

Deploying a Sensor Network on an Active Volcano



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Overview

We have undertaken two deployments of wireless sensor networks on active volcanoes in Ecuador: Tungurahua and Reventador

- Tungurahua deployment was proof-of-concept
- Reventador deployment was significantly more complex

Nodes monitored seismic and infrasonic activity

- Automatic triggering to download data following seismic events

Tested many sensor network concepts in the real world

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

Many lessons learned

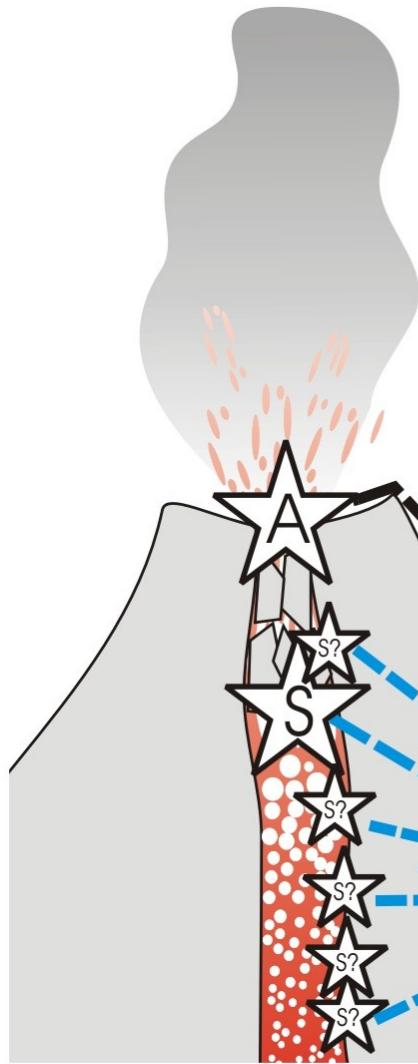
- Many challenges involved with deployment at remote site
- Software robustness is a major concern
- Postprocessing and analysis of data is as difficult as initial acquisition

Disclaimer

I A N A S*

* I am not a seismologist

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.

Why do seismologists study volcanoes?

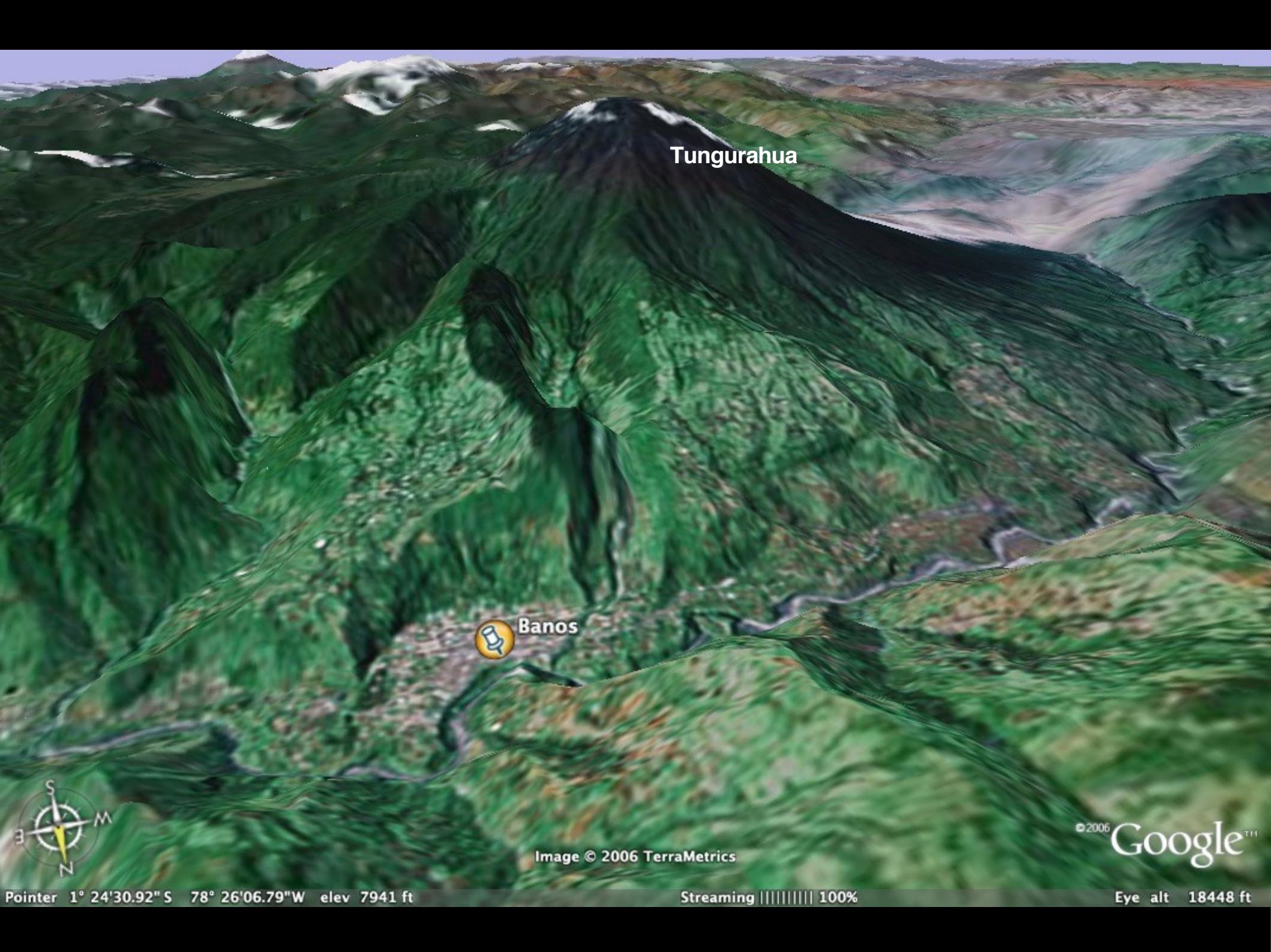
Two non-exclusive reasons:

