# Monitoring Volcanic Activity at Reventador Volcano, Ecuador with a Wireless Sensor Network


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# Summary

We deployed a 16-node wireless sensor array on Reventador in July/August 2005

- Nodes monitored seismic and infrasonic activity of the erupting volcano
- Automatic triggering to download data following seismic events

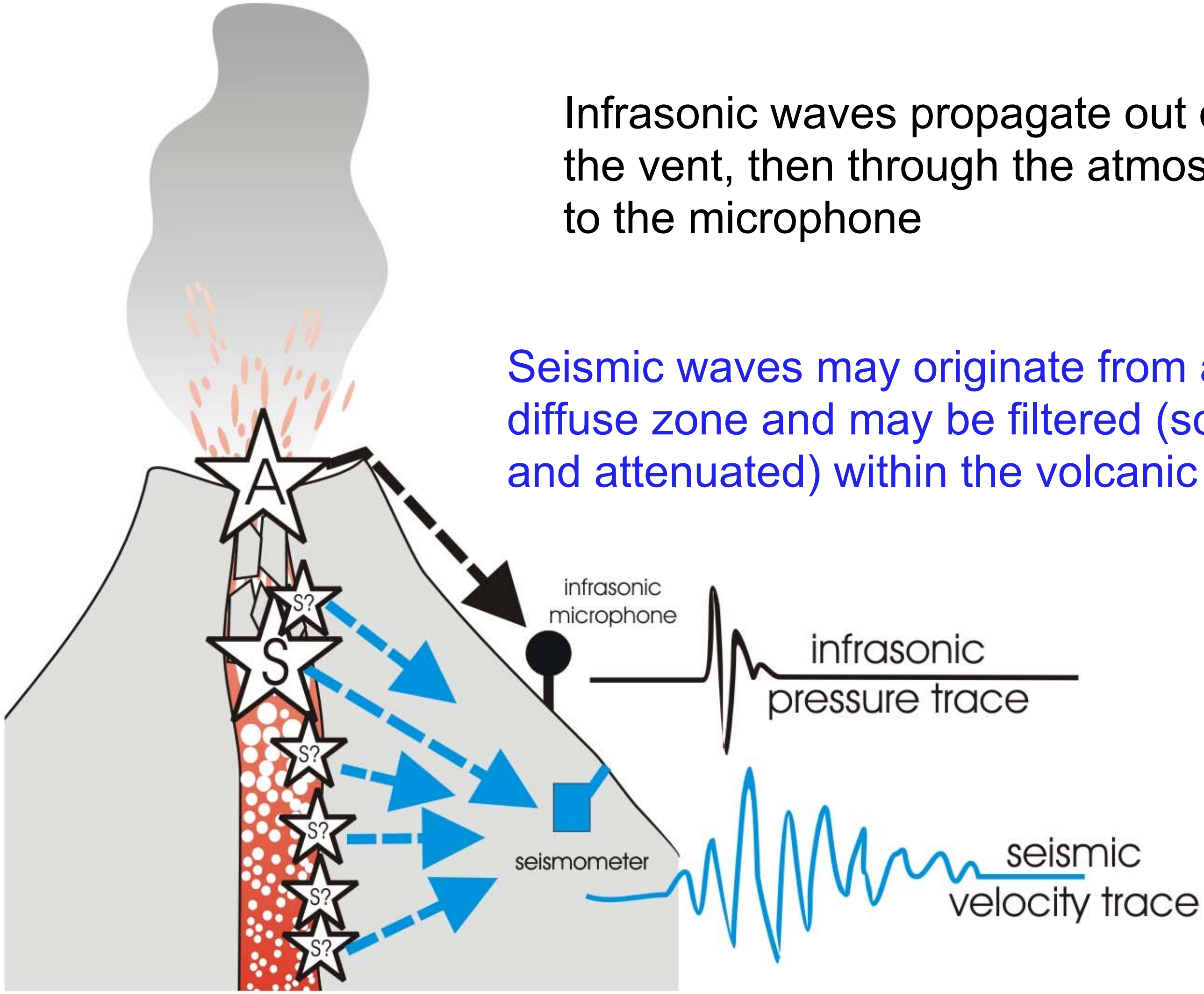
Tested sophisticated data collection, routing, and time synchronization in the real world

- Very challenging environment, remote deployment site
- Science goals involve high data fidelity requirements

Many lessons learned

- Many challenges involved with deployment at remote site
- Software robustness is a major concern
- Postprocessing and analysis of data is as difficult as initial acquisition

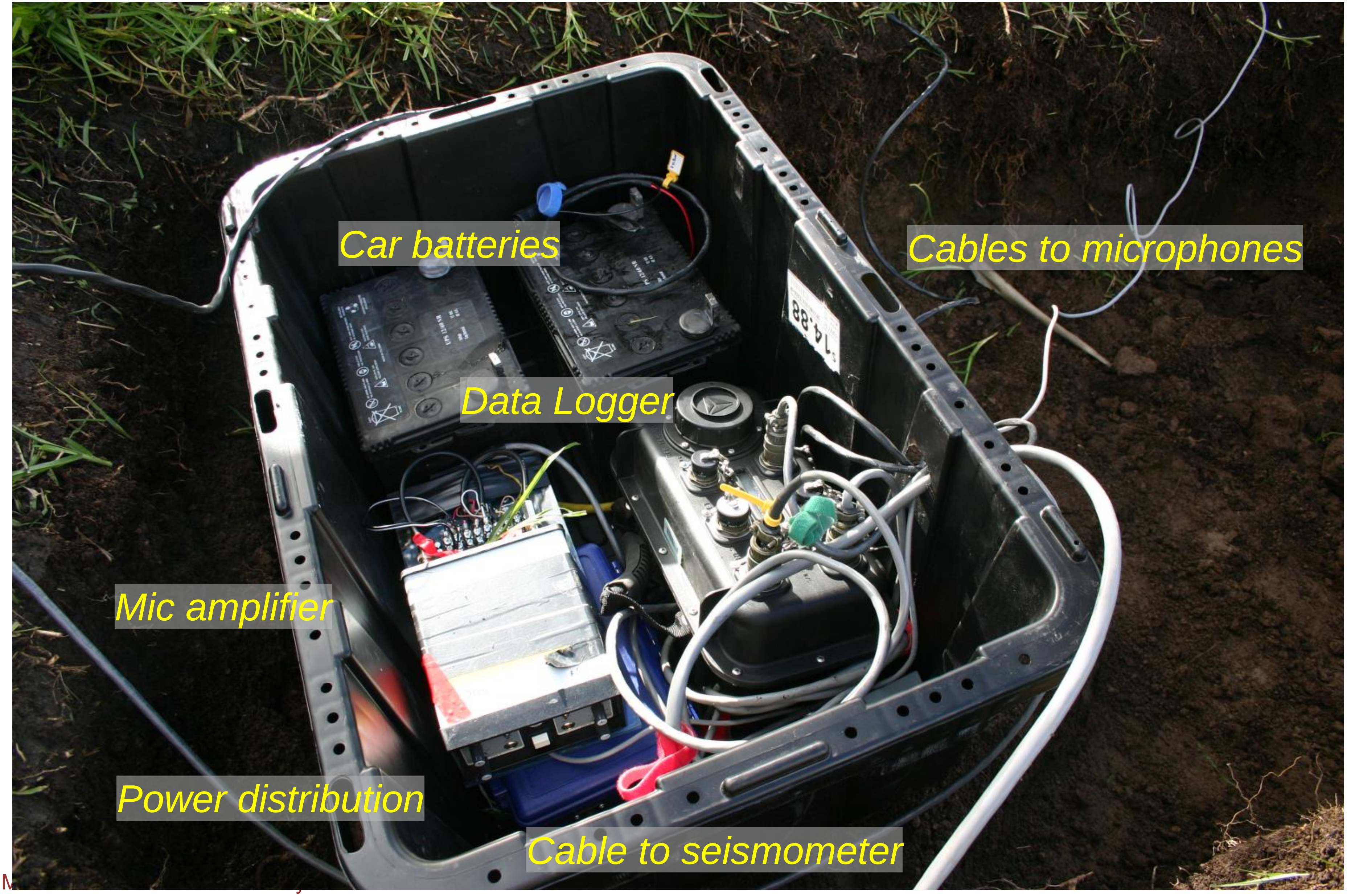
# Sensor Arrays for Volcanic Monitoring




Infrasonic waves propagate out of the vent, then through the atmosphere to the microphone

Seismic waves may originate from a diffuse zone and may be filtered (scattered and attenuated) within the volcanic edifice.

