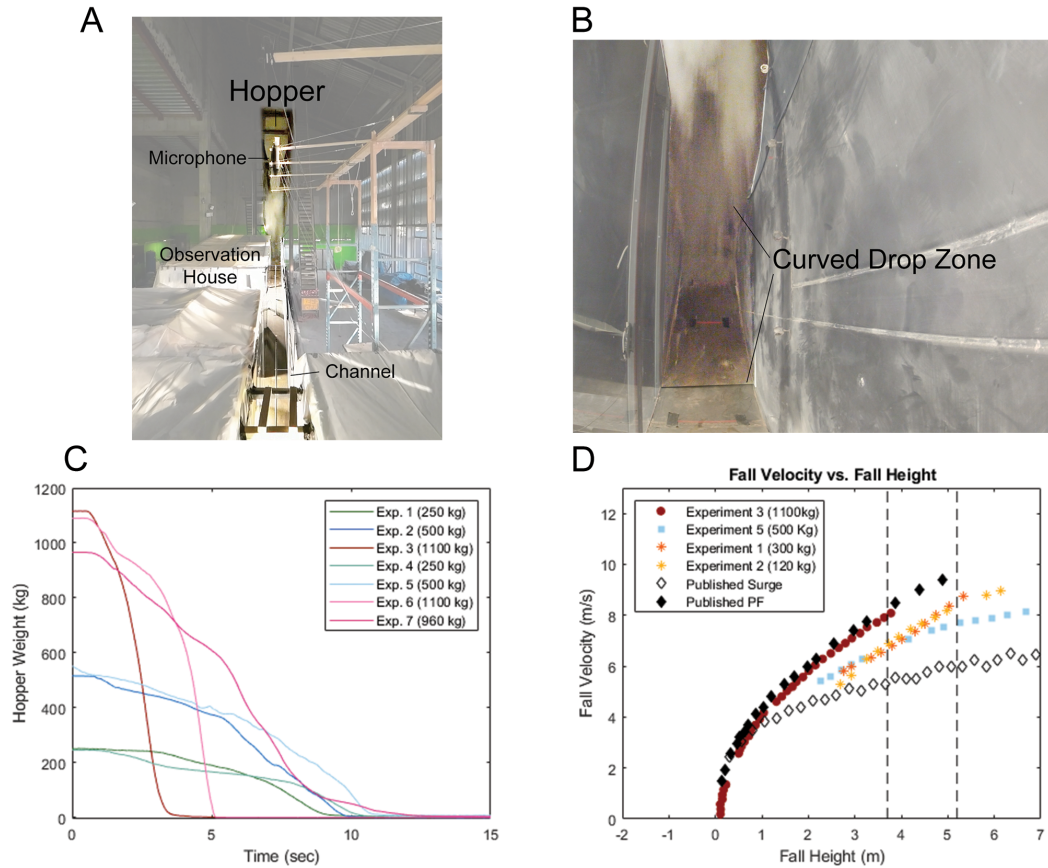


Figure 4.2: Material discharge and fall velocities. (A) Example of the GoPro overview camera view showing the channel, location of observation houses and hopper. The location of the microphones above the channel is also shown. (B) View from inside the channel of the drop zone focused on the curved drop zone part of the channel. (C) Data extracted from the load cell were used to track the weight of the hopper through time as the material was released. (D) The tracked fall velocity of the different experiments where camera views were available, alongside the results published in Lube et al., (2015) in black diamonds for surge and PF-type experiments.

For experiments 1 and 3, the hopper material temperature was set to approximately 100°C before the experiment, producing a temperature differential between material and atmosphere of 80°C – 90°C (ambient temperatures are shown in Table 4.1). In Experiment 2, the material cooled to around 30°C , resulting in a temperature differential of approximately 20°C . According to the manufacturer of the dynamic pressure sensors, exposure to a temperature increase does not impact the quartz crystal, but expansion of the sensor case produces a negative signal output. The infrasound sensors are also not temperature-independent. High-speed camera imagery and thermocouple data were used to determine when each sensor first experienced the flow temperature increase. The visual arrival of the flow and temperature increase corresponded to a large-amplitude negative output on both sensor types (dynamic pressure and infrasound). This characteristic sensor output drop defined the beginning of the window requiring a temperature correction to the data.

To remove the temperature response from the time-series data, single sample spikes of more than 150 Pa were removed, and a moving average filter was used to calculate the long-period sensor response to the temperature change. This response was subtracted from the time series starting at the time of flow arrival. For the dynamic pressure sensors, the subsequent data were windowed over 5 ms, and peak-to-peak amplitude was calculated following the manufacturer guidance, which states that absolute pressure is not always preserved but peak-to-peak amplitudes are, as the sensors re-center on zero. Importantly, this study focused on signals recorded before the flow reached the sensor profiles, ensuring that there was no anticipated temperature correction required. The dynamic pressure sensors are not designed to detect the acoustic arrivals of interest, and so their amplitude response to this type of wave remains unknown.

4.3.5 Pressure Data (Infrasound, Microphone, Dynamic Pressure Sensors)

The experiments compared PDC dynamics across a spectrum of flows, from dilute surge flows (Figure 4.3) to dense PF flows with a dense underflow (Figure 4.4). After

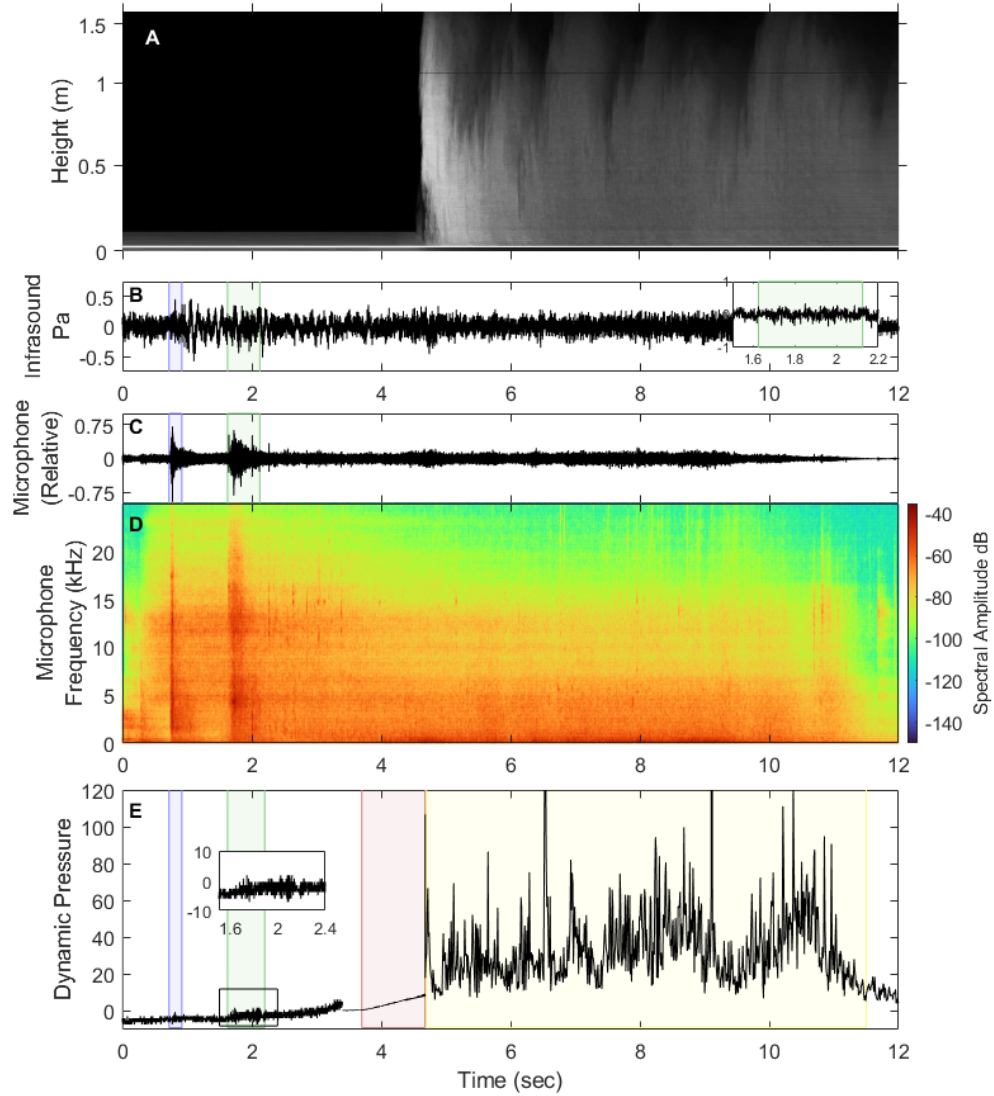


Figure 4.3: Overview of lower mass “surge” experiments where Experiment 1 is the type example for this manuscript. All data are plotted from data sources at around 8–9 m along the channel with the same time axis. (A) Vertical line of pixels extracted from a camera view plotted through time to illustrate the arrival and character of the flow. (B) Infrasound data for Experiment 1 with electronic noise removed; the green window is further filtered over 15 Hz in the inset. (C) Waveform data for a microphone; (D) the linear spectrogram for that waveform. (E) Dynamic pressure with the sequence of signals highlighted. Blue is the timing of the “click” seen in the microphone above, green is the first acoustic arrival seen in all three sensors, red is the increase of pressure only in the dynamic pressure sensor, and yellow is the temperature-corrected peak-to-peak dynamic pressure of the flow.

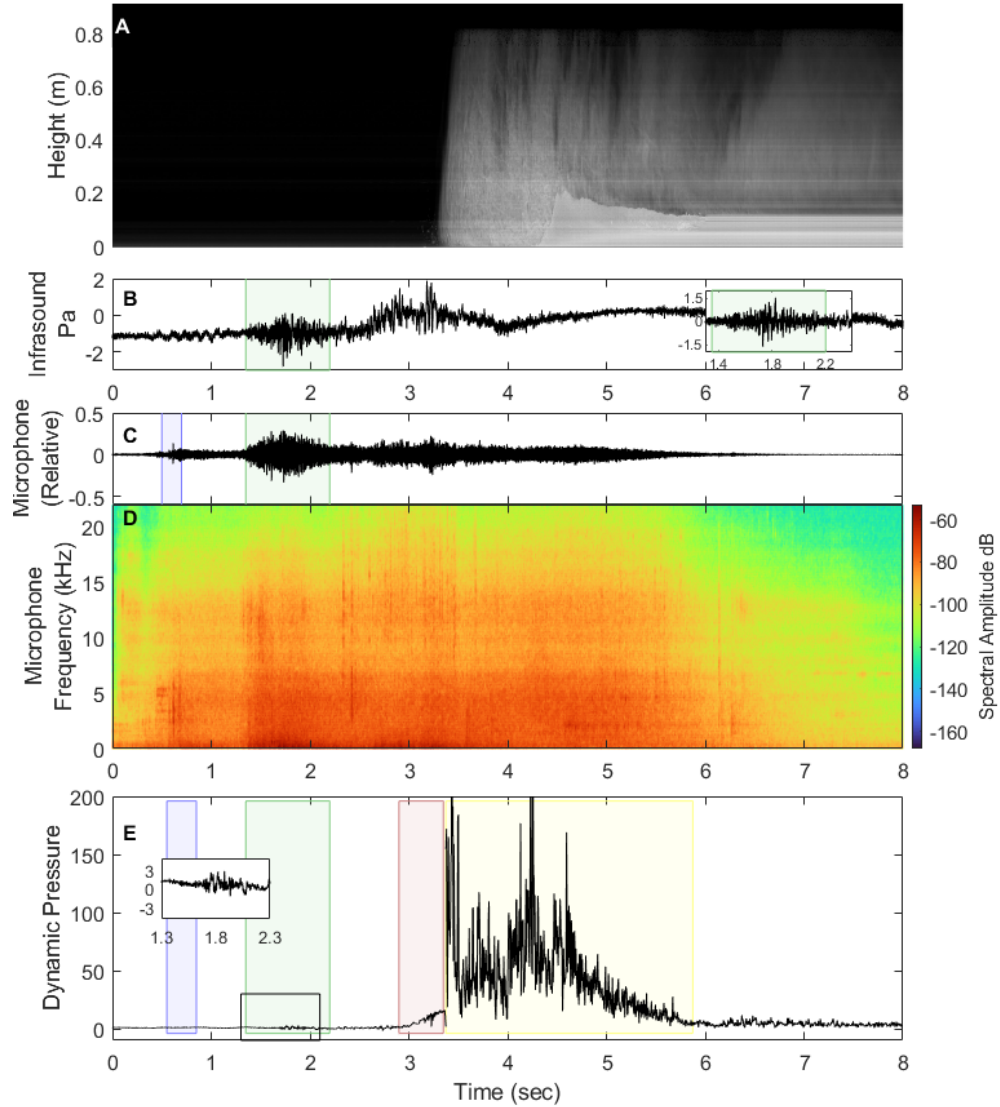


Figure 4.4: Overview of larger mass "PF" experiments where Experiment 3 is the type example for this manuscript. All data are plotted from data sources at around 8–9 m along the channel with the same time axis. (A) Vertical line of pixels extracted from a camera view plotted through time to illustrate the arrival and character of the flow. (B) Infrasound data for Experiment 3 with the electronic noise removed and in the inset further filtered over 15 Hz. (C) Waveform data for a microphone; (D) Linear spectrogram for that waveform. (E) Dynamic pressure with the sequence of signals highlighted. Blue is the timing of the "click" seen in the microphone above; green is the first acoustic arrival seen in all three sensors, which is much longer in the PF than it is in the surge; red is the increase of pressure only in the dynamic pressure sensor; and yellow is the temperature corrected peak-to-peak dynamic pressure of the flow.

pre-processing (temperature correction and electronic noise removal), the data were visually inspected to identify signals across all sensors and experiments. Figure 4.3 and Figure 4.5 show that lower mass experiments produced low signal-to-noise in the infrasound sensors. In Experiment 1, several signals appeared before the arrival of the flow. Figure 4.4 and Figure 4.5 demonstrate that higher mass experiments had higher amplitude signals and exhibited improved signal-to-noise, and similar signals appeared before the arrival of the flow, with some differences. In experiments 1–3, noise sources within the facility were minimized. Auditory processing indicates that several signals observed in the first 2 s originated from the triggering system rather than from the experiments themselves.

For all identified signals, the onset was manually picked for each sensor and all experiments, and arrival times were compared with distance using the expected speed of sound for each experiment, which was calculated for each experiment using the ambient temperature (Figure 4.5 and Figure 4.6).

4.3.6 Acoustic Signal Analysis

Spectral Analysis

After removing electronic noise, FFT analysis was performed on all available sensors, keeping window lengths constant between sensors. The FFT was calculated over two 0.6 s windows for each signal of interest with the first ending at the manually picked signal end, and the second 0.6 s window starting at the signal onset (Figure 4.7C). This was calculated for both the infrasound sensors as well as the microphones. Dominant frequencies were extracted from the resulting FFT (Figure 4.7A and B). For sensors of different sample rates, the window length was maintained.

Localization

To further characterize the signals of interest, a localization was determined using a grid search minimization. For each of the signals of interest, the initial step was to manually pick arrival times and durations of the signal. The average duration was

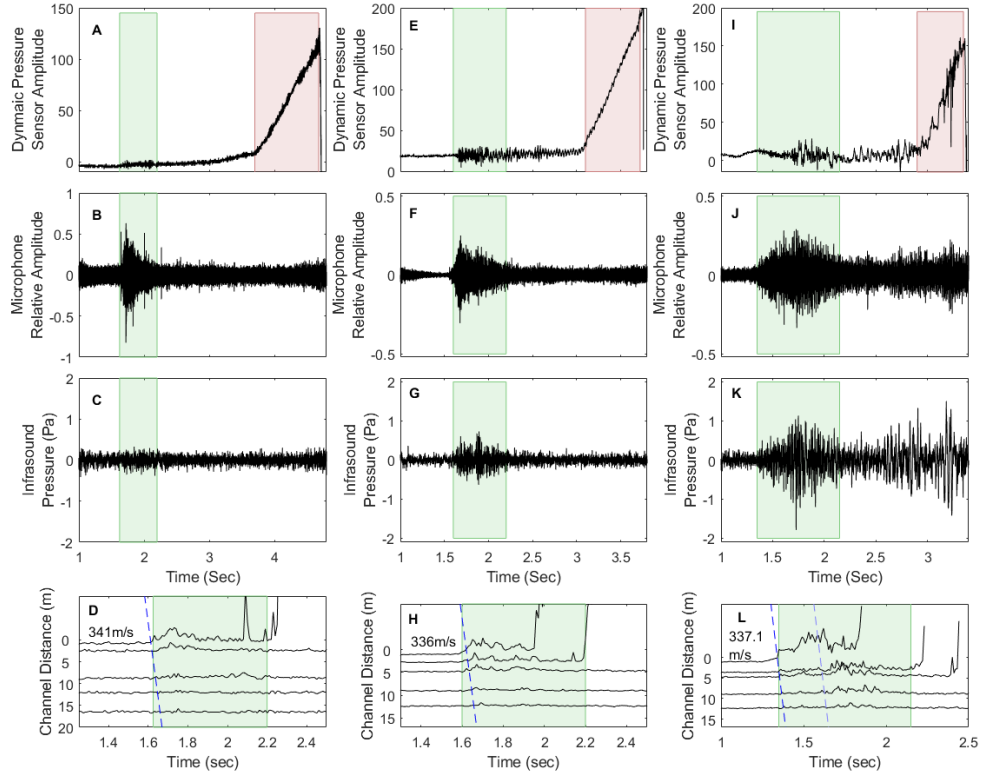


Figure 4.5: Overview of pressure signals from the three sensor types: dynamic pressure (top A, E, and I), microphone (B, F, and J), infrasound (C, G, and K), and finally the arrival of the first signal through the channel from peak-to-peak dynamic pressure (D, H, and L) for experiments 1 (left A–D), 2 (center E–H), and 3 (right I–L). The air wave (first signal of interest) is in the green box, and the pressure increase (second signal of interest) is only seen in the confined channel in red. The arrival of the air wave (in green) is plotted through the channel with the peak-to-peak amplitude of the dynamic pressure sensors at 45 cm; for comparison the calculated speed of sound through the channel calculated for each experiment is plotted in blue.

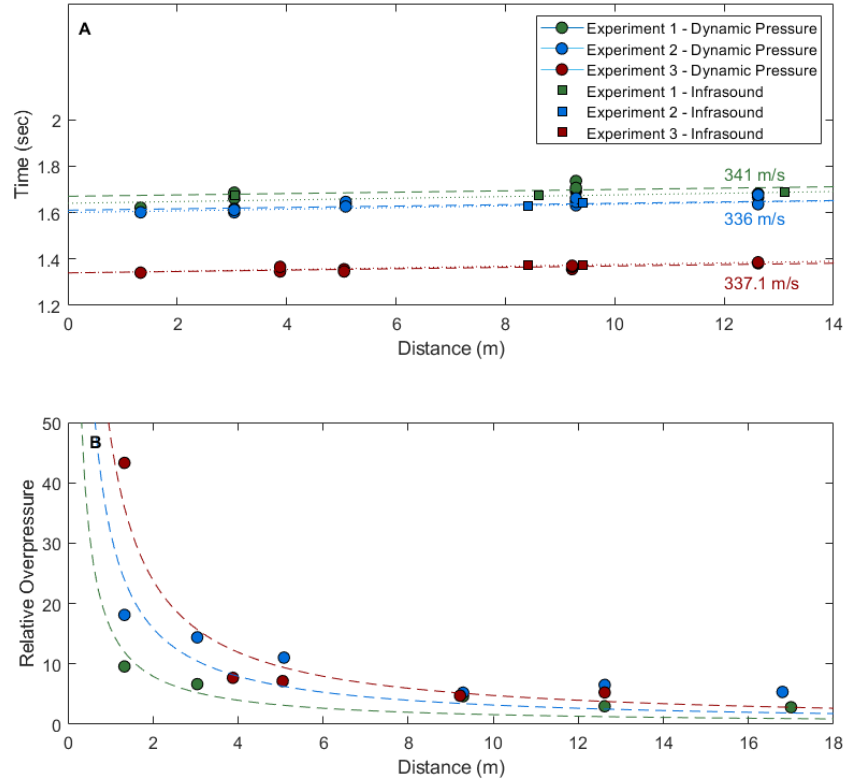


Figure 4.6: Signal arrival time vs. expected arrival of an acoustic signal. (A) Manually picked arrival times for the first acoustic arrival plotted vs. distance along the channel. The expected arrival time with the calculated acoustic speed for each experiment conditions is plotted as a dashed line. Experiments are color coded with Experiment 1 green, 2 blue, and 3 red. The different sensor types are also noted with the circles representing the dynamic pressure sensors and the squares the infrasound sensors. (B) Peak-to-peak amplitudes of the first arrival, with the mean taken for each profile location. The range of sensor results are plotted as a linear error bar. An inverse distance line is added for reference for each experiment. The amplitude in the channel was expected to be elevated owing to the confined channel, with normal attenuation (geometric spreading) hampered by the walls.

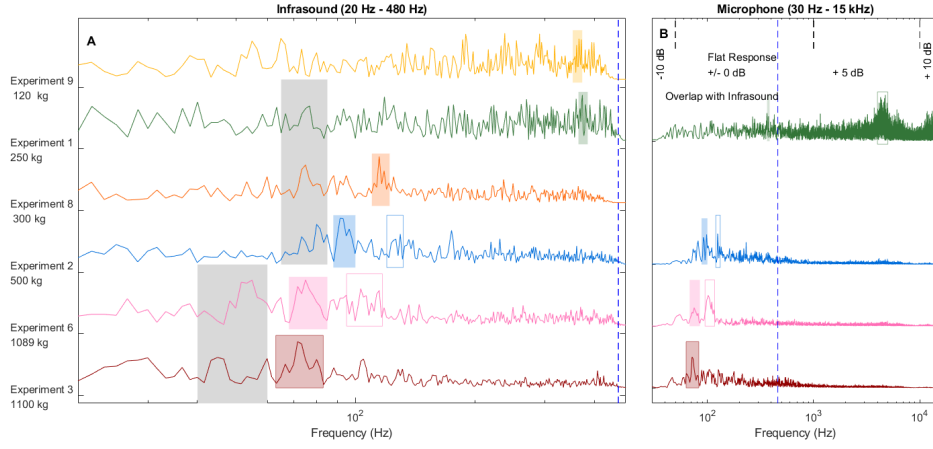


Figure 4.7: FFT analysis of all the experiments. FFT of the (A) infrasound sensors and (B) microphones; their overlap is plotted as the Nyquist (blue dashed line). Noise surveys and calculations identified that the channel and tower had a strong resonance between 5 and 10 Hz. The frequency content can be seen shifting lower with larger mass. The window length is consistent for comparison between sensors and is a 0.6 s window starting at the arrival of the first signal at each sensor. The gray band is the frequency consistent with the characteristic fluid time scale discussed in conceptual model section 4.5.5.

used as a window length and the start time of the window was adjusted for the arrival at each sensor. Then, to increase the temporal resolution of the intra-sensor arrival times, the signals were cross correlated with each other to determine the optimum offset between the signals at each sensor. The signal at each sensor was filtered with a bandpass based on the FFT results, and the upper envelope was used for the cross correlation (Figure 4.8 and Appendix B). These inter-sensor offsets were calculated in samples. The manual start time of the first arrival was taken as the 0 time, and the sample offsets were corrected based on this time; these arrival times were used with the sensor locations for the grid search minimization (Figure 4.9D,E, and F).

The grid search minimization used the mean absolute error (MAE) to estimate the source location and initiation time. MAE is a statistical measure of the errors of observations of the same phenomenon, and minimizing these errors finds a solution for the dataset. The mean of the absolute error between all sensor arrival times and the predicted arrival time for each grid point within the grid search error was calculated. The grid was set within the channel and drop zone ahead of the first sensor. This

assumed that the signal was generated ahead of the first sensor. The grid was 20 by 20 cm, and arrival times were calculated with the speed of sound based on the conditions of the day for each experiment. The solution was the grid point with the smallest MAE calculation for the given dataset (Figure 4.9A, B, and C).

Once a solution was calculated, the grid search results were tested using a jackknife approach, removing one sensor from analysis at a time to confirm solution consistency (Appendix B). In Experiment 3, a camera was placed inside the channel to capture the drop zone and compare material location with the grid search results. For each additional identifiable arrival, the identical process was repeated, giving a series of location solutions through time that where possible could be compared with the material location within the channel.

Acoustic Power

Acoustic power was computed following the method described by Perttu et al. (2020b), for both the source-sensor distance and reduced distance of 1 cm from the sensor. A reduced sensor distance refers to a specified distance from the sensor, analogous to reduced source distance, which is a specified distance from the source. Acoustic power is expressed as:

$$\Pi_a = \Omega \frac{1}{\rho_0 c} \Delta P^2 \quad (4.2)$$

where Π_a is acoustic power; Ω is the attenuation term, dominated at this scale by geometric spreading ($\Omega = \gamma \pi r^2$, with $\gamma = 2$); r is the distance to the specified source (see Perttu et al. (2020b)); ρ_0 is the air density in the channel; c is the local speed of sound; and ΔP^2 is the overpressure term. Air density and local speed of sound were calculated from reported weather conditions at the time of the experiment (Table 4.1). Acoustic power was calculated for infrasound sensors positioned above the channel between 3.10 and 4.15 m, and located at similar distances of 8.4–8.6 m along the channel to minimize effects from potential radiation patterns, allowing for comparison between experiments. Owing to the channel design, positions horizontal from the channel (like in the field)

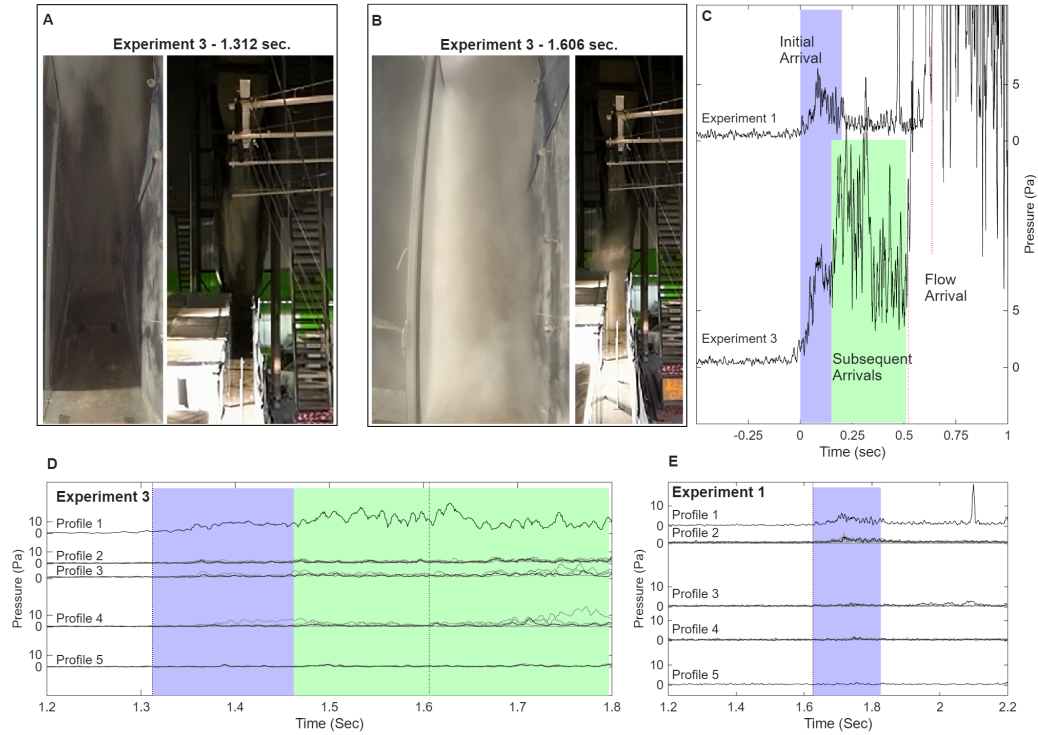


Figure 4.8: Comparison of waveform and visual data of initial signals. (A) Extracted frames from both the GoPro within the channel and the overview of the whole channel with the hopper in view at the signal generation time of 1.312 s in Experiment 3. (B) Same set of cameras at the time of one of the subsequent signals generated at 1.606 s in Experiment 3. (C) First dynamic pressure sensor station for experiments 1 and 3 aligned by the initiation time of the first signal (blue); signals generated after the initial signal (green) are only present in Experiment 3. (D) Data from throughout the channel for Experiment 3 colored by the initial signal (generated at the time of the frames in A) and the subsequent signals (generated at the time in frames B). The same view is plotted in (E) for Experiment 1.

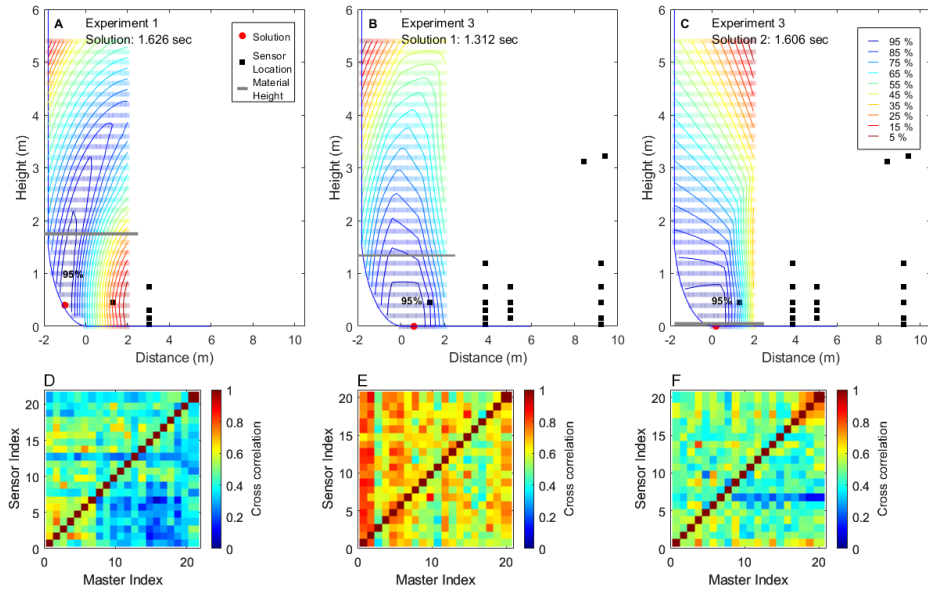


Figure 4.9: Localization results for experiments 1 and 3. (A) Localization grid search results for Experiment 1. The grid and contours of the solution are plotted in 5% confidence intervals; sensors are shown in black and the solution in red. The calculated origin time for Experiment 1 was 1.626 s after the trigger signal. (B) Localization of Experiment 3 and the first arrival. (C) Localization of one of the subsequent arrivals that was tracked through the channel. (D, E, and F) Cross-correlation results. On the x axis is the index of the sensor used as the template waveform, and on the y axis is the index of the sensor compared with the master template. The maximum cross correlation is plotted for the localization results above each panel.

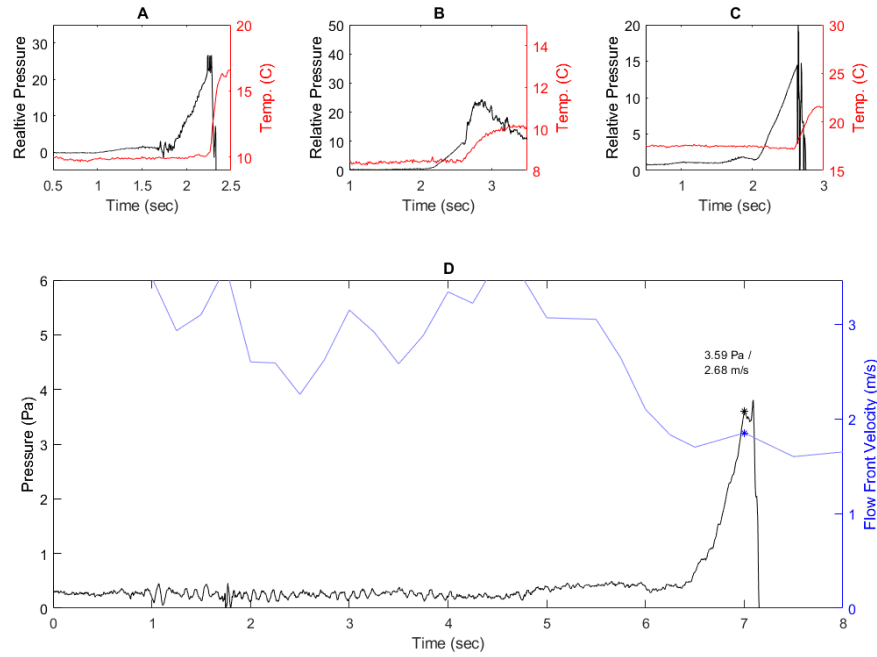


Figure 4.10: Pressure increase examples for experiments 1 (A), 2 (B), and 3 (C). In A, B, and C, black denotes the dynamic pressure sensor data and red the associated temperature data, illustrating that the temperature increase was not related to temperature. (D) Calculated flow front velocity (in blue) for the whole flow, and the infrasound data in the channel in black showing the relative agreement between the calculated velocity based on dynamic pressure and the estimated velocity from visual methods.

were not possible.

4.3.7 Pressure Increase

Channel sensors, predominantly dynamic pressure sensors and an infrasound sensor, recorded a distinct signal that precedes the arrival of the flow. This signal, observed in all channel pressure sensors across all experiments (Figure 4.5), manifested as a gradual increase in pressure beginning at least 0.5 s before the flow arrival. The timing of signal initiation was carefully compared with the location of the flow in the channel (see flow arrival above) and timing of measured temperature changes (Figure 4.10). The example shown in Figure 4.10 derives from the infrasound sensor located in the unconfined area. The pressure recorded was converted to a velocity through the equation for dynamic

pressure:

$$P_{dyn} = \frac{1}{2} \rho_{air} u^2 \quad (4.3)$$

where the dynamic pressure P_{dyn} is related to the fluid velocity u and density of the fluid, in this case the air in the channel ρ_{air} .

4.4 Results

4.4.1 Signals of Interest Identification

Auditory analysis linked several minor signals to the sequence of mechanical components in the triggering system, appearing in both microphone and infrasound datasets. The triggering mechanism was a pressure-operated solenoid that opens the hopper doors, which then swing open and lock into place with an audible click. Dry runs of the triggering mechanism confirmed this interpretation. Signals related to the discharge of material and flow occurred only after the triggering system signals, typically between 0.5 to 1 s. The sequence between the triggering system and flow arrival at the sensors consisted of a series of acoustic arrivals and a pressure increase signal.

Several signals exhibited an emergent character, producing a potential error in manual picking calculations, which can be significant given the distances and sample rates involved. Despite this, signals displayed arrival timing consistent with an acoustic arrival (Figure 4.6). With the difference in velocity of sound and flow front, the time lag between the first signal and arrival of the flow at the sensors increased with distance along the channel. In surge experiments, exemplified by Experiment 1, only a single arrival was recorded at the sensors (Figure 4.3 C, E, and Figure 4.5 A–C), whereas larger experiments produced multiple arrivals with similar properties (Figure 4.4 B, C, E and Figure 4.5 E–H, I–L). All of these signals arrived with an apparent velocity consistent with the speed of sound on the day of the experiment. This is in stark contrast to the flow front velocity, for which the mean velocity ranged from 2 to 4 m/s with a maximum of 12 m/s across experiments 1–3. Analysis of amplitude decay indicates a

general inverse relationship with distance down the channel, although greater variation was observed between sensors, potentially due to issues with the dynamic pressure sensor amplitudes (discussed above), complex wavefield within a confined channel, and restricted geometric spreading.

Across all experiments, sensors inside the channel (dynamic pressure and infrasound sensors) captured a pre-arrival signal distinct from the thermal response of the instruments. This signal began roughly 0.5 s before the flow reached the sensors, and its amplitude varied between instruments. At the distal end of the channel, within the unconfined section, the infrasound sensor installed for Experiment 1 recorded the same pressure rise (Figure 4.10). The amplitude of this rise was consistent with dynamic pressure expected for the flow front velocity at that location. Despite this agreement, co-located infrasound and dynamic pressure sensors registered markedly different amplitudes for the same signal, which we attribute to different sensor types and responses. The temporal scale of this signal closely matched the temporal scale of the flow front head within the channel.

4.4.2 Spectral Analysis

Spectral analysis of a background noise window, containing the first “click” (identified as the opening of the hopper doors) was compared to an additional window before the “click”. These windows contain both the ambient noise of the facility and initial falling of the material. The dominant frequency of the PELE structure was identified as sitting between 5 and 15 Hz, starting as soon as the hopper opened, and was consistent with theoretical calculations based on the structure dimensions. Accelerometer data during Experiment 1 confirmed that this resonance resulted from channel vibrations. This was used to identify several peaks within the two processing windows around the acoustic arrival.