Scientific study:

- Understand source processes – what's going on inside the volcano?
- Understand magma flow and gas expansion during eruptions
- Try to understand internal structures causing earthquakes
- What causes volcanoes to form and how do they evolve over time

Hazard monitoring:

- Mitigate hazards to communities near the volcano
- Give warnings of imminent activity to civil authorities
- Tungurahua (Ecuador) is right on top of Banos, a town of 20,000 people (with another 15,000 or so living in the immediate area)
- Merapi (Indonesia) 30 km from Yogyakarta, with over 500,000 people



Tungurahua

Banos



Image © 2006 TerraMetrics

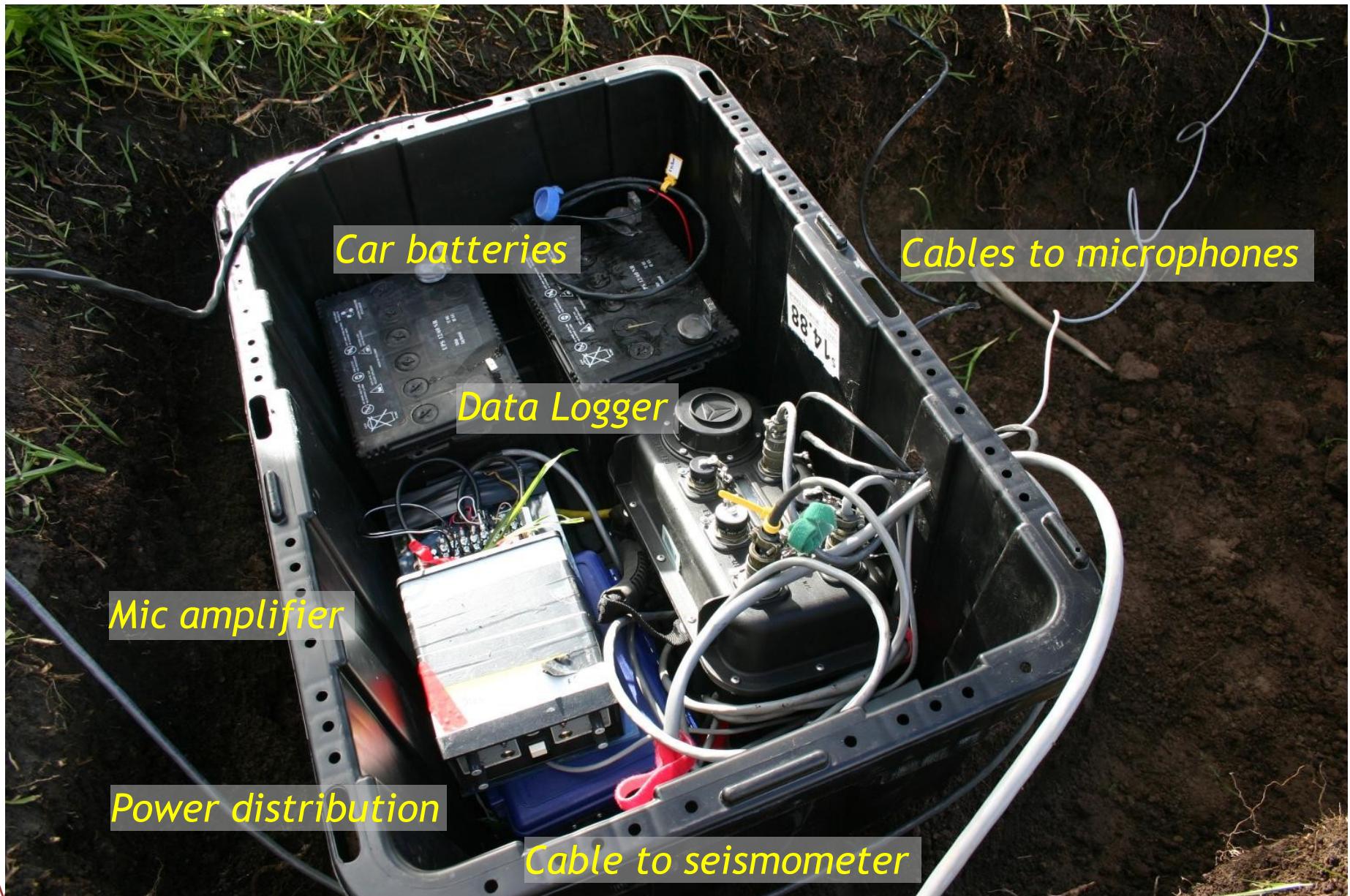
©2006 Google™

Pointer 1° 24'30.92"S 78° 26'06.79"W elev 7941 ft

Streaming ||||||| 100%

Eye alt 18448 ft

Existing Volcanic Sensor Station



Wireless Sensor “Motes”

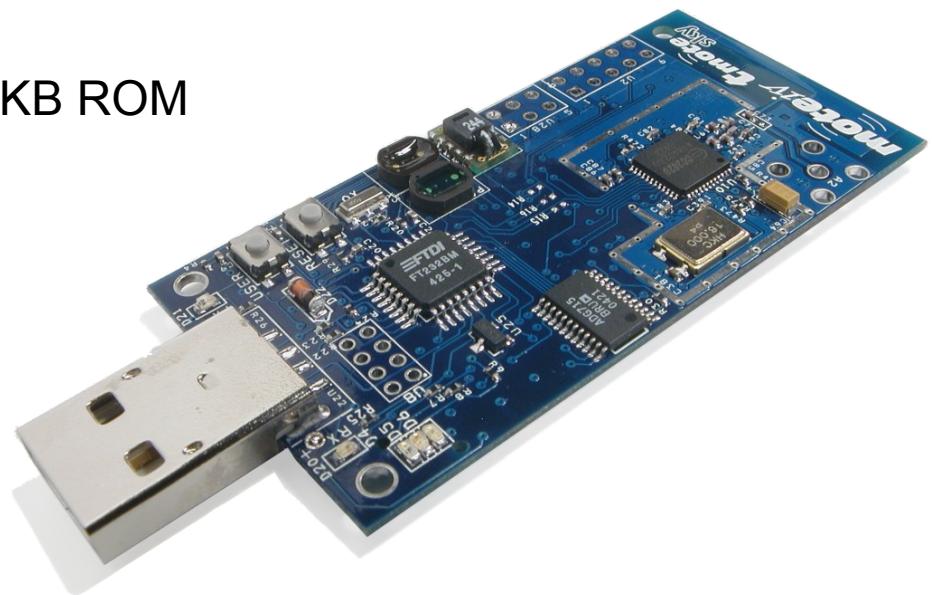
Tmote Sky platform (Moteiv, Inc.)

- 8 MHz (TI MSP430) CPU, 10 KB RAM, 60 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 or packaging)