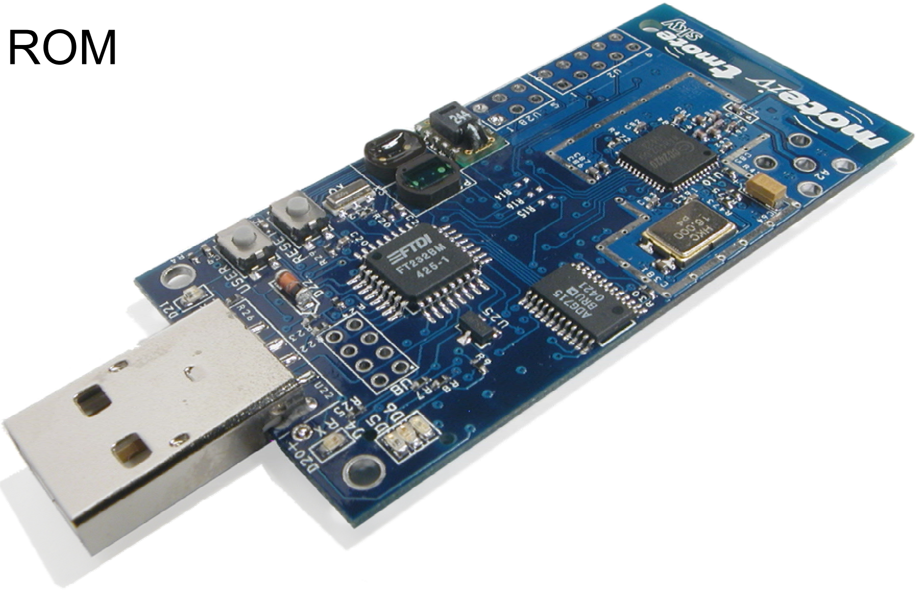
# Existing Volcanic Sensor Station



# Wireless Sensor Mote Technology

Telos “mote” platform

- 8 Hz (TI MSP430) CPU, 10 KB RAM, 40 KB ROM
- 2.4 GHz IEEE 802.15.4 (“Zigbee”) radio (Chipcon CC2420)
- 1 MByte flash for data logging



Designed for low power operation

- 1.8 mA CPU active, 20 mA radio active
- 5 uA current draw in sleep state

Cost: About $75 with no sensors

# The Role of Wireless Sensor Networks

Wireless sensors are smaller, lower power, and much easier to deploy than existing data logger systems

Can provide real time monitoring of volcanic activity

- ... as opposed to manually collecting a CF disk from each station every week

Can enable studies with a large number of sensors

- Large numbers of sensors are needed for detailed studies of volcanic processes
- e.g., tomography -- image interior of volcano using wave arrivals at many locations

# Challenges

## High data rate sampling

- Seismometers and microphones typically sampled at 100 Hz, 24 bits per channel
- 1200 Bytes/sec per node, or > 4 MB per hour

## Reliable communication

- Cannot tolerate dropped packets or samples in recorded data stream

## Fine grained time synchronization

- Must be able to correlate signals from separate nodes to millisecond resolution

## Long telemetry distances between nodes

- Sensors typically placed 100's of meters apart in highly variable/rough terrain

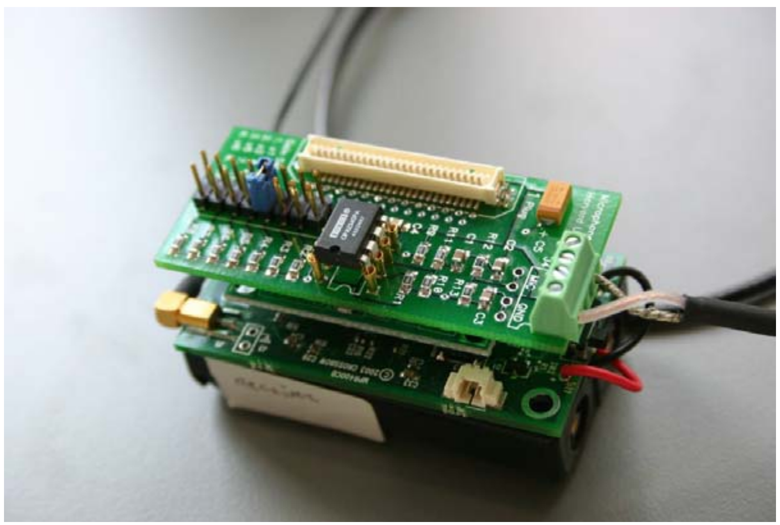
## Automatic event detection

- Radio bandwidth precludes continuous transmission
- Must detect interesting events and trigger downloads automatically

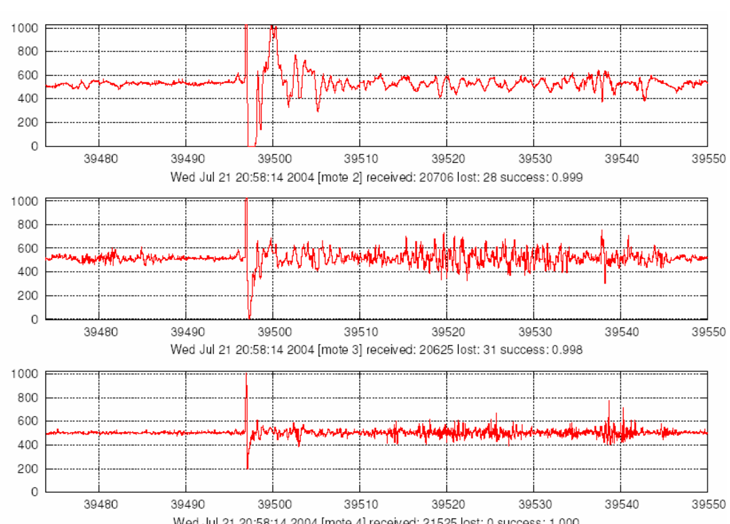
# Previous Work: Volcán Tungurahua, Ecuador, July 2004

## Small-scale network of MicaZ motes with infrasonic microphones

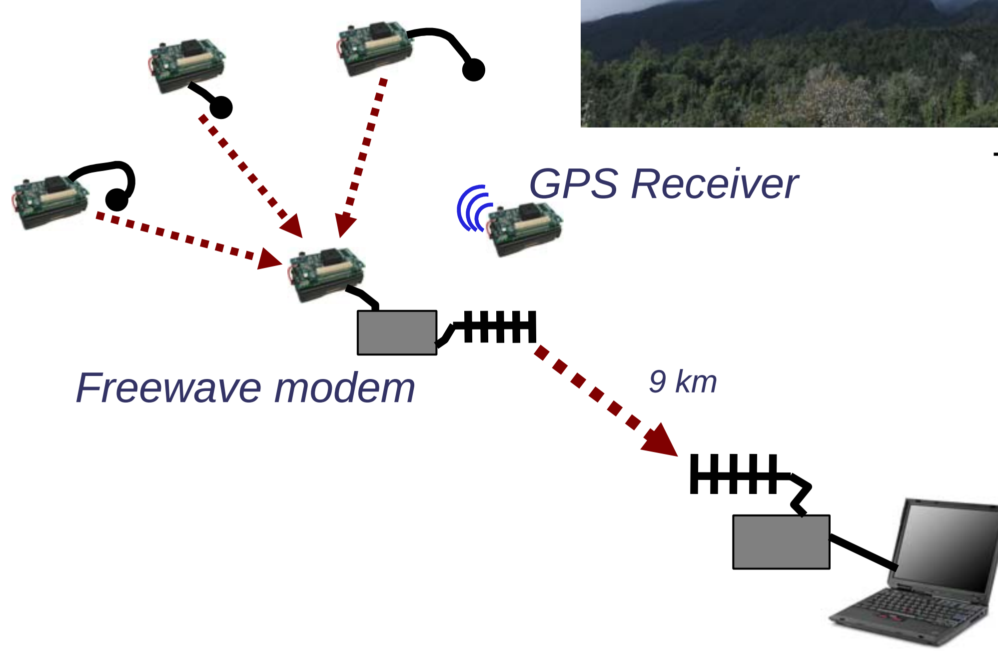
- Proof-of-concept deployment to establish groundwork