The infrasound and microphone spectra overlapped between 50 and 500 Hz, and microphone amplitudes were scaled to match the infrasound spectral levels, allowing relative amplitude comparison across the acoustic frequency range (Figure 4.7). There

was a generalized trend of decreasing dominant frequencies with increases in experimental mass. Two processing windows were defined for spectral and acoustic power calculations. The first was defined to separate the initial arrival from subsequent arrivals, and the second started at the time of the first arrival and included the subsequent signals. This second window was the window of interest for the spectral analysis.

The surge experiments did not exhibit a clearly defined dominant frequency within the infrasound sensor range (15–500 Hz). The addition of the microphone data revealed a distinct energy peak near 4 kHz, although microphone data were not available for the other surge experiments. Experiments with a mass of more than 300 kg exhibited a clearly distinguishable dominant frequency within the infrasound range (Figure 4.6). For the 300 kg experiment, the dominant frequency measured around 375 Hz, with the dominant frequency of the increasing mass experiments decreasing as mass increased. In several cases (experiments 2 and 6) overlapping microphone data clearly displayed the dominant frequency in the infrasound sensor data and revealed an additional, larger peak. These additional peaks also shifted towards lower frequency with increasing mass. In addition to the dominant frequencies, several peaks were consistent throughout the experiments. In the largest PF experiments, this peak occurred between 40 and 60 Hz, whereas in the 250–500 kg experiments, it occurred between 70 and 80 Hz. These experiments also differed in drop distance, as the PF experiments released material from the large hopper with a shorter drop distance, while the smaller mass experiments use the smaller hopper with a longer drop distance. In both cases, the microphone spectra also displayed this peak.

4.4.3 Localization

The first signal related to the flow was identified as an acoustic pressure wave. Initial analysis focused on the dynamic pressure sensors within the channel. With a sample rate of 1,000 Hz and an approximate sound speed of 340 m/s, each sample represented ~ 30 cm spatial resolution. Manual picking introduced a timing uncertainty that corresponded to a spatial error of around 30 cm per sample. The first arrival was localized to

a source near the head of the channel. Vertical localization carried a larger uncertainty owing to the sensor spacing and sample resolution. Despite this, grid search solutions consistently placed the source along the slope at the head of the channel and not at the hopper opening or within the falling material.

4.4.4 Acoustic Power

The acoustic power equation assumes idealized conditions that may not hold in all applications. In this study, the complex geometry of the confined channel and drop tower modified attenuation, preventing a simple geometric radiation pattern. Given ideal isotropic radiation and geometric spreading, acoustic power measured across sensors should converge to a single source value. However, the source acoustic power calculations did not converge in this case. To enable comparison between experiments, our analysis applied a reduced distance of 1 cm from each sensor for acoustic power estimation at the sensor. As the sensors remained at similar distances and heights relative to the source, inter-experimental differences primarily reflect source variations. Acoustic power analysis of the second processing window, including the initial arrival and subsequent arrivals, indicated that acoustic power increased with experimental mass (Figure 4.7).

4.4.5 Flow and Fall Characterization

The flow front velocities for experiments 1–3 ranged from 1 to 13 m/s with a mean front velocity of 2.8 m/s for Experiment 1, 4 m/s for Experiment 2, and 4.2 m/s for Experiment 3. All experiments started with an elevated velocity at the beginning of the flow and falling throughout the channel (Figure 4.1). Fall-velocity data were obtained for only a subset of experiments. When direct measurements were unavailable, experiments were matched either to the theoretical fall-velocity curve of Lube et al. (2015) or to the closest comparable experiment. Cameras positioned at the end of the confined channel facing the drop zone were used to calculate fall velocities. Fall-velocity data were available for experiments 3, 5, 8, and 9, while the drop-zone camera

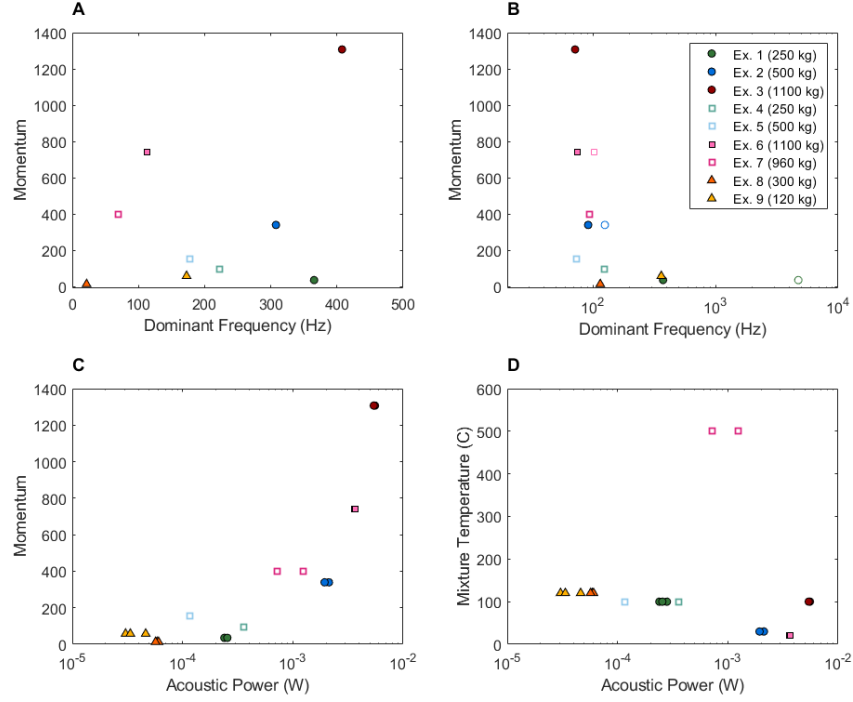


Figure 4.11: Relationships between physical parameters and signal properties. (A) Initial window (ending at the end of the first arrival) calculated dominant frequency vs. momentum showing no clear relationship. (B) Calculated dominant frequency with the window starting with the first arrival vs. momentum showing a clear relationship. (C) Calculated acoustic power from the window starting at the first arrival vs. the momentum, also showing a relationship. (D) Acoustic power vs. the mixture temperature showing no clear relationship.

was available for experiments 3 and 4. These views confirmed the position of the material relative to the confined channel and timing of impact. For Experiment 3, where the camera inside the channel was available, it confirmed that the initial signal was produced as the flow entered the confined channel (Figure 4.8).

4.5 Discussion

4.5.1 Signals of Interest

Combining the auditory and signal identification results, the timeline of signals produced before the arrival of the flow at a given location was as follows:

- Mechanical triggering mechanism ending with an audible "click"
- Initial displacement signal as the flow entered the confined channel
- In experiments with a mass over 250 kg, a series of signals generated as the material collapsed onto the channel slope
- Increasing pressure as the flow approached the sensor

4.5.2 Acoustic Arrivals

The localization methodology consistently identified the source of the first acoustic wave within the confined channel, coinciding with the material drop zone. Although the spatial resolution was limited by the PELE experimental setup geometry, signal-to-noise ratio, and sampling rate, this result remains robust. Comparison of timing results with available visual data of the drop zone showed that wave arrival coincided with the initial material entry into the confined channel. This signal is therefore interpreted as likely representing air displacement caused by material entering the confined channel. Subsequent signals corresponded to material impacts on the curved floor of the drop zone and transition into a flow.

The proposed mechanism resembles a monopole, a volumetric change source commonly invoked for explosive eruptions (Woulff and McGetchin, 1976; Perttu et al., 2020b). A monopole provides highly efficient energy transfer into acoustic power as a point source (Woulff and McGetchin, 1976). However, in the PELE setup, the gravitationally driven material fall geometry, including the confined channel with two solid walls, a solid floor, and an open top, complicated the resulting signal. A monopole also requires that the source be compact relative to the distance to the sensor. Given the directed nature of the falling material, the source may be better approximated as a dipole. Nevertheless, potential reflections and the complex shape of the material as it enters the channel likely produced a more complex wavefield than can be captured by these simplified models. Despite these complexities, the signal characteristics of the first signal generated by the materials on entry into the channel (velocity, attenuation,

and acoustic power) are clearly acoustic in nature and controlled by both the source dynamics and channel geometry. Within this first window, there was no relationship between experiment parameters and frequency or acoustic power.

Signals encompassing the transition from falling material to flow (second processing window) were compared to several calculated physical parameters of the experiments to determine if there was a relationship (Appendix B). The most significant trend appeared between the dominant frequency, acoustic power, and material momentum at channel entry (Figure 4.11). As experiments 3, 6, and 7 showed differences in acoustic power, the analysis also examined the effect of temperature. Despite the large temperature difference in Experiment 7 relative to the others, no strong temperature dependence was observed. The experimental data demonstrate a strong positive relationship between momentum and acoustic power, and an inverse relationship between momentum and dominant frequency. Field data and additional external experiment datasets enabled examination of these trends across several orders of magnitude.

This stage was modeled as the material impacting the channel drop zone and transitioning from vertical fall to a gravity-driven laterally propagating current. During this transition, interstitial air changed from downward velocity to lateral velocity along the channel. This period corresponded to material fluidization and the onset of flow. Following the entry of material into the channel, the flow front may have acted as an additional acoustic source. All relevant signals, however, arrived at the sensor before the flow arrival, while material was still actively discharging. These signals therefore represent overlapping, spatially and temporally differentiated source functions, producing measurements at a single sensor that are difficult to fully separate into distinct sources. Nevertheless, the initial portion of the experimental signal remains indicative of flow source parameters.

Experiments exceeding 300 kg, exhibited multiple distinct arrivals, whereas smaller mass or surge experiments displayed only a single arrival. This observation may indicate that in the surges, only the later and larger signal was recorded, or that signals associated with the collapse and flow initiation were absent owing to low flow density.

Table 4.2: Parameters calculated from the additional data used as a comparison.

Event	Momentum	Dominant Frequency	Acoustic Power	References
Experiment (jet)	250 - 2000	207 Hz	NA	(Dellino et al., 2007)
Avalanche	3×10^6	3 Hz	3.47×10^4	(Marchetti et al., 2021)
Mount St. Helens	4.5×10^{13}	0.0033 Hz	3.13×10^{15}	(Perttu et al., in review.)

The current dataset does not allow differentiation between these possibilities.

4.5.3 External Data and Field Data

To determine if any of these relationships hold in a natural flow, a combination of additional field data from experiments and other flows was compiled. An experimental apparatus in Italy generates a jet of material that then collapses (Dellino et al., 2007), compared with PELE that drops material from an elevated hopper. A video of one experiment was used to determine whether a similar signal sequence occurs in these experiments. For this experiment, the total mass and jet height were provided. The audio track of the video was extracted for analysis, and the same FFT analysis was applied; however, acoustic power measurements were not available owing to unknown amplitude conversion. The camera microphone does not necessarily have a flat response over the frequency range of interest; therefore, although similar FFT analysis was applied, the relative heights of frequency peaks are approximate owing to the unknown sensor response. Microphone amplitude is also a relative value and cannot be used to calculate acoustic power. For this example, the estimated mass, fall velocity, and dominant frequency are reported for comparison (Figure 4.12).

Published datasets of PDC infrasound remain limited; however, two well documented examples provide valuable insight and points of comparison with experimental results. Early work at Unzen volcano (Yamasato, 1997; Yamasato et al., 1993) captured signals attributed to the detachment, fall, impact, and transition of dome blocks into flowing material. Literature on this sequence of events reports signals corresponding to

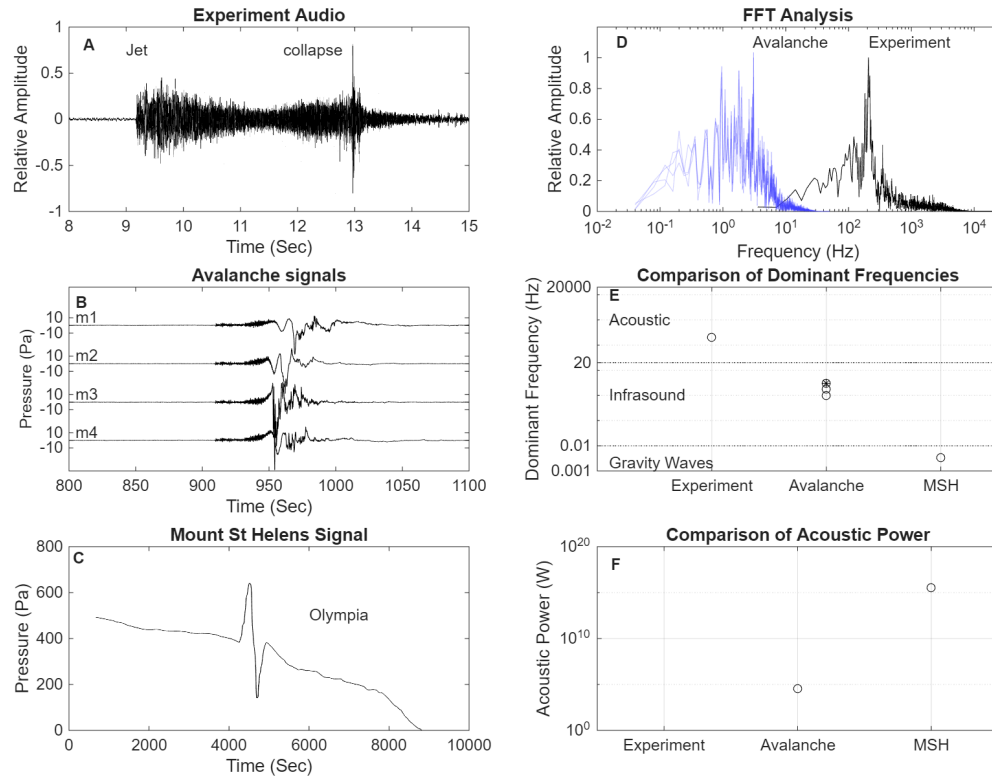


Figure 4.12: Additional data used to compare with our experimental results. (A) Audio extracted from the video of the experiment published in (Dellino et al., 2007). (B) Waveforms provided with the publication of Marchetti et al. (2021), of the array that recorded the avalanche. (C) Digitized barograph from Olympia, WA for the May 18, 1980 eruption. (D) Dominant frequency from the experiment and avalanche data. (E) Comparison of dominant frequencies where the results from all channels from the avalanche data are plotted and the picked solution of 3 Hz is highlighted. (F) Comparison of acoustic power available.

the block detachment and collapse onto the slope, observed in both the seismic dataset and infrasound/microphone datasets, although waveform parameters remain limited. At a much larger scale, the May 18, 1980 lateral blast of Mount St. Helens produced a PDC whose acoustic signals were recorded locally, regionally, and globally on barometers, microbarometers, regional seismic networks, and via eyewitness accounts (Perttu et al., in review, Chapter 3). This event has been extensively studied, resulting in robust characterizations of flow properties, and the geophysical dataset provides information such as dominant frequency and in some cases acoustic power.

Additionally, considering the use of snow avalanches as an analog signal for PDCs, a study providing comparable data was identified. Marchetti et al. (2021) document acoustic signals from avalanches recorded on an infrasound array at a local range, whose waveform data are available online. Available signals from these examples are plotted in Figure 4.12.

Analysis of the (Dellino et al., 2007) experiment acoustic data reveals a signal that appears to be consistent with the timing of the collapse and initiation of the flow. It is important to note that an acoustic jet, which represents the assumed source for the experimental jet configuration, is known to have inefficient transfer of energy into sound and exhibits a strong azimuth-dependent radiation pattern relative to the nozzle of the jet. Consequently, a collapse or impact signal, which generates sound more efficiently and radiates more isotropically, produces the higher amplitude signal (Figure 4.11A).

Using the published waveforms from the additional external experimental dataset and natural events enabled calculation of acoustic power and dominant frequency across several orders of magnitude. These results were combined with momentum estimates derived from published volumes, nominal densities, and fall heights (Table 4.2). The analysis tested whether the relationships established in the experimental facility scale to natural flows, increasing confidence in the application of these relationships to field phenomena. Despite the limited number of additional data points, the results support the validity of the observed relationships (Figure 4.13).

This mechanism of falling material, impact, and transition to flow is analogous

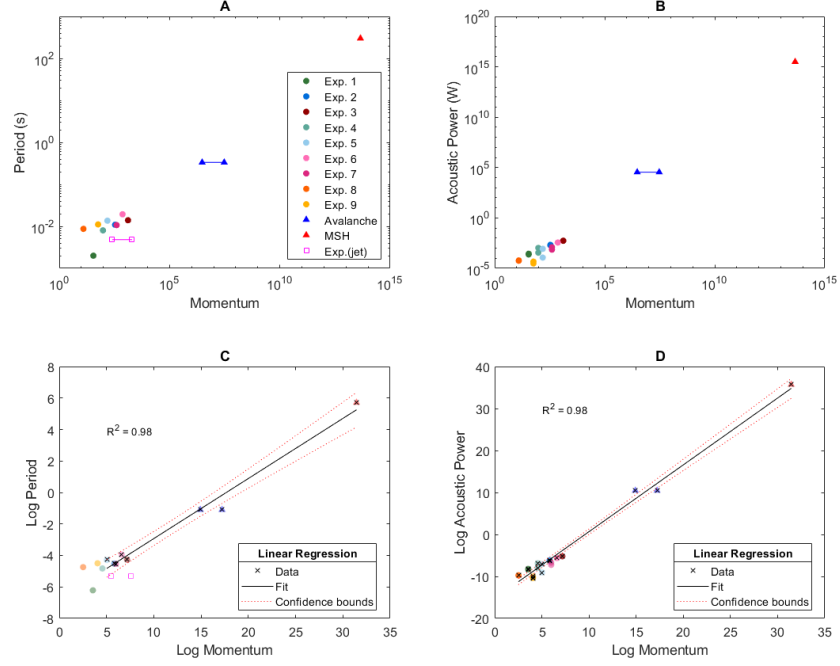


Figure 4.13: Combination of experimental data and additional data. (A) Period (inverse of frequency) of the signals vs. the calculated or estimated momentum. (B) Acoustic power vs. the calculated momentum. (C) Linear regression for a log/log fit for period vs. momentum. (D) Linear regression for a log/log fit for acoustic power and momentum.

to signals reported at Unzen (Oshima and Maekawa, 2001; Yamasato et al., 1993; Yamasato, 1997), where the first acoustic arrival in a PDC signal sequence was attributed to dome material detaching and intruding into the atmosphere (Yamasato, 1997). Perttu et al. (in review.) (Chapter 3) identified that the 18 May 1980 Mount St. Helens landslide and lateral blast generated an acoustic gravity wave, identified as a Lamb wave, which acted as a unidimensional force, producing an atmospheric acoustic gravity wave. Snow avalanches are frequently used as analogs; for example, (Marchetti et al., 2021) reported that an ice collapse-triggered avalanche on Mt Eiger, Switzerland, produced a similar broadband signal, which was used to constrain source parameters. Despite uncertainties and the limited number of available data points, the results suggest that these relationships hold (Figure 4.13). A large dataset of well-characterized field signals is required for confirmation and to establish a robust empirical relationship.

The literature generally attributes PDC signals to turbulence at the flow front (Allstadt et al., 2018; Delle Donne et al., 2014; Ripepe et al., 2009). Results from the present experiments indicate that field datasets may also contain signals generated by the initial material intrusion into the ambient atmosphere, material collapse, and transition to flow, as also observed by Yamasato et al. (1993). Natural PDCs, however, originate from a variety of triggering events (such as plume collapses, dome collapses, and plume overflow) that themselves generate acoustic signals. These natural sources are inherently more complex than experimental sources, and the presence of a plume or explosive activity may obscure and mask initial displacement signals.

4.5.4 Pressure Increase

The pressure increase in Figure 4.10 likely reflects air within the channel accelerating from rest to the velocity of the flow front, generating a dynamic pressure recorded by the sensor. In the confined channel, air displacement was restricted, whereas in an unconfined setting, a more complex velocity field would develop around a flow. Eyewitness observations of the 18 May 1980 Mount St. Helens eruptions report strong winds and pressure increases preceding the lateral blast PDC arrival, including trees falling and people being knocked to the ground (Perttu et al., in review.; Waite, 2014). For flow velocities approaching the speed of sound, the resulting dynamic pressure could reach 57.8 kPa, and could produce a significant dynamic pressure without any direct contact with the flow. In the Mount St. Helens lateral blast zone, measured velocities of 80–20 m/s yield dynamic pressures of 10–35 kPa from tree damage (Guinn et al., 2022). The air acceleration alone near the flow front generated 3–7 kPa, representing up to ~30 % of the total reported dynamic pressure. This illustrates that substantial dynamic pressure loading can occur ahead of a PDC purely from the atmospheric acceleration, potentially explaining the Mount St. Helens reports of wind damage and human impacts before contact with the flow.

4.5.5 Conceptual Model

The pre-arrival acoustic signals generated during the pyroclastic flow (PF) experiments (experiments 3, 6, and 7) have characteristics distinct from the pyroclastic surge experiments (experiments 1, 4, 8, and 9). In the PF experiments, the initial signal was followed by one or more higher amplitude peaks. These secondary pressure pulses immediately followed those associated with the entry of the falling suspension into the confined channel, and could be tracked between the different sensor locations. Similarly to this first signal, subsequent signal localization also yielded a solution within the impact zone. This second signal, consisting of one or more peaks, coincided with the material collapsing onto the channel in the drop zone.

The dynamics of impact of the multiphase particle-gas mixture with the channel slope was different between the surge- and PF- experiments. In both cases, a strongly air-entraining fine ash-rich, and dilute frontal region was the first to impact the slope. On impact with the ground, which was a curved slope at the head of the channel (Figure 4.1) the resulting dilute suspension changed direction from vertical fall into that of the channel slope relatively unhindered. In the PF experiments, the dilute frontal tip of the falling suspension was followed by an increasingly denser region of the falling material. At its periphery, falling material was also strongly entraining air. This led to a concentration of particles in the core of the falling suspension. This more concentrated central region was oriented vertically above a flatter portion of the curved impact zone before the transition to the 6° slope of the inclined channel. On the impact of the denser trailing region of the falling suspension, particles accumulated to form a ~0.2–0.3 m-thick concentrated suspension. This generated the PDC underflow region, which trailed the ash-cloud surge frontal region of the experimental PDC.

Sweeney and Valentine (2017) and Valentine and Sweeney (2018) analyzed the vertical collapses of polydisperse gas-particle mixtures in numerical multiphase simulations. These simulations were most similar to the PF experiments conditions, where their simulation of bi-disperse mixtures collapsed to the ground at subsonic conditions. They observed that the smaller-sized particles of the mixture followed the motion of the gas

phase from vertical fall to horizontal outflow relatively unhindered. However, the larger particles tended to accumulate upon impact. This resulted in an energetic expelling and immediate strong acceleration of the interstitial gas occupying the interparticle space in the coarse-dominated, accumulating particle-gas region.

Sweeney and Valentine (2017) explained this behavior through variable coupling of the small and large particles to the gas phase. They expressed this behavior as an impact Stokes number St_{imp} , defined as:

$$St_{imp} = \frac{T_{particle}}{T_{imp}} \quad (4.4)$$

where the impact Stokes number (St_{imp}) is the ratio of $T_{particle}$, the characteristic response time of the particles, and T_{imp} is the characteristic fluid timescale of the impact. The characteristic fluid timescale for this problem is the time over which the fluid drastically changes direction from the vertical fall to channel floor parallel outflow as a gravity current. This is equal to:

$$St_{imp} = \frac{\left[\frac{\Delta \rho d^2}{18\mu} \right]}{\left[\frac{\delta}{\Delta U} \right]} \quad (4.5)$$

where the characteristic length scale δ is the length over which the multiphase flow is changing its direction where the vertical component of velocity suddenly decreases to zero over a velocity change scale ΔU , μ is the viscosity of the gas, and d is the particle diameter. Sweeney and Valentine (2017) argued that the velocity change scale ΔU was limited by the maximum vertical velocity of the jet during impact with the channel U_{imp} . Within our experiments, the maximum vertical velocity ranged from 8 to 9 m/s. The characteristic length-scale δ in our PF experiments can be approximated by the thickness of the resulting underflow. The separation of the coupled and poorly coupled particles from the gas phase during the impact was governed by the condition where:

$$St_{imp} = O(1) \Leftrightarrow T_{particle} = T_{imp} \quad (4.6)$$

At this condition, where St_{imp} is on the order of one, we can solve equation 4.5 using

the measurements of the dense underflow thickness δ at the channel entry. In this case, for Experiment 3, that thickness was $\sim 0.2\text{--}0.3$ m and $\Delta U = \Delta U_{fall} - 0$, which, for the range of fall velocities at impact, yields a ΔU 8–9 m/s for equation 4.5. This yields a range of characteristic fluid time scales of 0.02 to 0.0375 s, illustrating the short time window over which this occurred and the signals were generated. The frequency range associated with this time scale was 27–50 Hz. These frequencies corresponded with a prominent frequency seen in the FFT spectra for the infrasound signals for the PF experiments (30–50 Hz), highlighted by the gray bar in Figure 4.7A.

This overlap in frequency suggests that a possible source mechanism for the second pre-arrival wave was associated with the strong acceleration of the interstitial air, which was then expelled from the denser core of the falling suspension during this close-to-instantaneous particle deceleration at impact. This finding suggests that end member surge and PF currents may be distinguished by characterizing the signals recorded before the moving source signal of the flow. In practice, this source mechanism may only occur in the case of falling material, which occurs when the source is that of the collapse or partial collapse of an eruption column, or blocks falling from a dome. During eruptions, it is expected that the differentiation of this signal from the eruption or plume jet would be challenging. However, the experimental results confirm the numerical modeling of Sweeney and Valentine (2017), whose results demonstrate that when the fall velocity approaches the local speed of sound, the dynamics of the accelerated gas may be accompanied by shocks.

Our results suggest that the displacement of the atmosphere by the initiation of a PDC generates pressure waves that can be related to source geometry, volume, mass, and velocity. The first signal of the initial displacement of the atmosphere is likely controlled by the geometry of the displacement, whereas the subsequent signals are related to the collapsing material and generation of an underflow related to the mass and velocity of the material. For field data, topographic effects, other propagation complications, and overlapping signals add uncertainty; however, despite this, such a relationship could be useful for repetitive events from consistent sources to constrain

source parameters. As the source scale increases, the generated signal may range from acoustic to infrasonic, and on the largest scales, an atmospheric gravity wave. Large-scale events, such as the Hunga-Tonga Hunga-Ha’apai Volcano eruption (Matoza et al., 2022), demonstrated that such waves can trigger meteotsunamis in distant unconnected water bodies.

The mechanisms presented contrast with the signals generated by rockfall mass movements. Those signals generally produce an impulsive signal with a clear dominant frequency (Allstadt et al., 2018), while PDC signals and the experimental signals are emergent and broadband. Thus, there is potential for differentiation of rockfalls, which have already been noted to be significantly different from other mass movements (Allstadt et al., 2018), and a PDC-generating detachment.

4.6 Conclusions

This study highlights the value of laboratory experiments for understanding how PDCs generate pressure signals. Across a range of flow dynamics, from dilute to concentrated, the experiments demonstrate that PDCs produce two distinct types of pressure signals at flow initiation as they intrude into the atmosphere. The first signal is an acoustic wave generated by the displacement of ambient air at the onset of the flow. In denser, pyroclastic flows, high-energy pressure waves are generated by the acceleration of gas expelled on impact from the interstitial space of a particle-accumulating region that eventually forms the PDC underflow region. The second is a dynamic pressure increase caused by air accelerating to the flow front velocity. The magnitude of dynamic pressure of this pre-flow arrival pressure can be substantial. This may explain the observation of strong mechanical damage occurring immediately before the arrival of a PDC (Waite, 2014). Both signals appeared consistently through all experiments. Spectral analysis of the initial signal produced by the flow entering the channel (including the collapse and flow initiation), indicates that there is a relationship between the initial momentum of the falling PDC-generating suspension and the dominant frequency. Similarly, the

acoustic power of this same window indicates that there is an increase in acoustic power with increasing momentum. While this relationship is less pronounced in dilute experimental flows, the relationship extends from the higher mass experiments into natural signals.

Field data ranging from small dome collapse at Unzen volcano, to the lateral blast of May 18, 1980 at Mount St. Helens, as well as analog snow avalanche events exhibit similar patterns to those found in the experiments. This suggests that the mechanism producing pressure signals is similar across these scales. Additional well-characterized field events are needed to confirm these findings. The results indicate that the initial signal may provide constraints on PDC source parameters. Expanding this work in the future with field data could support the development of the use of infrasound monitoring as a component of PDC early warning systems.

4.6.1 Future Work

Experimental PDCs provide a promising foundation for understanding how natural PDCs generate pressure signals. This study demonstrates that initial displacement of ambient air by the intrusion of the PDC into the surrounding atmosphere can generate a detectable signal, which, with further investigation, could yield insight into initial source parameters. The results also highlight that the dynamic pressure increase before the arrival of the flow can be significant.

Advancing this work requires two primary developments: additional further experiments and expanded field datasets. While the current experiments provided a valuable initial dataset, future experiments should incorporate additional instruments with higher sampling rates and lower noise floors. Increased sensor density and placement in the unconfined areas at the end of the channel would improve localization and resolution. To connect experimental results with natural flows, data from multiple well-characterized and documented PDCs are needed. Progress is currently limited by the sparse reporting of recorded PDCs at volcanoes with infrasound installations, and by the limited number of volcanoes with the necessary instrumentation.

As infrasound monitoring becomes more prevalent in volcano monitoring networks, existing and forthcoming datasets are expected to provide the necessary datasets to further test and refine these relationships.

Chapter 5

Acoustics of Experimental Pyroclastic Density Currents

Prepared for publication. In this publication only 2 experiments were utilized, and so Experiment 3 from the previous chapter is referred to as Experiment 2 for this chapter.

5.1 Abstract

Pyroclastic Density Currents (PDCs) are deadly, highly destructive, fast-moving, ground-hugging, mixtures of hot gas and volcanic particles. PDC high velocities, dynamic pressures, and temperatures make direct field measurements extremely challenging. Due to the combination of high-impact to the natural and built environment, and the difficulty of obtaining direct measurements, remote detection methods would be of benefit to their study and early warning systems. Acoustic methods have been proposed in the past for this application, however, due to sparse field data, there remains a limited understanding of the fundamental question regarding the source of the recorded acoustic signals. The Pyroclastic flow Eruption Large-scale Experiment (PELE) is a large-scale experimental facility designed to synthesize pyroclastic density currents (PDCs) within a laboratory environment. PELE has been augmented with acoustic sensors allowing for the direct observation of physical properties and the location of the experimental

flow with time-synchronized acoustic data. This study examines the location and source of the acoustic signals that have been previously identified in field data. Combining signal cross-correlation between sensors with known offsets within the experimental channel, and high speed imaging of the experimental flow, the resulting dataset showed that there are multiple pulses of signal sources within a single flow. These signals seem to be associated with the interface of the flow and the atmosphere. This result highlights that, while previously the source of the field signals was attributed to the front of the flow, there are multiple sources within the flow. Further research should be undertaken to further explore the role of these different sources and topography and path in the field. Additionally, this insight should be taken into account for sensor deployment design and early warning system development.

5.2 Introduction

5.2.1 Pyroclastic Density Currents (PDCs)

Pyroclastic density currents (PDCs) are highly destructive, fast-moving, ground-hugging mixtures of gas and volcanic particles that cause more than a third of volcanic fatalities worldwide (Auker et al., 2013). Their high velocities, dynamic pressures, temperatures, complex dynamics, and limited direct observations make them challenging to measure and model (Breard et al., 2025). Direct measurements are rare, and most field data are indirect, derived from damage surveys (e.g., Clarke and Voight (2000) and deposit mapping (e.g., Charbonnier et al. (2023)). More direct measurements have been obtained from visual observations, seismic data (Allstadt et al., 2018), and recently, radar (Scharff et al., 2019; Syarifuddin et al., 2022).

PDCs form when a mass of volcanic material fails to become positively buoyant or the material collapses to form a gravity-driven current that propagates laterally through the atmosphere. They can develop as part of an eruption plume, when that plume fails to become entirely buoyant, through rapid lateral explosions, or from lava-dome collapse, phreatomagmatic, phreatic, and hydrothermal explosions. This diversity of

source mechanisms produces a broad spectrum of flow dynamics and behaviors.

This complexity is commonly described along a conceptual spectrum of behavior with two end members: dilute currents (pyroclastic surges) and denser or concentrated flows (pyroclastic flows) (Lube et al., 2020). Dilute turbulent PDCs (including surges and blasts), are envisioned as having a low bulk volumetric concentration of particles above a thin concentrated basal bed-load. Concentrated PDCs (also termed pyroclastic flows, PF) also include a turbulent ash cloud surge region, but it overlays a concentrated underflow that carries the bulk of the flow mass.

The dense underflow is considered the predominant source of seismic signals; however, these signals can be difficult to differentiate from other eruption-related signals. These signals usually begin with a signal associated with the initiation of the PDC (dependent on the source mechanism) followed by a broadband emergent signal that persists for the remainder of the event (Allstadt et al., 2018). With the exception of the source signal, no observable differences in spectral content associated with different source mechanisms of PDC generation have been reported. The seismic signal is generated through the contact between the particles within the flow and the ground (Watson et al., 2023), which also allows the tracking of PDCs over time. However, this relies on a strong coupling between the underflow and the solid ground. Owing to its significantly lower particle concentration, the overlying ash cloud likely does not have sufficiently strong coupling with the ground to generate a significant seismic signal. However, the interaction of the ash-cloud surge region with the surrounding atmosphere through a combination of turbulent shear, entrainment, and buoyancy may induce pressure signals that can be recorded and interpreted.

5.2.2 PDC Infrasound

Recent studies proposed the use of infrasound (acoustic waves below 20 Hz) as a valuable tool for observing and quantifying active PDCs in real time (Allstadt et al., 2018; Taisne et al., 2025; Watson et al., 2022b). The PDC infrasound literature is limited to two main case studies: activity at Unzen volcano in the early 1990's (Oshima and

Maekawa, 2001; Yamasato et al., 1993; Yamasato, 1997) producing PDCs through dome collapse, and activity at Soufriere Hills Volcano in the 2000’s (Barfucci and Ripepe, 2018b; Delle Donne et al., 2014; Ripepe et al., 2010, 2009), which also produced PDCs through dome collapse. From these studies, the key observations were the presence of a moving source that produced a measurable Doppler shift (Yamasato, 1997), and broadband signals. The literature described signals of both the initiation of the PDC and the propagating PDC. The source of the moving signal is interpreted to be due to turbulent processes at the front of the flow (Ripepe et al., 2010; Taisne et al., 2025; Yamasato, 1997). Allstadt et al. (2018) states that “PDCs are [...] well documented sources of infrasound”, implying that there are many more examples of PDC infrasound signals that are included in event catalogs but not utilized in research studies. Within this limited set of studies on PDC infrasound, most publications state that the source is inferred to be the turbulence of the flow front, specifically the movement of the turbulent head of the flow coupling with the atmosphere, oscillations of the front due to turbulence, and displacement of the atmosphere by the flow (Yamasato et al., 1993); however, these have not been systematically examined across events and volcanoes.

5.2.3 Turbulence in PDCs

In PDCs along with other similar type multiphase, particle-laden gravity currents, like powder snow avalanches and underwater turbidity currents, turbulence is mainly produced by the occurrence of large shear stresses at a free shear boundary (in this case the atmosphere) and a solid shear boundary (the ground) driving the turbulence. This is generally illustrated by the presence of Kelvin-Helmholtz instabilities at the outer flow surface, and the formation of lobe-and-cleft structures within the leading and lateral lower flow region, where strong entrainment of ambient air occurs (Breard and Lube, 2017). PDCs also exhibit vertical density stratification that limits turbulence production through buoyancy, except within the dilute and less stratified upper flow regions (Brosch and Lube, 2020). Turbulence can also be generated as a PDC interacts with underlying topography or emplaced bedforms, and due to the interactions of

sedimentation, air entrainment, and buoyancy of the hot concentrated underflow regions (Andrews and Manga, 2011; Corna et al., 2025a,b; Wohletz, 1998).

Experimental PDCs have recently been used to obtain direct measurements of the energy spectra of flow velocity, internal flow velocity, dynamic pressure, and temperatures (Brosch et al., 2021; Uhle et al., 2024). Similar studies have also focused on natural PDCs, including those at Whakaari/White Island, and for snow avalanches in Vallée de la Sionne (Switzerland) (Brosch et al., 2021). Within these studies, the largest and most energetic source of turbulence for dilute PDCs is cited as the largest turbulent eddies, which are also a dominant source of energy for the whole flow. These studies also illustrate that the concentration and clustering of inertial particles occur at eddy peripheries, causing localized amplification of the turbulence energy (Uhle et al., 2024).