The Role of Wireless Sensor Networks

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

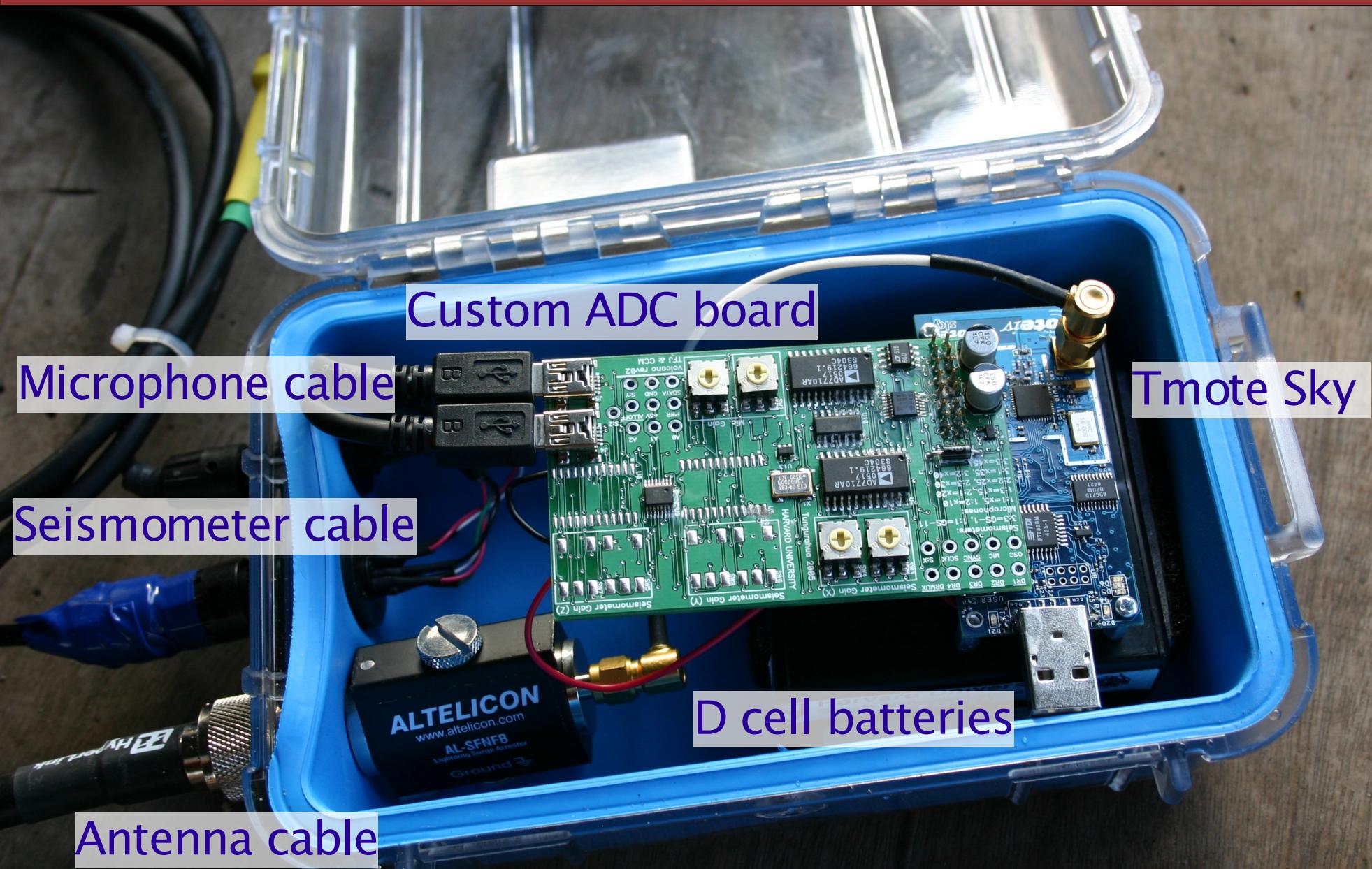
Can provide real time monitoring of volcanic activity

- ... 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

Our Wireless Volcano Monitoring Sensor Node



Science Goals and CS Challenges

(or, what is hard about this?)

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

High fidelity data acquisition

- Reliable communication
 - *Cannot tolerate dropped packets or samples in recorded data stream*
- Fine grained time synchronization
 - *Must correlate signals from separate nodes to millisecond resolution*

