Chapter 2

Case Study and Related Work

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2.1 Case Study: Volcano Monitoring

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Scientists monitor volcanoes for two non-exclusive reasons: (1) to monitor hazards by assessing the level of volcanic unrest; and (2) to understand physical processes occurring within the volcano, such as magma migration and eruption mechanisms [23, 13]. The most common instrument used is the seismometer, which measures ground-propagating elastic radiation from both sources internal to the volcano (e.g., fracture induced by pressurization) and on the surface (e.g., expansion of gases during an eruption) [13]. In addition, microphones are sometimes employed to record *infrasound*, low-frequency (< 20 Hz) acoustic waves generated during explosive events. Infrasound is useful for differentiating shallow and surface seismicity and for quantifying eruptive styles and intensity [6].

2.1.1 Existing volcano instrumentation

The type of instrumentation used to study volcanoes depends on the the science goals of the deployment. We are focused on the use of wireless sensors for temporary field deployments involving dozens of sensor stations deployed around an expected earthquake source region, with inter-node spacing of hundreds of meters. A typical campaign-style deployment will last weeks to months depending on the activity level of the volcano, weather conditions, and science requirements.

Geophysicists often use standalone dataloggers (e.g., Reftek 130 [22]) that record signals from seismometers and microphones to a flash drive. These data loggers are large and power-hungry, typically powered by car batteries charged by solar panels. The sheer size and weight precludes deployments of more than a small number of stations in remote or hazardous areas. Additionally, data must be retrieved manually from each station every few weeks, involving significant effort. Analog and digital radio telemetry enables real-time transmission of data back to an observatory. However, existing telemetry equipment is very bulky and its limited radio bandwidth is a problem for collecting continuous data from multiple channels.

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Typical volcano monitoring studies employ GPS-synchronized data loggers recording both seismic and acoustic signals. These provide high data fidelity and yield but are bulky, power hungry, and difficult to deploy. Existing analog and digital telemetry is similarly cumbersome. The use of wireless sensors could enable studies involving many more sensors distributed over a larger area. However, the science requirements pose a number of difficult challenges for sensor networks. First, seismoacoustic monitoring requires high data rates, with each node sampling multiple channels at 100 Hz. Second, signal analysis requires complete data, necessitating reliable data collection. Third, volcano studies compare signals across multiple sensors, requiring that collected data be accurately timestamped against a GPS-based global clock.

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Beginning in 2004, computer scientists from Harvard University joined forces with seismologists from the University of New Hampshire, the University of North Carolina, and Instituto Geofísico, Escuela Politécnica Nacional, Ecuador, to begin a collaboration aimed at using sensor networks to further the study of active volcanoes. As of early 2009 our collaboration has spanned three successful deployments, multiple scientific publications and generated a large number of interesting ideas to explore. We have been fortunate to be a part of this long-running partnership.

From a simple starting point — a handful of nodes streaming continuous data from a single sensor per node — we have developed a sophisticated resource-aware architecture carefully balancing the value of the data to the application against the network-wide cost of extraction. These design changes were motivated by the science goals, responsive to changing hardware platforms, and driven by experience gained deploying prior iterations. Because each of the three deployments is already well-documented, one of our goals is to illuminate the design process by linking successive artifacts together while maintaining the thread of data quality as an application driver.

From the beginning of our work, providing high quality data has remained a part of our research agenda. This focus emerged out of both the scientific goals, and constraints of the devices we have deployed. Because seismologists are used to processing high-resolution data from multiple stations, wireless sensor networks — while considerable less burdensome than existing instrumentation — must provide data of similar quality before they can be used for scientific study. The scale made possible by rapid deployment promised by augmenting existing seismological instrumentation with wireless sensor network hardware is new, but the existence of data processing techniques means that the requirements are already firmly in place.

Designing wireless sensor network applications in this space has required work to meet some of the data quality requirements while finding ways of creatively relaxing others. Specifically, we have found it necessary to deliver high-resolution data meeting strict timing requirements, but found flexibility in terms of providing a complete data set from every node covering all moments of time.