Brosch and Lube (2020) showed that in experimental PDCs, the characteristic period of the energetic turbulence oscillations of several flow properties measured inside a dilute PDC, and its outer boundary, could be related to a characteristic thickness and velocity for the flow. If this characteristic period of oscillation were to be easily identifiable and recordable by remote methods, it could lead to improved hazard mitigation strategies.

5.2.4 Experimental PDCs and PELE

Owing to the complexities of studying and measuring PDCs in the field, and the lack of a large field dataset, this study utilized experimentally derived PDCs. Experimental PDCs have been established within the literature (Lube et al., 2015; Breard and Lube, 2017; Brosch et al., 2022; Dellino et al., 2007; Andrews and Manga, 2012; Dufek et al., 2015; Dufek, 2016; Doronzo and Dellino, 2011; Kueppers et al., 2012), and this study utilized a facility and set of pre-established methods for characterizing the flows. Experimental PDCs allow for the ability to vary parameters (e.g., initial mass and temperature) while using real pyroclastic material within a context where documentation of dynamics is possible.

This research was motivated by the lack of direct internal measurements of PDC dynamics in the field, and the potential for combining and leveraging the seismic measurements of PDCs with infrasound methods to fill this gap. However, to achieve this, further understanding of the generation of acoustic signals generated by PDCs must be constrained before field measurements from infrasound can be compared with conceptual models of PDC dynamics.

This study, therefore, synthesized dynamically and kinematically scaled behavior of PDCs in large-scale experiments with the ability to characterize the evolving internal flow characteristics, and compared them with near field infrasound and acoustic sensors. This research was driven by two research questions: what is the source of the acoustic signals generated by the propagating PDCs, and can these signals be used to constrain aspects of the flows? This study used acoustics to refer to atmospheric pressure waves in both the infrasonic and audible ranges. The units of both acoustic and dynamic pressure are the same and all pressures reported herein should be assumed to acoustic unless otherwise described. Additionally, the number and time scale of oscillations is referred to as the period, while acoustic data use frequency (Hz).

5.3 Methods

5.3.1 Experimental Setup

PELE Overview

The Pyroclastic flow Eruption Large-scale Experiment (PELE) facility is a large-scale experimental facility designed to synthesize pyroclastic density currents (PDC) within a lab environment where they can be viewed and the internal dynamics measured. This facility is located at Massey University in New Zealand. PELE is designed to repeatedly synthesize experimental PDCs using natural volcanic material (see supplemental materials).

The PELE facility is comprised of a 13-m high tower structure with an elevated

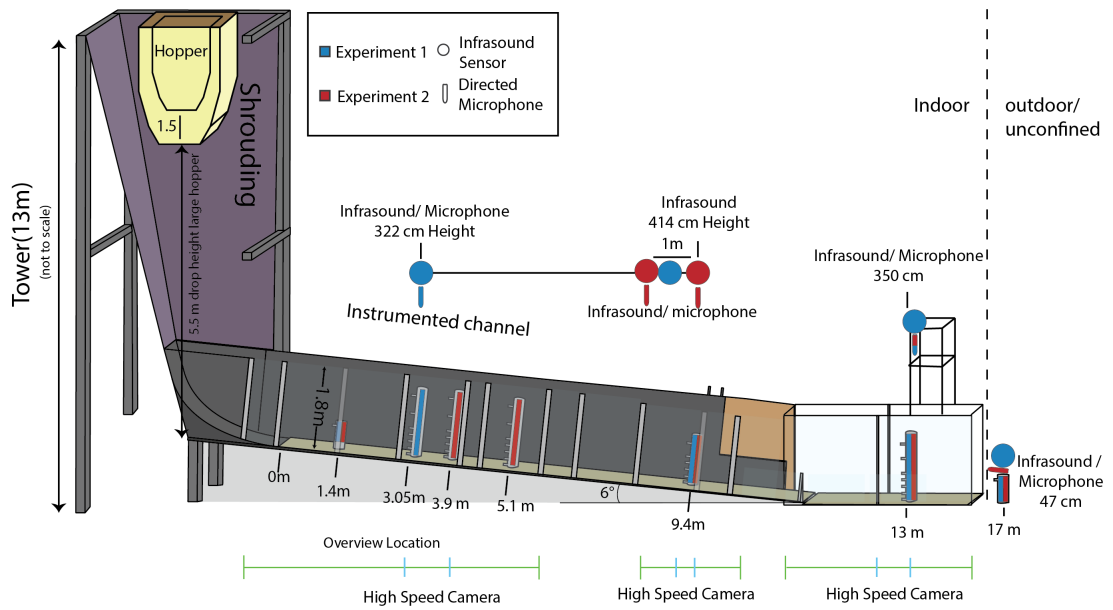


Figure 5.1: Setup and configuration of the PELE facility depicting relative locations within the Boiler House building. Sensors are depicted with different shapes and colored by experiment number. The infrasound sensor locations were changed between Experiment 1 and Experiment 2. Profiles are aligned with the sensor towers within the channel; there are five profiles for Experiment 1 (1: 1.4 m, 2: 3.05 m, 3: 9.4 m, 4: 13 m, 5: 17 m) and six profiles for Experiment 2 (1: 1.4 m, 2: 3.9 m, 3: 5.1 m, 4: 9.4 m, 5: 13 m, 6: 17 m). For Experiment 1, infrasound was located above profiles 2, 3, 4, and within the channel at profile 5. Only two sensors were available for Experiment 2, and the sensors were moved to a 1-m horizontal spacing above profile 4.

Table 5.1: Scaling of the PELE facility established within the literature (Lube et al., 2015; Brosch et al., 2021; Breard and Lube, 2017). This table covers the range of values from both natural cases and PELE experiments, where U is flow velocity; h is flow height; $\Delta\rho$, ρ_C , and ρ_A , are the difference between flow and ambient density; f is frequency; and μ_c is the dynamic viscosity of the flow.

Parameter	Variable / Symbol	Units / Equations	PELE Values	Natural Values
Particle Size		m	$10^{-6} - 10^{-2}$	$10^{-6} - 10^{-1}$
Velocity	U	m/s	$< 0.5-9$	10–200
Characteristic Length	L	m		
Characteristic Frequency	f	Hz		
Reynolds	Re	$Re = \frac{\rho_C U h}{\mu_c}$	$4.8 \times 10^4 - 1.5 \times 10^6$	$3.3 \times 10^6 - 6.7 \times 10^9$
Richardson	Ri	$Ri = \frac{\Delta\rho h g}{\rho_A U^2}$	0.01–10	0–10
Strouhal	Str	$Str = f \frac{L}{U}$	0.24 - 0.31	0.3
Froude	Fr	$Fr' = \frac{U}{\sqrt{g L \frac{\rho_C - \rho_A}{\rho_A}}} =$	0.75 - 2	~ 1

hopper system, including small (0.7 m^3) and large (4.2 m^3) hoppers, and an instrumented confined channel that is 0.5 m wide and 1.8 m tall, ending with an unconfined outdoor run-out area on a flat concrete pad (Figure 5.1). The large and small hoppers can hold between 100 and 4150 kg of material, with the ability to release the material at variable heights, variable temperatures (up to 500°C), and variable discharge rates. The material falls through a shrouded fall section into a chute with a curved base where the material mixes with the ambient air in the facility and accelerates under gravity. The material then collapses on the chute and flows as a density current through the confined channel. The channel slope is adjustable and is currently set at 6° for the first 12 m, and continues with no slope for the following 5 m until it exits the channel onto an unconfined concrete slab outside of the building up to a natural slope at 33 m.

The PELE facility has been specifically designed with the aim of achieving dynamic and kinematic scaling similarities with natural PDCs. The facility uses natural pyroclastic material and air for the solid and fluid phases of the flow. The facility is

capable of generating scaled dilute pyroclastic surges and highly concentrated pyroclastic flows. These experimental flows are fully turbulent and scaled with the use of key non-dimensional numbers related to the flow velocity, length, time, and temperature (Table 5.1). This scaling is discussed in detail in Brosch et al. (2021) and Lube et al. (2015).

Previous studies at the PELE facility have included high speed cameras and cameras with a wide range of view throughout the facility (overview cameras), thermocouples, deposit sampling, and dynamic pressure sensors within the channel. Given the previous experience of researchers at PELE, and insight gained through an unpublished acoustic test study, a set of three experiments were designed to explore the acoustic wavefield of PDCs, the results from two of these presented here.

This research focused on what and where acoustic signals are generated from the experimental PDCs. The experiments were designed to encompass a wide range of properties and dynamics to compare and contrast signals.

Experiments and Instrumentation

The experimental design for the acoustic wavefield study utilized a doubling of mass over three experiments. For this study, we focused on two of these experiments, the lowest and highest masses. Herein, we refer to these two experiments as experiments 1 and 2. Experiment 1 consisted of 250 kg of material heated to 100°C, and Experiment 2 consisted of 1100 kg of material also heated to 100°C. Full initial conditions of the specified experiments are listed in Table 5.2. The natural ignimbrite material used for these experiments was derived from the 232 CE Taupo eruption and the mixture contained particles with a size range of 2 μm to 16 mm, with ~ 26.5 wt % fine ash ($< 63 \mu\text{m}$). Additional material characteristics are included in the Appendix D.

Visual data for the experiments were recorded by a combination of cameras. Filming the broad overview of the flow were a variety of GoPro cameras positioned throughout the facility. The GoPro cameras were a range of models and recorded between 30 and 120 frames per second. At specified locations throughout the channel were three high

Table 5.2: Properties of the two experiments used in this study. Differences in mass represent end member cases of the PELE experimental flows.

	Experiment 1	Experiment 2
Mass (kg)	250	1100
Temperature (C)	100	100
Discharge Average (kg/s)	36.2	383.9
Discharge Time (s)	8.2	3.1
Runout Distance (m)	29.3	27.5 (Underflow 19.4)
Ambient Temperature (C)	17	10
Calculated Speed of Sound (m/s)	341	337
Air Density (kg/m^3)	1.211	1.2272
Average Flow Front velocity (m/s)	2.75	4.15

speed camera profiles (see locations in Figure 5.1). The high-speed cameras recorded at 1000 frames per second.

Temperature within the experimental flows was recorded with profiles of various heights of thermocouples. TC Direct model number 410-345 Type K sensors were used and have an operating range up to 250°C. The sensors were sampled at 72 Hz and recorded both the flow temperature and ambient temperature within the channel. They were installed on the channel wall behind the profile towers for the dynamic pressure sensors depicted in Figure 5.1.

The acoustic wavefield was sampled with both infrasound microphones and acoustic microphones. The infrasound sensors were PCB Piezoelectric ICP Infrasound sensors (378A07) sampled at 1000 Hz with a flat response between 0.25 Hz and Nyquist at 500 Hz, and ACO Type 7744N infrasound sensors designed for the volcanic environment sampled at 1000 Hz with a flat response from 0.1 Hz to Nyquist. To extend the frequency range, the infrasound sensors were augmented with Sony ECM-674 directional microphones sampled at 50 kHz for Experiment 1 and 44.1 kHz for Experiment 2 with a flat response between 40 Hz and 20 kHz, and a Nyquist of 25 kHz for Experiment 1 and 22 kHz for Experiment 2. Infrasound and microphone placement for the experiments was constrained by available mounting locations and the limited number of sensors. Experiment 1 used four infrasound omni sensors mounted above the channel at 3, 8.6,

Table 5.3: Location of infrasound and microphone sensors within the channel and in height above the floor of the channel. Note that the height is impacted by the slope of the channel and sensors installed horizontally above the channel have different heights relative to the floor of the channel. There were four infrasound sensors for Experiment 1 and two for Experiment 2, and two microphones for Experiment 1 and four microphones for Experiment 2.

Sensor	Location in Channel (m)		Height (m)	
	Experiment 1	Experiment 2	Experiment 1	Experiment 2
Infrasound 1	3.045	8.42	3.22	3.115
Infrasound 2	8.605	9.42	4.14	3.22
Infrasound 3	13.1		3.5	
Infrasound 4	17		0.47	
Microphone 1	8.605	8.42	2.952	2.847
Microphone 2	13.1	9.42	3.232	2.952
Microphone 3		11.38		3.1578
Microphone 4		17		0.47

13, and 17 m with directed microphones installed at 8.6 and 13 m directed down towards the channel. The heights relative to the channel floor were 3.2, 4.15, 3.5, and 0.47 m for the infrasound and 2.95 and 3.23 m for the microphones. For Experiment 2, two sensors were deployed at a 1 m spacing at 8.4 and 9.4 m (Table 5.3 and Figure 5.1).

The density and particle volume concentration were measured with the use of square tubes with one open end and one end with a fine mesh allowing only the gas phase to exit. These tubes were placed at several heights for several profiles, and were filmed with a GoPro. This allowed us to trace the filling of the tubes over time and obtain a time series of sediment volume at that location. This was combined with the high speed camera average velocities within the time frame derived using PIVLab (Thielicke and Stamhuis, 2014). Then, the weight and density of the accumulated material for each time interval were used to calculate the time dependent flow density and particle concentration following Brosch et al. (2021).

5.3.2 Flow Characterization

The flows were characterized through location, velocity, and temperature through time. Flow location through time was mapped using a combination of overview cameras

throughout the channel and in the unconfined area. The timing of the locations was synchronized with the LED trigger light and converted into a flow front velocity through time. In addition to the flow front velocity, the high speed camera data were used to obtain internal velocities. High speed camera data were processed with (Thielicke and Stamhuis, 2014) to produce a two-dimensional velocity field dataset (Figure 5.3). The internal flow velocities were extracted for specific heights that corresponded to the heights of different sensors. The flow height at a specific location was also mapped using the overview cameras. Additionally, the location of the underflow and several visible trackable pulses were mapped to determine propagating through the channel. The height of the underflow through time was also mapped at several locations. The temperature sensors were used to calculate the temperature through time at a given height, along with the average temperature through time. The weight of the hopper was also tracked through time and was used to track the discharge of material, the discharge rate through time, and the average.

The time series of the datasets represented time series of different temporal lengths and sample rates. The FFT was calculated for these datasets; however, the datasets were resampled to the lowest sample rate of the comparison set to ensure similarity of method and window between disparate data types. To determine the similarity of the signals in the frequency domain, a cross-correlation was taken with resampled data for consistent sampling rate.

5.3.3 Acoustic Signals

Noise

The instrumented time series datasets were initially examined as waveforms, and then through simple spectrograms and FFTs. A dominant noise source within the instrumented datasets (infrasound, acoustic, temperature) was electronic noise from the power grid. The New Zealand electrical system operates at 50 Hz, and a clear peak at 50 Hz was visible in the sensors' FFT, with overtones and semi tones characterized by very narrow spectral bandwidths. These peaks were removed from the data with a $\pm$

1 Hz notch filter around 50, 100, and 150 Hz for all datasets where they were visible. The other overtone and semitone peaks did not significantly degrade the signal-to-noise ratio. Within the larger experiment, there were additional broader semitones around 310 and 410 Hz, which were not removed through this process.

The secondary noise issue was related to the infrasound sensors' responses to heating when engulfed by the experimental flow. Overview cameras and thermocouples installed with the infrasound sensors (Experiment 2) were used to identify when sensors were engulfed. The response was characterized by a long-period signal with an initial voltage drop when the sensor housing expanded with increased temperature. Most of the data processing in this study used sensors that did not experience a significant thermal response.

The experiments took place in an enclosed space that was open to the environment; in addition to the common infrasound noise sources like wind, microbarom, and anthropogenic noise, there was an additional room response and vibration of the channel and tower. The boiler house is 25 m by 18 m with a height of 16 m, and the modes of the room may excite frequencies within the 3 and 10 Hz range, coincident with the channel vibration (Appendix D). These frequencies were kept in mind throughout interpretation.

5.3.4 Signal Identification

Utilizing the flow characterization information, segments of the data in time were identified and separated into phases: when the flow had not entered the channel (discussed in detail in Chapter 4), when the flow was traveling towards the sensor, and when the flow front had passed the sensor (Figure 5.5, Figure 5.6). The data were filtered into decades of frequency of 0.1–1, 1–10, 10–100, and 100–500 Hz (Nyquist) for both experiments, and the largest signal-to-noise was for Experiment 2. We used the decade with the most visible signal details (10–100 Hz) for the flow for further processing. The vibration of the PELE structure is between 5 and 12 Hz, which can be clearly seen in Figure 5.6, further details in the Appendix D.

5.3.5 Spectral Characteristics

To characterize the spectral content of the signals, we used two complementary approaches: fast Fourier transform (FFT), and power spectral density (PSD). We used FFT to identify the frequencies present in all datasets and to compare between different datasets. PSD was used to quantify how the acoustic energy was distributed across the frequency spectrum through time. The PSD method provides a physically meaningful measure of energy per unit frequency that can be expressed in Pa^2/Hz or converted into decibels (dB). This enables characterization of the signal intensity throughout the spectra with reference to the global noise curves (Le Pichon et al., 2009b).

To refine the spectral resolution, we modified the previously used PSD method designed for the long term study of infrasound array noise (Taisne et al., 2019) for this study. The major difference is within the windowing and filtering of the data. Previously used overlapping Hanning windows were replaced with Tukey windows with an overlap to minimize amplitude loss between windows. Additional information on the processing method are presented in Appendix D.

5.3.6 Localization

Although the PELE sensor configuration does not fully support array processing or beamforming, relative arrival times and signal correlation between sensors provide a first-order constraint on signal source direction. Under several assumptions, these constraints enable an approximate estimate of the signal source within a defined processing window. We developed the following workflow to constrain the source azimuth of any signal in a specified time window. Based on the frequency analysis of the signal, the passband of interest was selected as 10–100 Hz with a 0.1 s processing window.

For this workflow we first bandpass filtered the data between 10 and 100 Hz. We used windows of 0.1 s with a 1 sample step. We chose the window length based on ensuring we had sufficient samples for the full frequency range. Second, we calculated the cross-correlation between the reference sensor (1) and test sensor (2), which had been shifted one sample at a time from -6 to 6 samples. We repeated this calculation

over a sliding window of 1 sample to increase temporal resolution, and for each time window, we recorded the maximum cross-correlation value and corresponding shift of samples for that value.

Third, windows with a maximum cross-correlation above 0.6 were kept and other windows were discarded. From these subset windows, we further filtered the data into where shift values were ± 3 samples. These requirements ensured that the resulting data were characterized by high cross-correlation and therefore represented the same source, and were consistent with a signal generated within the channel. These thresholds were based on the calculated sample shifts for a grid with a 10 cm spacing, which was generated within the channel, the speed of sound, and the theoretical sample offsets (Figure 5.8). This allowed for localization of the signal within a region of the channel, with the resolution set by both the distance of the sensors, the sample rate of the data, and the length-scale of the experimental facility.

This process was repeated for both experiments, and the same process was completed with the microphone data, with a shift window of 0.001 s, the length of a sample in the infrasound data. However, the microphone data did not pass the data quality filters (Appendix D).

5.4 Results

5.4.1 Experimental Flows

General Characteristics of Experimental Dilute and Dense PDCs

The experimental PDCs differed in terms of initial mass of the experiment, 250 kg for Experiment 1 and 1110 kg for Experiment 2, which in turn resulted in different flow dynamics. For Experiment 1, the temperature difference between the mixture and ambient temperature at the time of the experiment was 83°C, and 90°C for Experiment 2. Experiment 1 used the smaller hopper with a drop height of 7 m, while Experiment 2 used the larger hopper with a drop height of 5.5 m. The speed of sound based on ambient atmospheric conditions was 341 m/s for Experiment 1 and 337.1 m/s for

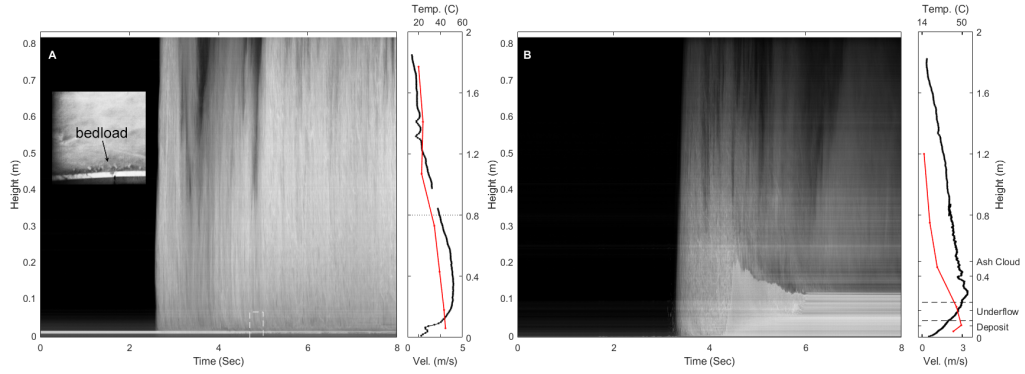


Figure 5.2: Overview of (A) Experiment 1 and (b) Experiment 2. (A) Depiction of the flow as a single column of pixels extracted from the overview cameras to depict the flow through time at a specific location (Profile 2 for Experiment 1 and Profile 3 for Experiment 2). The inset is a frame from the high speed camera depicting the bedload at the time highlighted in the box. To the right of this is the time averaged velocity for the time range plotted (black) and average temperature at different heights (red) for the experiment. (B) Depiction of Experiment 2 as a single column of pixels from the overview camera through time. To the right is the time averaged velocity and temperature through height for Experiment 2.

Experiment 2. The calculated density of the ambient atmosphere was 1.211 kg/m^3 for Experiment 1 and 1.2272 kg/m^3 for Experiment 2 (parameters listed in Table 5.2)

Dilute Experimental Flow (Surge)

Experiment 1 was predominantly an ash cloud surge propagating 29.3 m with a limited underflow confined to the initial few meters of the channel and a 0.5–2 cm-thick bedload region (Figure 5.2). At Profile 2 (3.9 m), the height of the flow reached a maximum of 2.3 m within the flow front or head of the flow, and the front flow arrived at 2.7 s with a velocity of 3.5 m/s. From the PIV dataset, the average velocity at Profile 2 peaked at 4.2 m/s at 35 cm.

Time series of velocity at a representative height of 70 cm, marking the center of the jet region of the ash cloud surge, which was characterized by several pulses (Figure 5.3). The thermal data from the closest height at 73 cm is also plotted in Figure 5.3. The flow height, PIV velocity, and temperature datasets all show oscillations with periods around 1–1.1 s. Within a defined window from 2.5 to 10.2 s from the triggering of the

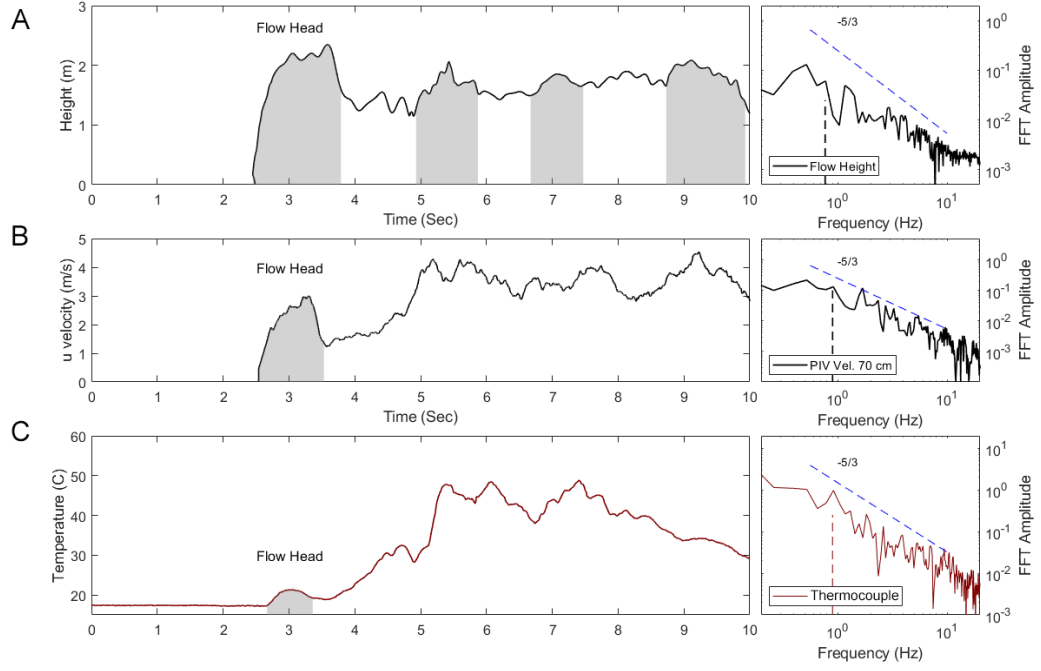


Figure 5.3: Results for Experiment 1, the surge experiment. (A) surge experiment flow height at Profile 2 at around 3 m down the channel through time with the flow head highlighted, with further pulses highlighted with alternating gray and white. On the right is the FFT within the processing window for the flow height dataset showing the characteristic frequency at the peak 0.77 Hz of a Kolmogorov decay (the slope of $-5/3$ is plotted above the FFT for reference). (B) Time series of the PIV-calculated downslope velocity at a height at 70 cm with the flow head highlighted. On the right is the FFT for the processing window of the velocity at 70 cm with a peak at 0.9 Hz. (C) Temperature recorded within the flow by the thermocouple installed at 73 cm with the flow head highlighted. On the right is the associated FFT for the processing window for the temperature dataset with a peak at 0.9 Hz.

system, the dominant frequency of the flow oscillations for all datasets centers around 1 Hz, with a characteristic height of 1.1 m, which are associated with a time - and depth-averaged velocity of 3.28 m/s.

Dense Experimental Flow (Pyroclastic Flow)

Experiment 2 consisted of an ash cloud surge that propagated 27.5 m, overlaying an energetic underflow that propagated outside the building to 19.4 m. At Profile 2 (3.8 m), the flow reached a maximum height of 2.2 m and arrived at 2.18 s with a velocity of 7.07 m/s (Figure 5.4). As with Experiment 1, PIV data were calculated from the high speed cameras. From this dataset, the maximum time-averaged velocity (per height) within the flow was 2.9 m/s at 29 cm at this location. The third underflow pulse was the most energetic and was tracked out to 17 m through the channel and up to 6 s. Compared with Experiment 1, the discharge was significantly higher and the discharge time was significantly shorter (Table 5.2). Owing to ash sticking to the window and the occurrence of an underflow, there was a limited time frame for which reliable flow velocities could be derived by PIV. However, within the first few seconds of the flow, the period of oscillations in the velocity was 1.17 s at 70 cm, and the dominant period of the oscillations in the underflow was 0.9 s. The oscillation of the flow height had a dominant period of 1.3 s. The characteristic height of the oscillations was 78 cm and the time and height averaged velocity within this segment of the flow was calculated as 3.43 m/s.

5.4.2 Acoustic Signals

Signal Identification

Acoustic signals in the infrasound dataset of Experiment 1 are only visible as an increase in amplitude with no significant impulsive features. Within the acoustic microphone data there are two clear impulses, the first being the click of the opening of the hopper at around 0.8 s and the signal associated with the flow entering the confined channel at around 1.7 s (examined in detail in Chapter 4). For Experiment 2, the signal in the

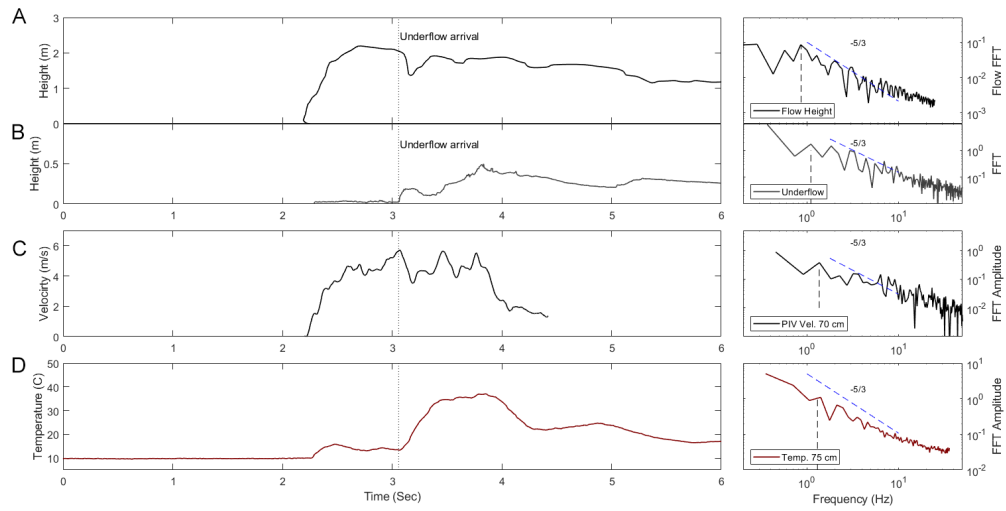


Figure 5.4: Results for Experiment 2, the PF experiment. (A) Flow height through time at Profile 2, around 3 m down the channel. The arrival of the underflow at the observation point is highlighted. On the right is the FFT for the flow height within the processing window with a peak at 0.86 Hz. (B) Underflow height at the same location as the flow height with its FFT on the right with a peak at 1.1 Hz. (C) Velocity calculated with the PIV at 70 cm with the location of the underflow arrival also highlighted. To the right is the FFT of the velocity data, where available, with a peak at 1.36 Hz. (D) Temperature recorded at 75 cm through time with the arrival of the underflow highlighted, and on the right the FFT with a peak at 1.4 Hz.

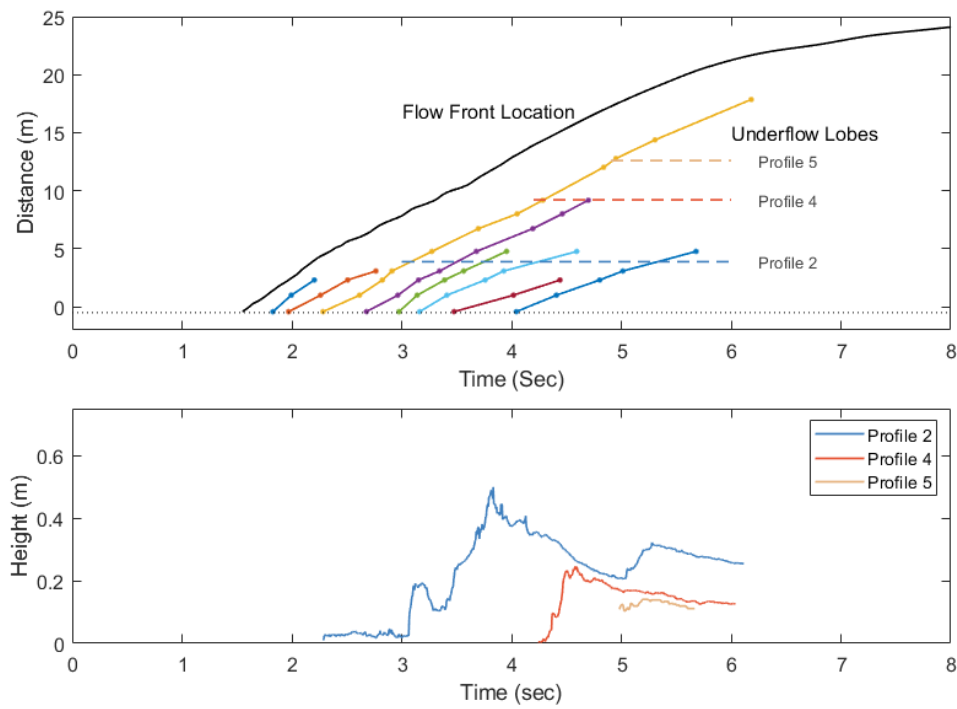


Figure 5.5: Experiment 2 had an energetic underflow with several identifiable lobes. (A) Distance of the flow front through time (black) along with lobes traced through the channel (colored lines) with the arrival at each profile location highlighted with a horizontal line. The number of lobes observable decreased with increasing distance down the channel. (B) Mapping of the underflow heights through time at the associated profile locations. The most lobes were captured at Profile 2, and the overall height of the underflow reduced with distance down the channel.

infrasound waveform data is more visible than Experiment 1. The infrasound sensors recorded an emergent signal followed by an overall increase in pressure with several higher amplitude peaks before a lowering of overall pressure back to the background amplitude before the experiment. The microphones picked up a large emergent signal with several pulses before decaying back to background.

For the FFT analysis, all datasets were resampled into the lowest sample rate for the collection of datasets, in this case 50 Hz. Additionally, we used identical time windows to allow for a quantitative comparison of FFT results. The reduced sample rate lowered the Nyquist to 25 Hz and below the frequency roll-off for the microphone data, which were therefore excluded. We chose the window as the time before the signal passed under the infrasound sensors, thereby isolating the signal to the approaching flow. This reduced contamination with signals from multiple directions. The infrasound FFT was compared to the flow height, thermocouple, PIV velocity (using the same height as the thermocouple data), and for Experiment 2, the time series of the thickness of the underflow at static observer locations. Owing to the consistent time window and sample rate, the FFT length and frequency were identical and could be compared with a standard cross-correlation (Figure 5.9).

Experimental Signal Characteristics

The acoustic characteristics for Experiment 1 (surge) were dominated by a low signal-to-noise. The mean recorded signal-to-noise ratio amplitude for the infrasound sensors generated by the surge was 1.26, with a maximum of 2.38. Even after pre-processing, the noise floor of the experiment was 0.41 Pa in peak to peak amplitude. The signal for Experiment 2 (PF) had a more significant signal-to-noise than did Experiment 1; the mean was 2.2 with a maximum of 15 in the infrasound sensors. The noise floor was slightly higher at 0.48 Pa peak to peak. The acoustic signals generated by Experiment 1 had a higher signal-to-noise in the audible range and were broadband, with energy up to 17 kHz (Figure 5.5). Within the infrasound sensor range from 0.1 to Nyquist at 500 Hz, energy was focused below 15 Hz with some energy across the band.

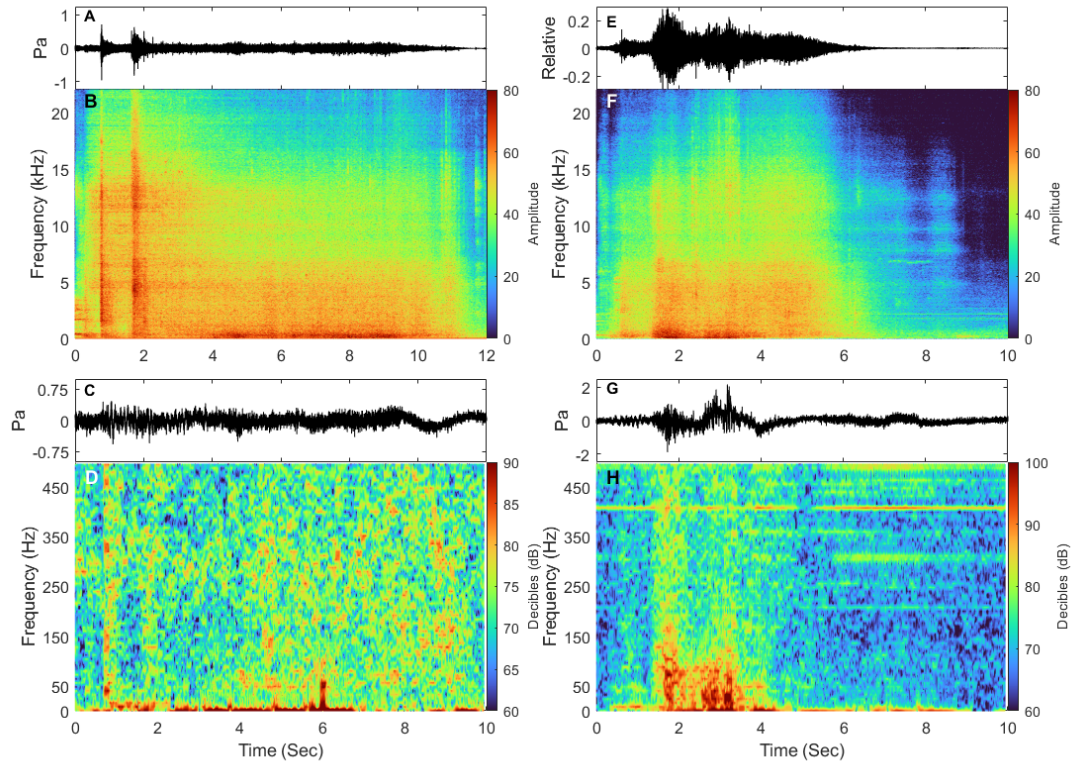


Figure 5.6: Characteristics of the waveforms from experiments 1 and 2, with noise reduction applied to the infrasound data. (A) Microphone waveform for Experiment 1 and (B) the associated spectrogram. (C) Infrasound waveform and (D) the associated spectrogram. Note that the triggering mechanism sounds are clearly visible in the microphone data where the air compressor turned on after 0.3 s and the hopper clicked open at 0.8 s; the pre-arrival signal reported in Chapter 4 was at around 1.7 s. The directional microphone had a higher signal-to-noise after the flow passed under the sensor, just after 3 s, and continued to detect the flow below the sensor. (E) Microphone waveform for Experiment 2 and (F) the associated spectrogram. (G) Infrasound waveform for Experiment 2 and (H) the associated spectrogram. Experiment 2 had a significantly higher signal-to-noise than did Experiment 1.