MicaZ with custom infrasonic microphone sensor board

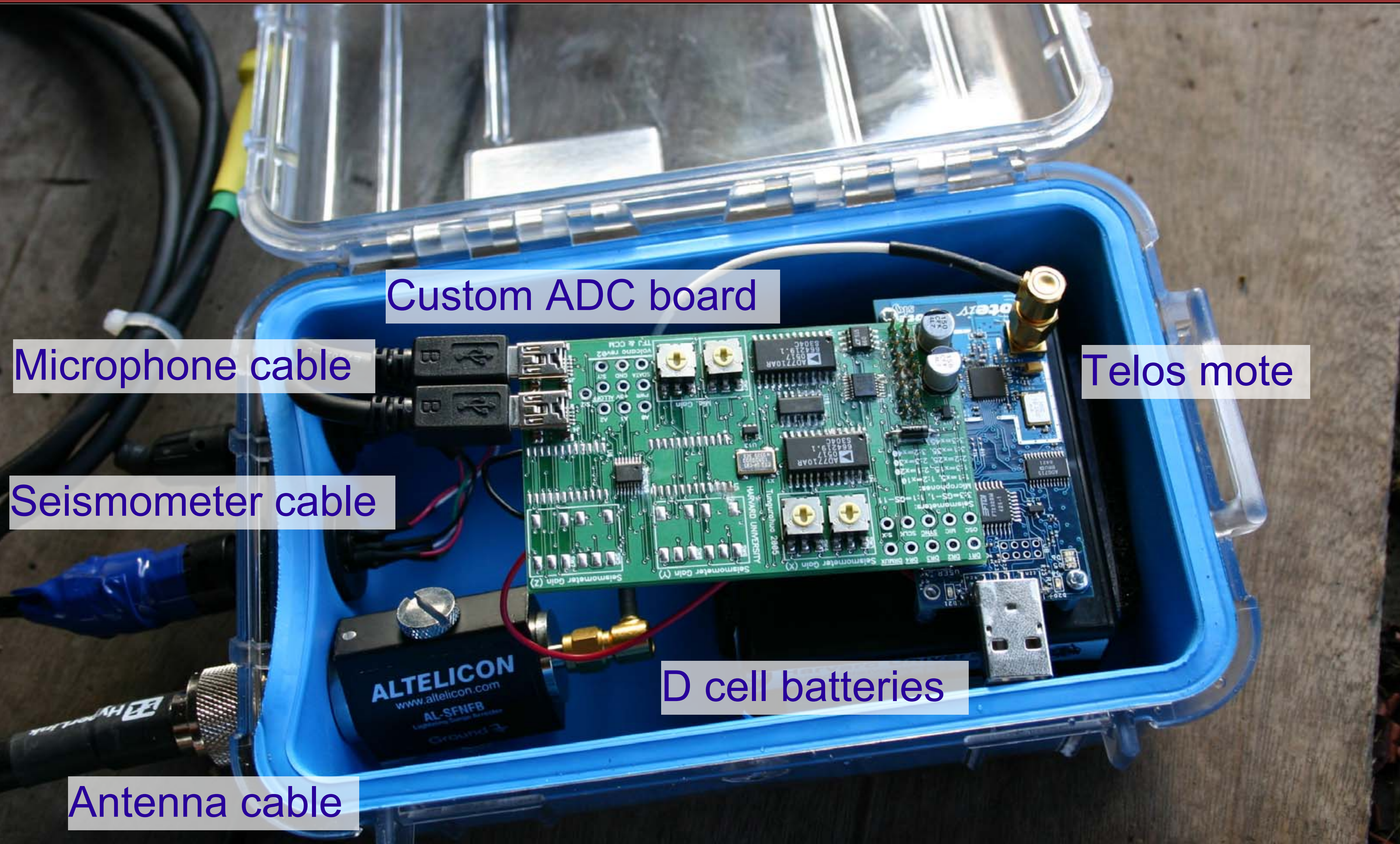



Example eruption data




Tungurahua

# Our Wireless Volcano Monitoring Sensor Node



# Enhancements and Add-Ons

Custom four-channel, 24-bit analog-to-digital conversion board

- Based on AD7710 sigma-delta ADC
- 40 mA current draw for two-channel board
- Multiple gain settings with hardware switch and software

Large external antenna for long telemetry distances

- 8.5 dBi omnidirectional antenna mounted on 1.5 m PVC pipe
- Measured 400+ m range

D-cell batteries for increased lifetime

Pelican weatherproof case

- External milspec connectors  to sensors

# Sensor Types

Geospace Industrial GS-11 geophone

- 4.5 Hz corner frequency, single-axis, inexpensive ($80)