High spatial separation 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

Deployment Site: Reventador Volcano, Ecuador





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

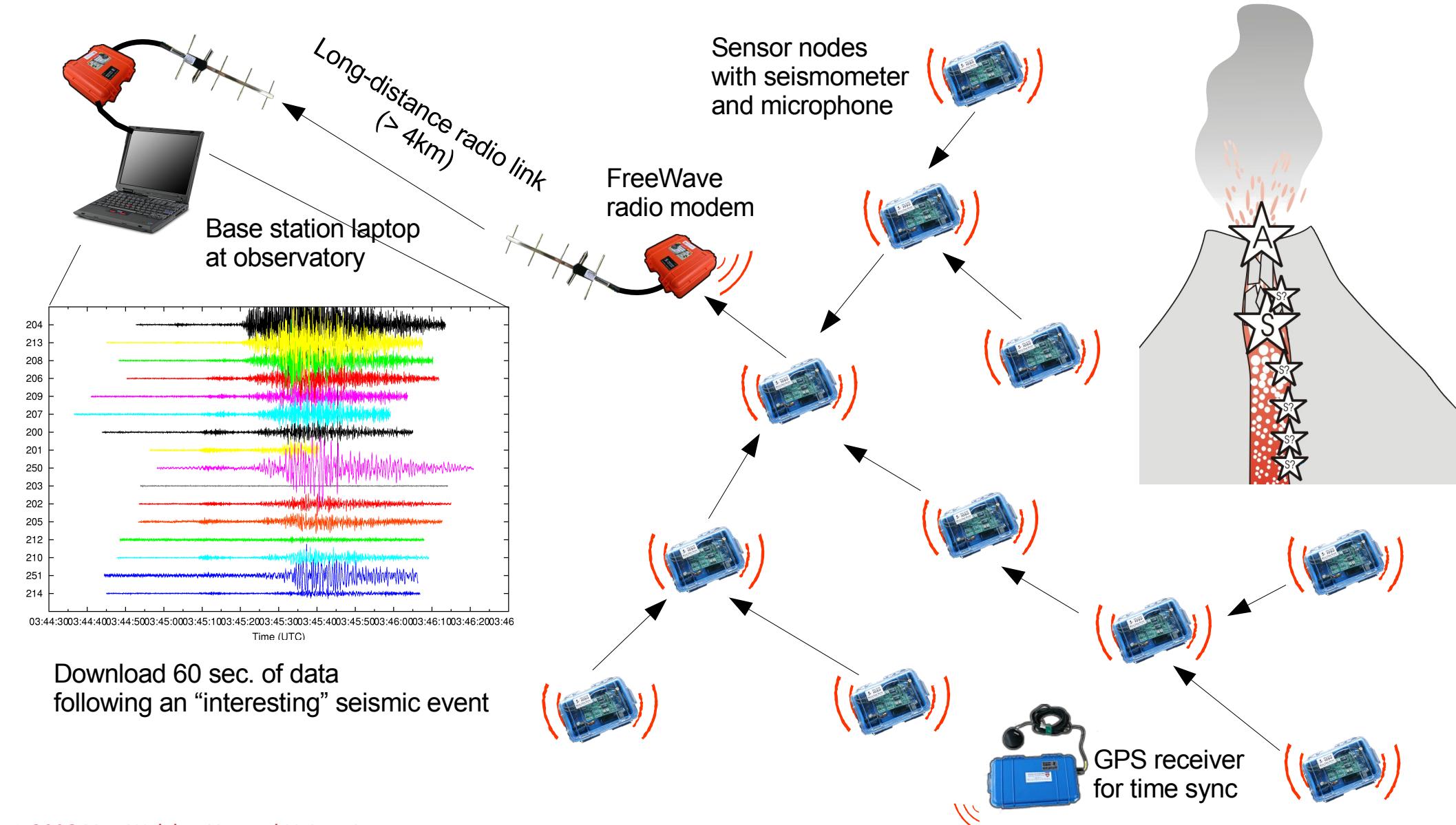
Recent activity (since November 2004)

- 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

- Area was decimated by 11/2002 eruption – no vegetation
- 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

System Design



System Design

Motes sample data continuously and store to flash

- 100 Hz sampling rate at 24 bits per sample
- Flash can store ~ 20 minutes worth of data



GPS receiver used as common timebase

- FTSP protocol [Vanderbilt] used to synchronize rest of network



Each mote detects “interesting” seismic activity

- Sends report to base station using multihop routing
- FreeWave modems used for long-distance radio link



When enough nodes detect event, initiate download cycle

- Download 60 sec of data from each node following event
- Use reliable transfer protocol called “Fetch”