The processing window for Experiment 1 for the flow characterization was 2.5–10.2 s and within this window, the peak frequency for the infrasound was around 0.5 Hz, with another significant peak between 0.9 and 1.1 Hz (Figure 5.9). The peak frequency in the acoustic data in this time frame was around 177 Hz. The processing window for Experiment 2 was 1.62–10.6 s, which encompassed a portion of the post-event signal. The experiment itself was short enough that in order for a sufficient number of samples for the lowest frequencies, the time window had to be expanded beyond the signal. The peak frequency for the infrasound was focused below 150 Hz with some windows of full spectrum (0.1–Nyquist) signal. In the acoustic sensors, the energy was again broadband, with energy mostly below 17 kHz but a window of full spectrum (40–Nyquist 22 kHz) energy. The dominant frequency within the infrasound sensor data was 0.488 Hz with a secondary significant peak at 1.22 Hz in the PSD; for the same time period the peak in the FFT spectra was 1.3 Hz. The peak frequency in the directed microphones was 74 Hz (Figure 5.9).

Localization

The results from the localization methodology were mixed. The results from Experiment 1 infrasound did not result in windows of high cross-correlation. However, given the large sensor distance and the different sensors with different sensor responses, this is not surprising. The higher signal-to-noise for Experiment 2, and the sensor spacing of 1 m, contributed to a segment of time with high cross-correlation and signals consistent with locations within the channel. Between 0.5 and 4 s, the cross-correlation between the two infrasound sensors consistently exceeded 0.6 (Figure 5.7). Within this time window, the high correlation signal offsets between -2 to 2 samples were isolated as these values are consistent with signals within the channel. These results are consistent with several moving sources within the channel within this time window.

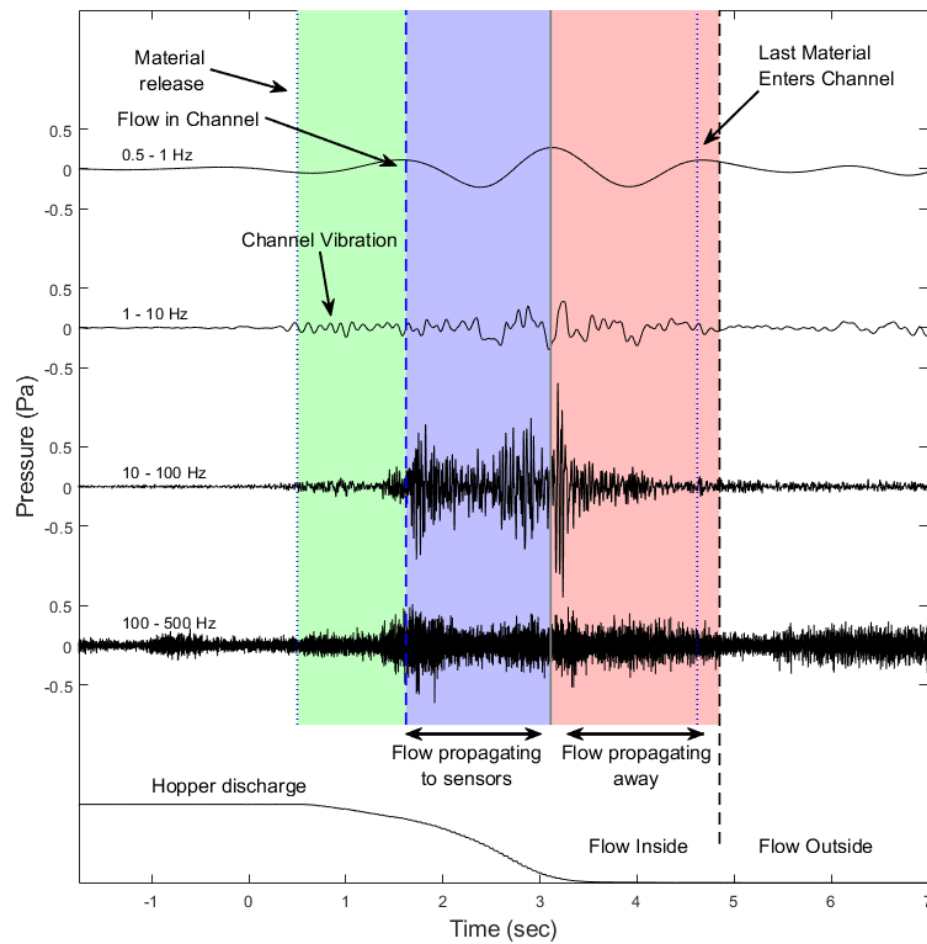


Figure 5.7: Example sequence of signals from Experiment 2, which had a higher signal-to-noise ratio than did Experiment 1. The data were filtered into decades between 0.5 and 500 Hz. Within the highest frequency decade, before the trigger time (0 s), the vocal call alerting to the triggering is visible. The green segment is the time frame between the material release from the hopper and the fall into the channel. This is followed by the pre arrival signal (within the green) and entering the channel, propagation as a flow (in blue), passing under the sensor (red), and the flow passing outside the building. The vibration of the channel is highlighted, and hopper discharge is plotted for reference.

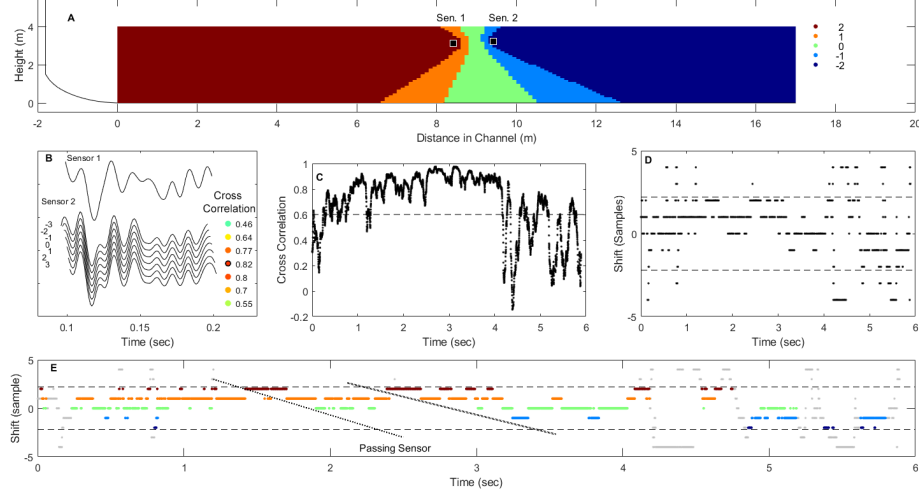


Figure 5.8: Localization method and results for Experiment 2. (A) Over a grid in the channel, each grid point is colored by the calculated offset. At any point within a 2D plane of the channel a signal generated and recorded by the two sensors (black squares) will have a delay time based on their distance and the speed of sound. The travel time offsets were converted into samples based on the sampling rate of the data. For example a signal generated at distance 0 in the channel and a height of 45 cm traveled to the sensors and arrived at sensor 1 (up slope) first (positive) and arrived at sensor 2 with a delay of 2 samples or 0.002 s later. (B) Illustration of the shifting and cross-correlation calculation. A time segment of sensor 1 is isolated. Within the same time frame, sensor 2 is shifted by 1 sample each and the cross-correlation between the two sensors is calculated. In this sample you can see that the cross-correlation peaks at no shift with a cross-correlation of 0.82. (C) Time series of cross-correlation through time of the dataset with a threshold of 0.6. (D) Associated shift in samples for the cross-correlation plotted in C with the threshold of -2 to 2 sample shift. (E) Full dataset with only the results that are over 0.6 cross-correlation and between -2 to 2 samples colored. Highlighted is a section where the signal appears to move towards the sensor.

Table 5.4: Calculated parameters from the two experimental flows used within the study

	Nominal Value	Experiment 1	Experiment 2
Characteristic Frequency (Flow height)	1 Hz	1 Hz	1.36 Hz
Characteristic Height	1	1.1	0.78
Characteristic Velocity	3.5	3.28	3.43
Strouhal Number	0.3	0.3	0.31
Time Window		2.5–10.2 s	1.62–10.6 s

5.4.3 Spectral Comparisons Between Datasets

To constrain and quantify the similarities in spectra between different datasets, we calculated the cross-correlation between each infrasound sensor and the FFT of the different datasets. This allowed for a quantification of which datasets were most similar to the infrasound data. Once selected, we used peak picking of the FFT results to identify specific frequencies between datasets that could be further investigated in terms of source dynamics. From this analysis, the highest correlation between infrasound FFT and other datasets between experiments was consistently the upstream flow height. For Experiment 1, the cross-correlation between the infrasound FFT and the flow height dataset was 0.79, and for Experiment 2 the cross-correlation between infrasound and flow height was 0.94. This high correlation suggests that this was the most likely source of the infrasound signals. The cross-correlation results for the flow height and thermal couples are plotted in Figure 5.9, while the cross-correlation between the infrasound and PIV height profiles were significantly lower and have been omitted.

5.5 Discussion

Previous studies identified two key characteristics of the signals generated by PDCs: a broadband emergent signal, that they originate from moving sources, and that they exhibit a Doppler shift. The Doppler shift arises from the moving sources relative to the sensor location. Within the experimental facility there was insufficient geometry to detect a Doppler shift within the experimental dataset. The literature also does not distinguish between types of PDCs or differences in their signals. However, Ripepe

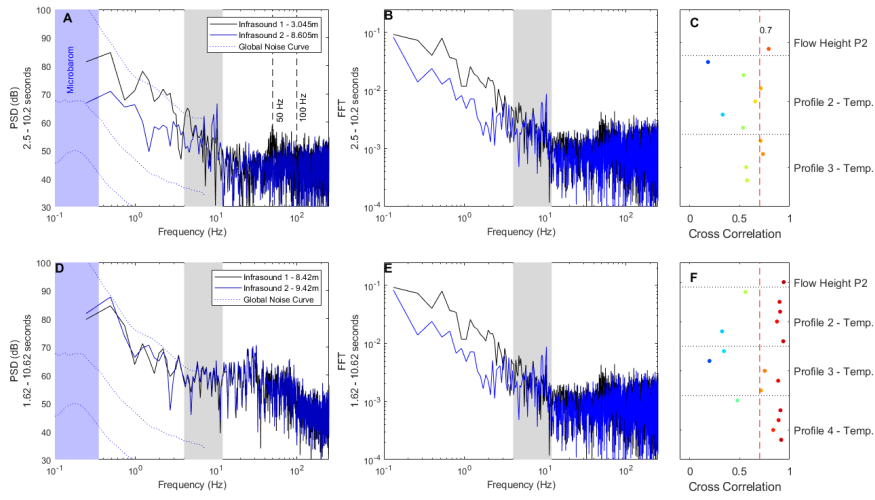


Figure 5.9: Calculation of the infrasound power spectral density (PSD) and FFT for Experiment 1 (A,B) and Experiment 2 (D,E). The PSD calculations (A,D) include the global noise curve (dashed lines) for low medium and high ambient atmospheric noise expected for infrasound stations, along with the microbarom band highlighted (in blue) and the 5–10 hz range associated with the channel and room (in gray). This gray section is also highlighted in the FFT results (B,E). The FFT for the infrasound was cross-correlated in the frequency domain with the other datasets including the flow height, temperature, and PIV velocity within the flow for Experiment 1 (C) and Experiment 2 (F). Consistently, the flow height ahead of the sensors showed the highest correlation in the frequency domain, along with temperature channels with a general trend to higher cross-correlation at higher elevation in the flow.

et al. (2010) states that "According to preliminary field observations [...], we speculate that the frequency of the dominant spectral peak may scale inversely to the size of the flow [...]" We also observed this relationship in signals produced by the intrusion of an experimental PDC into the channel (Chapter 4), a signal which was not clearly differentiated by Ripepe et al. (2010, 2009); Delle Donne et al. (2014). The following discussion differentiates between the two end member PDC types: pyroclastic surges and pyroclastic flows.

5.5.1 Surge (Dilute)

The surge experiment, Experiment 1, was characterized by a low signal-to-noise. The highest amplitude signal was generated by the displacement of the air in the channel due to the intrusion of the flow into the confined area (discussed in Chapter 4). There was also a signal generated by the vibration of the channel due to materials' movement through the structure. This was a clear peak between 5 and 12 Hz with the largest peak around 9–10 Hz. There was an additional peak around 3 Hz that may have been related to a room mode. In characterizing the flow, the dominant frequency of the turbulence at the front of the flow was between 0.8 and 1 Hz, and this frequency peak was identified in the infrasound spectra. It is likely that the source of the sound generated from the surge was related to the interaction of flow boundary shear with the ambient air. However, limits in sensor design location and signal-to-noise did not allow further constraining the location of the signal along the flow surface. The experimental surge suggests that one of the sources of infrasound within the field data was the shearing of the flow boundary with the atmosphere.

5.5.2 Flow (Dense)

The pyroclastic flow experiment, Experiment 2, was characterized by a high cross-correlation between sensors and a higher signal-to-noise than that of Experiment 1. This allowed for the localization of the signal to areas within the experimental channel. While these calculations are not sufficient to obtain a definitive source location of the

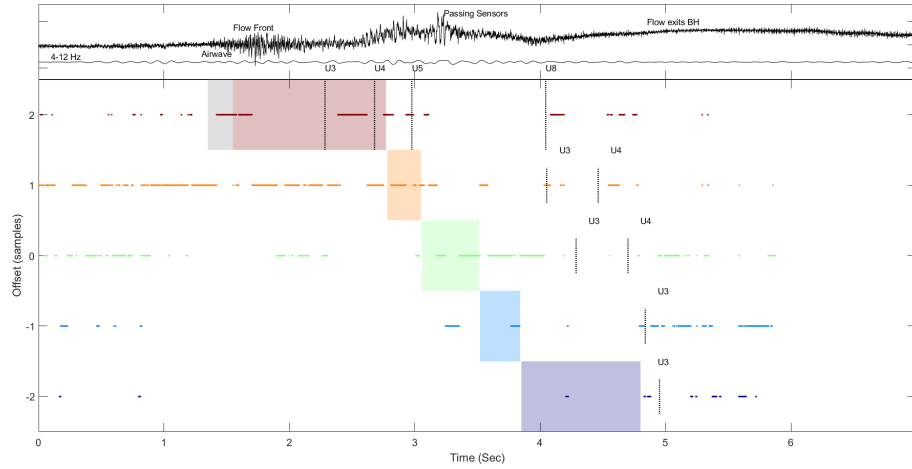


Figure 5.10: Combining the location of the flow (colored in rectangles by the anticipated signal offsets) and the 2D localization data, the relative timing between signals and location can be compared. In the top panel is the annotated signal of the infrasound from Experiment 2. The unfiltered data is plotted on top with an airwave associated with the displacement of air in the channel by the intrusion of the flow. This is also colored with a gray box in the plot below. Below this waveform is the 4–12 Hz band showing the vibration of the channel. Below is the output of the location processing. The location of the flow front colored and plotted by the associated inter-sensor sample offset is highlighted to show where the plotted data agree with this location. The location of the different underflow lobes are also plotted as a vertical dashed line and numbered where their location agrees with the localization results. The underflow lobe 3 appears to have had recordable signal through the channel as well as the flow front. While this method is not likely to be well suited to distinguish between multiple sources, it appears that there were several sources that moved down the channel past the sensors.

source of the signal, they suggest multiple pulses passing the sensors. In Figure 5.10 the sample offset consistent with the flow front location through time has been highlighted along with the calculated signal offset between the observed flow front in the channel and the sensors. The location of the most energetic underflow pulses are also illustrated. The data suggest that while the flow front was a major source of the signal generated, it was also likely that the shearing of the ash-cloud surge (ACS) against the atmosphere continued to be a source through time; when there was an energetic underflow, the reaction of the ACS to this passing could also be detected, implying that like the surge experiment, the source of the infrasound represented the interaction of the flow boundary with the atmosphere.

5.5.3 Theory vs. Experimental Results

Source

At the initiation of this study, the understanding of acoustics from PDCs was dominated by the following: consistent reports of a lack of signal in the acoustic band, consistent infrasound band detections of broadband, moving sources with an observable Doppler shift, and an assumption that the source of the infrasound was due to turbulence at the flow front. While we were not able to observe a Doppler shift within our experiments, we were able to identify a moving source and a frequency consistent with the characteristic frequency of the turbulent structures in the ACS component of the flows. We were also able to identify additional sources (not just the flow front) of infrasound, through multiple moving sources in Figure 5.8, and the strong correlation in the frequency domain between the infrasound and flow height data. This updated understanding would suggest that the dominant mechanism of infrasound recordings from PDCs are due to the shearing of the outer flow boundary with the ambient air, which is dominated by, but not constrained to, the initial turbulence of the flow head. Owing to the constraints of reducing the localization to a 2D problem, we were not able to take the location question further.

Frequencies

One of the dominant frequencies of the flow signal can be attributed to the characteristic period of the turbulence-induced oscillations driven by the flow head. This frequency is also referred to as the characteristic frequency of turbulence. This frequency is associated with the most energetic and coherent turbulence structures of the ash-cloud surge region of the flow within the experimental PDCs. This turbulence is generated through a combination of solid shear with the substrate, and free shear with the ambient air (Brosch et al., 2022). Brosch et al. (2021) compared the turbulence structures to natural PDCs and powder snow avalanches through scaling of the Strouhal number, Str :

$$Str = f \frac{L}{U} \quad (5.1)$$

where L is the characteristic thickness, U is the characteristic velocity of the PDC, and f is the characteristic turbulence frequency. The calculated value for Experiment 1 was 0.3 and that for Experiment 2 was 0.31, which closely matches the typical value of $Str \cong 0.3$ associated with high Reynolds number multiphase and continuum fluid flows (eg. Bursik and Woods (1996); Cerminara et al. (2016); Crow and Champagne (1971); Strouhal (1878); Turner (1969). Figure 5.11B illustrates this relationship for frequencies ranging from 0.01 to 100 Hz, indicating the wide range of frequencies, velocities, and thicknesses. Expected frequencies due to flow oscillation at the frequency of the most energetic eddies can be constrained further to PDC flow characteristics by considering the characterization of the propagation of particle-laden gravity currents through the balance of the inertial and gravitational forces (e.g., Brosch et al. (2022); Bursik and Woods (1996); Huppert and Simpson (1980)). Here, we considered the non-dimensional velocity, the Froude number Fr' , which in its non-Boussinesq form is defined as:

$$Fr' = \frac{U}{\sqrt{gL \frac{\rho_c - \rho_A}{\rho_A}}} \quad (5.2)$$

where g is the acceleration due to gravity; ρ_C and ρ_A are the density of the PDC and the surrounding ambient air, respectively; U is the velocity; and L is the length scale. Fr' takes a value of $Fr' \sim 1.19$ (Huppert and Simpson, 1980). We can then combine equation 5.1 and equation 5.2 to estimate the characteristic frequency as a function of flow velocity alone. For natural cases, we can then use a nominal range of flow densities from 2.5 to 10 kg/m^3 (based on Breard et al. (2015); Brosch et al. (2021)) to constrain the frequency range (Figure 5.11). Combining this density range with the velocity range, constrained by natural ranges of characteristic PDC velocities, the expected characteristic frequencies were below 1 Hz and down to 0.05 Hz. In a recent study by Syarifuddin et al. (2022), the velocity of a PDC at Sinabung was measured at 60 m/s, which would result in a frequency range of 0.075–0.5 Hz. However, given the range of

expected frequencies for PDCs from 0.05 to 1 Hz, there is overlap with several known infrasound sources, like the microbarom and expected dominant frequency ranges of both short impulsive and large sustained volcanic eruptions (Dabrowa et al., 2011); for the low frequency range, there may also be impacts due to the response of the specific instruments.

Speed of Sound and Attenuation within the Multiphase flow

Given that PDCs are not a homogeneous medium, but a multiphase medium, there are changes in the relationships of the speed of sound, dispersion, and attenuation. In a multiphase medium, counterintuitively, as the volume fraction of the particles increases there is an initial drop in the speed of sound. However, this is also frequency dependent and related to the relationship between the wavenumber and the median size of the particle radius. When the non-dimensional value of the product of the wavenumber (k) and the particle radius (a) ka is close to 1 or more than 1, the decrease in speed of sound is no longer present and the speed of sound increases as expected (Atkinson and Kytömaa, 1992). When ka is below 1, there is a decrease in the speed of sound dependent on the volume fraction of the two phases of the flow (Atkinson and Kytömaa, 1992) and their physical properties. This can also lead to dispersion of frequency within the medium. For PDCs, this would apply to high frequency signals within a flow with large particle, when the wavelength is no longer significantly longer than the size of the particles.

Attenuation studies have shown that for multiphase media, there is significant scatter between theoretical attenuation and measured experimental results. However, there also appears to be a relationship with the solid fraction and with frequency (Brennen, 2005). Thus, any signals generated within the interior of a PDC or traveling through the PDC are subject to variable velocity and attenuation, which depends on the size of particles, concentration of particles, and physical properties of the fluid and particles. Atkinson and Kytömaa (1992) illustrates that at higher ka values, the dimensionless attenuation is significantly greater than lower ka . This could be a factor in why there are

reports of PDCs being “silent” (Global Volcanism Program, 1986; Loughlin et al., 2002; Perret, 1950), as the acoustic range of signals is more likely to be disproportionately attenuated.

Wohletz (1998) states that the interaction between the reduced speed of sound, flow velocity, and topography “suggest that sound can be effectively damped within a moving surge, [... and] where surges produce little or no sound, they may have their highest destructive potential”. Survivors of a deadly PDC-producing event in 1997 at Soufriere Hills Volcano state “... *it did not give any sound. If I had heard some sound I would have moved away earlier*” (Loughlin et al., 2002) highlighting the need for early warning systems for those living and working within runout regions.

5.5.4 Implications for Monitoring

The most significant addition to the knowledge of PDC infrasound is that the signal generation is not limited just to the flow front. It is possible that a single event could produce several moving sources generated by different pulses of the ACS or the response of the ACS to an energetic underflow. Owing to this updated understanding on the source of infrasound, the location of the moving source may not necessarily be the flow front; therefore, any calculated flow front velocity should be constrained to the initial moving source and not subsequent arrivals. Additionally, this study did not address how signal generation is impacted by changes in topography during propagation. This initial study has contributed to the understanding of PDC-generated infrasound signals; however, it should also be noted that field studies to validate these findings are essential to understand how these results can be applied to field studies.

5.5.5 Future Work

These experiments were sufficient for an initial study of the acoustic signature of PDCs. However, due to several of the complications reported here and the limited resources and number of experiments, additional work is required to address our initial questions and questions that arose during the research. One important question relates to the

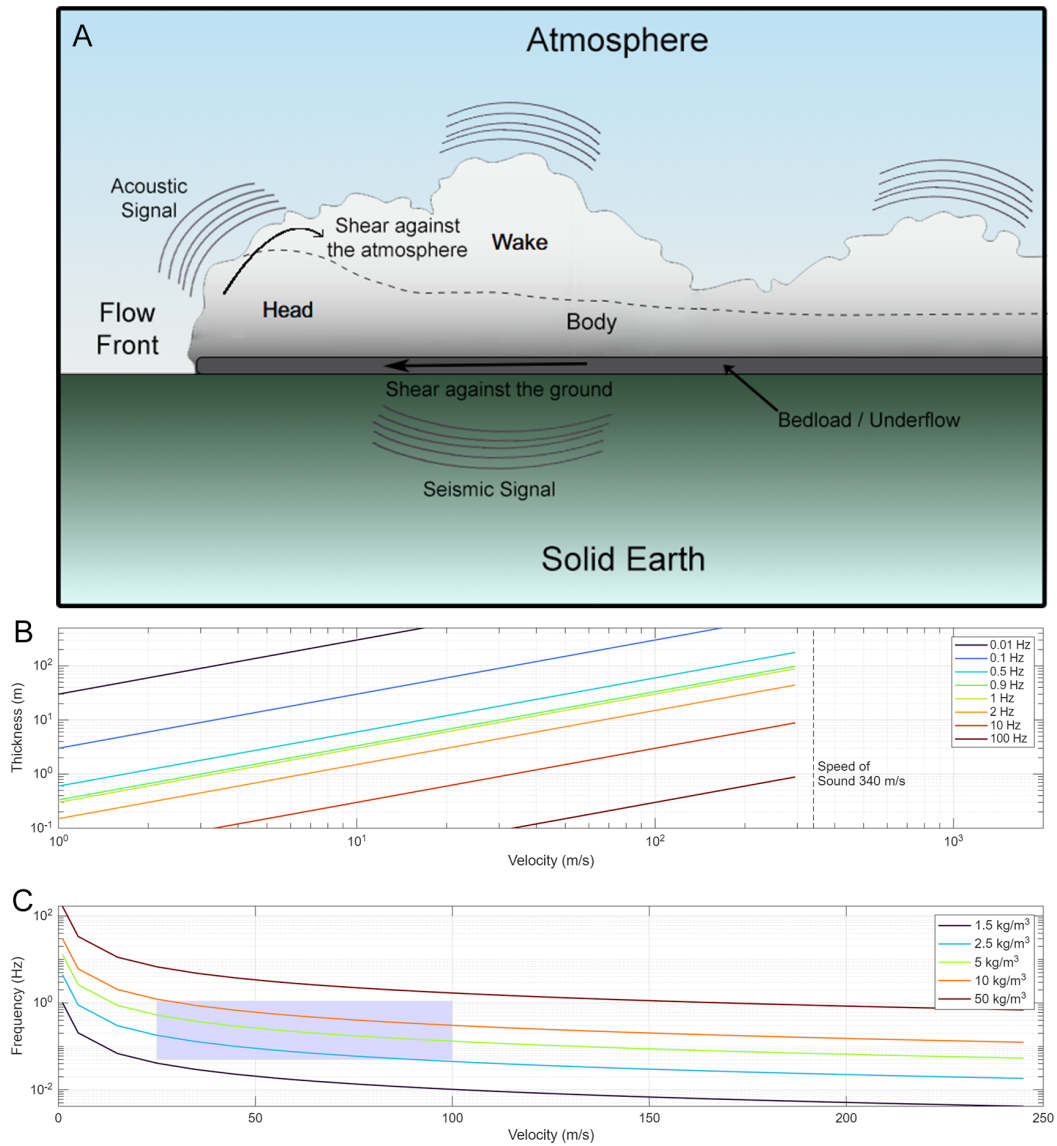


Figure 5.11: (A) Conceptual model of the generation of acoustic signals from a propagating PDC. The flow front and head of the flow are the most energetic source of shear against the atmosphere, and signals can be generated all along the flow surface. The bedload or underflow of the flow shears with the solid Earth generating the seismic signals that are recorded. (B) Relationship between the characteristic length L , velocity, and frequency can be explored through setting the Strouhal number at 0.3. The frequency is a tradeoff between the length and velocity. (C) Combining the Froude number and Strouhal number yields the relationship between the density, velocity, and frequency. The gray box includes typical ranges for PDCs. This plot also illustrates that the characteristic frequency decreases with increasing velocity.

partitioning of energy from the coherent turbulent structures within the ash cloud surge region of PDCs into seismic (ground) or acoustic (air) phases, and how signals generated inside the flows propagate.

5.6 Conclusions

Observations of PDCs within monitoring infrasound data are well known (Allstadt et al., 2018); however, the source of the infrasound was not well understood. This first-of-its-kind study utilizing experimental PDCs aimed to address this lack of understanding. Knowledge of the source of PDC infrasound is essential if infrasound is to be used as a tool to obtain direct measurements of propagating flows and to study their dynamics. This study has shown that while the front of the flow, theorized to be the source of the infrasound, is indeed an energetic source of infrasound; however, it is not the only source of infrasound. In a previous study (see Chapter 4), the initial intrusion of the PDC into an ambient atmosphere generated a relatively significant signal. Along with this signal, the shear of the outer flow boundary against the atmosphere as it propagated was the main source of infrasound of the propagating flow. The flow front can indeed be the dominant source of infrasound; however, it is not the only source. For larger denser flows with an energetic underflow that propagates behind the flow front, the reaction of the overlying ACS can generate additional signals. Thus, the moving sources from PDCs cannot be assumed to be solely due to the flow front propagation, and several moving sources may be present within a signal propagating flow. A set of well characterized field datasets are required to further test this hypothesis; however, the literature is limited and while these datasets may exist within monitoring data, they have not been published at this time.

Chapter 6

Thesis Synthesis and Conclusions

This chapter reviews the main findings of this thesis, discusses them in the context of the research aims, and examines the implications for further research, early-warning systems, and instrumentation. Finally, this chapter outlines potential future directions for the study of PDC-generated infrasound.

This thesis aimed to characterize the acoustic signatures of PDCs for use in the context of both research and volcanic early warning and monitoring systems. Given the difficulty in obtaining field measurements of actively propagating flows, infrasound has been suggested to fill this gap. However, there was limited understanding of the source of the observed infrasound signals and variety of signals generated. This thesis addresses this issue by using experimental PDCs to characterize the wave field they produce as well as comparing these observations with case studies. In addition, this thesis also expands the diversity of PDC-related infrasound sources in the literature based on a case study of the Mount St. Helens lateral blast.

6.1 Thesis Objectives

This PhD research focused on the acoustic signals generated by PDCs. While such signals have been reported since the beginning of the volcano-infrasound renaissance in the 1990s (Oshima and Maekawa, 2001; Yamasato et al., 1993; Yamasato, 1997), there

has been limited research into the physical source of these signals, revealing a gap in the understanding of volcanic infrasound. In addition to this research gap, infrasound has been proposed as a method for obtaining direct measurements of propagating PDCs in order to better constrain their poorly constrained internal flow structures and dynamics. However, understanding the mechanism responsible for generating these signals is essential if they are to be used as reliable field constraints in other research.

This research was guided by three main research aims:

1. Determine the state of field-based understanding of audible and infrasonic signal generation by and within PDCs using published case studies. Assess whether there is an example of a well-characterized PDC event with complementary infrasound data that could complement existing PDC-infrasound studies.
2. Design and conduct a series of PDC infrasound experiments. Investigate if, similar to other analog natural events, experimental PDCs generate infrasound signals that arrive before the flow, and how these relate to constrainable physical characteristics of the PDC or PDC generation.
3. Characterize the source of infrasound generated by PDCs, with a focus on the moving signals reported in the literature.

These research aims were addressed in three research papers represented as Chapter 3, Chapter 4, and Chapter 5. The first research objective revealed that published studies on PDC infrasound are limited to dome collapse events, with and without associated eruptions. A survey of potential case studies found that one of the major issues was overlap of characterized events and infrasound installations, followed by data access issues. The case study of the Mount St. Helens May 18, 1980 lateral blast presents a very well characterized PDC, with associated barometer measurements and eyewitness accounts describing pressure phenomenon. The second research objective was accomplished with three large scale experiments within the PELE facility, and taking advantage of other experiments with appropriate instrumentation. Identification of several different signals of both propagating acoustic waves and dynamic pressure

signals expanded the known signals produced by propagating PDCs. The results of this objective were reinforced by the detailed case study for objective 1. The final research objective focused on the signal that had been widely reported in the literature and utilized specially designed experiments to interrogate the signal character and source. This study has improved our understanding of the signals recorded by monitoring networks.

6.2 Case Study – Mount St. Helens

The Mount St. Helens case study provided critical insight into the signals produced by a large scale lateral blast. In the context of renewed scientific interest in acoustic-gravity waves following the 2022 Hunga eruption, the identification of the globally recorded Mount St. Helens pressure signal as a Lamb wave produced by the lateral blast with an inclined source is significant. This finding demonstrates that volcanic eruptions can generate a broader diversity of atmospheric wave types than traditionally assumed and underscores the need to revisit long-standing interpretations of eruption acoustics. The Mount St. Helens analysis also revealed substantial pressure amplification ahead of the PDC front, with the amplitude capable of felling trees in advance of the flow. Importantly, this pre-front pressure impulse had not been reconstructed from post-event deposit mapping alone, highlighting the value of integrating multiple datasets, including geophysical and eyewitness accounts, into physical volcanology.

Recent studies of major eruptions have revealed a diversity of atmospheric wave types, including additional examples of Lamb waves, a type of surface wave. While such wave types and frequencies (acoustic gravity waves) are typically attributed to plume dynamics, the Mount St. Helens pressure record reveals a unique radiation pattern that suggested a different source. Chapter 3 constrains this large acoustic gravity wave at Mount St. Helens to a brief interval containing the large landslide and lateral blast. Although the age of the dataset and associated reduced timing resolution prevents distinguishing between these two sources, there is currently no example of a

large landslide producing an acoustic gravity wave in the literature, suggesting that it was the lateral blast that produced the Lamb wave. As Lamb wave attenuation and propagation differ from those of acoustic waves, their presence underscores the need to expand the wave types modeled in volcano infrasound. A remaining question posed by this research is whether atmospheric surface waves can also be produced at a higher frequency.

Large pressure transients are known to pose significant hazards to human health, structures, and the natural environment; however, existing threshold values primarily derive from shock-wave behavior, which differs from the slower rise time signals recorded at Mount St. Helens. Dynamic pressure is often inferred from damage proxies, such as tree fall, and these complex pressure histories are reduced to single values, which may not reflect heterogeneous pressure histories and how that impacts the proxies. In addition to highlighting the potential difference in dynamic pressure thresholds depending on rise time histories, this also has implications for barotrauma at volcanoes. Historical reports, such as those of the 1883 Krakatau eruption, show that barotrauma has the potential to impact a large number of people. However, the thresholds in barotrauma research are also based on the sharp rise time assumption, which since the human body can tolerate graduate pressure changes more gradually than abrupt ones, highlights another knowledge gap. It appears that this ability to tolerate the same pressure over a longer range of time prevented more widespread pressure damage (e.g., broken windows) in the surrounding area, and prevented widespread eardrum ruptures. Rise time therefore introduces a variable not taken into account for the pressure thresholds used in the field to estimate dynamic pressures within PDCs.

6.3 PELE Pre-Arrival Signals

Chapter 4 explores the pressure signals recorded ahead of experimental flows produced in the PELE facility. Two distinct signals were identified: (1) a displacement signal that scales with the momentum of the material entering the channel, and (2) a dynamic

pressure signal generated by the acceleration of the atmosphere ahead of the flow front. Although these observations were made in a controlled environment, there is compelling evidence that these signals also occur in the natural environment.

The first pressure signal arises from atmospheric displacement during flow initiation. The acoustic power of this signal increases and its dominant frequency decreases with increasing momentum as the material enters the channel. This behavior is consistent across several natural scale events, demonstrating that the signal is present in real PDCs and that the experimental relationship holds. This displacement mechanism also aligns with the Lamb wave produced at Mount St. Helens, described in Chapter 3. Owing to this early arrival and strong link to initial flow conditions, this signal has significant potential for exploitation for early warning applications and constraining source conditions for PDC research.

The second signal is a substantial dynamic pressure with an elongated rise time immediately preceding the arrival of the flow at the sensors. It is interpreted as the pressure due to the acceleration of the atmosphere up to the velocity of the oncoming flow front. This finding indicates that hazardous dynamic pressure exists not only at the moment of flow impact but also ahead of and around the margins of the PDC. A similar phenomenon was observed at Mount St. Helens where eyewitness accounts describe trees being knocked down ahead of the flow front; (Waitt, 2014) report a complex, rapidly changing pattern of “winds” before impact. These observations suggest that flow–atmosphere interactions are far more complex in natural settings than can be reproduced in the confined experimental channel.

6.4 PELE Flow Signals

The generation of infrasound by PDCs is well documented (Allstadt et al., 2018); however, the physical signal source is not well constrained or understood. By utilizing experimental PDCs, assumptions about signal generation in PDCs could be tested.

Despite numerous challenges due to sensor number, design constraints, and signal-to-noise issues, several key observations were made. The first is that the main source of the infrasound observed from PDCs is generated at the boundary of the flow with the atmosphere. The shearing of the flow front against the atmosphere and solid Earth leads to oscillations in the flow that generate infrasound. While the flow front may be the most energetic of these sources, signals are generated all along this boundary. Secondly, while the signal is a moving source, the flow front is not the only signal, and multiple moving sources can be observed within a single event.