2.2 Overview of Seismoacoustic Monitoring

Volcanic monitoring has a wide range of goals, related to both scientific studies and hazard monitoring. Figure 2.1 displays an overview of several instruments that might be used, the signals that they collect and example configurations used during deployments. The type and configuration of the instrumentation depends on the goals of a particular study. Traditionally, dispersed networks of seismographs, which record ground-propagating elastic energy, are utilized to locate, determine the size of, and assess focal mechanisms (source motions) of earthquakes occurring within a volcanic edifice [3]. At least four spatially-distributed seismographs are required to constrain hypocentral (3D) source location and origin time of an earthquake, though using more seismic elements enhances hypocenter resolution and the understanding of source mechanisms. Understanding spatial and temporal changes in the character of volcanic earthquakes is essential for tracking volcanic activity, as well as predicting eruptions and paroxysmal events [14].

Another use of seismic networks is the imaging of the internal structure of a volcano through tomographic inversion. Earthquakes recorded by spatially-distributed seismometers provide information about propagation velocities between a particular source and receiver. A seismically-active volcano thus allows for three-dimensional imaging of the volcano's velocity structure [1, 20]. The velocity structure can then be related to material properties of the volcano, which may be used to determine the existence of a magma chamber [9, 15]. Dense array configurations, with as many as several dozen seismographs, are also an important focus of volcanic research [4, 16]. Correlated seismic body and surface wave phases can be tracked as they cross the array elements, enabling particle motion and wavefield analysis, source back-azimuth calculations, and enhanced signal-to-noise recovery.

2.3 Opportunities for Wireless Sensor Networks

Networks of spatially-distributed sensors are commonly used to monitor volcanic activity, both for hazard monitoring and scientific research [24]. Typical types of sensing instruments include seismic, acoustic, GPS, tilt-meter, optical thermal, and gas flux. Volcanic sensors range from widely dispersed instrument networks to more confined sensor arrays. An individual sensor station could consist of a single sensor (e.g., seismometer or tilt sensor), or an array of several closely-spaced (10^2 to 10^3 m

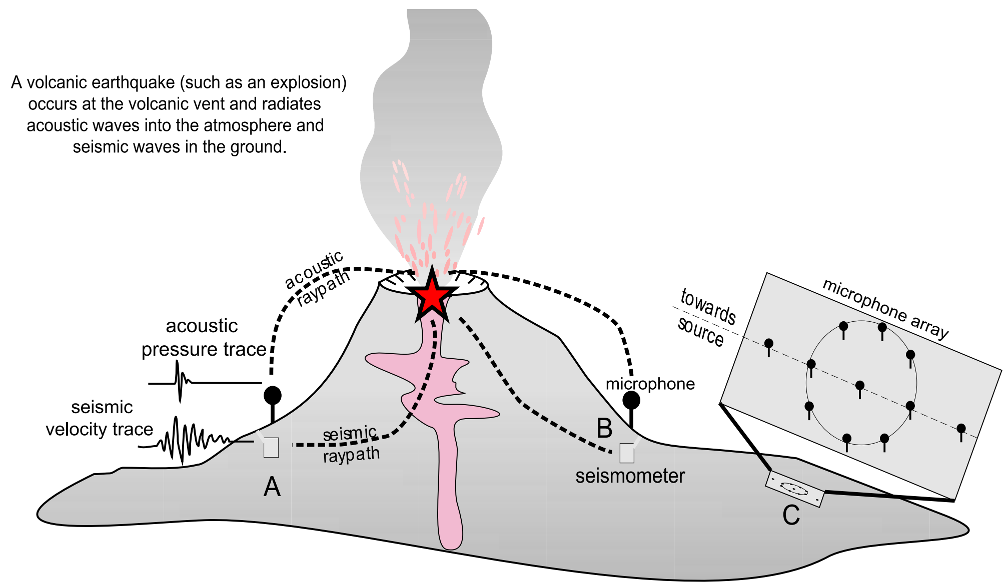

Figure 2.1: **Sensor arrays for volcanic monitoring.**

aperture) wired sensors, perhaps of different types. Multiple stations may be integrated into a larger network installed over an extended azimuthal distribution and radial distance (10^2 to 10^4 m) from the volcanic vent. Data from various stations may be either recorded continuously or as triggered events and the acquisition bandwidth depends upon the specific data stream. For instance, seismic data is often acquired at 24-bit resolution at 100 Hz, while tilt data may be recorded with 12-bit resolution at 1 Hz or less.

Unfortunately, the number of deployed sensors at a given volcano is usually limited by a variety of factors, including: monetary expenses such as sensor, communication, and power costs; logistical concerns related to time and access issues; and archival and telemetry bandwidth constraints. Due to their small size, light weight, and relatively low cost, wireless sensor nodes have an important role to play in augmenting and extending existing seismic instrumentation, providing the increased spatial resolution necessary to support seismic applications like tomography.