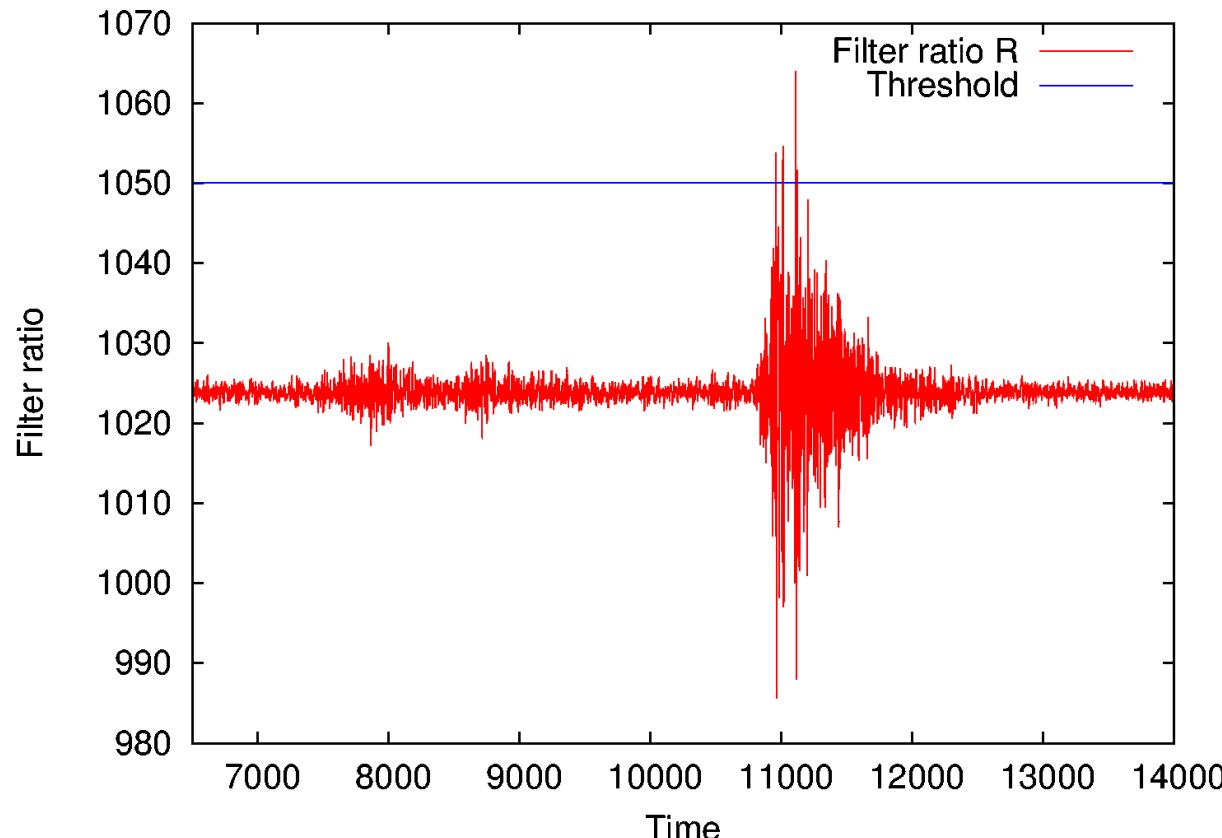
Eruption Detection Algorithm

Each node samples continuously and stores data to flash

- 1 Mbyte flash can store ~ 20 minutes of data

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

- If 5 or more reports in a 10 sec window, initiate a download cycle



Time Synchronization Protocol

Used FTSP time-sync protocol from Vanderbilt

GPS receiver acts as “root”

- All other nodes attempt to synchronize their clock to the root

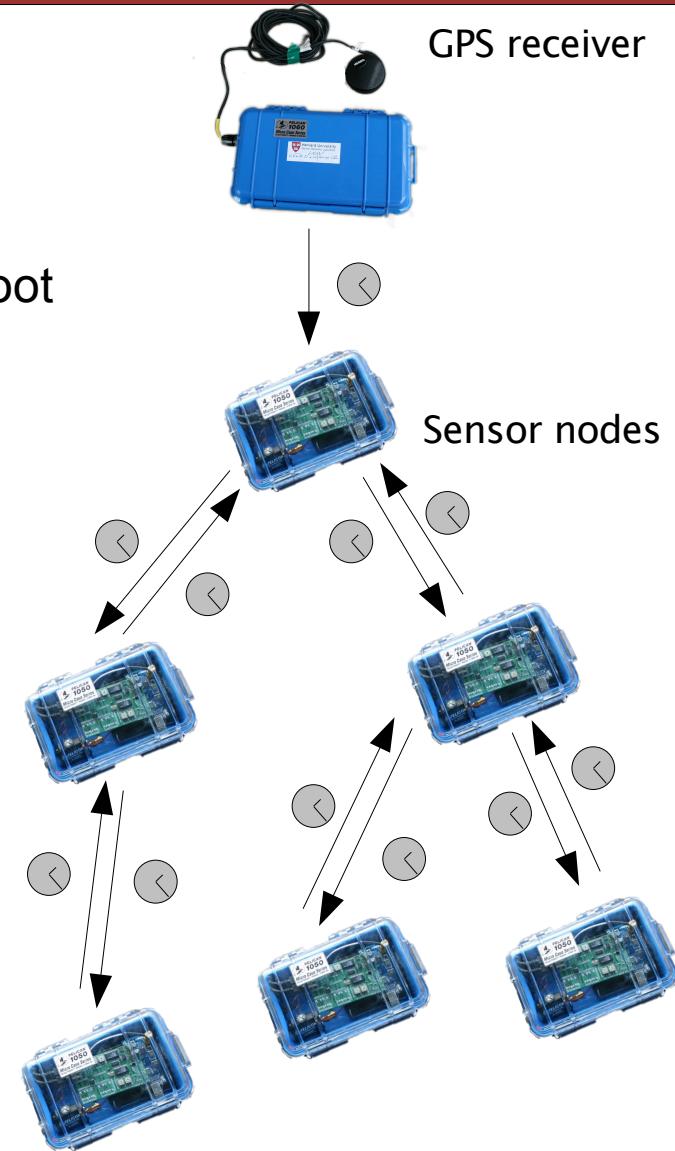
Each node broadcasts periodic *beacon* with global time of transmission