This research has confirmed that a dominant source of infrasound from PDCs is the turbulent flow front, but has also highlighted that this is not the only source. Instead of being just the front of the flow, the source is the interaction of the flow edge with the atmosphere. This research also shows that the frequency content of this signal can be tied to the characteristic frequency of the turbulent structures of the PDC, thus giving a window into the dynamics of the flow. The source of the flow boundary will be the same across the spectrum of activity, as ash cloud surge components are found in both dilute surges and overlying energetic underflows in denser flows.

The findings of multiple moving sources within a single flow have implications for the field measurements of flow front velocities. Infrasound can be used to track moving sources with the installation of arrays and the calculation of signal back azimuths through time. However, while the source of infrasound from the flow is moving, it is not confined to the front of the flow. While the signal is generated by the interaction of the flow edge with the atmosphere, dynamics within the flow and the propagation of an underflow can influence this boundary. A more constrained dataset would be required to determine if there is an observable difference between a signal generated through the flow front or the reaction of the flow to a passing underflow. However, it is important to be aware that a single event could have multiple moving sources and therefore only the initial moving source should be used to calculate a flow front velocity in the field.

6.5 Wider Implications of the Main Findings

6.5.1 Implications for Monitoring and Early Warning Systems

As with the seismic record of an eruption or PDC, there is a need to differentiate the signal of a PDCs from the generation source signal. Based on the results presented herein, a revised description of PDC-generated infrasound is as follows:

- a PDC signal is comprised of two signals: flow initiation and flow propagation;
- the initial intrusion into the atmosphere generates a signal that can be used to constrain an initial size parameter of the flow through amplitude and frequency, where larger sources generate a lower frequency signal with a higher amplitude;
- there is an additional non-acoustic pressure signal that is generated by the acceleration of the ambient atmosphere ahead of the flow, which is likely to be confined to the actively propagating front;
- the propagating flow generates a signal at the boundary with the atmosphere;
- the flow signals are broadband moving signals that are likely to only extend into the lower range of the audible spectrum;
- the characteristic frequency of the turbulent flow front is recorded in the infrasound;
- only the initial propagating front can be constrained to calculate velocity; subsequent signals may be not be new flows but pulses or aspects of the previous flow, like the passing of an energetic underflow;
- for very large signals (like the Mount St. Helens later blast), the intrusion signal could be a wave in the atmosphere that is not a p-wave, and could generate an atmospheric surface wave, as in the case of the Mount St. Helens Lamb wave.

The implications of these changes for the characterization of PDC infrasound signals could lead to the development of an early warning system. The initial signal generated

by the intrusion into the atmosphere is an important signal for early warning; therefore, the ability to detect this signal and have a constraint on size is important. Vulnerable populations live and work in the paths of potential PDCs at numerous volcanoes, especially those at risk from dome collapse events. For example, the PDC eyewitness accounts described in Loughlin et al. (2002) were from a variety of people, including those who knowingly stayed in the exclusion zone of Soufriere Hills Volcano, those who entered the exclusion zone during the day for various reasons, including tending to their crops and livestock, and those who regularly returned for other reasons, including to watch the volcano. The ability to generate early warnings for events like dome collapses is important for communities like this, especially where farmers are returning to their land despite an evacuation.

No clear differentiating signal characteristic was found that could easily differentiate a PDC signal from other types of signals generated during an eruption, with the exception of it being a moving source. Therefore, array configurations of sensors with the ability to track signals are essential for the positive identification of infrasound signals from PDCs (Figure 6.1). Potentially, the combination of an array with broadband seismic data could differentiate between a new flow front and a propagating underflow through the further understanding of energy partitioning of different types and portions of flows. Given the multiple potential sources within a flow, only the initial moving source should be taken to be a flow front.

The dynamic pressure pulse in front of the flow could also be the subject of early warning systems. Given the proliferation of small, low-cost sensors, a pressure sensor could be placed within the flow path, with the intention of sending an alert when there is a large increase in pressure followed by destruction of the sensor. More study and development would be required.

Currently, Lamb waves are known to be generated in the acoustic gravity wave frequency spectrum. However, this does not exclude atmospheric surface waves from potentially being generated at higher frequencies. As these waves have a different propagation velocity, it is important to identify the type of wave before using timing

information in reconstruction. While this is likely to be negligible in most cases, it is something that could use further work.

6.5.2 Implications for Additional PDC Experiments

The frequency range recorded within the experiments is such that future experiments could utilize additional tools from the field of acoustics. One recent tool that could greatly improve the experiments is the use of microphone arrays combined with video, in what are now called “acoustic cameras”. These systems use large N microphone arrays and beamforming to record sound, identify the source of that sound, and layer these results with video, thereby highlighting the location of the sound source. One example is CAE software and systems, with the company offering several systems that categorize sound source localization (<https://www.cae-systems.de/en/products/acoustic-camera-sound-source-localization.html>). These are marketed for the location of noise sources in industry, environmental noise, or wildlife studies.

Additionally, these experiments highlight the need for a low noise floor in the instruments and a higher sample rate. While the signal is broadband, it does extend into the audible range, and given the length scales of the experiments, more samples would improve the spatial resolution of the solutions. These experiments also highlighted that a temperature effect reduction strategy should be implemented for sensors within the channel, or sensors with a reduced temperature response should be chosen. For future research, experiments incorporating the following should be considered:

- grounding of the recording system;
- updated digitization and increased sample rate;
- temperature response reduction;
- increased number of sensors in tight arrays;
- increased number of sensor array locations.

6.5.3 Applications and Implications for Field Measurements of PDCs

A major inspirations for this research project was the desire to obtain flow parameter measurements from infrasound in the field. Based on the results, the following recommendations are suggested:

- use array configurations to locate where a signal is being generated;
- only use the initial moving source to calculate flow front velocity;
- frequency and acoustic power of the source generation signal (intrusion into the atmosphere), if isolated from other signals, can be used to at minimum to give the relative size of events in the field;
- frequency content of the flow contains information about the characteristic frequency of flow turbulence, but this may not be the most energetic peak;
- the dynamic pressure rise in front of a flow can also be used to calculate flow front velocity.

Given that a specific signal characteristic unique to PDCs was not identified, the moving source and location of a signal is essential information for differentiating PDC signals. Therefore, it is recommended that array installations are used for detecting and characterizing PDCs with infrasound. Arrays also provide the ability to track a signal throughout the channel; however, as discussed in this thesis, only the first arrivals should be used to calculate a flow front velocity as any subsequent propagating front may or may not be a new flow. If isolated from other signals (e.g., eruptions), the initial intrusion into the atmosphere can be used to constrain the relative sizes of events, although this should only be used as a relative measure until further studies can be completed. The frequency content of the moving source contains the characteristic frequency, although care must be taken in identifying this within the other signals. If recorded, the dynamic pressure at the flow front can be used to calculate the flow front velocity, and the reverse is also true, where the flow front velocity can constrain the initial pressure increase.

These recommendations could lead to field-based measurements of relative event size, which could be further constrained with additional ground truth data, flow front velocities, and the characteristic frequency of the flow. While several challenges remain for field measurements, infrasound does offer the chance for field measurements regardless of accessibility and visual conditions. The location of sensors should be motivated by the application of interest (research data sets vs. monitoring), and array configurations are needed to confirm signal source. As energy is likely partitioned from within the flow into the ground and atmosphere at varying rates, it is advisable to also co-locate a broadband seismometer with any infrasound array.

6.5.4 Limitations

There are several existing limitations with PDC infrasound. The first and most significant is the lack of a diverse field dataset available for wider research or within the published literature. The literature is dominated by the case studies of Unzen and Soufriere Hills volcanoes, both of which cover PDC-producing activity from dome collapse events. While the addition of the Mount St. Helens dataset gives a valuable perspective for larger magnitude events, more variety of sources, behaviors, volcanoes, and magnitudes is essential. Given the proliferation of infrasound sensor deployment in the last 25 years, it is likely that there are signals within existing datasets that could be exploited.

The second key limitation within experimental PDCs is the instrumentation. The high noise floor leads to a low signal-to-noise ratio for most experiments, hampering single characterization. Moreover, the geometry and number of sensors does not allow for the natural radiation of acoustic waves from a PDC, and with a low number of sensor locations, sources within and around the flow are difficult to constrain. In both field and experimental cases, there is also the issue of multiple simultaneous acoustic sources generating a complex wave field. In both cases, arrays or multiple sensors are needed to further constrain and differentiate signals.

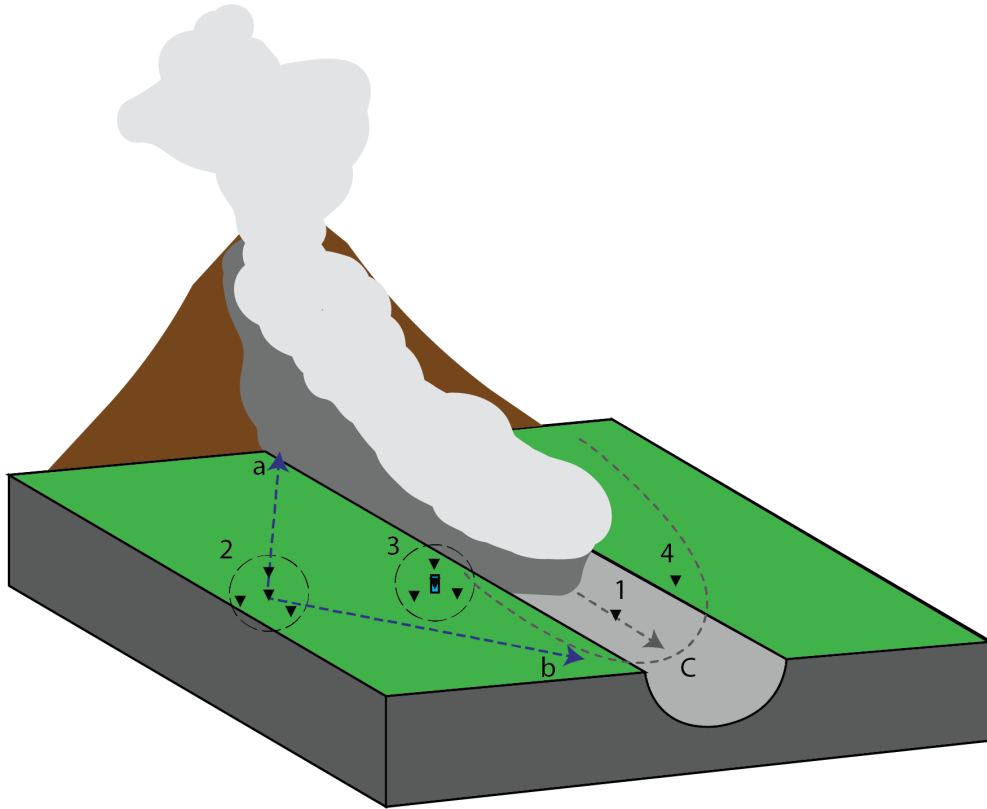


Figure 6.1: Implications of sensor locations. A sensor located at position 1 is vulnerable to the flow but will record the highest amplitude given a radiation pattern similar to the jet noise model, where the amplitude is a function of azimuth. An array at location 2 will have a nice sweep of back azimuths to record the movement of the flow. Sensors deployed at array at location 3, with a collocated seismic sensor will have inferior azimuth resolution compared with that at location 2, but the proximity will give better amplitude for more events and localized seismic particle motions for comparison. A single sensor at location 4 could be useful to identify topographic jumping or channel overflow and propagation in another direction. Sensors 1 and 4 represent sacrificial sensors. The azimuth sweep from a to b would be known directions and distances and could be converted to velocity of a signal down the channel. Direction C would be the direction with the highest amplitude.

6.6 Future Research

One major aspect of the experiments that is not addressed in this thesis is the radiation pattern of the generated signals. In Chapter 3, the radiation pattern of the amplitudes for the Lamb wave generated by Mount St. Helens is used as an argument for the directionality of the signal; however, this was not addressed in the experiments. This was partially owing to the geometry of the experiments. In PELE, the channel is a stiff wall that does not allow for horizontal expansion of the signal, which may artificially increase the amplitude of the signal within the confined area.

The source of the sound will also have an impact on the radiation pattern of the signal. For a monopole source, like a volumetric change, the amplitude is expected to radiate equally in all directions. For a source of this type, only the source to sensor distance impacts the recorded amplitude. However, for more complex source radiation patterns, from a dipole to jet noise turbulence, radiation is not radially uniform. Matoza et al. (2013b) addressed this within the context of the turbulent jet source of a volcanic eruption, highlighting that the amplitude is dependent on the distance and angle from the nozzle.

For a PDC, the source is more likely to be complex, with non-uniform radiation of acoustic energy. This has important implications for a dependence not only on source to sensor distance but also on azimuth from the source. Using an approximation of a jet for a PDC where the nozzle is modeled as horizontally pointing downslope, the maximum amplitude would be within the path of the flow. This has major implications for sensor placement. Given that the amplitude is expected to be impacted by the azimuth from the channel, not only the distance but also the azimuth could reduce the detectability of smaller events. This would make amplitude comparisons between volcanoes and even channels on the same volcano difficult.

The first signal discussed in Chapter 4, the signal generated by the intrusion of the flow into the atmosphere, is likely to be a monopole source type; therefore the amplitude and moving source of the flow boundary discussed in Chapter 5 is likely to

be complex. Thus, the sensor design for a specific volcano would depend on the signal of interest and application. Amplitude comparisons would also only be valid for the initial signals (Chapter 4), and amplitude comparisons for the flow signal should only be used for repeated events in the same location with the same sensors. Figure 6.1 illustrates the different locations and implications for sensor location on a volcano.

Finally, while significant progress has been made on the wave field and other pressure signals generated by a flow in the atmosphere, the partitioning and propagation of signals within the flow is not constrained. The speed of sound within a changing atmosphere is relatively well constrained, whereas in the interior of a PDC this is considerably more challenging owing to the complexities of pressure wave propagation within multiphase flows. Owing to the multiphase composition of these flows, general relationships between the density and acoustic velocity of a fluid or solid cannot be used. An acoustic wave traveling through a single-phase fluid travels at a velocity that depends on the density and compressibility of that fluid. However, in a fluid with a suspended load of particles, the wave speed can counterintuitively drop with an increase in solid particles. Future research into the effects of multiphase concentrations with PDCs may reveal limiting factors on frequency content that contribute to the silent reputation of PDCs. Energy partitioning with seismic stations may also reveal additional information useful for constraining physical properties in the field.

Appendix A

Supplemental for Chapter 3 - Reanalysis of Atmospheric Pressure Waves and Lamb Wave Generation from the May 18, 1980 of Mount St. Helens Eruption

A.1 Data Availability

Timeseries data is available in the following Data Repository:

<https://github.com/aperttu/MSHDataArchive>

A.2 Supplemental Tables

Table A.1: Stations from the literature. B82 = Bath, 1982, B84 = Banister, (1984), BT = Bolt and Tanimoto 1981, D85 = Dewey 1985, DB = Donn and Balachandra 1981, F80 = Fairfield 1980, JM = Johnson and Malone 2007, K83 = Kanamori 1983, L82 = Liu 1982, R80 = Reed, 1980a and 1980b, R87 = Reed, 1987, NOAA = NOAA archive, L85 = Liu 1985, DB90 = Declose 1990, and data from Dewey 1985 location names and locations are estimated from a map within the paper.

Station / Name	Lat.	Lon	Dist. (km)	Az. (deg)	Station Type	Source
Toledo, WA	46.48 N	122.82 W	54	307	Barograph	B84, R80, R87, F80, NOAA
Portland, OR	45.59 N	122.59 W	76	206	Barograph	R87, R80
Dallesport, Wa	45.62 N	121.17 W	99	132	Barograph	B84, R87, R80
Olympia, WA	46.98 N	122.90 W	102	330	Barograph	B84, R80, R87
Astoria, OR	46.15 N	123.88 W	117	270	Barograph	R87, B84, R80
Yakama, WA	46.57 N	120.54 W	125	69	Barograph	R87, R80, B84
Stampede Pass, WA	47.39 N	121.39 W	130	24	Barograph	B84, R80, R87

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Table A.1 – continued from previous page

Station	Lat.	Lon	Dist.	Az.	Type	Source
SEA-TAC airport, WA	47.45 N	122.30 W	140	356	Barograph	B84, R80, R87
Hoquiam, Wa	46.97 N	123.93 W	153	306	Barograph	B84, R87, R80
Salem, OR	44.91 N	123.01 W	158	203	Barograph	R87, R80, B84
Seattle, Wa	47.66 N	122.41 W	161	357	Barograph	B84, R80, R87
Wenatche, WA	47.40 N	120.21 W	195	42	Barograph	R87, R80, B84
Corvallis, OR	44.50 N	123.29 W	199	204	Barograph	B84, R87, R80
Pendleton, OR	45.69 N	118.84 W	248	104	Barograph	B84, R87, R80
Eugene, OR	44.12 N	123.21 W	250	198	Barograph	B84, R87, R80
Quillayute, WA	47.94 N	124.56 W	256	321	Barograph	B84, R87, R80
Victoria BC	48.46 N	123.27 W	265	17	Barograph	D85
Walla Walla, WA	46.09 N	118.28 W	277	92	Barograph	B84, R87, R80
Victoria Air- port BC	48.65 N	123.43 W	289	18	Barograph	D85
Bellingham, WA	48.79 N	122.53 W	300	356	Barograph	R87, B84, R80
Delta BC	49.01 N	123.09 W	321	12	Barograph	D85
Continued on next page						

Table A.1 – continued from previous page

Station	Lat.	Lon	Dist.	Az.	Type	Source
Chilliwack South BC	49.1 N	121.63 W	326	353	Barograph	D85
Chemainus BC	48.94 N	123.74 W	327	20	Barograph	D85
Chilliwack BC	49.18 N	121.95 W	333	357	Barograph	D85
Vancouver BC	49.25 N	123.18 W	348	12	Barograph	D85
Roseburg, OR	43.24 N	123.36 W	348	195	Barograph	R87, B84
Lewiston, ID	46.37 N	117.02 W	370	85	Barograph	B84, R87, R80
Spokane, Wa	47.68 N	117.32 W	371	63	Barograph	B84, R80, R87
Keremeos BC	49.2 N	119.82 W	379	333	Barograph	D85
Amohitrite Point BC	48.92 N	125.53 W	394	38	Barograph	D85
Ucluelet Kennedy Camp BC	48.95 N	125.53 W	397	38	Barograph	D85
Boston Bar CA	49.87 N	121.43 W	413	352	Barograph	D85
Tofino Vil- lage BC	49.15 N	125.91 W	432	39	Barograph	D85
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Table A.1 – continued from previous page

Station	Lat.	Lon	Dist.	Az.	Type	Source
Christina Lake BC	49.04 N	118.21 W	436	318	Barograph	D85
Peachland BC	49.77 N	119.75 W	438	336	Barograph	D85
Nakusp BC	50.45 N	122.2 W	474	0	Barograph	D85
Vern BC	50.27 N	119.25 W	504	335	Barograph	D85
Kitchner BC	49.16 N	116.34 W	550	309	Barograph	D85
Revelstoke Airport BC	50.96 N	118.18 W	608	332	Barograph	D85
Port Alice BC	50.39 N	127.46 W	609	38	Barograph	D85
Coal Harbour BC	50.6 N	127.5 W	628	37	Barograph	D85
Lorsta Williams Lake BC	51.97 N	122.35 W	643	1	Barograph	D85
Avola BC	51.78 N	119.32 W	657	342	Barograph	D85
Cape Scott BC	50.78 N	128.43 W	688	40	Barograph	D85
Alexis Creek BC	52.55 N	123.18 W	711	5	Barograph	D85
Bella Bella BC	52.19 N	128.11 W	794	31	Barograph	D85
Prince George BC	53.78 N	122.85 W	846	3	Barograph	D85
Continued on next page						

Table A.1 – continued from previous page

Station	Lat.	Lon	Dist.	Az.	Type	Source
Kushiro, Japan	43.0 N	144.4 E	6,945	305	Infrasound	R87, L
Akita, Japan	39.7 N	140.1 E	7,453	304	Infrasound	R87, L
PPT (Pa- matai)	17.57 S	149.58 W	7600	208	infrasound	DB90
Tokyo, Japan	35.7 N	139.8 E	7,778 3	01	Infrasound	R87, L
Wajima, Japan	37.4 N	136.9 E	7,833	304	Infrasound	R87, L
DeBilt, Netherlands	52.2 N	5.3 E	7982	31	Infrasound	R87
GRA (Granville)	48.85 N	1.57 W	7990	37	infrasound	DB90
Hamburg FRG	53.5 N	10.1 E	8000	28	Infrasound	R87, DB, L
Buchholz FRG	53.4 N	9.9 E	8010		Infrasound	R87, DB
POL (Pold- ers)	48.62 N	1.58 W	8010	37	infrasound	DB90
FLE (Flers)	48.76 N	0.48 W	8050	36	infrasound	DB90
AUB (St Aubin)	49.04 N	1.22 E	8100	35	infrasound	DB90
BRU (Bruy- eres)	48.6 N	2.2 E	8180	35	infrasound	DB90
Tonago, Japan	35.4 N	133.4 E	8211		Infrasound	R87, L
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Table A.1 – continued from previous page

Station	Lat.	Lon	Dist.	Az.	Type	Source
HAU (Haudompre)	48.01 N	6.35 E	8410	33	infrasound	DB90
VAL (Valensole)	43.83 N	6.01 E	8785	35	infrasound	DB90
LAM (Lamto)	6.22 N	5.03 W	11520	66	infrasound	DB90
Yueqing	28.13 N	120.96 E	9618.85	308	infrasound	L85
Longmire (LON)	46.75 N	121.81 W	67	206	Seismic	K83, JM
GSM	47.20 N	121.79 W	117	195	Seismic	JM
NAC	46.73 N	120.82 W	121	241	Seismic	JM
YAK	46.53 N	120.52 W	134	254	Seismic	JM
ELL	46.91 N	120.57 W	148	238	Seismic	JM
SPW	47.55 N	122.25 W	152	178	Seismic	JM
SMW	47.32 N	123.34 W	153	145	Seismic	JM
GMW	47.55 N	122.79 W	158	163	Seismic	JM
TBM	47.17 N	120.60 W	164	229	Seismic	JM
HTW	47.80 N	121.77 W	182	190	Seismic	JM
VTG	46.96 N	119.99 W	190	244	Seismic	JM
MDW	46.61 N	119.76 W	193	257	Seismic	JM
RSW	46.39 N	119.59 W	202	265	Seismic	JM
BLN	48.01 N	122.97 W	211	163	Seismic	JM
GBL	46.60 N	119.46 W	215	259	Seismic	JM
BDG	46.23 N	119.32 W	222	270	Seismic	JM
JCW	48.20 N	121.93 W	224	185	Seismic	JM
WIW	46.43 N	119.29 W	226	264	Seismic	JM
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Table A.1 – continued from previous page

Station	Lat.	Lon	Dist.	Az.	Type	Source
CRF	46.83 N	119.39 W	227	253	Seismic	JM
EPH	47.36 N	119.60 W	237	238	Seismic	JM
OHW	48.32 N	122.53 W	239	174	Seismic	JM
ETP	46.46 N	119.06 W	243	264	Seismic	JM
CBW	47.81 N	120.03 W	244	223	Seismic	JM
WRD	46.97 N	119.15 W	249	251	Seismic	JM
WGW	46.04 N	118.93 W	253	275	Seismic	JM
DYH	47.96 N	119.77 W	270	224	Seismic	JM
SAW	47.70 N	119.40 W	271	233	Seismic	JM
MCW	48.68 N	122.83 W	281	170	Seismic	JM
ODS	47.31 N	118.75 W	291	246	Seismic	JM
MFW	45.90 N	118.41 W	295	278	Seismic	JM
WBW	48.02 N	119.14 W	309	230	Seismic	JM
OMK	48.48 N	119.56 W	323	219	Seismic	JM
DAV	47.64 N	118.23 W	343	243	Seismic	JM
Dugway, UT	40.2 N	112.8 W	1000		Seismic	DB
Ann Arbor, MI	42.3 N	83.7 W	3056		Seismic	DB
Kings Bay, Norway	78.8 N	11.5 E	5748		Seismic	DB
Trinidad, West Indies	10.7 N	61.4 W	6918		Seismic	DB
Kirunna, Sweden	67.70 N	20.42 E	6982	332	Seismic	B82
Umea, Sweden	63.66 N	20.24 E	7375	333 S	eismic	B82
Continued on next page						

Table A.1 – continued from previous page

Station	Lat.	Lon	Dist.	Az.	Type	Source
Uppsala, Sweden	59.69 N	17.63 E	7701	331	Seismic	B82
DeBilt, Netherlands	52.1 N	5.1 E	8,000		Seismic	DB
Shillong, In- dia	25.6 N	91.9 E	11282		Seismic	DB

Table A.2: Results of amplitude and time from the stations listed above in Table A.1 from the literature.

Station	Latitude	Longitude	Range (km)	Bearing (degrees)	Station Type	Positive Pa	Negative Pa	Peak to Peak	Arrival time	Group Velocity	Period	References
Toledo, Wa	46.45 N	122.83 W	54	307	Barograph	350	none	767				B84
Toledo, Wa	46.45 N	122.83 W	54	307	Barograph	373.00			18/05/1980 15:47			R87, R80
Longmire (LON)	46.75 N	121.81 W	67	206	Seismic							JM
Longmire (LON)	46.75 N	121.81 W	67	206	Seismic			760				K83
Portland, OR	45.59 N	122.59 W	76	206	Barograph	131		253				R87, R80
Dallesport, Wa	45.62 N	121.17 W	99	132	Barograph	140	-50					B84
Dallesport, WA	45.62 N	121.17 W	99	132	Barograph	138		283				R87, R80
Olympia, Wa	46.98 N	122.90 W	102	330	Barograph	230	-5					B84
Olympia, WA	46.98 N	122.90 W	102	330	Barograph	235		459				R87, R80
GSM	47.20 N	121.79 W	117	195	Seismic				18/05/1980 15:47			JM
Astoria, OR	46.15 N	123.88 W	117	270	Barograph	170	-5					B84
Astoria, OR	46.15 N	123.88 W	117	270	Barograph	164		262				R87, R80
NAC	46.73 N	120.82 W	121	241	Seismic				18/05/1980 15:47			JM
Yakima, Wa	46.57 N	120.54 W	125	69	Barograph	145	none					B84
Yakama, Wa	46.57 N	120.54 W	125	69	Barograph	141		318				R87, R80
Stampede Pass, Wa	47.39 N	121.39 W	130	24	Barograph	170	-5					B84
Stampede Pass, WA	47.39 N	121.39 W	130	24	Barograph	167		331				R87, R80
YAK	46.53 N	120.52 W	134	254	Seismic				18/05/1980 15:48			JM
SEA-TAC airport, Wa	47.45 N	122.30 W	140	356	Barograph	185	none					B84
Seattle, SEA-TAC	47.45 N	122.30 W	140	356	Barograph	188		365				R87, R80
ELL	46.91 N	120.57 W	148	238	Seismic				18/05/1980 15:48			JM
SPW	47.55 N	122.25 W	152	178	Seismic				18/05/1980 15:48			JM

Hoquiam, Wa	46.97 N	123.93 W	153	306	Barograph	130	none					B84
Hoquiam, WA	46.97 N	123.93 W	153	306	Barograph	205		395				R87, R80
SMW	47.32 N	123.34 W	153	145	Seismic				18/05/1980 15:52			JM
GMW	47.55 N	122.79 W	158	163	Seismic				18/05/1980 15:48			JM
Salem, Wa	44.91 N	123.01 W	158	203	Barograph	105	none					B84
Salem, OR	44.91 N	123.01 W	158	203	Barograph	99		162				R87, R80
Seattle, Wa	47.66 N	122.41 W	161	357	Barograph	145	-5					B84
Seattle, WSFO	47.66 N	122.41 W	161	357	Barograph	146		276				R87, R80
TBM	47.17 N	120.60 W	164	229	Seismic				18/05/1980 15:49			JM
HTW	47.80 N	121.77 W	182	190	Seismic				18/05/1980 15:49			JM
VTG	46.96 N	119.99 W	190	244	Seismic				18/05/1980 15:50			JM
MDW	46.61 N	119.76 W	193	257	Seismic				18/05/1980 15:50			JM
Wenatche, WA	47.40 N	123.21 W	195	42	Barograph	106		203				R87, R80
Corvallis, OR	44.50 N	123.29 W	199	204	Barograph	99	none					B84
Corvallis, OR	44.50 N	123.29 W	199	204	Barograph	91		136				R87, R80
RSW	46.39 N	119.59 W	202	265	Seismic				18/05/1980 15:49			JM
BLN	48.01 N	122.97 W	211	163	Seismic				18/05/1980 15:48			JM
GBL	46.60 N	119.46 W	215	259	Seismic				18/05/1980 15:49			JM
BDG	46.23 N	119.32 W	222	270	Seismic				18/05/1980 15:48			JM
JCW	48.20 N	121.93 W	224	185	Seismic				18/05/1980 15:47			JM
WIV	46.43 N	119.29 W	226	264	Seismic				18/05/1980 15:47			JM
CRF	46.83 N	119.39 W	227	253	Seismic				18/05/1980 15:49			JM
EPH	47.36 N	119.60 W	237	238	Seismic				18/05/1980 15:47			JM

OHW	48.32 N	122.53 W	239	174	Seismic					18/05/1980 15:47		JM
ETP	46.46 N	119.06 W	243	264	Seismic					18/05/1980 15:48		JM
CBW	47.81 N	120.03 W	244	223	Seismic					18/05/1980 15:48		JM
Pendleton, OR	45.69 N	118.84 W	248	104	Barograph	32	None					B84
Pendleton, OR	45.69 N	118.84 W	248	104	Barograph	32		91		18/05/1980 15:52		R87, R80
WRD	46.97 N	119.15 W	249	251	Seismic							JM
Eugene, OR	44.12 N	123.21 W	250	198	Barograph	27	None					B84
Eugene, OR	44.12 N	123.21 W	250	198	Barograph	26		78		18/05/1980 15:51		R87, R80
WGW	46.04 N	118.93 W	253	275	Seismic							JM
Quillayute, WA	47.94 N	124.56 W	256	321	Barograph	140	-10					B84
Quillayute, WA	47.94 N	124.56 W	256	321	Barograph	129		194		18/05/1980 15:45:00		R87, R80
Victoria BC	48.46 N	123.27 W	265	17	Barograph					18/05/1980 15:49		D
DYH	47.96 N	119.77 W	270	224	Seismic					18/05/1980 15:49		JM
SAW	47.70 N	119.40 W	271	233	Seismic					18/05/1980 15:49		JM
Walla Walla, WA	46.09 N	118.28 W	277	92	Barograph	80	none					B84
Walla Walla, WA	46.09 N	118.28 W	277	92	Barograph	74		127				R87, R80
MCW	48.68 N	122.83 W	281	170	Seismic					18/05/1980 15:49		JM
Victoria Airport BC	48.65 N	123.43 W	289	18	Barograph					18/05/1980 15:50:00		D
ODS	47.31 N	118.75 W	291	246	Seismic					18/05/1980 15:49		JM
MFW	45.90 N	118.41 W	295	278	Seismic					18/05/1980 15:52		JM
Bellingam, Wa	48.79 N	122.53 W	300	356	Barograph	140	-10					B84
Belingham, WA	48.79 N	122.53 W	300	356	Barograph	133		198				R87, R80

WBW	48.02 N	119.14 W	309	230	Seismic				18/05/1980 15:51			JM
Delta BC	49.01 N	123.09 W	321	12	Barograph				18/05/1980 16:00:00			D
OMK	48.48 N	119.56 W	323	219	Seismic				18/05/1980 15:52			JM
Chiliwack South BC	49.1 N	121.63 W	326	353	Barograph				18/05/1980 16:00:00			D
Chemainus BC	48.94 N	123.74 W	327	20	Barograph				18/05/1980 15:45:00			D
Chiliwack BC	49.18 N	121.95 W	333	357	Barograph				18/05/1980 16:00:00			D
DAV	47.64 N	118.23 W	343	243	Seismic				18/05/1980 15:52			JM
Vancouver BC	49.25 N	123.18 W	347	348	Barograph				18/05/1980 15:50:00			D
Rosebury, OR	43.24 N	123.36 W	348	195	Barograph	32	None					B84
Roseburg, OR	43.24 N	123.36 W	348	195	Barograph	31		63				R87, R80
Lewiston, ID	46.37 N	117.02 W	370	85	Barograph	75	None					B84
Lewiston, ID	46.37 N	117.02 W	370	85	Barograph	74		138				R87, R80
Spokane, Wa	47.68 N	117.32 W	371	63	Barograph	71	None					B84
Spokane, WA	47.68 N	117.32 W	371	63	Barograph	73		125				R87, R80
Keremeos BC	49.2 N	119.82 W	379	333	Barograph				18/05/1980 16:00:00			D
Amohitrite Point BC	48.92 N	125.53 W	394	38	Barograph				18/05/1980 16:00:00			D
Ucluelet Kennedy Camp BC	48.95 N	125.53 W	397	38	Barograph				18/05/1980 16:00:00			D
Boston Bar CA	49.87 N	121.43 W	413	352	Barograph				18/05/1980 16:00:00			D
Tofino Village BC	49.15 N	125.91 W	432	39	Barograph				18/05/1980 16:10:00			D
Christina Lake BC	49.04 N	118.21 W	436	318	Barograph				18/05/1980 16:05:00			D
Peachland BC	49.77 N	119.75 W	438	336	Barograph				18/05/1980 16:00:00			D
Nakusp BC	50.45 N	122.2 W	474	0	Barograph				18/05/1980 16:10:00			D

Vern BC	50.27 N	119.25 W	504	335	Barograph				18/05/1980 16:00:00		D
Kitchner BC	49.16 N	116.34 W	550	309	Barograph				18/05/1980 16:10:00		D
Revelstoke Airport BC	50.96 N	118.18 W	608	332	Barograph				18/05/1980 16:00:00		D
Port Alice BC	50.39 N	127.46 W	609	38	Barograph				18/05/1980 16:10:00		D
Coal Harbour BC	50.6 N	127.5 W	628	37	Barograph				18/05/1980 16:10:00		D
Lorsta Williams Lake BC	51.97 N	122.35 W	643	1	Barograph				18/05/1980 16:15:00		D
Avola BC	51.78 N	119.32 W	657	342	Barograph				18/05/1980 16:10:00		D
Cape Scott BC	50.78 N	128.43 W	688	40	Barograph				18/05/1980 16:20:00		D
Alexis Creek BC	52.55 N	123.18 W	711	5	Barograph				18/05/1980 16:20:00		D
Bella Bella BC	52.19 N	128.11 W	794	31	Barograph				18/05/1980 16:30:00		D
Prince George BC	53.78 N	122.85 W	846	3	Barograph				18/05/1980 16:20:00		D
Fort Fraser BC	54.08 N	124.27 W	891	9	Barograph				18/05/1980 16:20:00		D
Cape St James BC	51.93 N	131.02 W	907	42	Barograph				18/05/1980 16:20:00		D
Berkeley, CA	37.9 N	123.3 W	925	186	Microbarograph	350			18/05/1980 16:22:00	308	300 BT
Berkeley, CA	37.9 N	123.3 W	925	186	Microbarograph		35				R87
Burns Lake	54.23 N	125.77 W	930	15	Barograph				18/05/1980 16:30:00		D
Ethelda Bay BC	53.05 N	129.68 W	935	33	Barograph				18/05/1980 16:30:00		D
Hazelton BC	54.2 N	127.73 W	975	22	Barograph				18/05/1980 16:20:00		D
Dugway, UT	40.2 N	112.8 W	1000	128	Seismic				18/05/1980 16:26:00	309	DB
Bonilla Island BC	53.49 N	130.64 W	1013	34	Barograph				18/05/1980 16:40:00		D
Salvus BC	54.3 N	129.37 W	1037	27	Barograph				18/05/1980 16:30:00		D
Prince Rupert BC	54.3 N	130.44 W	1076	30	Barograph				18/05/1980 16:40:00		D

Cinola Mine BC	53.5 N	132.13 W	1081	38	Barograph				18/05/1980 16:50:00			D
Green Island BC	54.57 N	130.71 W	1111	30	Barograph				18/05/1980 16:40:00			D
Langara BC	54.26 N	133.06 W	1184	37	Barograph				18/05/1980 16:45:00			D
Boulder, CO	40.0 N	102.2 W	1530	106	Microbarograph	46			18/05/1980 16:55:00	307	300	DB
Boulder, CO	40.0 N	105.2 E	1,530	106	Microbarograph	50						R87
Boulder, CO	40.0 N	105.2 E	1533	106	Micrbarograph				18/05/1980 16:56:00	304	300	L
Ann Arbor, MI	42.3 N	83.7 W	3056	84	Seismic				18/05/1980 18:18:00	307		DB
Washington, D.C.	39.0 N	77.1 W	3700	86	Microbarograph	21			18/05/1980 18:50:00	311	360	DB
Washington DC	39.0 N	77.1 W	3,700	86	Microbarograph	21						R87
Palisades, NY	41.4 N	73.9 W	3950	80	Microbarograph	20			18/05/1980 18:59:30	317	360	DB
Palisades NY	41.4 N	73.9 W	3,950	80	Microbarograph	20						R87
Honolulu, HI	21.3 N	157.6 W	4,156	241	Microbarograph	17						R87
Kings Bay, Norway	78.8 N	11.5 E	5748	10	Seismic				18/05/1980 20:43:00	308		DB
Trinidad, West Indies	10.7 N	61.4 W	6918	104	Seismic				18/05/1980 21:43:00	311		DB
Kushiro, Japan	43.0 N	144.4 E	6,945	305	Micrbarograph				18/05/1980 21:47:00	308	240-300	L
Kushiro, Japan	43.0 N	144.4 E	6,945	305	Microbarograph	14						R87
Kiruna	67.704 N	20.417 E	6982	15	Seismic				18/05/1980 21:42:00	314.5	360	B82
TPT (Tiputa)	14.98 S	147.62 W	7260	207	infrasound							DB90
Umea	63.662 N	20.237 E	7375	17	Seismic				18/05/1980 22:04:00	313.6	360	B82
HAO (Hao)	18.17 S	140.8 W	7400	199	infrasound							DB90
Akita, Japan	39.7 N	140.1 E	7,453	304	Micrbarograph				18/05/1980 22:15:00	308	240-300	L
Akita, Japan	39.7 N	140.1 E	7,453	304	Microbarograph	3						R87
PPT (Pamatai)	17.57 S	149.58 W	7600	208	infrasound							DB90

Uppsala	59.690 N	17.627 E	7701	20	Seismic				18/05/1980 22:20:00	314.6	360	B82
Tokyo, Japan	35.7 N	139.8 E	7,778	301	Microbarograph				18/05/1980 22:35:00	307	240-300	L
Tokyo, Japan	35.7 N	139.8 E	7,778	301	Microbarograph	10						R87
Wajima, Japan	37.4 N	136.9 E	7,833	304	Microbarograph				18/05/1980 22:39:00	306	240-300	L
Wajima, Japan	37.4 N	136.9 E	7,833	304	Microbarograph	11						R87
DeBilt, Netherlands	52.2 N	5.3 E	7,982	31	Microbarograph	40						R87
GRA (Granville)	48.85 N	1.57 W	7990	37	infrasound							DB90
Hamburg West Germany	53.5 N	10.1 E	8000	28	Microbarograph	14.2			18/05/1980 22:43:00	309	390	DB
DeBilt, Netherlands	52.1 N	5.1 E	8,000	31	Seismic				18/05/1980 22:43:00	309		DB
Hamburg FRG	53.5 N	10.1 E	8,000	28	Microbarograph	14.2						R87
Bucholz, West Germany	53.4 N	9.9 E	8010	28	Microbarograph	14.7			18/05/1980 22:46:30	307	390	DB
POL (Polders)	48.62 N	1.58 W	8010	37	infrasound							DB90
Buchholz FRG	53.4 N	9.9 E	8,010	28	Microbarograph	14.7						R87
Hamburg West Germany	53.5 N	10.1 E	8046	28	Microbarograph				18/05/1980 22:46:00	309	300	L
FLE (Fliers) AUB (St Aubin)	48.76 N	0.48 W	8050	36	infrasound							DB90
BRU (Bruyeres)	49.04 N	1.22 E	8100	35	infrasound							DB90
Yonago, Japan	48.6 N	2.2 E	8180	35	infrasound							DB90
Tonago, Japan	35.4 N	133.4 E	8,211	305	Microbarograph				18/05/1980 22:58:00	306	240-300	L
HAU (Haudompre)	35.4 N	133.4 E	8,211	305	Microbarograph	11						R87
VAL	48.01 N	6.35 E	8410	33	infrasound							DB90
(Valensole)	43.83 N	6.01 E	8785	35	infrasound							DB90

Yueqing	28.13 N	120.96 E	9618.85	308	infrasound	13.6				308.89	353	L85
Shillong, India	25.6 N	91.9 E	11282	329	Seismic				19/05/1980 00:38:00	302		DB
LAM (Lamto)	6.22 N	5.03 W	11520	66	infrasound							DB90

Table A.3: Weather observation measurements and parameters used in this calculation where the original values are in bold and the other values are calculated.