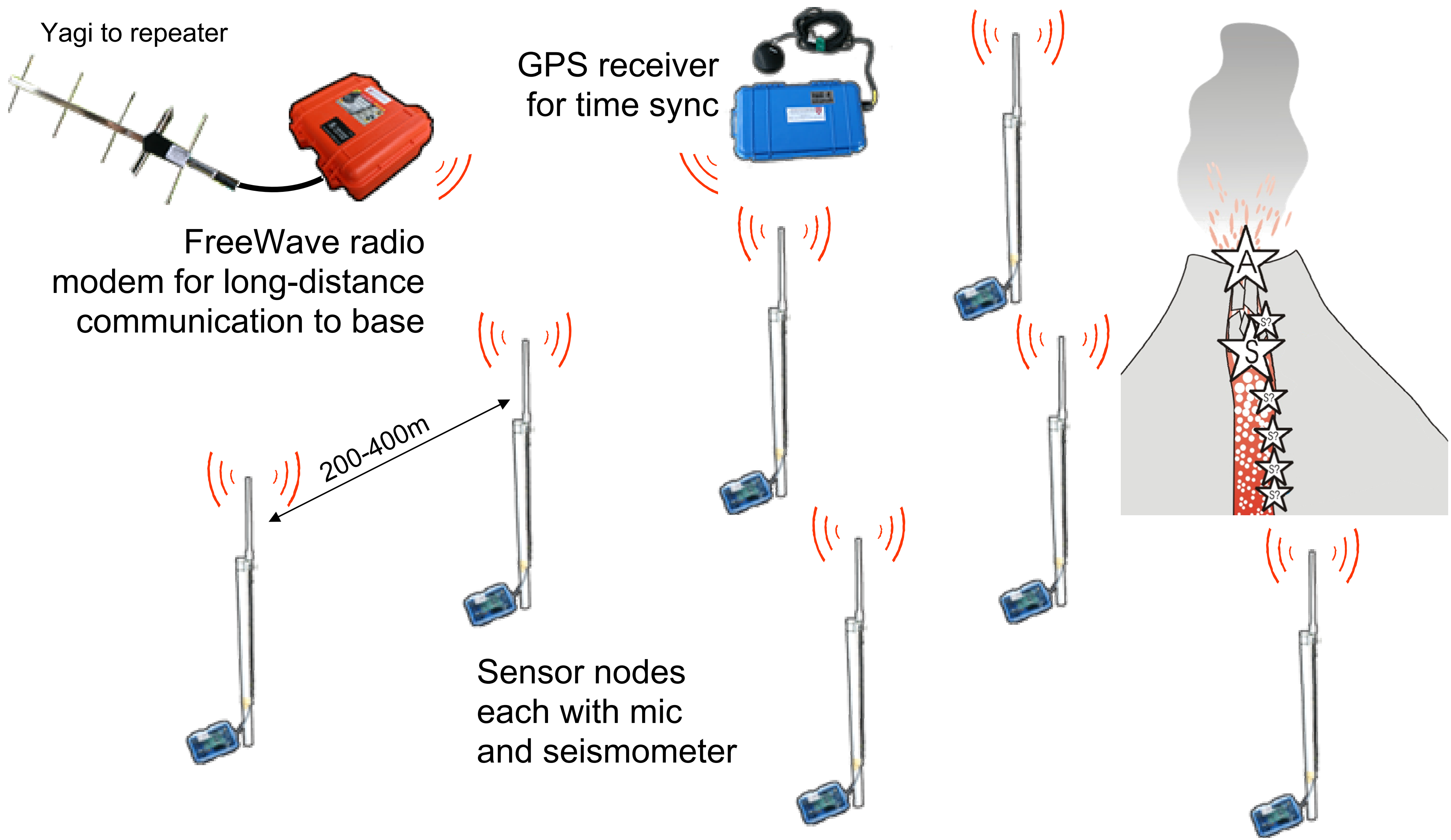
Geospace Industrial GS-1 geophone

- Triaxial, 1 Hz corner frequency, more sensitive, only on two motes

Microphones (Panasonic electret condenser)

- Very cheap, good frequency response with infrasound (< 20 Hz)

# Sensor Network Architecture



# Multihop Routing Protocol

Nodes self-organize into multihop routing tree

Protocol based on existing TinyOS routing code, with many enhancements

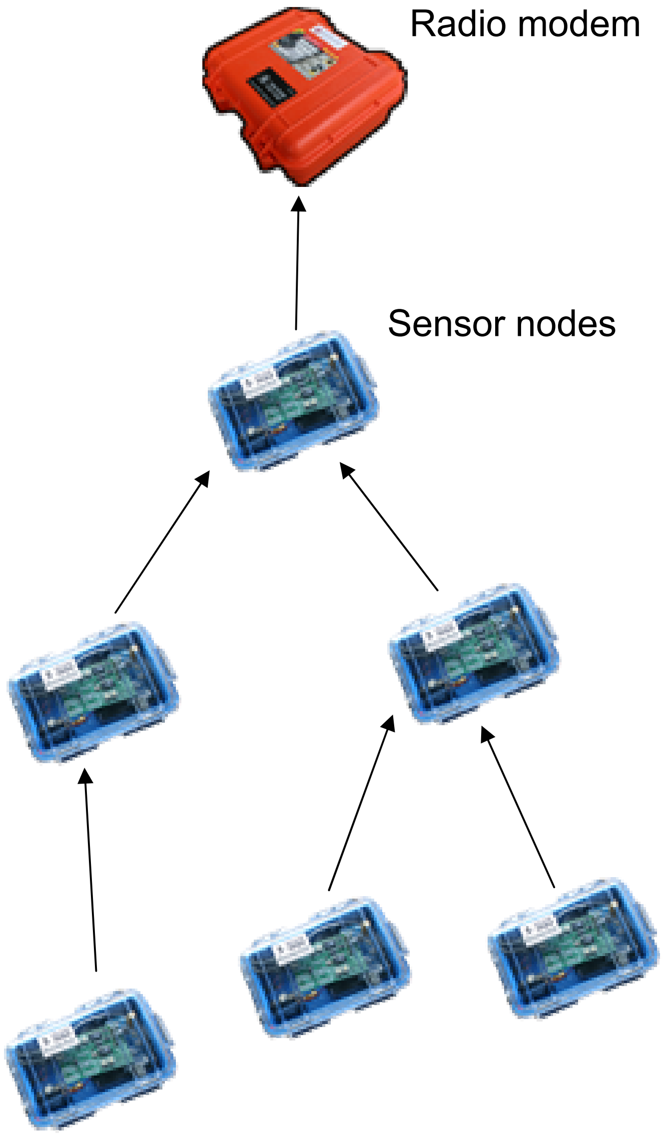
- Many bug fixes, revamped buffer management
- Hop-by-hop acknowledgement and retransmission

Nodes select parent with strongest link quality indicator (LQI) on received pkts

- May not work with asymmetric links
- Automatic detection of routing loops

Commands propagated to nodes with efficient flooding protocol

- Ensures high reliability for command distribution
- Variant of “Drip” codebase with various enhancements



# Long-distance telemetry

Deployment site is over 4km from observatory

- No line-of-sight visibility; cannot directly communicate via radio

Set of three FreeWave radio modems used to establish connectivity

- One each at sensor site and observatory, another used as a repeater on a tall hill
- Each powered by motorcycle or car battery, recharged by solar panels

# Time Synchronization

Time synchronization is critical for volcanic monitoring

- Must correlate signals across the sensor array with high precision

We made use of Vanderbilt FTSP multihop time sync protocol

- Required several changes and fixes
- Synchronizes nodes with accuracy of up to several microseconds
- However, highly variable

GPS receiver used to establish global timebase

- This node also acts as FTSP timesync root
- Periodically beacons GPS time and corresponding FTSP global time
- This data is logged at base station for later rectification

# Local Sampling and Data Storage

Nodes continuously sample each channel @ 100 and store to flash

- 1 MByte flash can store about 29 min. of data for 2-channel nodes
- Flash organized as a series of blocks, each block stores ~ 80 samples

Each block indexed by 32-bit block ID; flash used as circular buffer

- Each block has an associated timestamp from FTSP; corresponds to exact time of first sample in the block

