Chapter 1

Introduction

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.

1.1 Overview of Seismoacoustic Monitoring

Volcanic monitoring has a wide range of goals, related to both scientific studies and hazard monitoring. Figure 1.1 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 [2]. 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 [5].

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, 8]. 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 [4, 6]. Dense array configurations, with as many as several dozen seismographs, are also an important focus of volcanic research [3, 7]. 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.

1.2 Opportunities for Wireless Sensor Networks

Networks of spatially-distributed sensors are commonly used to monitor volcanic activity, both for hazard monitoring and scientific research [9]. Typical types of sens-

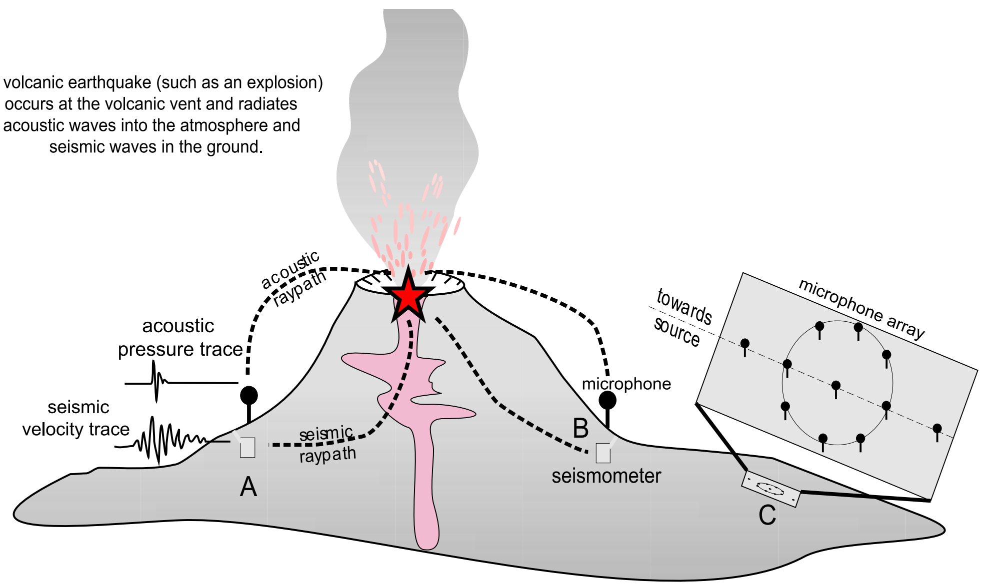


Figure 1.1: **Sensor arrays for volcanic monitoring.**

ing 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 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.