Parameter	Toledo	PDX	Coldwater
Distance from the Lateral Blast	54 km	76 km	8 km
Elevation	44 (m)	9.14 (m)	1300 (ft)
Temperature (time)	54 °F (15:55)	55°F (14:55) 58 °F (15:55)	10 °F (13:50)
Dew point (time)	46 °F (15:55)	48 °F (14:55) 49 °F (15:55)	5.7 °C (average humidity)
Relative Humidity (%)	74.28% (15:55)	77.22% (14:55) 71.94 % (15:55)	74.5 % (average humidity)
Pressure at station	29.72 inHg (15:00)	30.08 inHg (15:00)	9.641 kPa
Vapor Pressure	1.057 kPa	1.14 kPa (14:55)	
Mixing ratio	0.0066	0.007039	
Density of air	1.23734 kg/m^3	1.235828 kg/m^3	
Density of water vapor	8.07664 g/m^3	8.7 g/m^3	
Sea level pressure	101170.1 Pa	101862.6 Pa	

A.3 Supplemental Figures

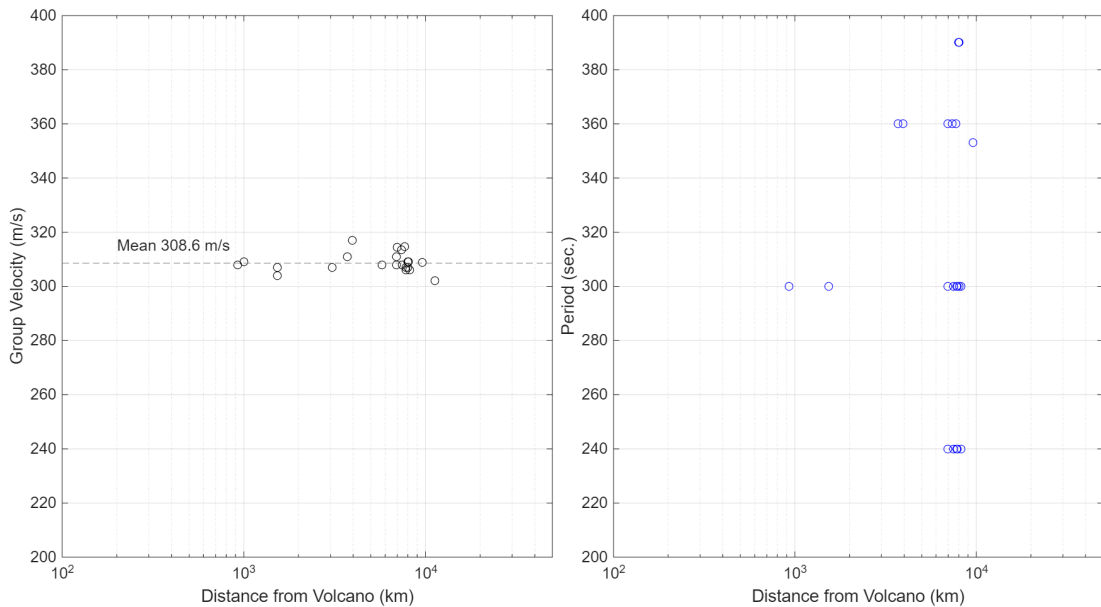


Figure A.1: Group velocities vs distance from volcano (left), and period vs. distance from the volcano (right).

A.4 Station Figures

Organized by station by distance from the volcano.

A.4.1 Toledo, WA

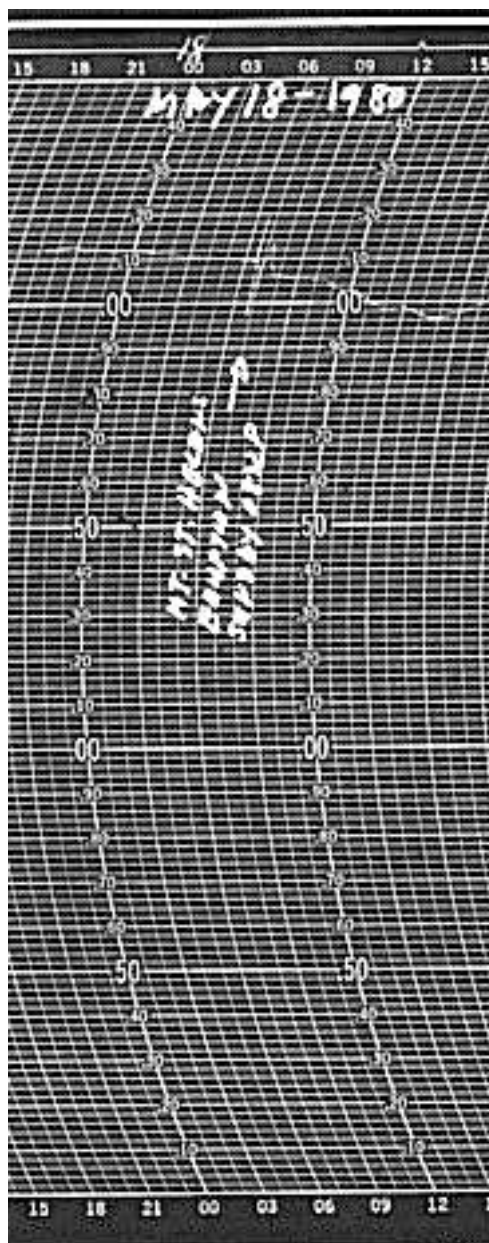


Figure A.2: NOAA provided data from the station at Toledo, WA.

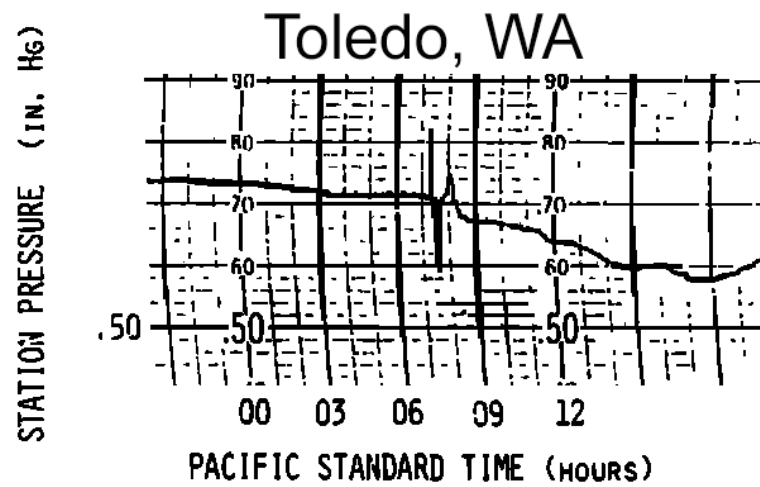


Figure A.3: Figure from Banister (1984) of Toledo, WA station.



Figure A.4: Figure from Fairfield (1980) of Toledo, WA.

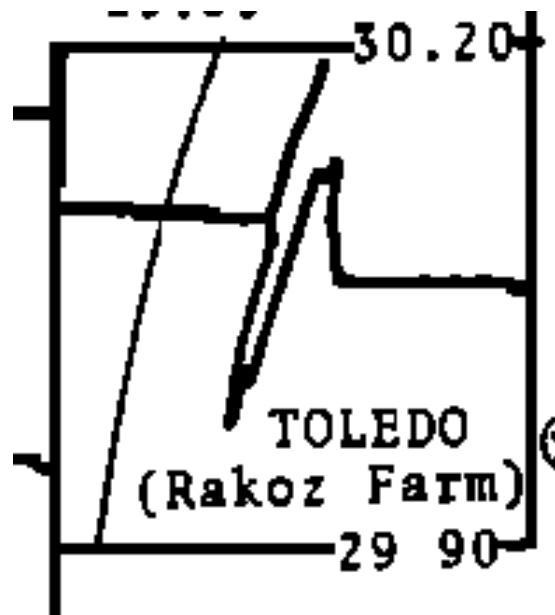


Figure A.5: Figure from Reed (1987) of Toledo, WA.

A.4.2 Longmire, WA

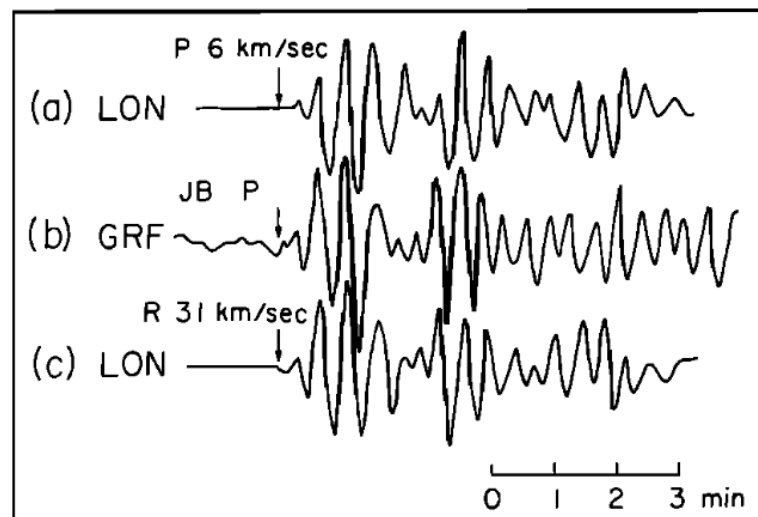


Figure A.6: Figure from Kanamori et al. (1984) of broadband seismic station in Longmire, WA.

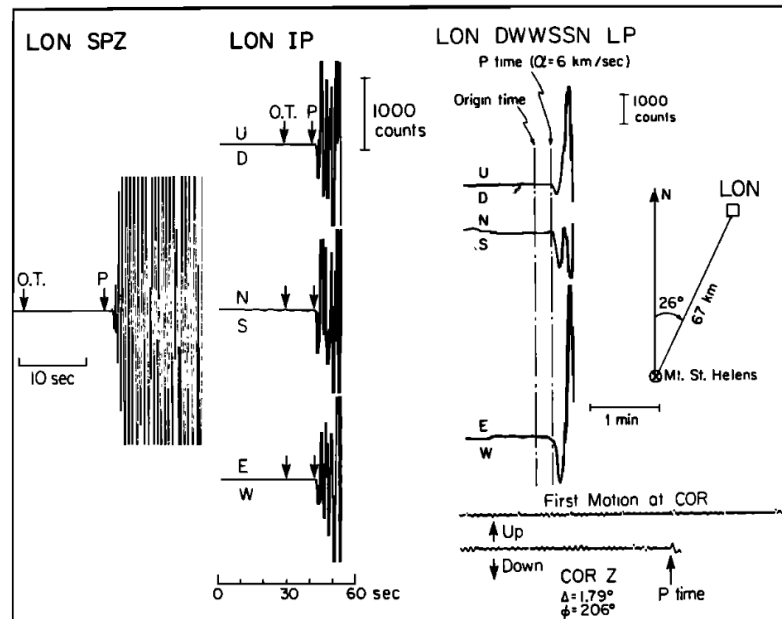


Figure A.7: Figure from Kanamori et al. (1984) of broadband seismic station in Longmire, WA.

A.4.3 Portland, OR

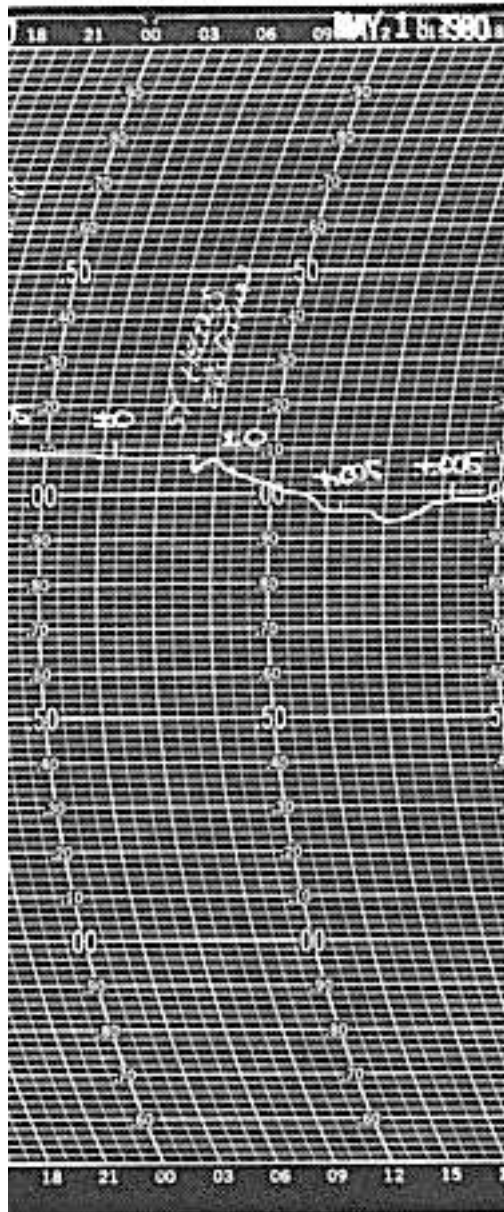


Figure A.8: NOAA provided data from the station at Portland, OR.

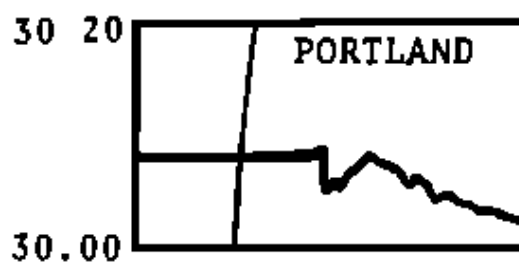


Figure A.9: Figure from (Reed, 1987) of the station in Portland, OR

A.4.4 The Dalles / Dallesport, WA

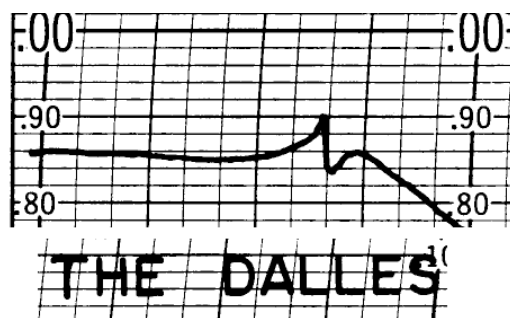


Figure A.10: Figure from Fairfield (1980) of the station at The Dalles, OR

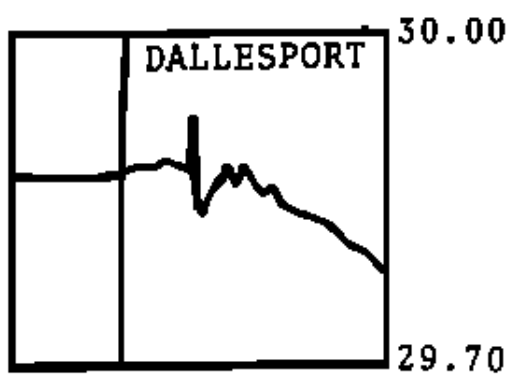


Figure A.11: Figure from Reed (1987) of the station at The Dalles, OR (also known as Dallesport, OR).

A.4.5 Olympia, WA

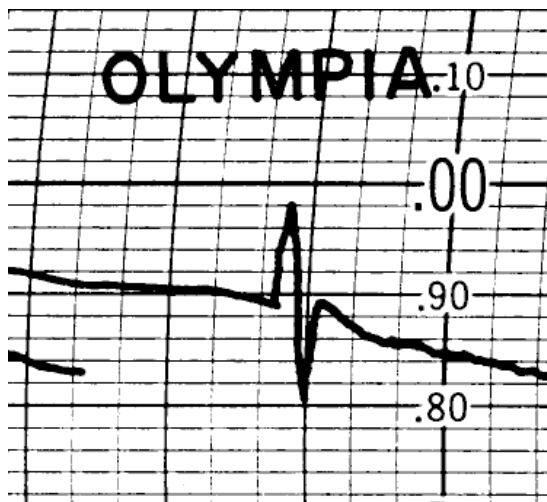


Figure A.12: Figure from Fairfield (1980) of the station in Olympia, WA.

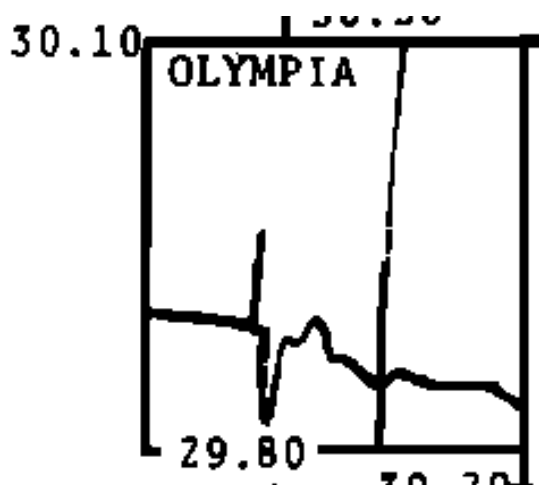


Figure A.13: Figure from Reed (1987) of the station from Olympia, WA.

A.4.6 Astoria, OR

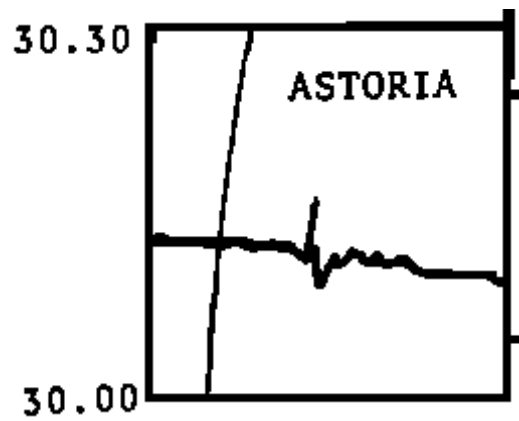


Figure A.14: Figure from Reed (1987) of the station from Astoria, OR.

A.4.7 Yakima, WA

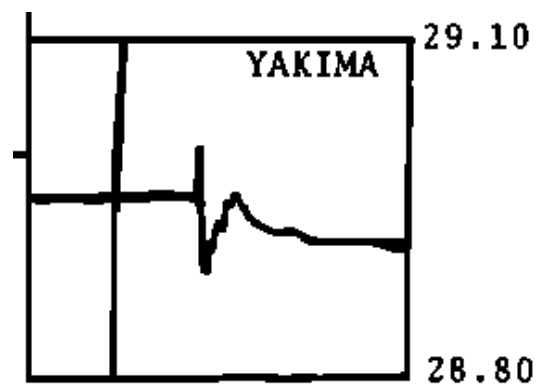


Figure A.15: Figure from Reed (1987) of the station from Yakima, WA.

A.4.8 Stampede Pass, WA

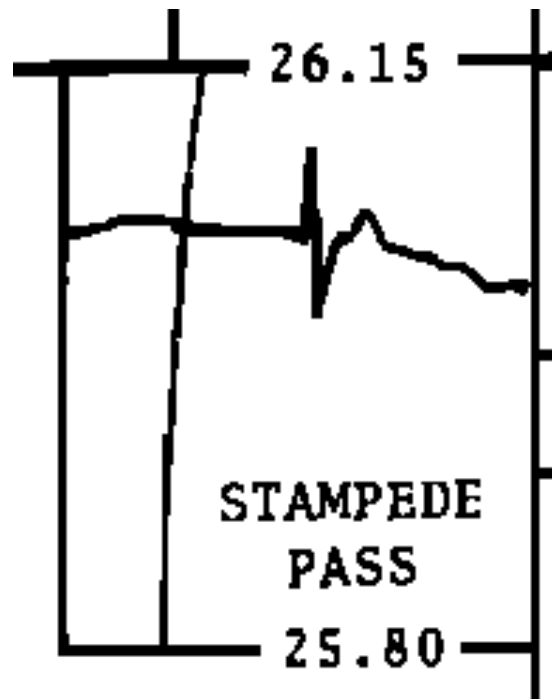


Figure A.16: Figure from Reed (1987) of the station from Stampede Pass, WA.

A.4.9 SEA-TAC, WA

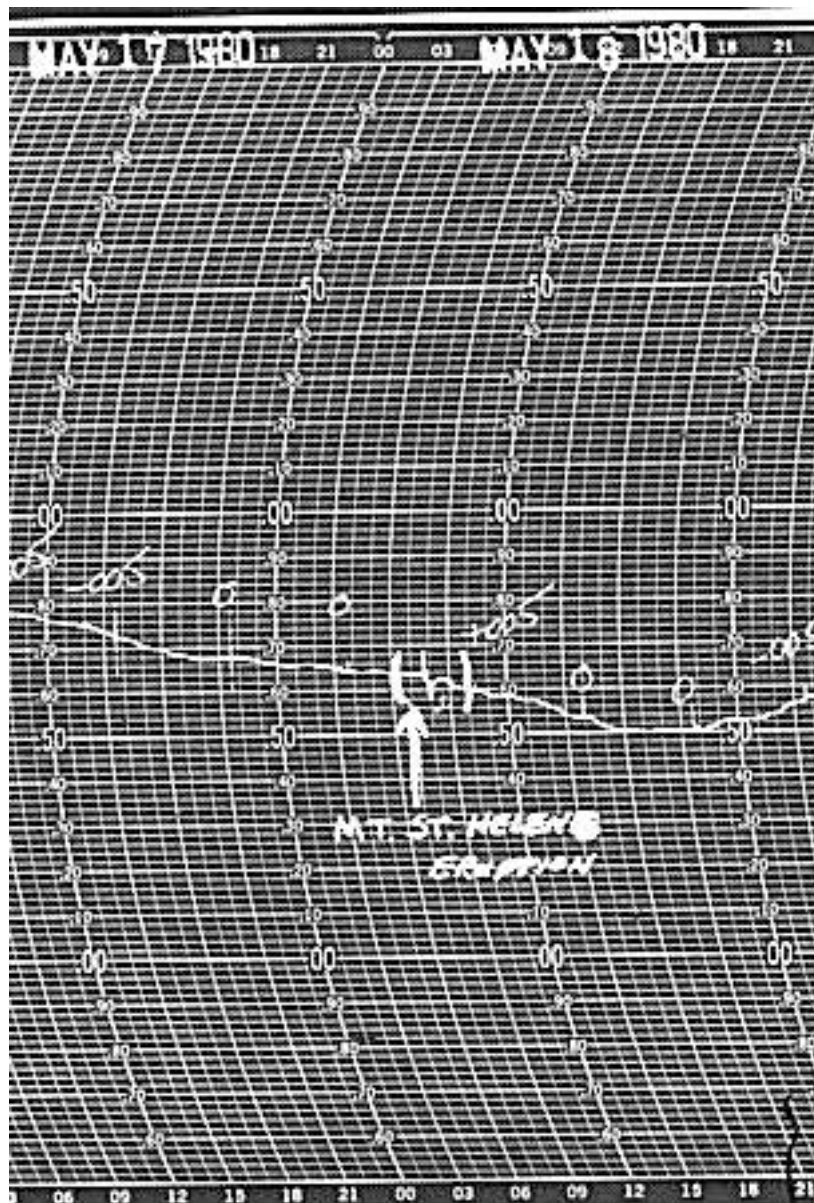


Figure A.17: NOAA provided data for the station at SEA-TAC, WA.

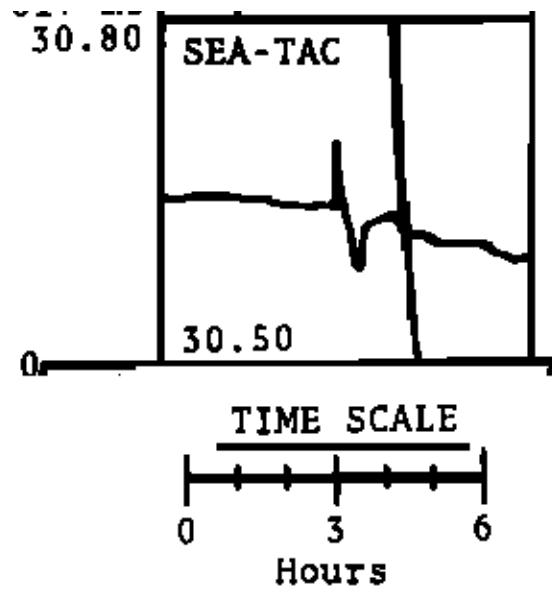


Figure A.18: Figure from Reed (1987) of the station at SEA-TC, WA.

A.4.10 Hoquiam, WA

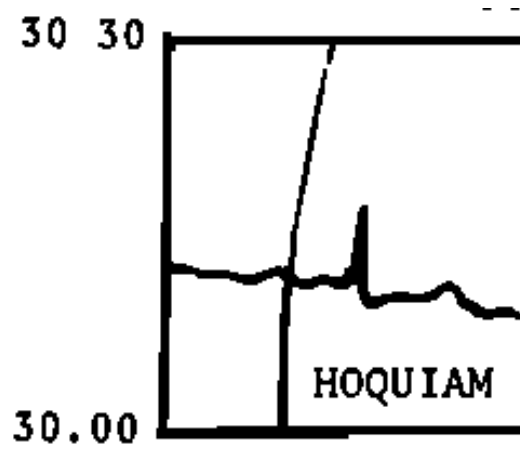


Figure A.19: Figure from Reed (1987) of the station at Hoquiam, WA.

A.4.11 Salem, OR

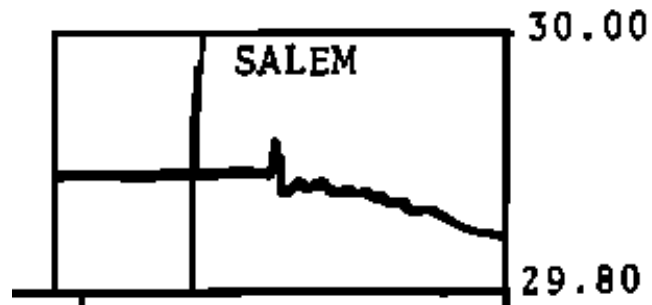


Figure A.20: Figure from Reed (1987) of the station at Salem, OR.

A.4.12 Seattle, WA

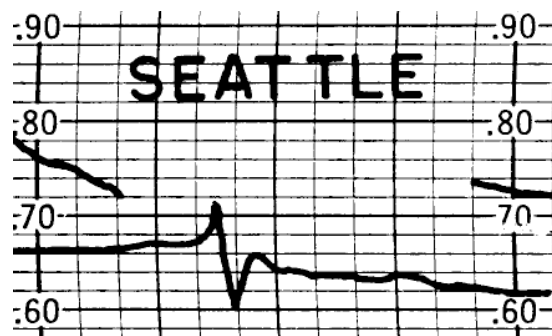


Figure A.21: Figure from Fairfield (1980) of the station at Seattle, WA.

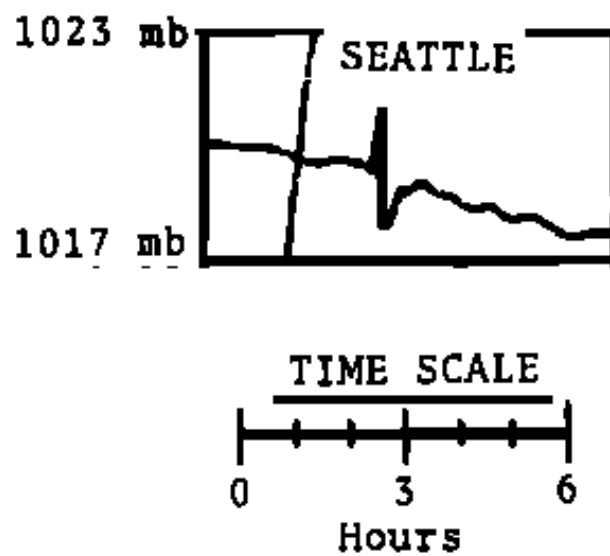


Figure A.22: Figure from Reed (1987) of the station at Seattle, WA.

A.4.13 Wenatchee, WA

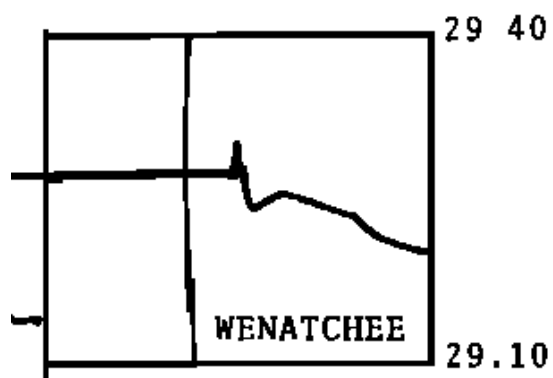


Figure A.23: Figure from Reed (1987) of the station at Wenatchee, WA.

A.4.14 Corvallis, OR

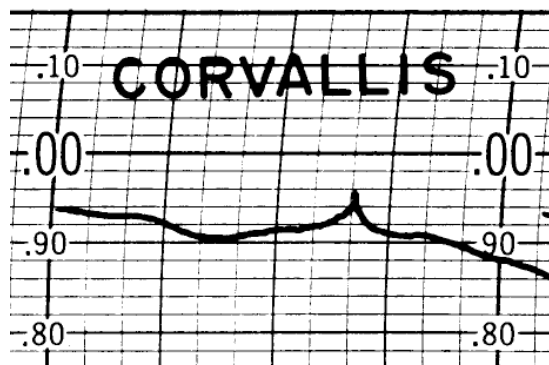


Figure A.24: Figure from Fairfield (1980) of the station at Corvallis, OR.

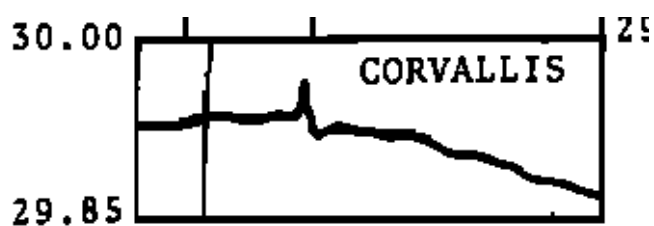


Figure A.25: Figure from Reed (1987) of the station at Corvallis, OR.

A.4.15 Pendleton, OR

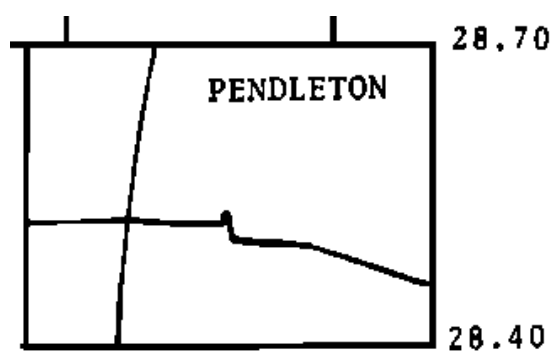


Figure A.26: Figure from Reed (1987) of the station at Pendleton, OR.

A.4.16 Eugene, OR

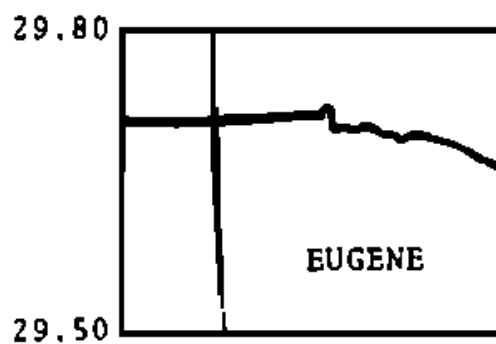


Figure A.27: Figure from Reed (1987) of the station at Eugene, OR.

A.4.17 Quillayute, WA

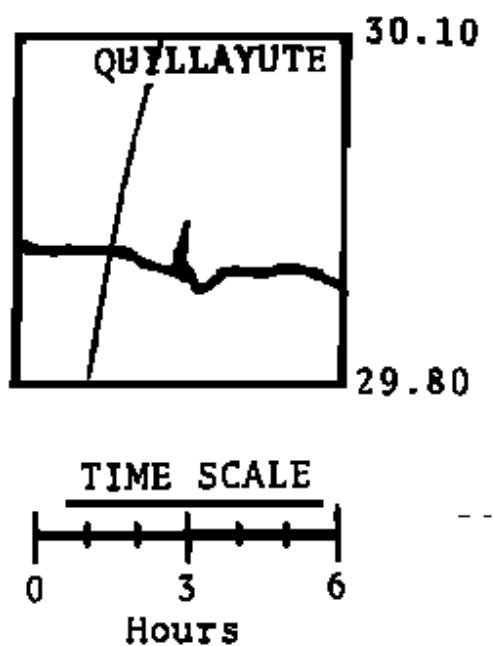


Figure A.28: Figure from Reed (1987) of the station at Quillayute, WA.