Nodes report status to base every 10 sec. via multihop routing tree

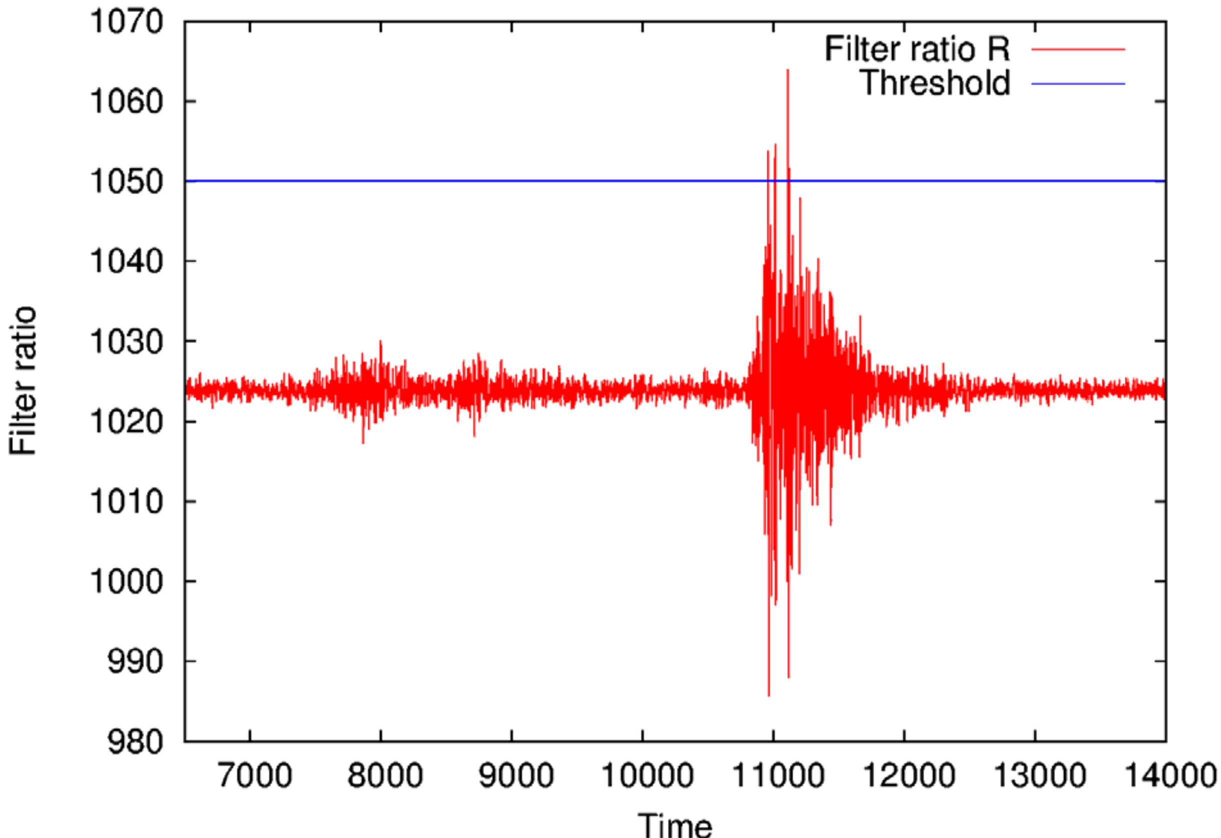
- Status message contains much useful information:
  - *Tail and head block IDs of flash*
  - *Total number of collected samples*
  - *Routing tree parent, depth, and link quality*
  - *Global and local time*
  - *Battery voltage and node temperature*
  - *Software version number*

# Automatic Eruption Detector

Nodes locally detect “interesting” events and report them to the base

Simple, robust algorithm for eruption detection:

- Maintain two EWMA filters on the incoming data with different gains
- If ratio between filters is above a threshold, trigger detection



# Fetch: Reliable Data Collection Protocol

Following an event, must reliably download complete signal

Approach: Download complete blocks from each node in turn

- Base station floods *Fetch Request* message containing:
  - *node ID, block ID, bitmap of required block chunks*
- Node replies with requested block chunk (one chunk per radio message)

Laptop issues fetch requests for required blocks following trigger

- Disable sampling on all nodes prior to fetch cycle (avoid data loss)
- Caveat: Cannot capture back-to-back eruptions

Default: Download 60 sec. of data from each node following an event

- Requires about 206 blocks, double that for four-channel nodes
- Takes between 3-5 minutes per node, depending on depth in routing tree

# Other system features

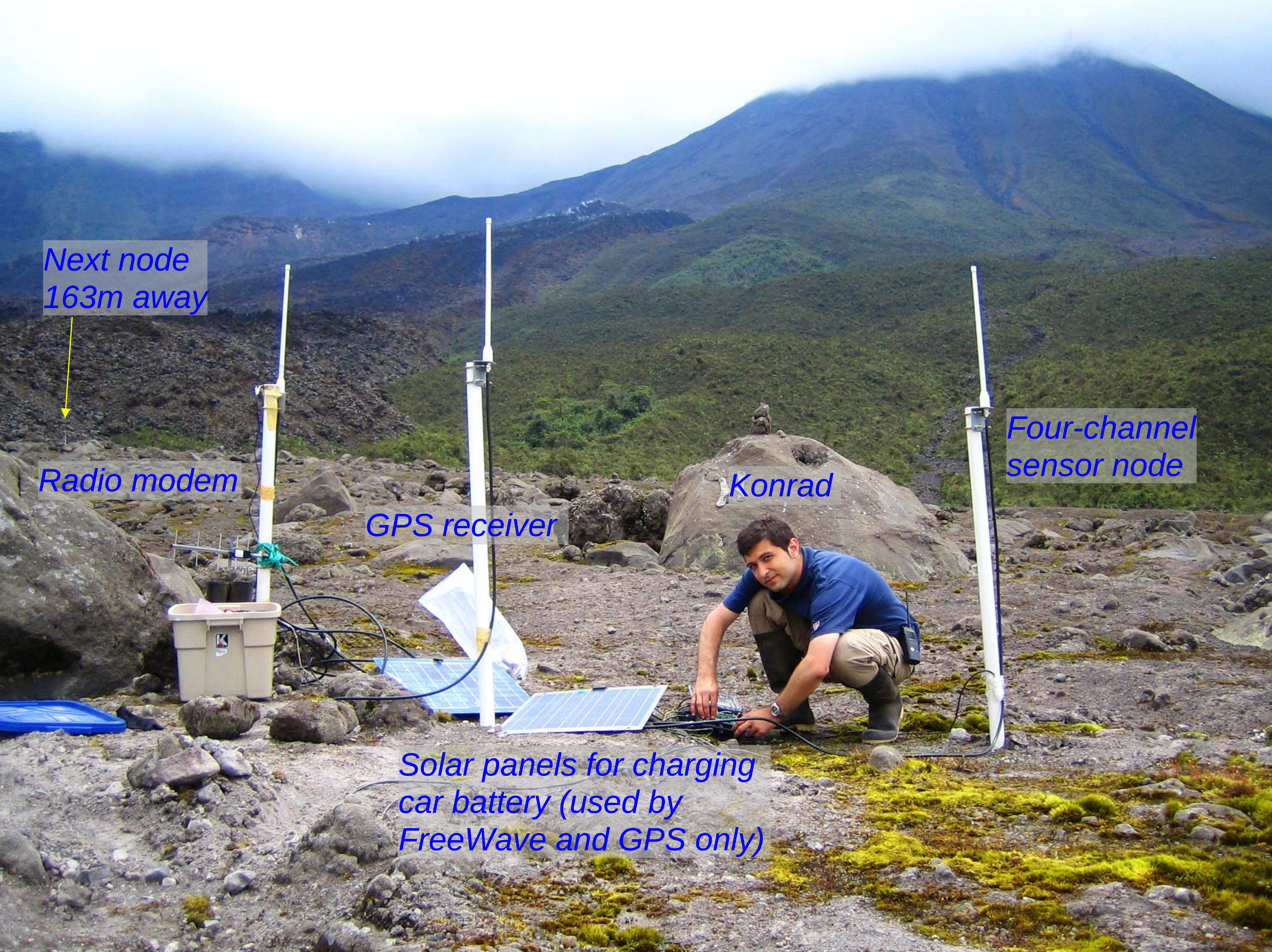
## Over-the-air network reprogramming using *Deluge*

- Allowed us to push bug fixes and code updates to live sensors after deployment
- However ... not always safe, and in some instances crashed the network
- Added support to our software to monitor current SW version

## Continuous (unreliable) sampling from individual stations

- Node collects samples in radio messages and broadcasts unreliably
- Only used on one node to conserve radio bandwidth
- Provides real-time view of volcanic activity; useful for tuning eruption detector

# Deployment Site:
# Reventador Volcano, Ecuador


Next node
163m away
Radio modem
GPS receiver
Konrad
Four-channel
sensor node
Solar panels for charging
car battery (used by
FreeWave and GPS only)

# Reventador Volcano

One of several very active volcanoes in Ecuador

- Last large eruption: November 2002
- Resulted in 17 km high eruption column and large pyroclastic flows extending for over 8km
- Ashfall reached Quito (95 km away) and closed down airport