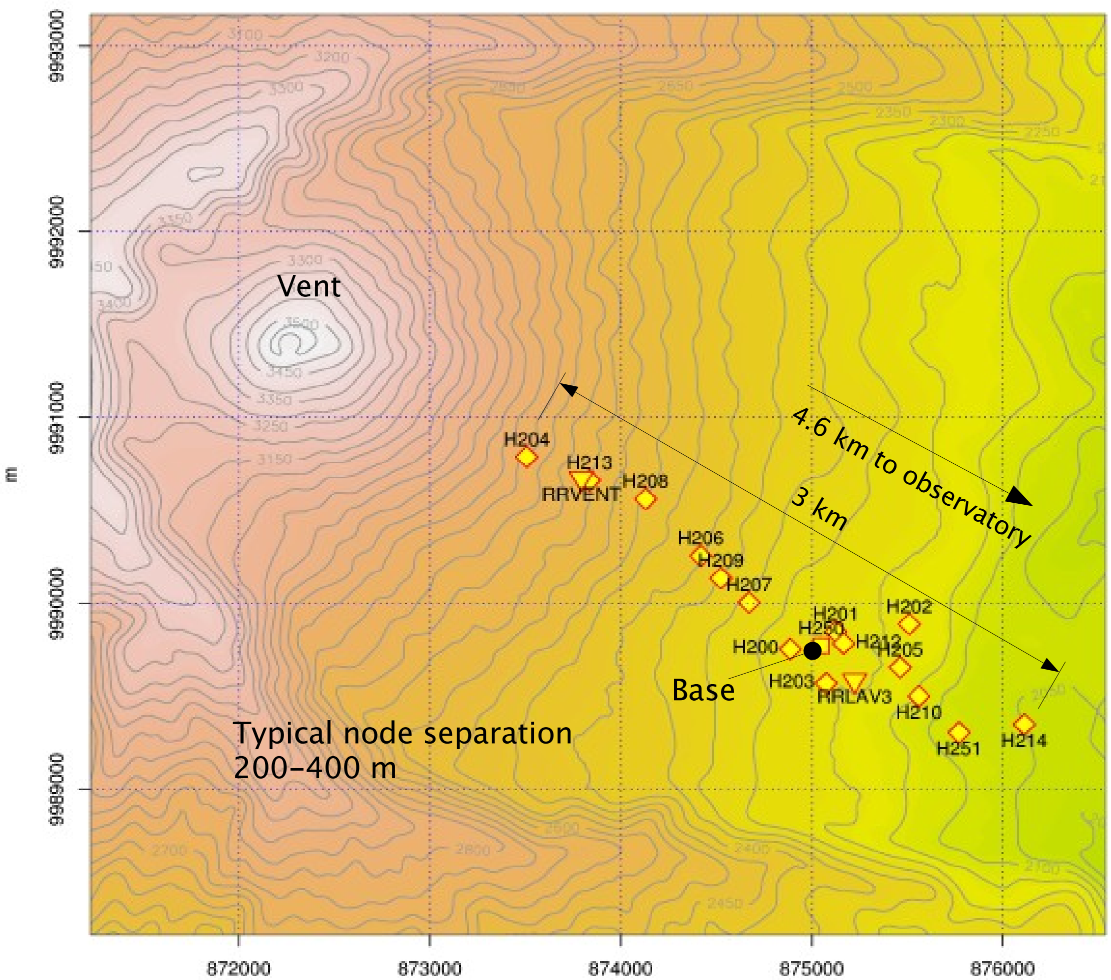
1.3 Overview of Three Deployments

In total, we have performed three deployments of iterations of our system at active volcanoes in Ecuador. Figure 1.2 shows the location and layout of the second and third deployment. All three are summarized below:

1. **July, 2004, Volcán Tungurahua:** We deployed three infrasonic monitoring nodes continuously transmitting at 102 Hz to a central aggregator node, which relayed the data over a wireless link to the observatory approximately 9 km away. Our network was active from July 20–22, 2004, and collected over 54 hours of infrasonic signals.

2. **August, 2005, Volcán Reventador:** This deployment featured a larger, more capable network consisting of sixteen nodes fitted with seismoacoustic sensors deployed in a 3 km linear array. Collected data was routed over a multi-hop network and over a long-distance radio link to a logging laptop located at the observatory 9 km away from deployment site. Over three weeks the network captured 230 volcanic events.

3. **July, 2007, Volcán Tungurahua:** We returned to Tungurahua Volcano in 2007 and deployed eight sensor nodes in order to test Lance, a framework for optimizing high-resolution signal collection. The network was operational for a total of 71 hours, during which time we downloaded 77 MB of raw data.


Vent
H204
H213
RRVENT
H208
H206
H209
H207
H201
H250
H202
H200
H212
H205
Base
H203
RRLAV3
H210
H251
H214
4.6 km to observatory
3 km
Typical node separation
200–400 m
m
9993000
9992000
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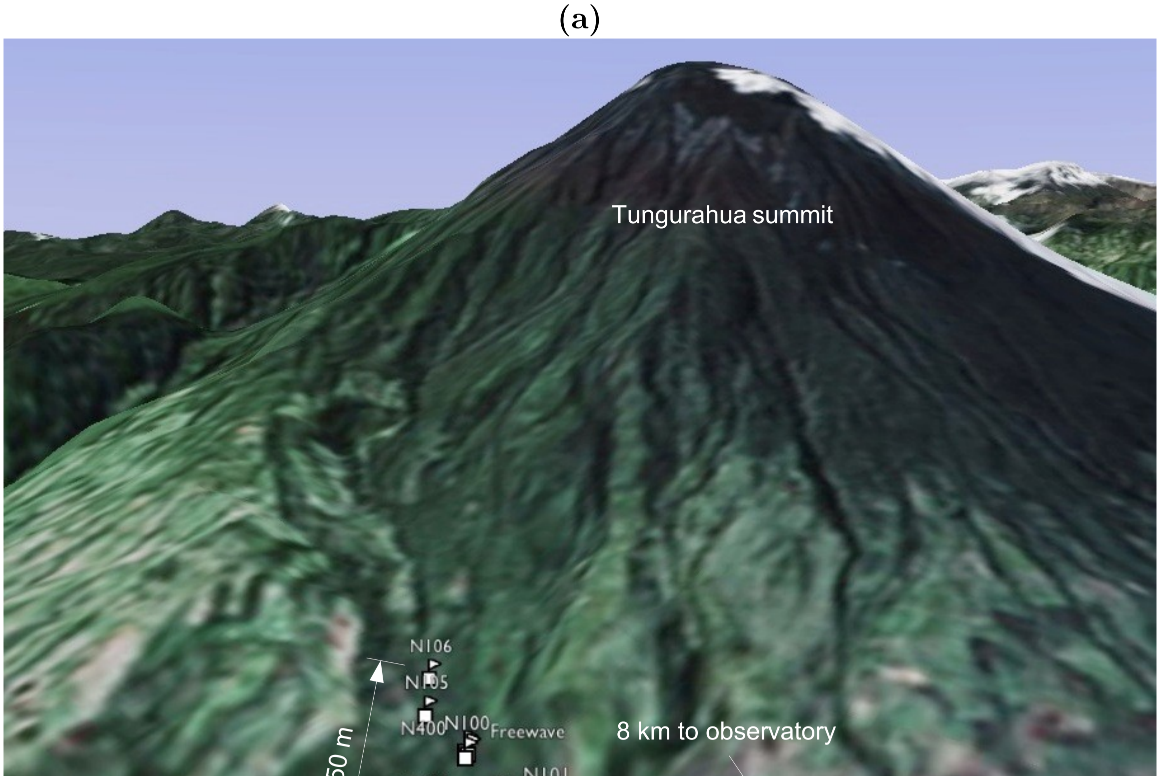
Tungurahua summit
N106
N105
N400
N100
Freewave
8 km to observatory

1.4 Dissertation outline

The remainder of the dissertation is organized as follows.

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