A.4.18 Walla Walla, WA

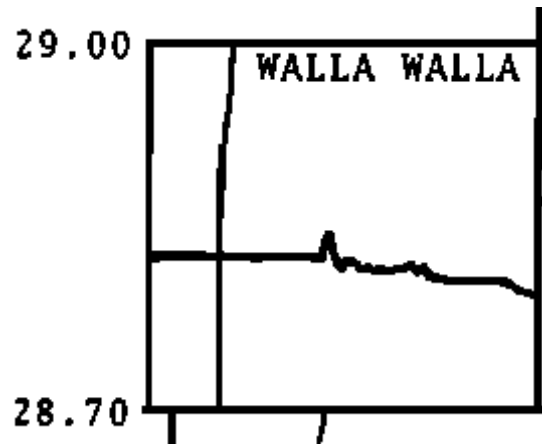


Figure A.29: Figure from Reed (1987) of the station at Walla Walla, WA.

A.4.19 Bellingham, WA

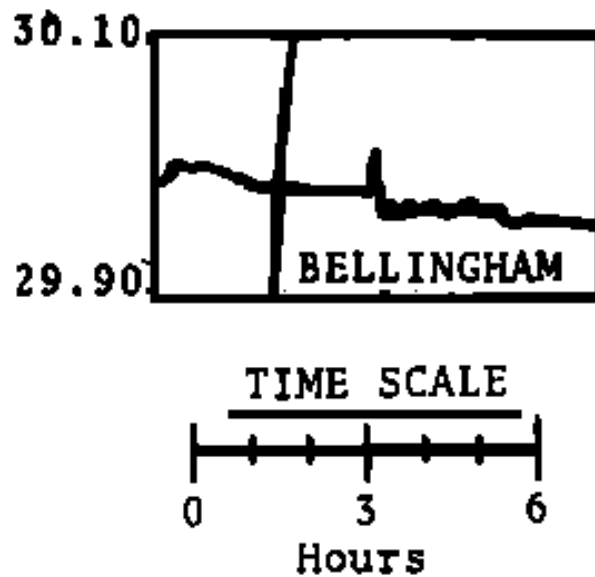


Figure A.30: Figure from Reed (1987) of the station Bellingham, WA.

A.4.20 Roseburg, OR

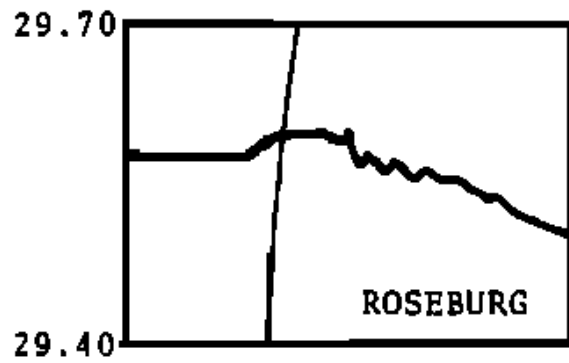


Figure A.31: Figure from Reed (1987) of the station Roseburg, OR.

A.4.21 Lewiston, ID

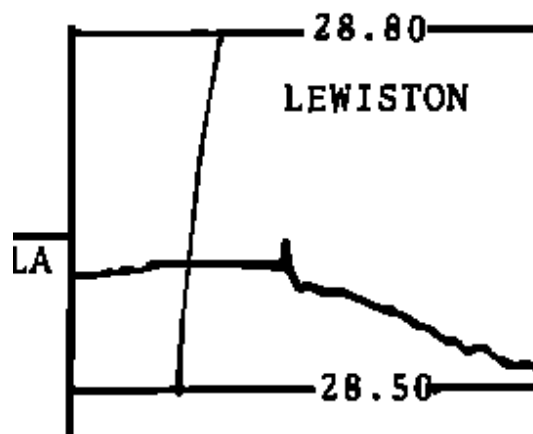


Figure A.32: Figure from Reed (1987) of the station at Lewiston, ID.

A.4.22 Spokane, WA

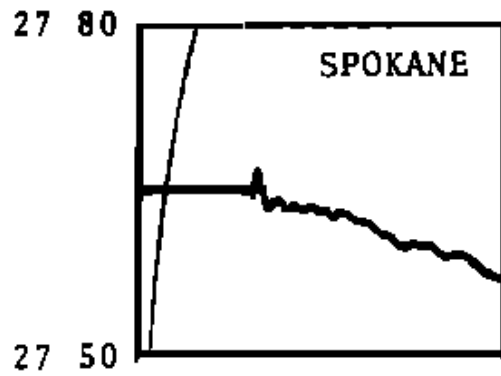


Figure A.33: Figure from Reed (1987) of the station at Spokane, WA.

A.4.23 Berkeley, CA



Figure A.34: Figure from Bolt and Tanimoto (1981) of the station at Berkeley, CA.

A.4.24 Boulder, CO

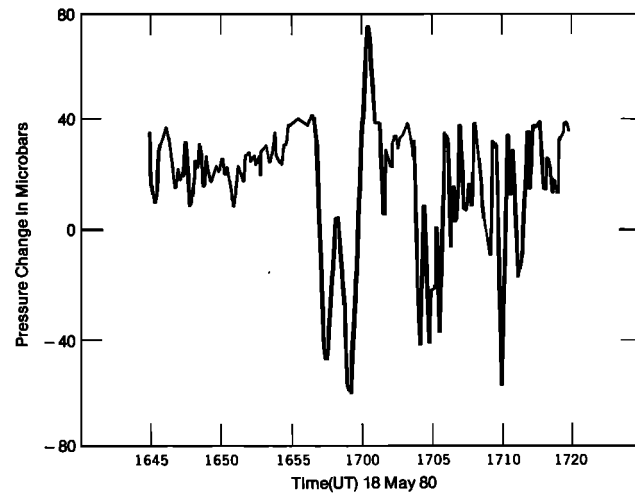


Fig. 1. One of three microbarograph records observed in Boulder, Colorado (40.1°N, 105.2°W).

Figure A.35: Figure from Liu et al. (1982) of the station at Boulder, CO.



Figure A.36: Figure from Donn and Balachabdran (1981) of the station at Boulder, CO.

A.4.25 Washington DC

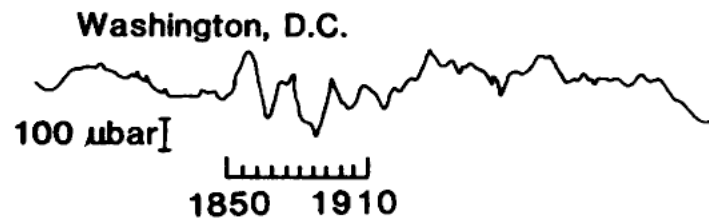


Figure A.37: Figure from Donn and Balachabdran (1981) of the station at Washington, DC.

A.4.26 Palisades, NY

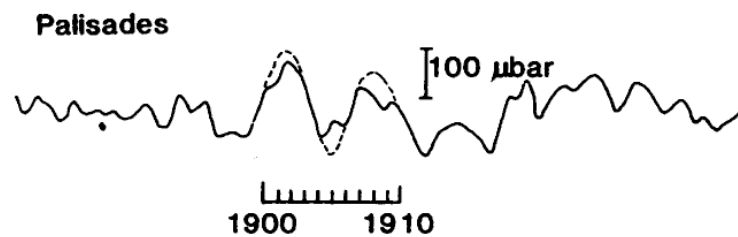


Figure A.38: Figure from Donn and Balachabdran (1981) of the station at Palisades, NY.

A.4.27 Kushiro, Japan

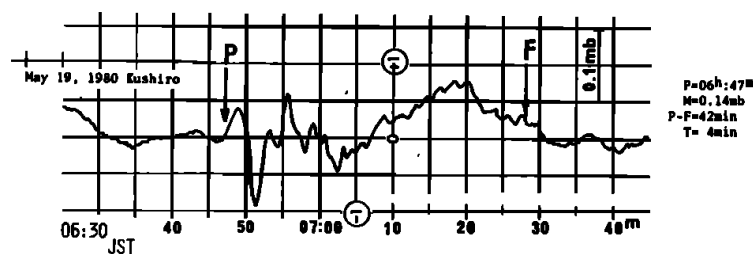


Figure A.39: Figure from Liu et al. (1982) of the station at Kushiro, Japan.

A.4.28 Akita, Japan

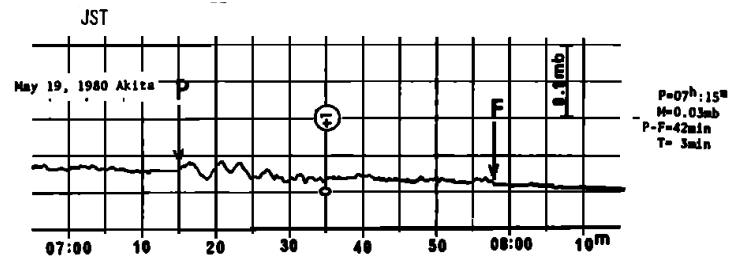


Figure A.40: Figure from Liu et al. (1982) of the station at Akita, Japan.

A.4.29 Tokyo, Japan

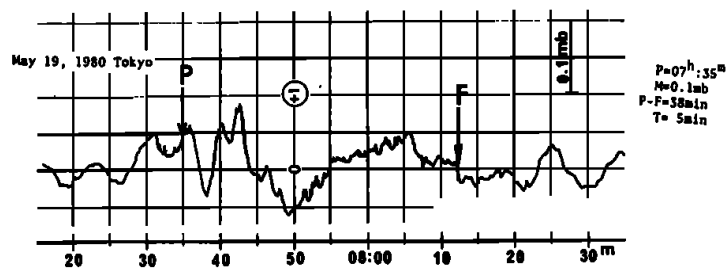


Figure A.41: Figure from Liu et al. (1982) of the station at Tokyo, Japan.

A.4.30 Wajima, Japan

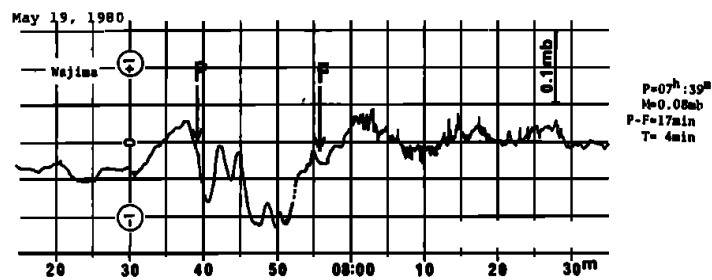


Figure A.42: Figure from Liu et al. (1982) of the station at Wajima, Japan.

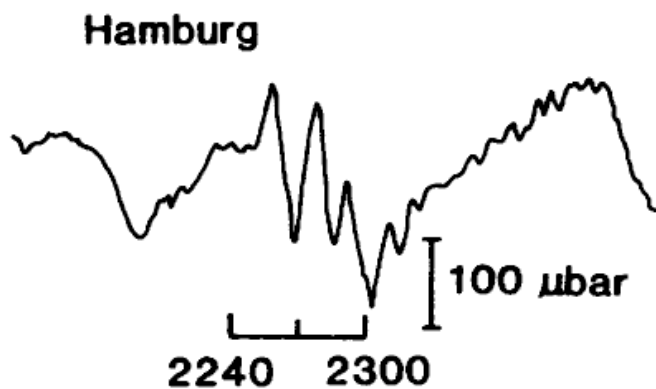
A.4.31 Hamburg, Germany

Figure A.43: Figure from Donn and Balachabdran (1981) of the station at Hamburg, Germany.

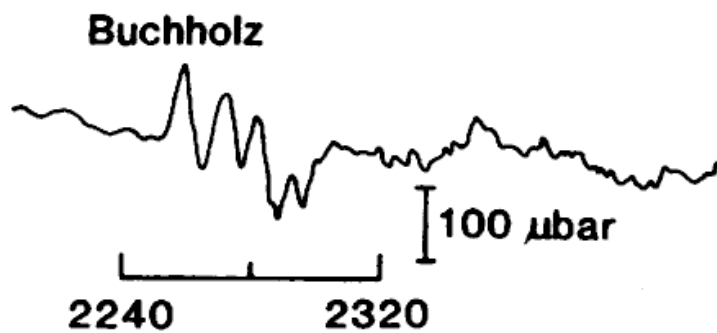
A.4.32 Buchholz, Germany

Figure A.44: Figure from Donn and Balachabdran (1981) of the station at Buchholz, Germany.

May 19, 1980

Yonago

P

F

0.1 mmHg

09:40 50 08:00 10 20 30 40 50^m

JST

P=07h:58^{mm}
 M=0.11^{mm}
 P-F=32^{min}
 T=4^{min}

Figure A.45: Figure from Liu et al. (1982) of the station at Yonago, Japan.

A.5 Additional Processing and Calculations

A.5.1 Canadian Barometer data interpretation

Data from (Dewey, 1985) are presented as times plotted on a map, and as a time vs. distance plot. From these figures the latitude and longitude, and azimuth of the stations were estimated from the map and then compared to known meteorological stations from historic Canadian datasets. From these locations the distance was recalculated and compared to the digitized distance values from the distance vs time plot. The time resolution of dataset is presented to the nearest 5 minutes, which corresponds to around 102 km of travel distance based on the speed of sound.

A.5.2 Calculating the dew point

In order to qualify the pressure drop needed to bring the air to saturation and generate a cloud or “mist” related to a passing pressure drop the author completed the following calculations. All meteorological data are available within the data repository <https://github.com/aperttu/MSHDataArchive>. On the morning of May 18th before the eruption David Johnston reported from Coldwater II (1300 ft elevation) that it was clear and still and around 10°C (Waitt, 2014). At the Toledo, WA station the hourly observations state that at 7:55 am local (15:55 UTC) the temperature was 54°F with a dew point of 46°F. Portland Airport (PDX) reported 06:55am (14:55 UTC) that the temperature was 55°F and the dew point was 48°F, and again at 07:55am (15:55 UTC) that the temperature was 58°F and the dew point was 49°F. The barometer readings for both the Toledo station and the PDX station were measured from the barometer data from NOAA, with the Toledo station having a pressure of 29.72 inHg, and PDX station having a pressure of 30.08 inHg.

Using a calculator available from the National Weather Service (<https://www.wpc.ncep.noaa.gov/html/dewrh.shtml>) the relative humidity after the eruption at Toledo was 74.28 % and the relative humidity at PDX was 71.94 % at the same time and 77.22 % before the eruption. The relative humidity can then be used to calculate

the actual vapor pressure and mixing ratio of the atmosphere. From there the density of water vapor in the air at the time can be calculated. Both stations reported around 8 g/m^3 of water vapor that morning.

Using these values at Coldwater II for a passing pressure wave to be visible the temperature change from the passing under pressure must be a drop of 4.3°C . Given the ideal gas law, the approximate drop in pressure needed for the relative humidity (4.3°C) is approximately 4.15 kPa. This makes the passing of the wave recorded on the barographs with the elevated amplitude to the north plausible as the source of the observed “fog/mist/cloud” moving north from the volcano.

A.6 Ray Tracing

The following are all the ray tracing results figures from the reanalysis we completed.

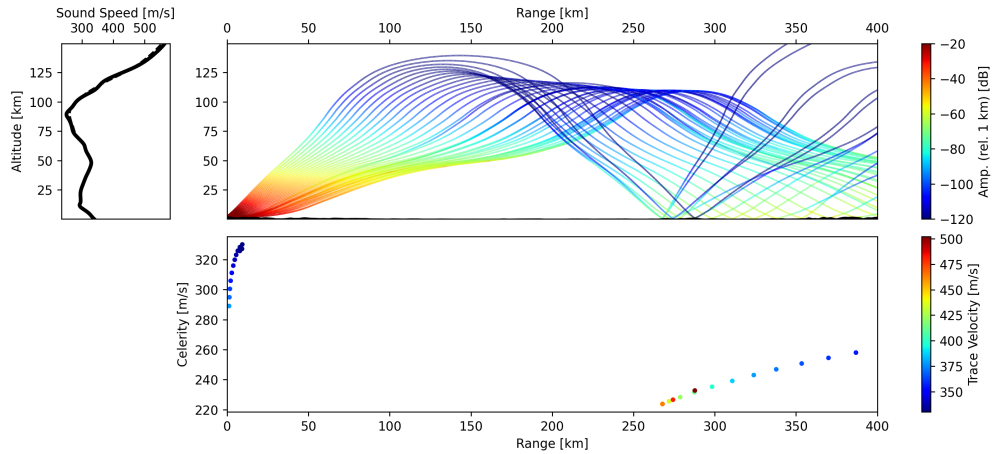


Figure A.46: Northward propagation with a source at 2400m

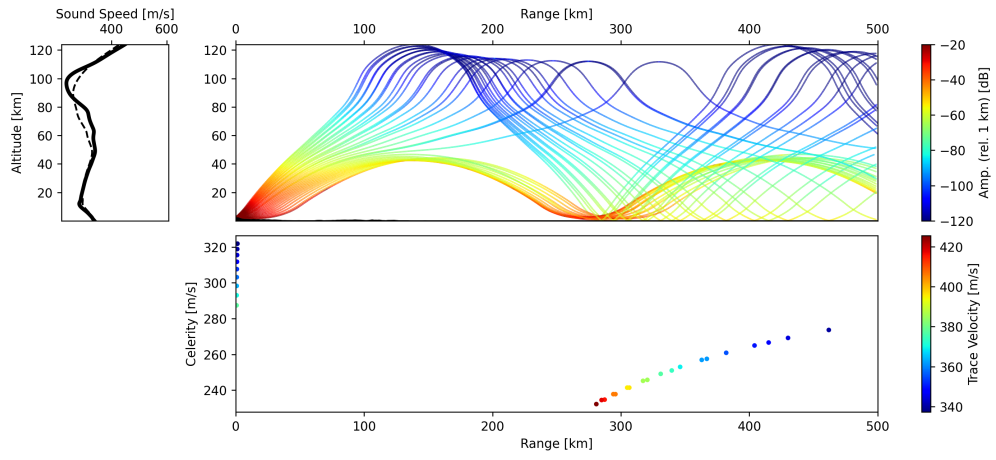


Figure A.47: Westward propagation with a source at 2400m

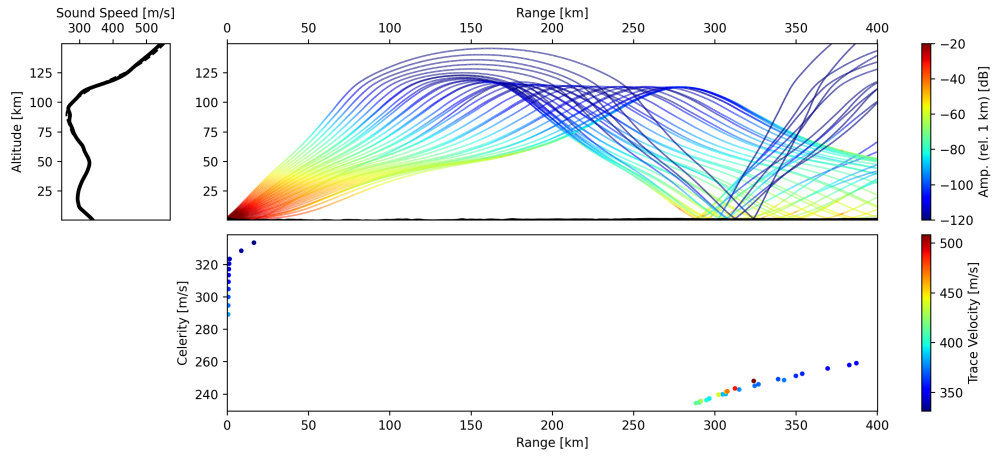


Figure A.48: Southern propagation with a source at 2400m

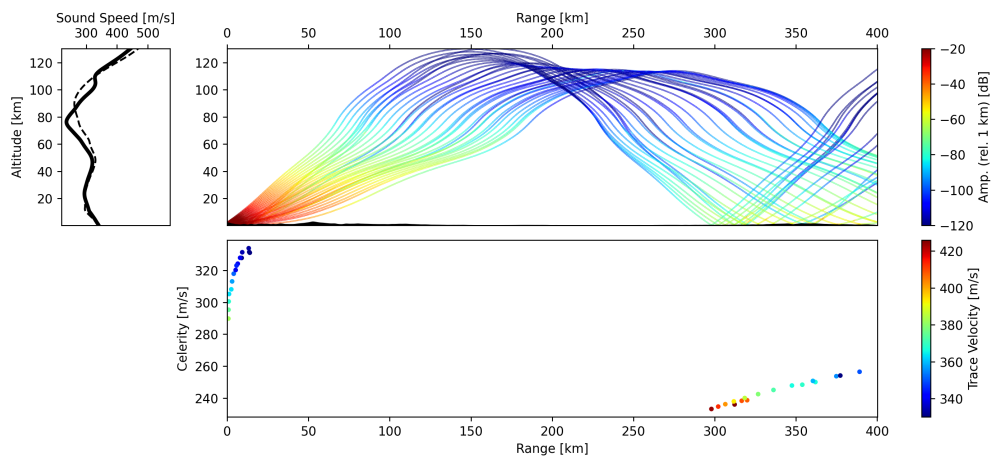


Figure A.49: Eastward propagation with a source at 2400m

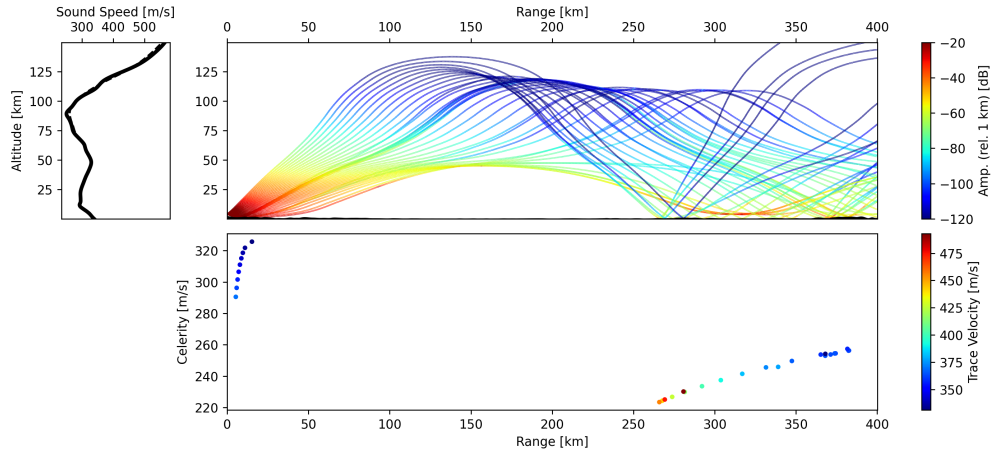


Figure A.50: Northward propagation with a source at 4000m

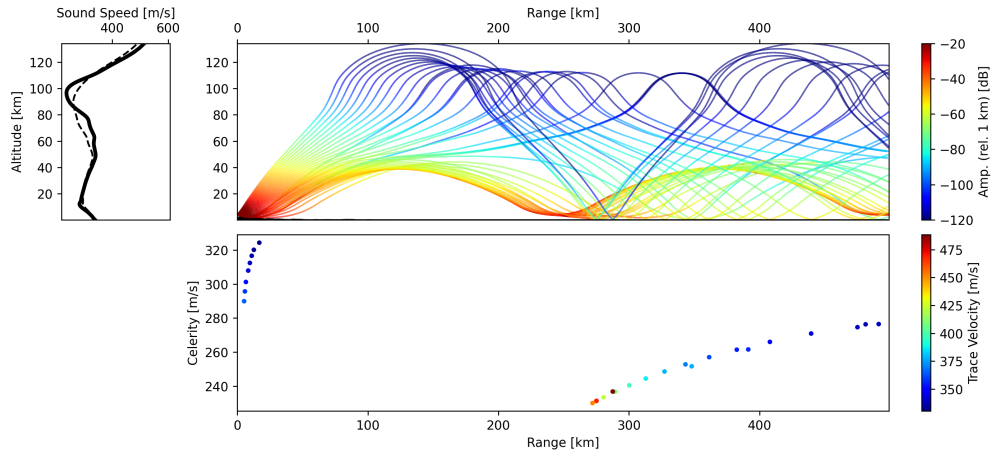


Figure A.51: Westward propagation with a source at 4000m

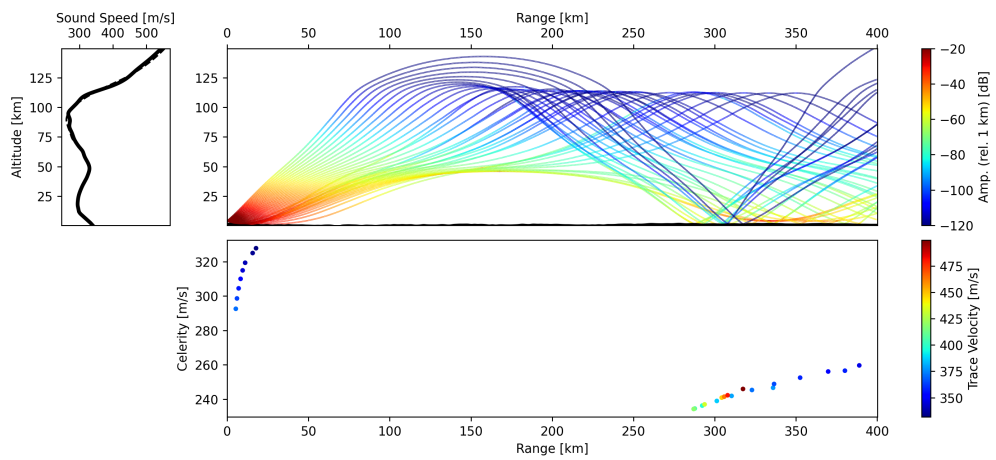


Figure A.52: Southern propagation with a source at 4000m

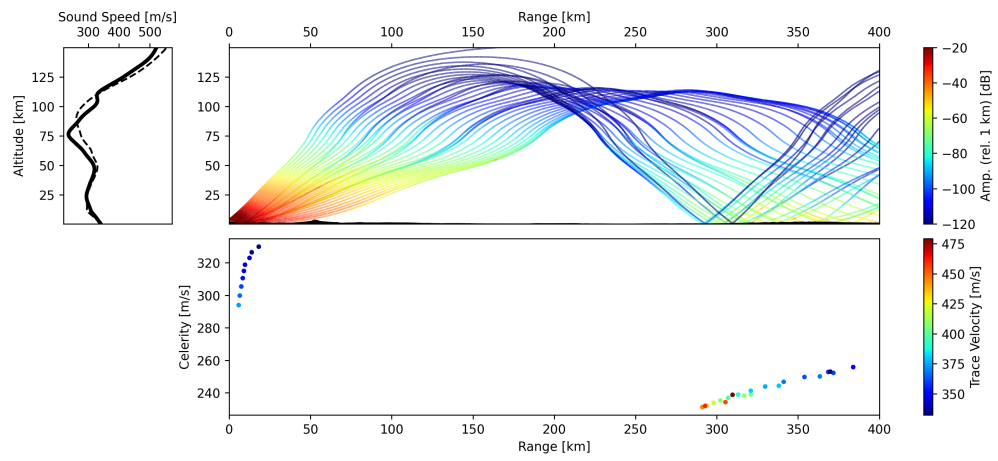


Figure A.53: Eastward propagation with a source at 4000m

Appendix B

Supplemental for Initial Acoustic signature of Experimental Pyroclastic Density Currents: Implications for initial flow magnitude

B.1 Data Availability

Timeseries data is available in the following Data Repository:

<https://dataverse.harvard.edu/dataverse/APerttuThesis>

B.2 PELE Configuration and Scaling

In this section you will see the configuration of the PELE facility for the experiments used in this manuscript.

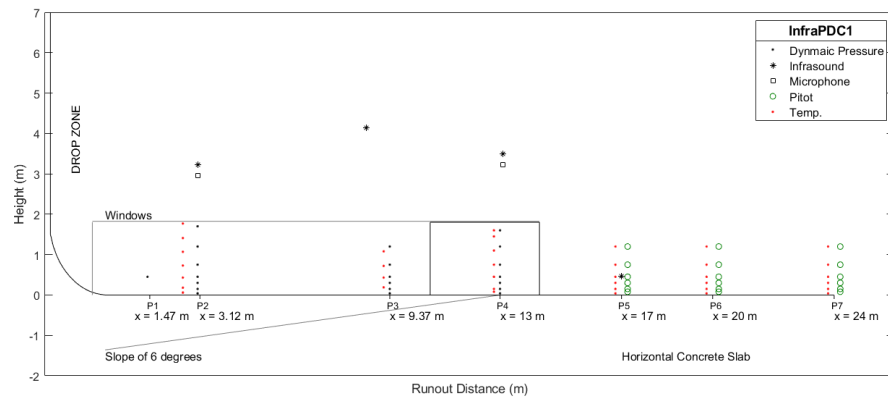


Figure B.1: Experiment 1 configuration

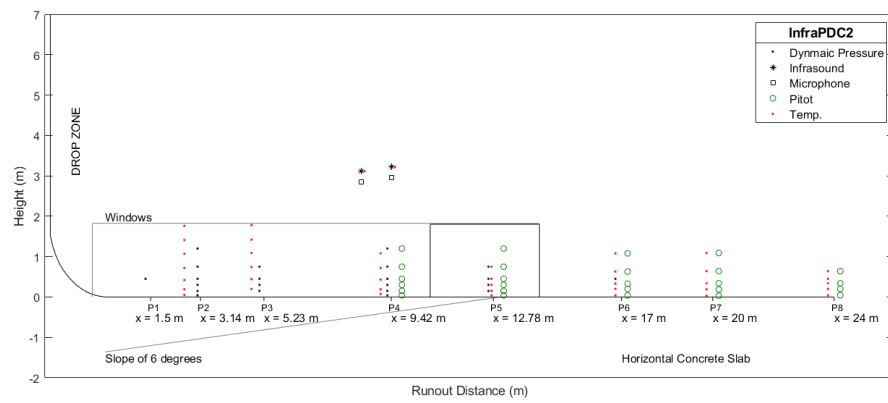


Figure B.2: Experiment 2 configuration

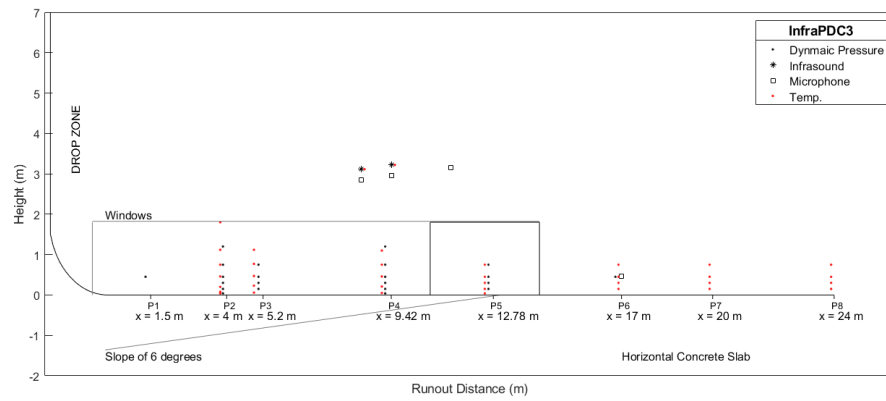


Figure B.3: Experiment 3 configuration

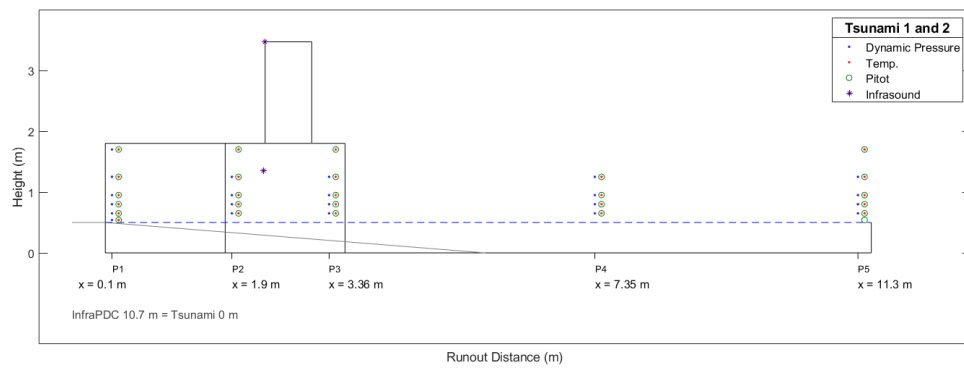


Figure B.4: Experiment 4 and 5 configuration

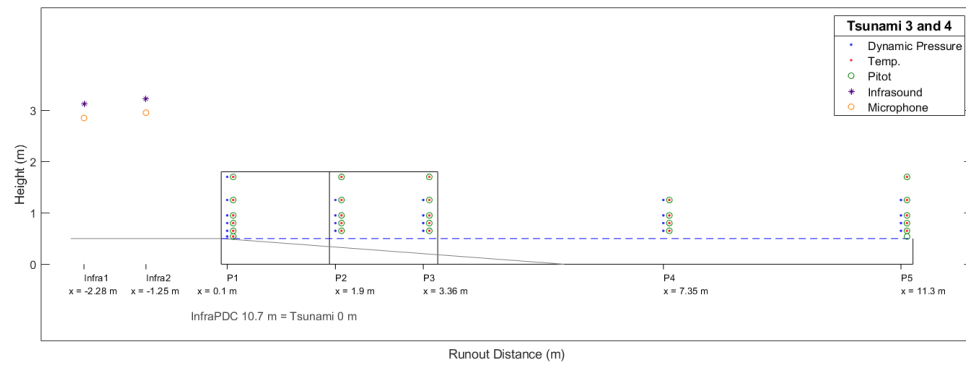


Figure B.5: Experiment 6 to 7 configuration

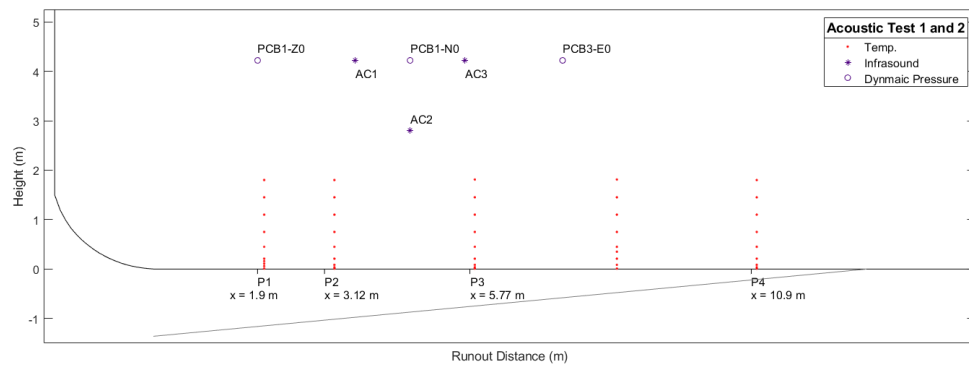


Figure B.6: Experiment 8 and 9 configuration

Table B.1: Scaling relationships for PELE using ranges of values from a range of experiments within PELE from Corna et al. (2025a); Brosch and Lube (2020)

Parameter	Definition / Units	PELE	Nature Dilute	Nature Dense
Particle Diameter	mm	0.002 - 16	0.002 - 1000	0.002 - 1000
Typical velocity	m/s	3 - 12	10 - 200	5 - 30
Ambient Density	kg/m^3	1 - 200	1 - 100	10 - 500
Solids Density	kg/m^3	350–2600	300–2600	300–2600
Reynolds	$\frac{\rho_c U h}{\mu_c}$	$10^4 - 10^7$	$10^6 - 10^9$	-
Richardson	$\frac{\Delta \rho h g}{\rho_a U^2}$	0.01 - 20	0-10	$10^{-4} - 10^1$
Stokes	$\frac{U_T \Delta U_i}{\delta g}$	$10^{-3} - 10^1$	$10^{-3} - 10^7$	-
Froude	$\frac{U}{\sqrt{g' h \cos(\theta)}}$	0.75 - 2	~ 1	1 - 10

B.3 Heights for all profiles

For the localization the dynamic pressure sensors are organized into profiles with a variety of heights as listed below.

Table B.2: PCB Dynamic pressure locations for the InfraPDC experimental series.