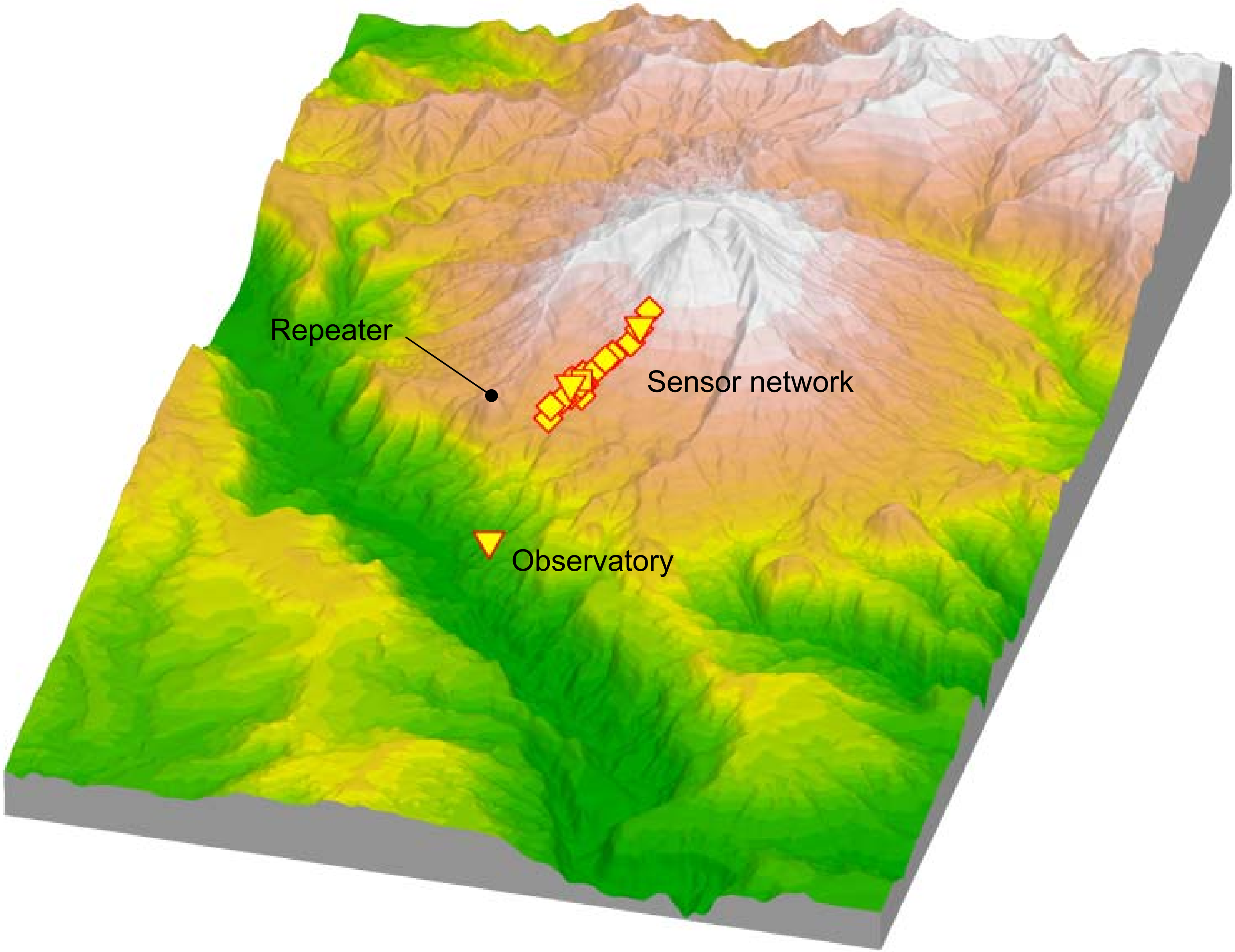
Recent activity (since November 2004)

- Andesitic lava flows extending 4 km from the vent – threat to nearby oil pipeline
- Intermittent ash-rich, ballistic-laden explosions, up to 6km above the vent

Deployment site is on upper flanks of volcano in area decimated by 11/02 eruption

- Extremely remote deployment site
- 3 hour hike from observatory through dense jungle, impassable for horses
- All equipment carried to site by research team with help from porters

# Sensor Deployment Map



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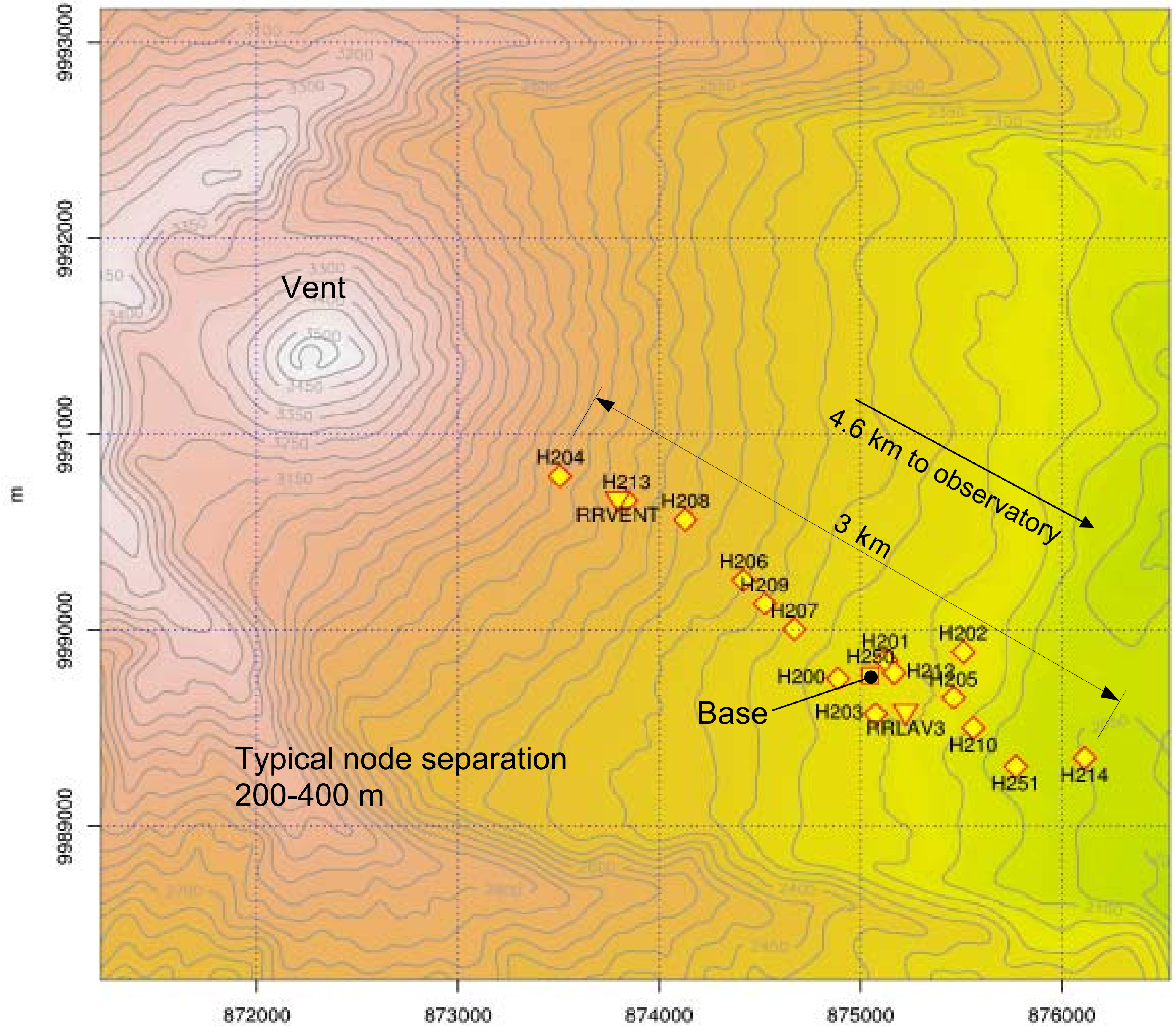
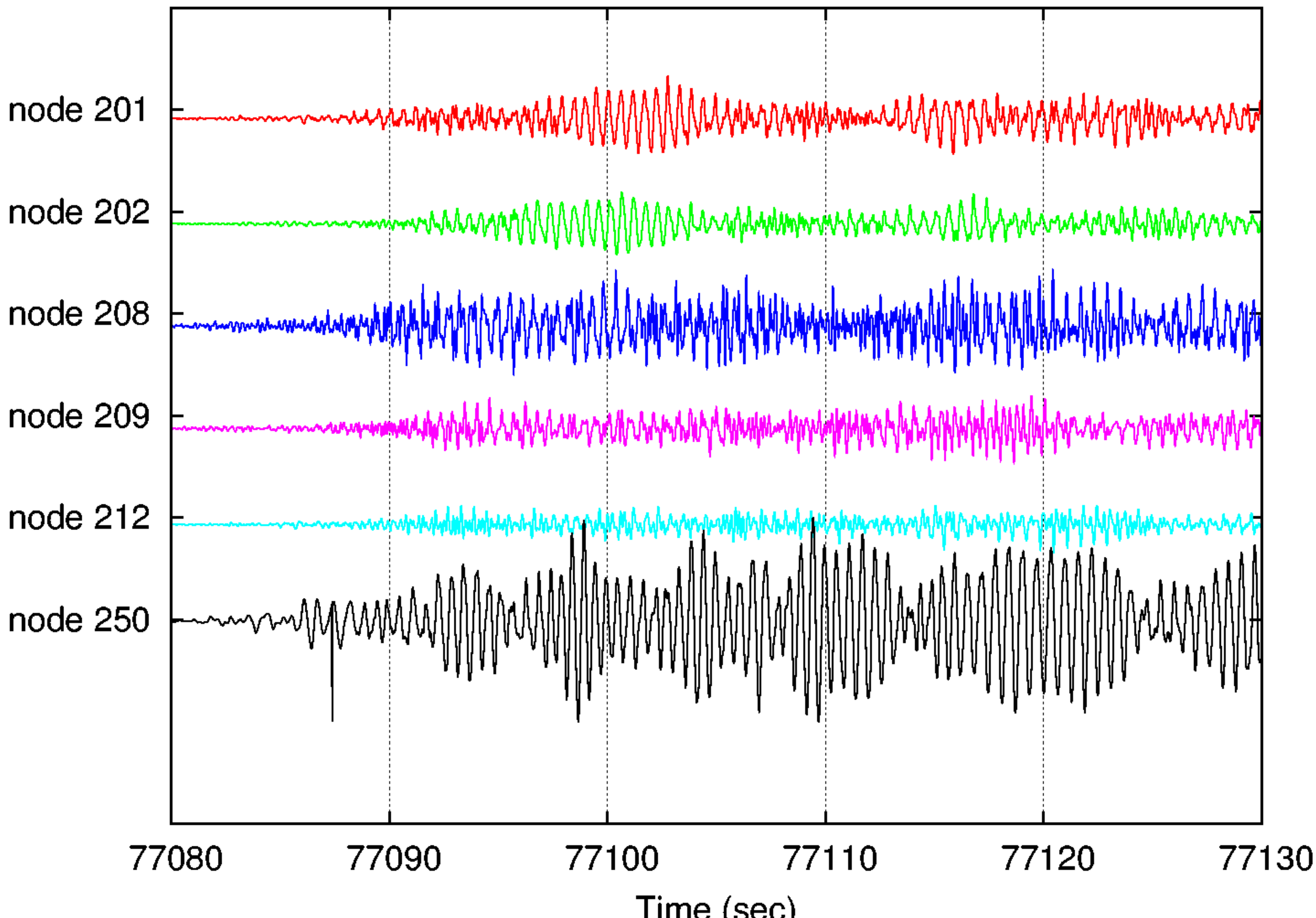