Sensor data at a station may be recorded locally or transmitted over long-distance radio or telephone links to an observatory located tens of kilometers from the volcano. At the receiving site, data is displayed on revolving paper helicorders for rapid general interpretation and simultaneously digitized for further processing. However, due to the expense and bandwidth constraints of radio telemetry, high-quality, multi-channel data acquisition at a particular volcano is often limited. These analog systems also suffer from signal degradation and communication interference.

As a result, many scientific experiments use a stand-alone data acquisition system at each recording station. The digitizer performs high-resolution analog-to-digital conversion from the wired sensors and stores data on a hard drive or Compact Flash card. However, these systems are cumbersome, power hungry ($\approx$ 10 Watts), and require data to be manually retrieved from the station prior to processing. Depending on the size of the recording media, a station may record several days or weeks' worth of data before it must be serviced. Deploying a wireless sensor network with telemetry to the base station allows real time data collection, network monitoring and retasking not possible with untelemetered systems.

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2.4 Sensor Networks for Volcanic Monitoring

Wireless sensor networks capable of assisting the study of volcanoes are exciting the geophysics community. The increased scale promised by lighter, faster-to-deploy equipment will allow them to address scientific questions beyond the practical reach of current equipment. Today's typical volcanic data collection station consists of a group of bulky, heavy, power-hungry components, difficult to move and requiring car batteries for power. Remote deployments often require vehicle or helicopter assist to install equipment and perform maintenance. Local storage is also a limiting factor. Stations typically log data to a local Compact Flash card which must be periodically retrieved, requiring researchers to regularly return to each station.

These limitations make it difficult to deploy large networks of existing equipment. Yet these large-scale experiments hold out the possibility of achieving important insights into the inner workings of volcanoes. For example, volcanic tomography [8] is the study of a volcano's interior structure. Collecting and analyzing signals from multiple stations can produce precise mappings of the internal structure of the volcanic edifice. In general the precision and accuracy of these mappings increases as stations are added to the data collection network. Studies such as these may help resolve debates over the physical processes at work within the volcano's interior.

2.4.1 Scientific Requirements

The geophysics community has well-established tools and techniques used to process the signals extracted by volcanic data collection networks. These analytical methods require that our wireless sensor network provide data of extremely high fidelity. A single missed or corrupted sample can invalidate an entire record. Small differences in sampling rates between two nodes can frustrate analysis. Samples must be accurately time-stamped to allow comparisons between nodes and between networks.

An important feature of volcanic signals is that much of the data analysis focuses on discrete events, such as eruptions, earthquakes, or tremor activity. Although volcanoes differ significantly in the nature of their activity, during our deployment many of the interesting signals at Reventador spanned less than 60 sec and occurred at the rate of several dozen per day. This allowed us to design the network to capture time-limited events, rather than continuous signals.

This is not to say that recording individual events is adequate to answer all of the scientific questions volcanologists pose. Indeed, understanding long-term trends requires complete waveforms spanning long time intervals. However, the low radio bandwidth of typical wireless sensor nodes makes them inappropriate for these types of studies and for this reason we have focused on triggered event collection.

Volcanic studies also require large inter-node separations to obtain widely-separated views of the seismic and infrasonic signals as they propagate. Array configurations used often consist of one or more, possibly intersecting, lines of sensors. The resulting topologies raise new challenges for sensor network design, as much previous work has focused on dense networks where each node has a large number of neighbors. Linear configurations also affect achievable network bandwidth, which degrades as data must be transmitted over multiple hops. Node failure poses a serious problem in sparse networks because a single node failure can obscure a large portion of the network.

2.4.2 Challenges for Sensor Networks

Wireless sensor networks have the potential to greatly enhance understanding of volcanic processes by permitting large deployments of sensors in remote areas. Our group is one of the first to explore the use of wireless sensor networks for volcano monitoring. We have deployed two wireless arrays on volcanoes in Ecuador: at Volcán Tungurahua in July 2004 [29], and at Reventador in August 2005 [30]. The science requirements give rise to a number of unique challenges for sensor networks, which we outline below.

High-resolution signal collection: Data from seismometers and microphones must be recorded at relatively high data rates with adequate per-sample resolution. A sampling rate of 100 Hz and resolution of 24 bits is typical. This is in contrast to sensor networks targeting low-rate data collection, such as environmental monitoring [25, 27].