InfraPDC1					
Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	
45	4	4	4	45	
	15	15	15		
	30	30	30		
	45	45	45		
	75	75	75		
	120	120	120		
	170		160		
InfraPDC2					
Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
45	4	15	4	15	45
	15	30	15	30	
	30	45	30	45	
	45	75	45	75	
	75			75	
	120			120	
InfraPDC3					
Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6
45	4	15	4	15	45
	15	30	15	30	
	30	45	30	45	
	45	75	45	75	
	75		75		
	120		120		

B.4 Localization methods

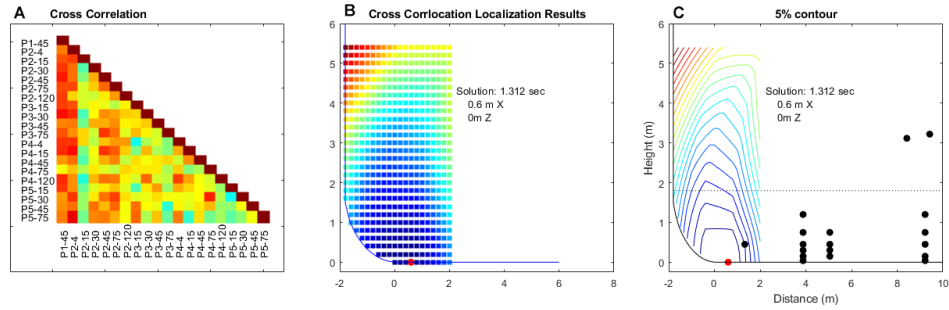


Figure B.7: Localization method. (A) is the cross correlation between the different sensors windows vs all other sensors. On the diagonal is the 1 to 1 where each sensor is compared to itself. Note that there is a large cross correlation throughout the channel when using Profile 1 45 cm as the template or Profile 2 4 cm. (B) the grid search solutions plotted on the grid with the data in (A). Note that the grid search is a minimization. The solution is plotted in red. (C) the grid search results are converted to contour lines with the solution in red and the sensor locations in black.

B.5 Relationship Comparisons

While exploring the relationship between physical parameters and the acoustic power for the first wave (all experiments) and the second wave (larger only), several different parameters were checked. Below all the figures use the plotting schema for all plots.

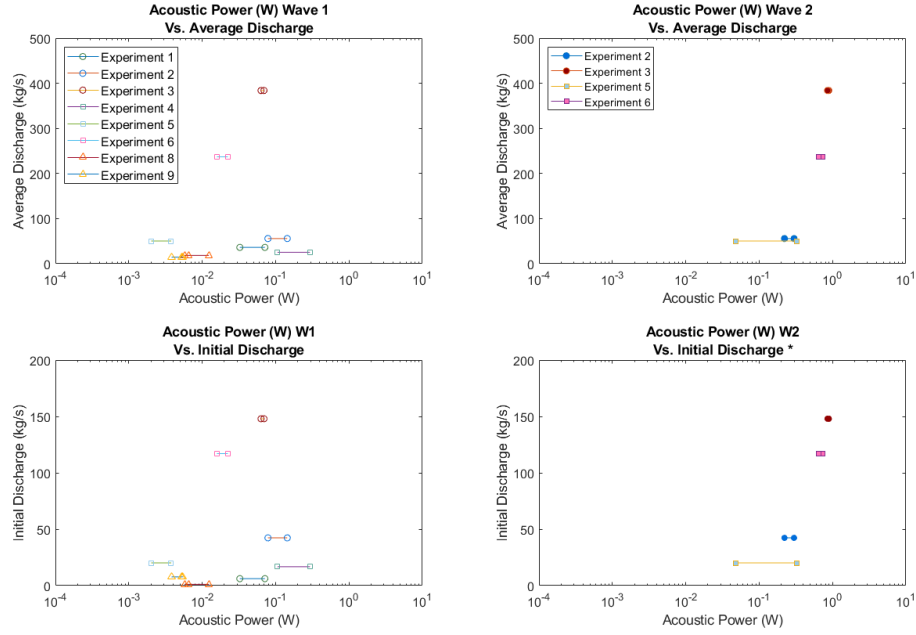


Figure B.8: On the top left is the plot of the acoustic power calculated for the window with the first wave vs the average discharge for the experiment. Below on the bottom left is the same acoustic power window vs the initial discharge (the discharge for the time before the signal). On the top right is the acoustic power of wave 2 (only available for the larger experiments) against the average discharge. Below on the bottom right is the acoustic power of wave 2 vs the initial discharge.

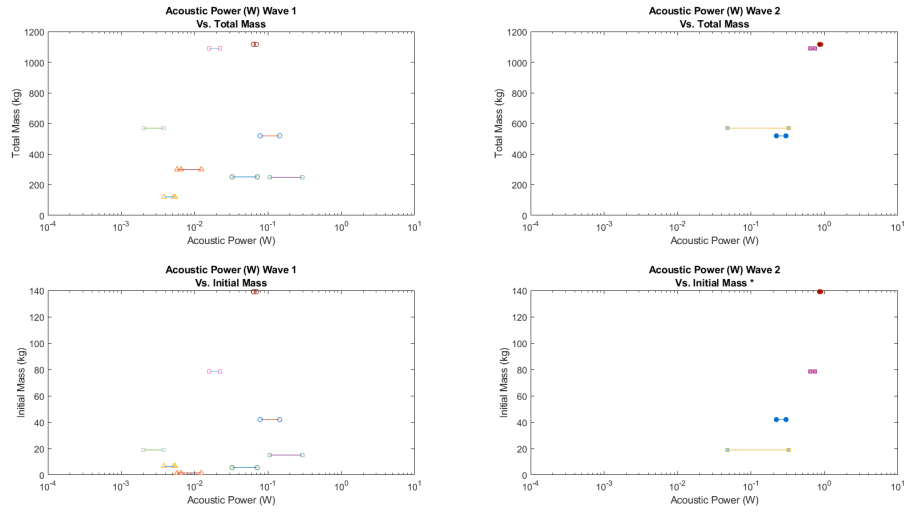


Figure B.9: On the top left is the plot of the acoustic power calculated for the window with the first wave vs the total mass for the experiment. Below on the bottom left is the same acoustic power window vs the initial mass (the mass for the time before the signal). On the top right is the acoustic power of wave 2 (only available for the larger experiments) against the total mass. Below on the bottom right is the acoustic power of wave 2 vs the initial mass.

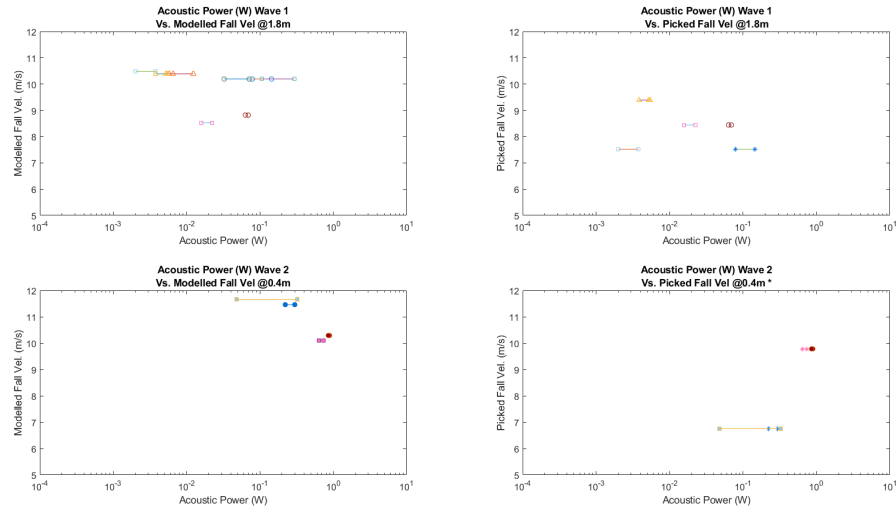


Figure B.10: On the top left is the plot of the acoustic power calculated for the window with the first wave vs the modeled fall velocity for the experiment. Below on the bottom left is the acoustic power of wave 2 (only available for the larger experiments) against the modeled fall velocity. On the top right is the acoustic power of the wave 1 window vs the picked (measured) fall velocity when available, and below is the acoustic power of the wave 2 window with the picked fall velocity.

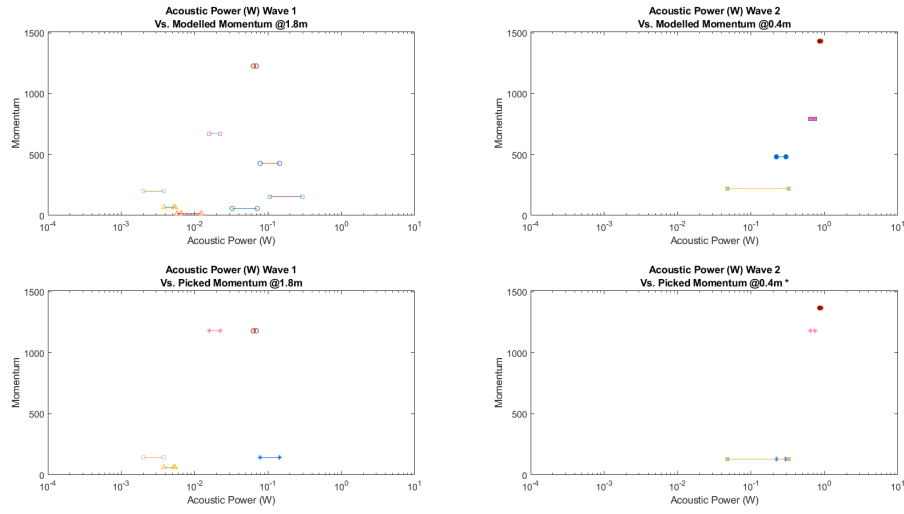


Figure B.11: On the top left is the acoustic power in the window for wave 1 vs the momentum calculated with the modeled fall velocity. Below on the bottom left is the same window acoustic power with the picked fall velocity. On the top right is the acoustic power of the window for wave 2 and the momentum from the modeled fall velocity. Below is the same window on the bottom right is the acoustic power vs the momentum using the picked velocity.

Appendix C

Supplemental for Acoustics of Experimental Pyroclastic Density Currents

C.1 Data Availability

Timeseries data is available in the following Data Repository:

<https://dataverse.harvard.edu/dataverse/APerttuThesis>

C.2 Volcanic Material used in the experiments

The volcanic material used in these experiments is the ash-rich facies of the 232 CE Taupo eruption ignimbrite. It was collected from the field, sieved to remove particles with diameter < 16 mm, and dried at a week at 100 C to remove all moisture. The mixture is polymodal, comprised of highly vesicular sub-rounded pumice, with angular class shards, free crystals, and some lithics. The particle sizes range from 2 mm to 16 mm, with a median particle diameter of 422 μm and a sorting coefficient of 93 μm . The deposit also contains c. 26.5 wt % extremely fine ash (particle diameter $< 63 \mu m$), and c. 27.5 wt % of lapilli clasts ($> 2 \mu m$). (Corna et al., 2025b)

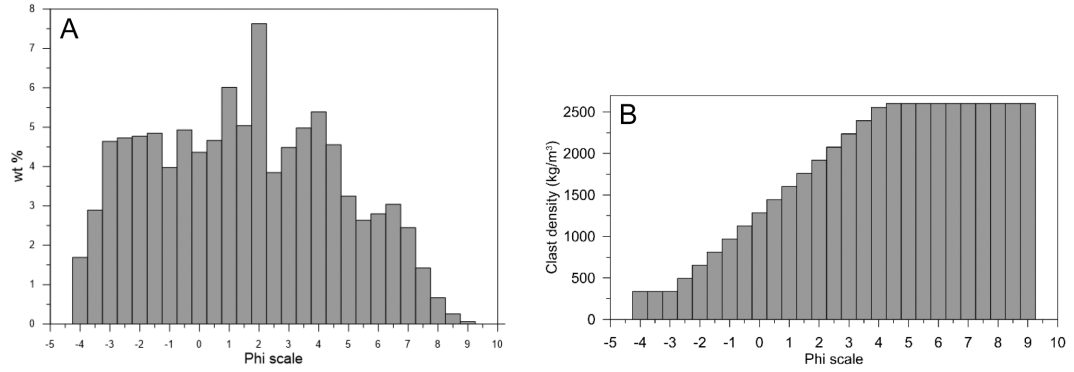


Figure C.1: (A) Grainsize distribution of the 2B material used in the experiments in weight percent in half phi intervals. This mixture is polymodal with a particle sizes range from 2mm to 16mm, with a median particle diameter of 422 μm and a sorting coefficient of 93 μm . The deposit also contains c. 26.5 wt % extremely fine ash (particle diameter < 63 μm), and c. 27.5 wt % of lapilli clasts (> 2 μm). (B) grainsize distribution in terms of the clast density with the average density of 1500 kg/m³. Figure modified from (Corna et al., 2025b).

C.3 Channel frequency and room vibrations

The energy within the frequency band of 5 – 12 Hz was identified as impacts of the channel vibrations through the timing of the onset, and the measurements from the accelerometers on the channel and tank. The signals began just after the triggering mechanism opened the door of the hopper at 0.8 Hz, before the material entered the channel. It was also observable within the accelerometer spectra.

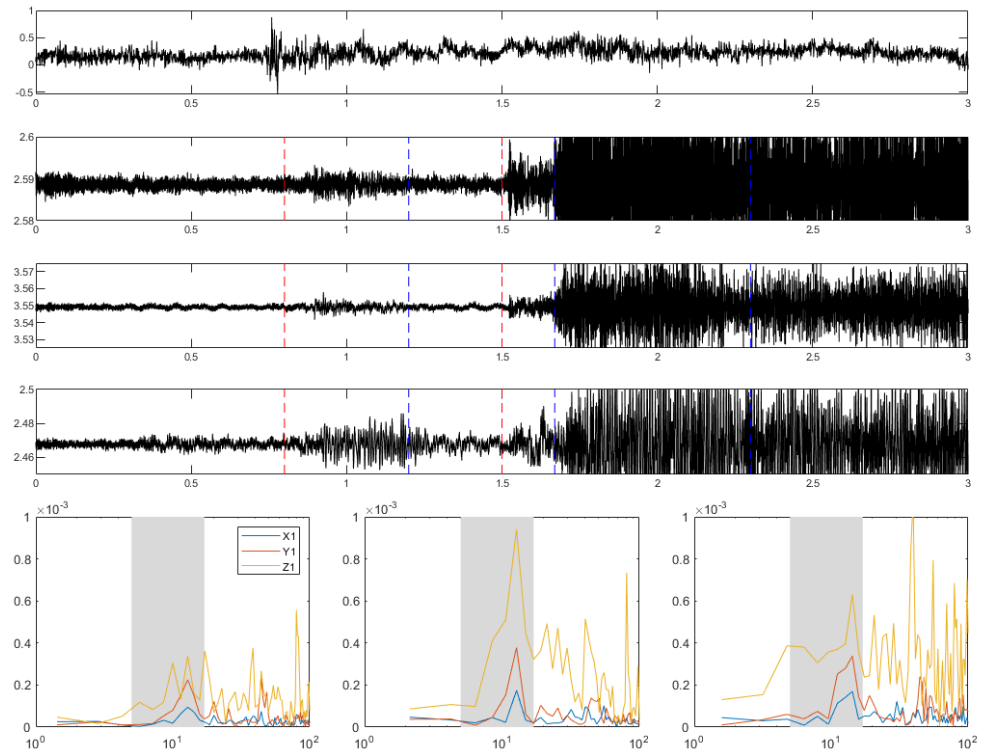


Figure C.2: (A) infrasound above channel location of accelerometer (B) X1, (C) Y1, (D) Z1, (E) window 1 (F) window 2 (G) window 3. Y is the vertical component, X is the horizontal up and down channel component. Z is the horizontal into the channel.

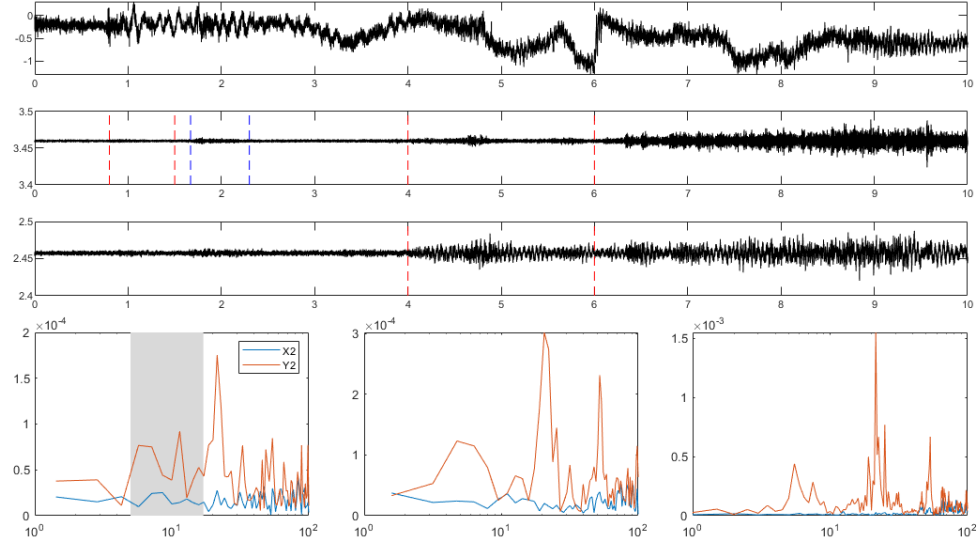


Figure C.3: (A) infrasound above channel location of accelerometer in this case the tank. (B) X1, (C) Y1, (D) window 1 (E) window 2 (F) window 3. Y is the vertical component, X is the horizontal up and down channel component. Z is the horizontal into the channel.

C.4 Workflow for the PSD

Workflow for the PSD modified from previous research.

1. Set the window length
2. Preprocess the data
 - (a) remove electronic noise
 - (b) high pass based on window length
3. Cut the data into window length and taper the waveform using a Tukey window with a 5 % window edge

Step 1 – 3 are illustrated with data from the infrasound signal from Experiment 1 in Figure C.2.

4. Calculate the Power Spectral Density (PSD) using the pwelch method with
 - (a) Define the PSD window length in seconds and set the number of samples based on using the next power of 2 method
 - (b) Overlap the windows by 5 %
 - (c) Defined a Tukey window with a 5 % taper for the PSD window
 - (d) Use this modified window for the pwelch method to calculate the PSD
5. Convert the output to decibels (dB) using the reference pressure of 20×10^{-6} to compare the output with other know references like the global noise curve

Steps 4 and 5 are illustrated with the same data in Figure C.3.

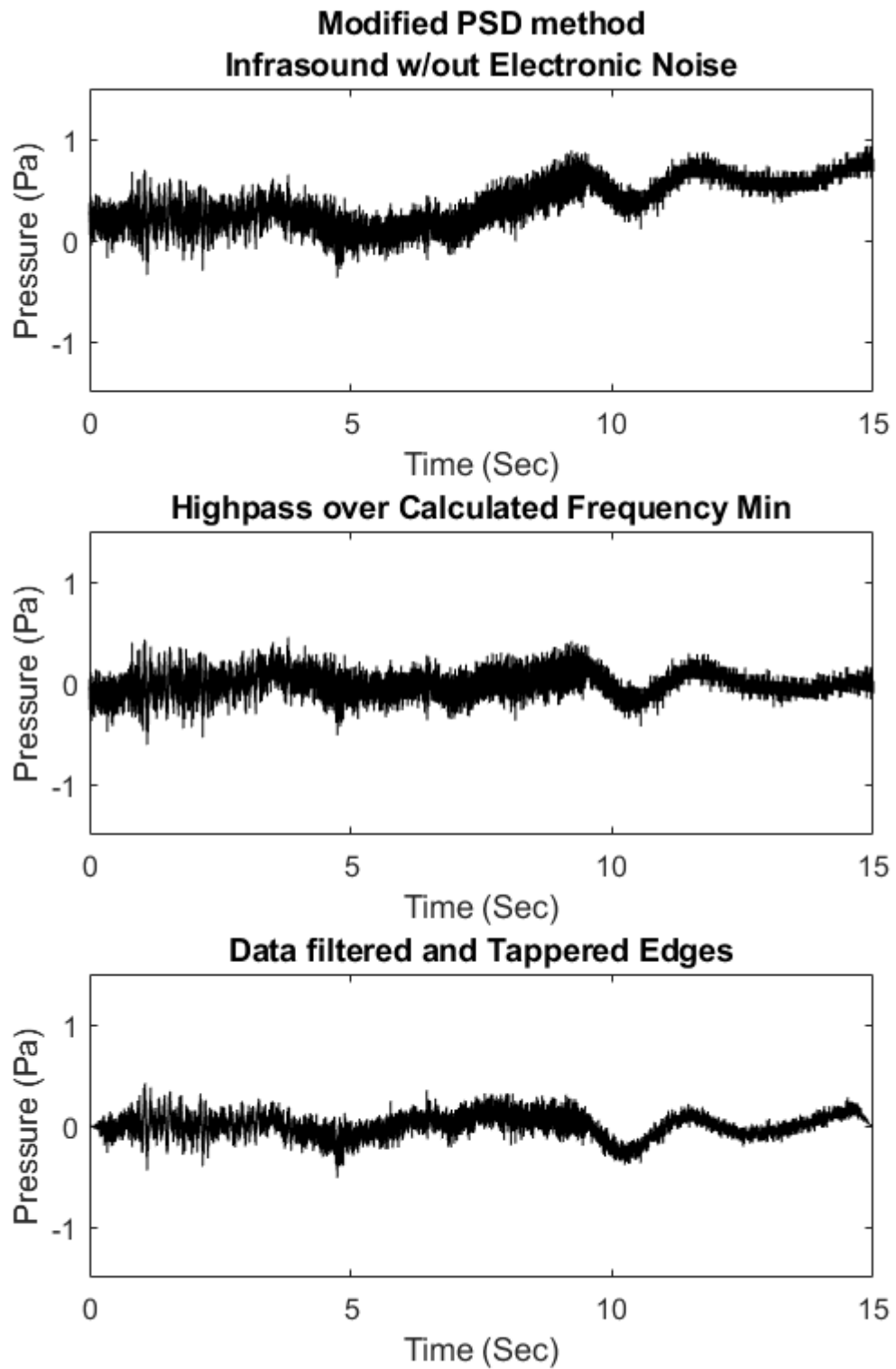


Figure C.4: Pre-processing for the PSD. The raw data with the electronic noise removed is subset into the processing window (top), the window length is used to calculate the minimum frequency which the data is high passed over (middle), and then a taper is added to the end to remove edge effects (bottom).

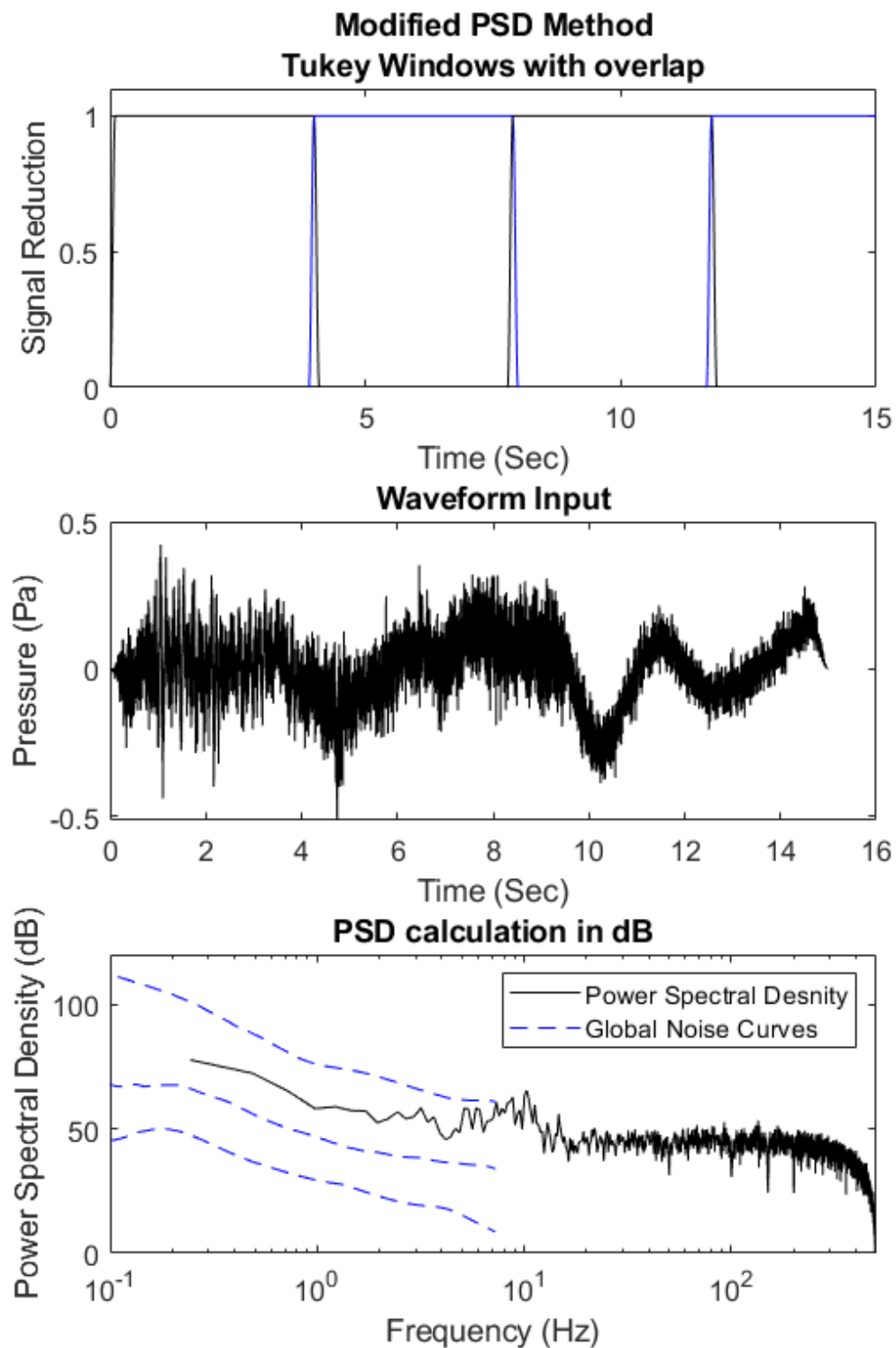


Figure C.5: PSD windowing method. The Tukey windows with the overlap of 5 % (top) show that the filter is 1 for the majority of the signal with the 5 % overlap preserving as much energy as possible. The input waveform (from the previous figure) (middle), and the resulting PSD plotted with the global noise curves (bottom).

C.5 Workflow for the Localization

The workflow for the localization method developed is illustrated as a flowchart in Figure C.6. Following are the results for Infrasound from Experiment 1 (Figure C.7) and Microphones from Experiment 2 (Figure C.8).

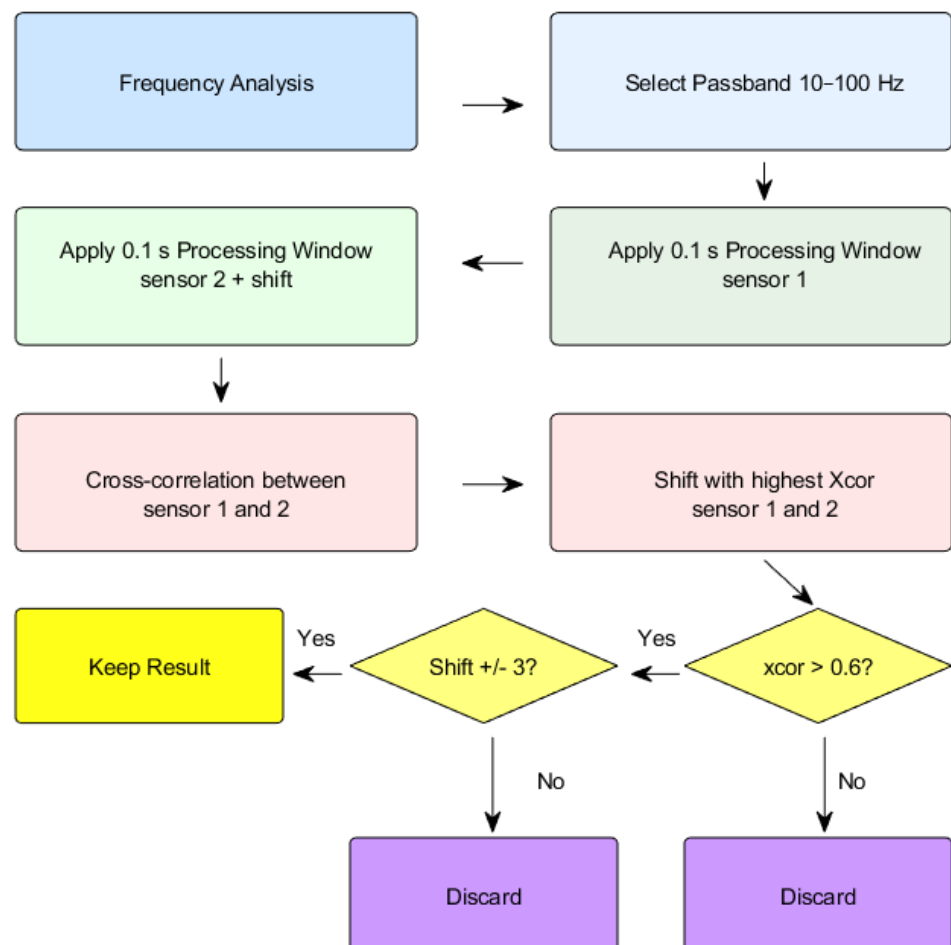


Figure C.6: Workflow of the localization method developed for the PELE infrasound experiments.

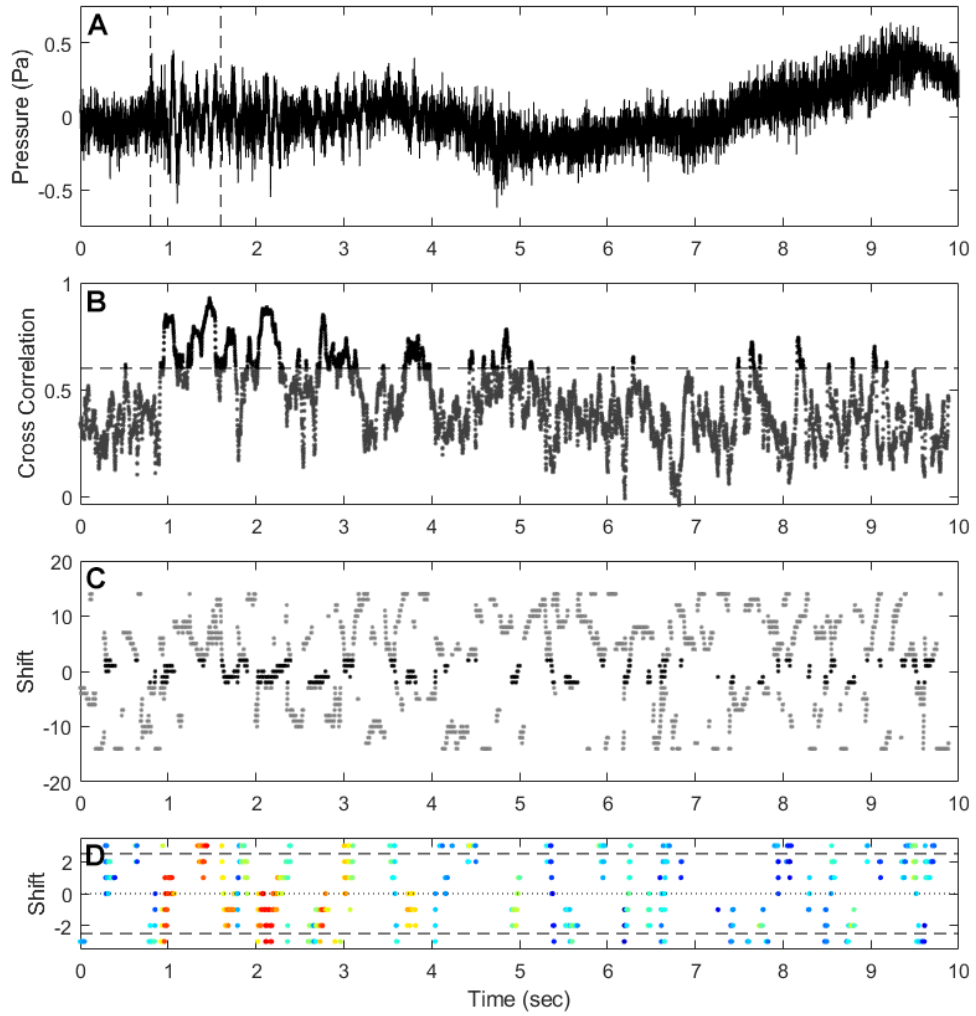


Figure C.7: (A) waveform of the infrasound signal for Experiment 1, (B) associated cross correlation of the localization methodology, (C) associated shift for the calculation, and (D) the shift within the channel plotted colored by correlation.

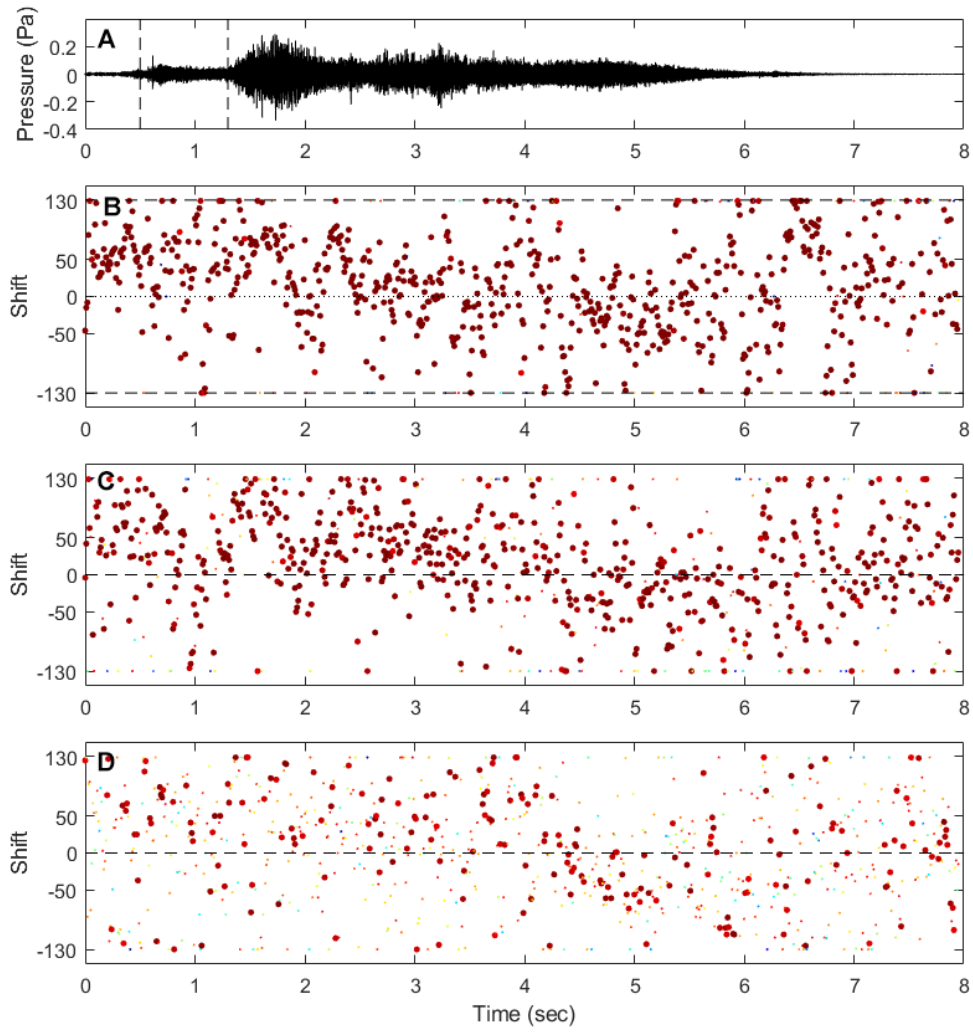


Figure C.8: (A) Waveform of microphone 1 from Experiment 2 with the “click” opening of the hopper highlighted. Passbands are based on the octave bands from acoustics within the cross over range with the infrasound sensors. (B) localization results for the passband of 28 - 57 Hz, plotted by shift and colored by cross correlation. (C) localization results for the passband of 57 - 113 Hz, plotted by shift and colored by cross correlation. (D) localization results for the passband of 113 - 226 Hz, plotted by shift and colored by cross correlation.

Appendix D

Statement of Contribution forms

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.			
Student name:	Anna Bellesiles Perttu		
Name and title of main supervisor:	Dr. Gert Lube, Professor in Volcanology and Research Lead		
In which chapter is the manuscript/published work?	Chapter 3		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:¹ This this paper, the student was responsible for the conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, and visualization. Co-author Kathleen McKee contributed one dataset and the processing results for this dataset, Co-author Jeff Johnson provided a dataset, Gert Lube and Art Jolly provided supervision			
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In which chapter is the manuscript/published work?	Chapter 5		
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