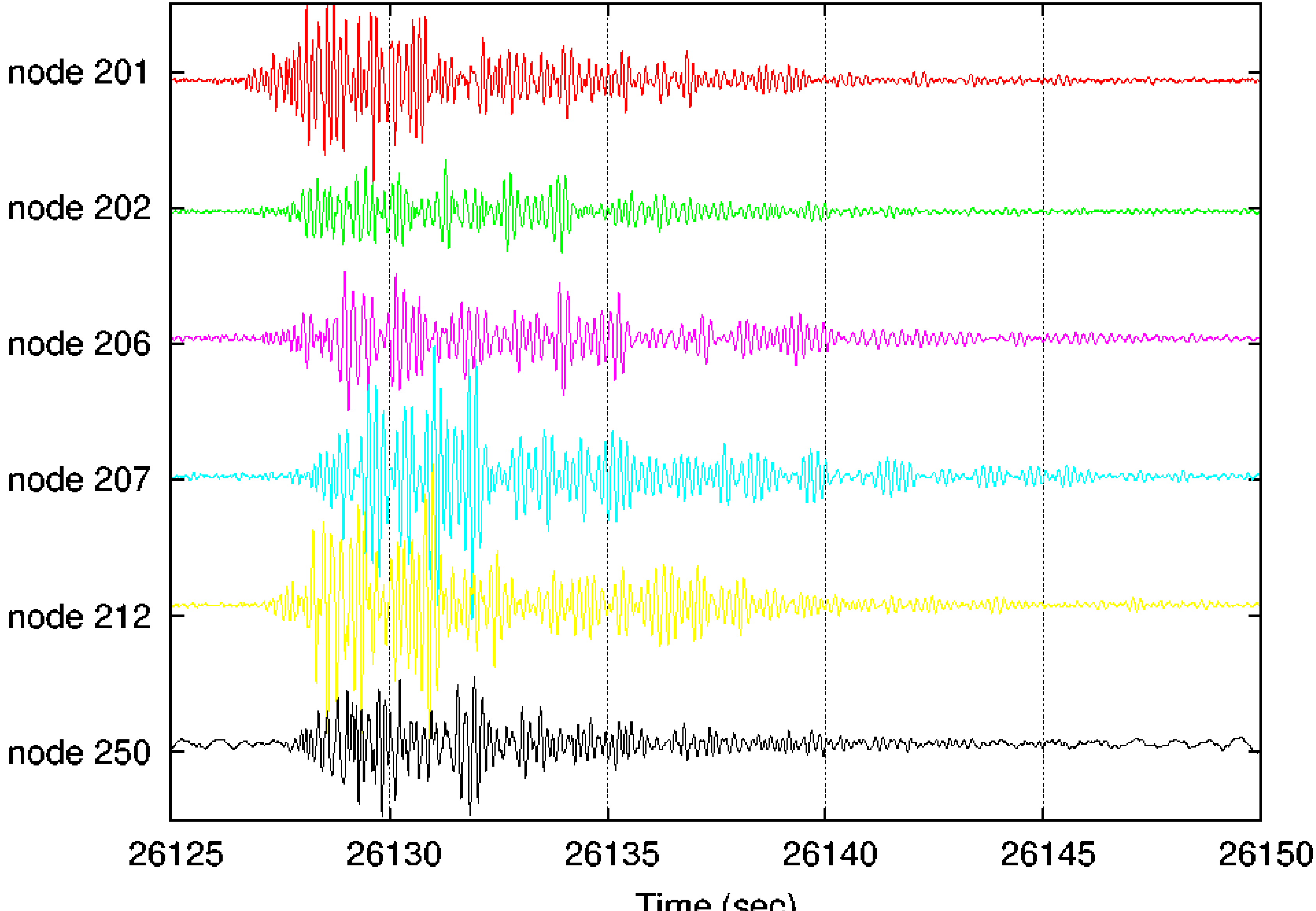
# Some Representative Events

## Monochromatic Tremor



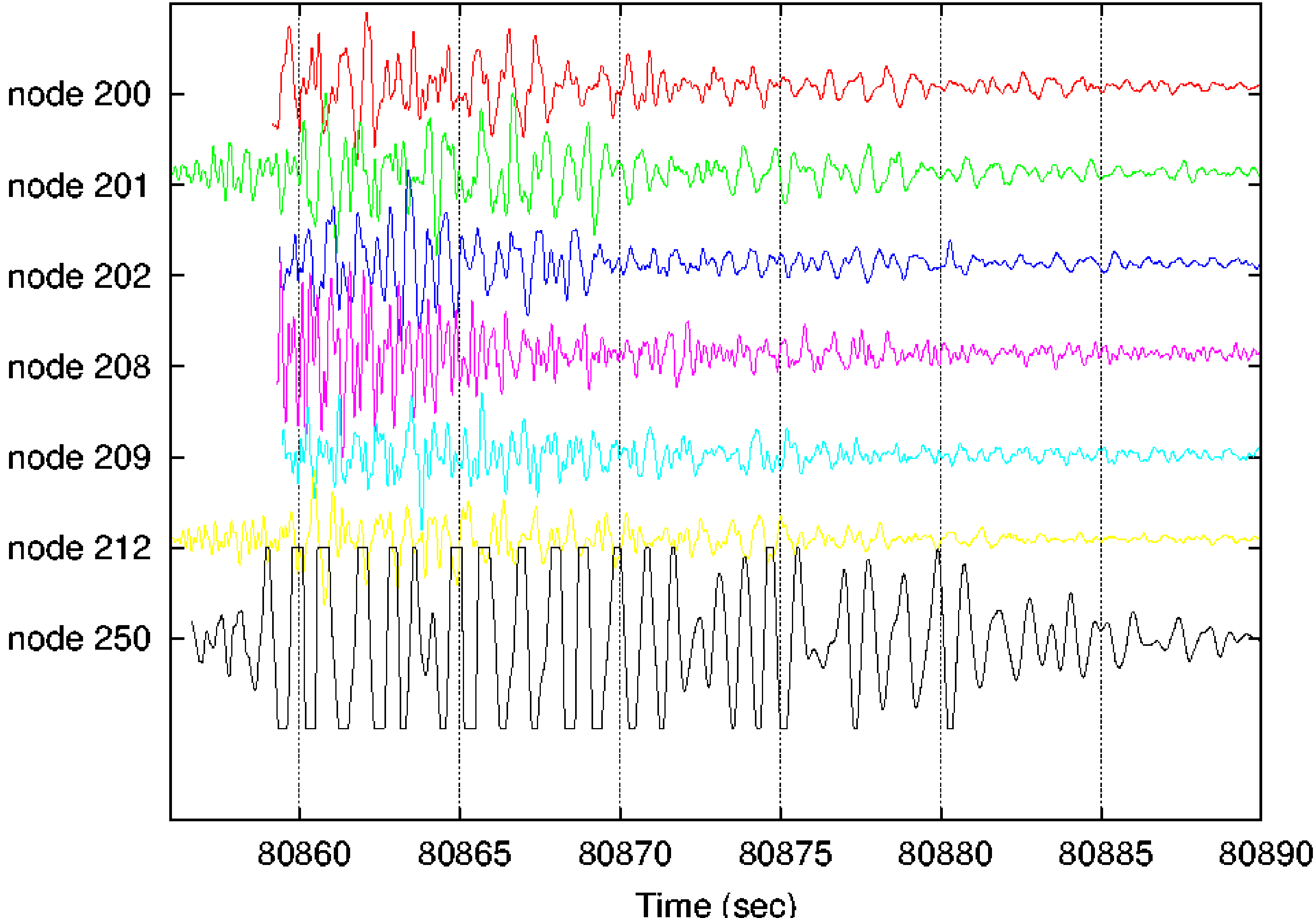
# Some Representative Events

## Volcano-Tectonic (VT) earthquake



# Some Representative Events

## Explosion – Note saturation of node 250's sensor



# Future Work and New Challenges

## Intelligent and adaptive event detection

- Existing code permits network to capture data from a single event at a time
- As a result, we may miss a large eruption following a small (but important) VT event
- Need better techniques for categorizing events and prioritizing data download based on event type, amplitude, and energy release

## Event-specific data aggregation and compression techniques

- Eruptions, VT, tremor, and other events can be compressed or aggregated in very specific ways
- Example: Extracting dominant frequencies from tremor event can greatly reduce size of reported signal
- Eruptions can be captured by representative signal trace from a few sensors plus RSAM (a measure of energy release) from other nodes
  - *Distill complex seismoacoustic signal to a very concise event report*

# Distributed Processing of Seismoacoustic Signals

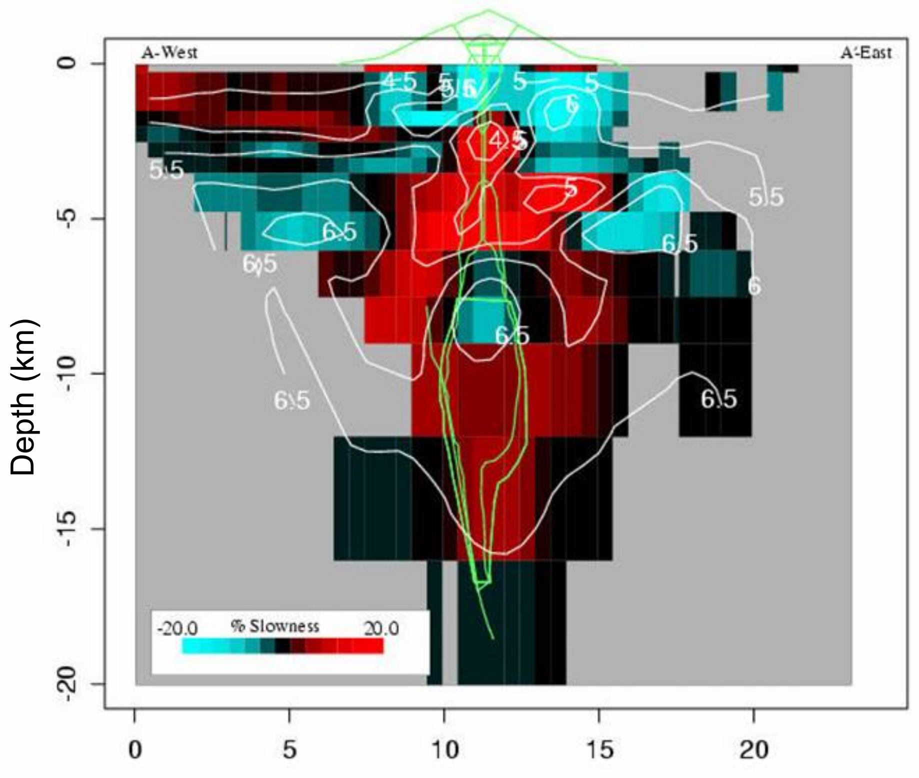
## Distributed event localization

- Sensor nodes can coordinate to localize source of eruption based on wave arrival times and intensities

## Tomographic inversion

- Recover 3D structure of the interior of the volcano using wave arrivals from many sensors
- Inspired by use of tomography in medicine (e.g., CT scans)
- Requires many sensors to yield many viewpoints on the volcano

## Exciting opportunity: Performing eruption localization and tomography in *real time*




Vertical cross-section of tomographic inversion of Mt. St Helens (J. Lees, UNC)

# Conclusions

Wireless sensor networks have tremendous potential for volcanological studies

- Easy to deploy, lightweight, and relatively inexpensive
- Can provide large telemetry distances (100's of meters) between stations
- Can capture real time data from many sensors simultaneously

This work is the result of a highly interdisciplinary effort:

- Computer Science (Harvard)
- Geophysics (UNH and UNC)
- Ecuadorean volcano monitoring agency (IG-EPN)

Bridging the gap from sensor network technology to real applications has been extremely rewarding!

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For more details, see: http://www.eecs.harvard.edu/~mdw/proj/volcano