Triggered data acquisition: Due to limited radio bandwidth (less than 100 Kbps when accounting for MAC overhead), it is infeasible to continuously transmit the full-resolution signal. Instead, we rely on triggered data collection that downloads data from each sensor following a significant earthquake or eruption. This requires sensor nodes to continuously sample data and detect events of interest. Event reports from multiple nodes must be collated to accurately detect *global* triggers across the network.

Timing accuracy: To facilitate comparisons of signals across nodes, signals must be timestamped with an accuracy of one sample time (i.e., 10 ms at 100 Hz). Data loggers generally incorporate a GPS receiver and use low-drift oscillators to maintain accurate timing. However, equipping each sensor node with a GPS receiver would greatly increase power consumption and cost. Instead, we rely on a network time synchronization protocol [5, 12] and a *single* GPS receiver. However, correcting for errors in the time synchronization protocol requires extensive post-processing of the raw timestamps.

2.5 Related Work

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While the number of sensor network deployments described in the literature has been increasing, little prior work has focused on evaluating sensor networks from a scientific perspective. In addition, the high data rates and stringent timing accuracy requirements of volcano monitoring represent a departure from many of the previously-studied applications for sensor networks.

Low-data-rate monitoring: The first generation of sensor network deployments focused on distributed monitoring of environmental conditions. Representative projects include the Great Duck Island [26, 21, 11], Berkeley Redwood Forest [27], and James Reserve [2] deployments. These systems are characterized by low data rates (sampling intervals on the order of minutes) and very low-duty-cycle operation to conserve power. Research in this area has made valuable contributions in establishing sensor networks as a viable platform for scientific monitoring and developing essential components used in our work.

This previous work has not yet focused on the efficacy of a sensor network as a scientific instrument. The best example is the Berkeley Redwood Forest deployment [27], which involved 33 nodes monitoring the microclimate of a redwood tree for 44 days. Their study focuses on novel ways of visualizing and presenting the data captured by the sensor network, as well as on the data yield of the system. The authors show that the microclimactic measurements are consistent with existing models; however, no ground truth of the data is established. This paper highlights many of the challenges involved in using wireless sensors to augment or replace existing scientific instrumentation.

High-data-rate monitoring: A second class of sensor network applications involves relatively high data rates and precise timing of the captured signals. The two dominant applications in this area are structural health monitoring and condition-based maintenance. In each case, arrays of sensors are used to capture vibration or accelerometer waveforms that must be appropriately timestamped for later analysis.

NetSHM [18, 17, 31] is a wireless sensor network for structural health monitoring, which involves studying the response of buildings, bridges, and other structures to localize structural damage, e.g., following an earthquake. This system shares many of the challenges of geophysical monitoring; indeed, the data rates involved (500 Hz per channel) are higher than are typically used in volcano studies.

NetSHM implements reliable data collection using both hop-by-hop caching and end-to-end retransmissions. Their work explores the use of local computations on sensors to reduce bandwidth requirements. Rather than a global time-synchronization protocol, the base station timestamps each sample upon reception. The *residence time* of each sample as it flows from sensor to base is calculated based on measurements at each transmission hop and used to deduce the original sample time.

Several factors distinguish our work. First, NetSHM is designed to collect signals following controlled excitations of a structure, which simplifies scheduling. In our case, volcanic activity is bursty and highly variable, requiring more sophisticated approaches to event detection and data transfer. Second, NetSHM has been deployed in relatively dense networks, making data collection and time synchronization more robust. Third, to date the NetSHM evaluations have focused more on network performance and less on the fidelity of the extracted data. Other systems for wireless SHM include one developed by the Stanford Earthquake Engineering Center [10, 28] and earlier work by Berkeley on monitoring the Golden Gate Bridge [19].

Condition-based maintenance is another emerging area for wireless sensor networks. The typical approach is to collect vibration waveforms from equipment (e.g., chillers, pumps, etc.) and perform time- and frequency-domain analysis to determine when the equipment requires servicing. Intel Research has explored this area through two deployments at a fabrication plant and an oil tanker in the North Sea [7]. Although this application involves high sampling rates, it does not necessarily require time synchronization as signals from multiple sensors need not be correlated. The initial evaluation of these deployments only considers the network performance and does not address data fidelity issues.

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