- Must account for MAC delays on sender!

Receivers mark time of beacon reception

Each node computes *offset* and *skew* from its local clock to global timebase

- Each sample tagged with FTSP global time



Base station at observatory



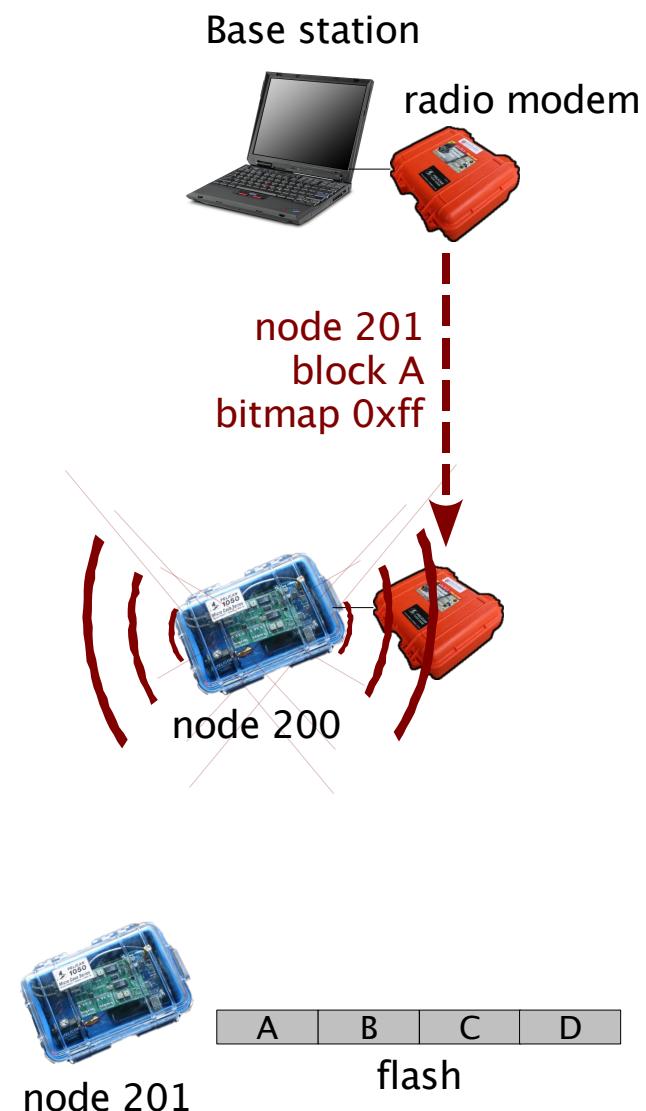
Fetch Reliable Transfer Protocol

Base station generates request containing:

- node ID, block ID, bitmap of needed chunks

Intermediate nodes flood request to network

- Eliminates need for forward routing path from base



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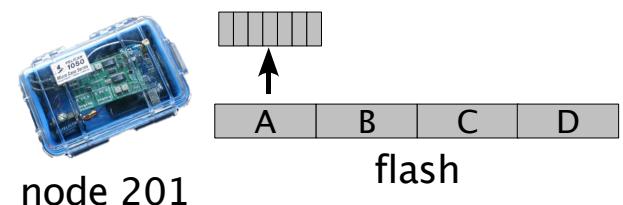
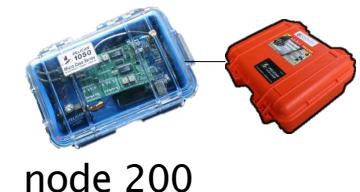
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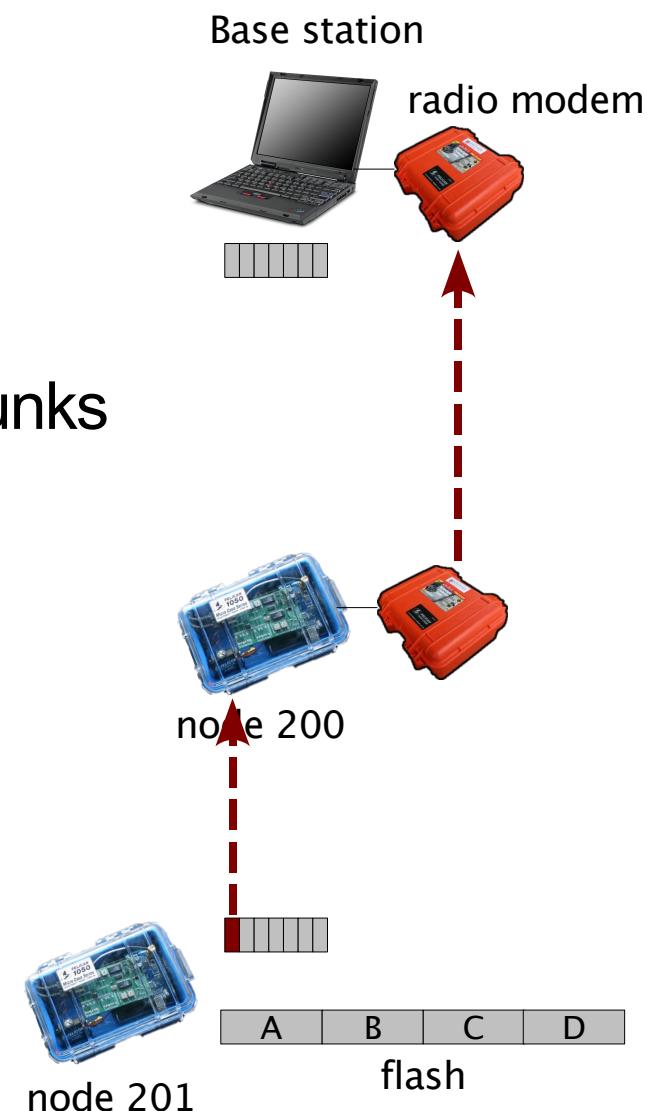
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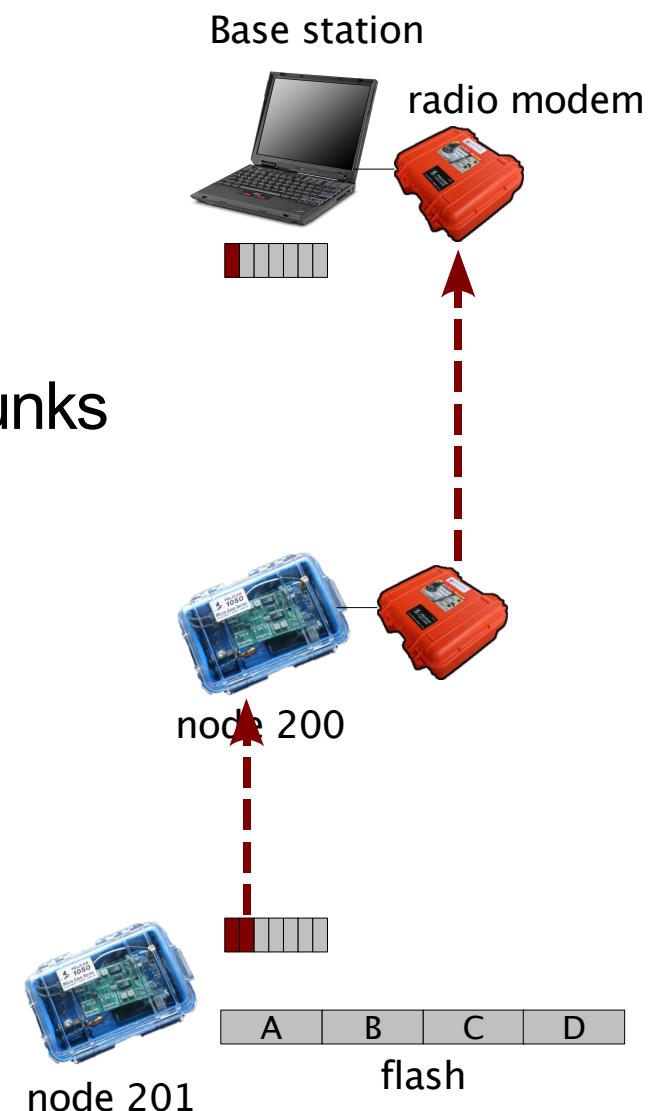
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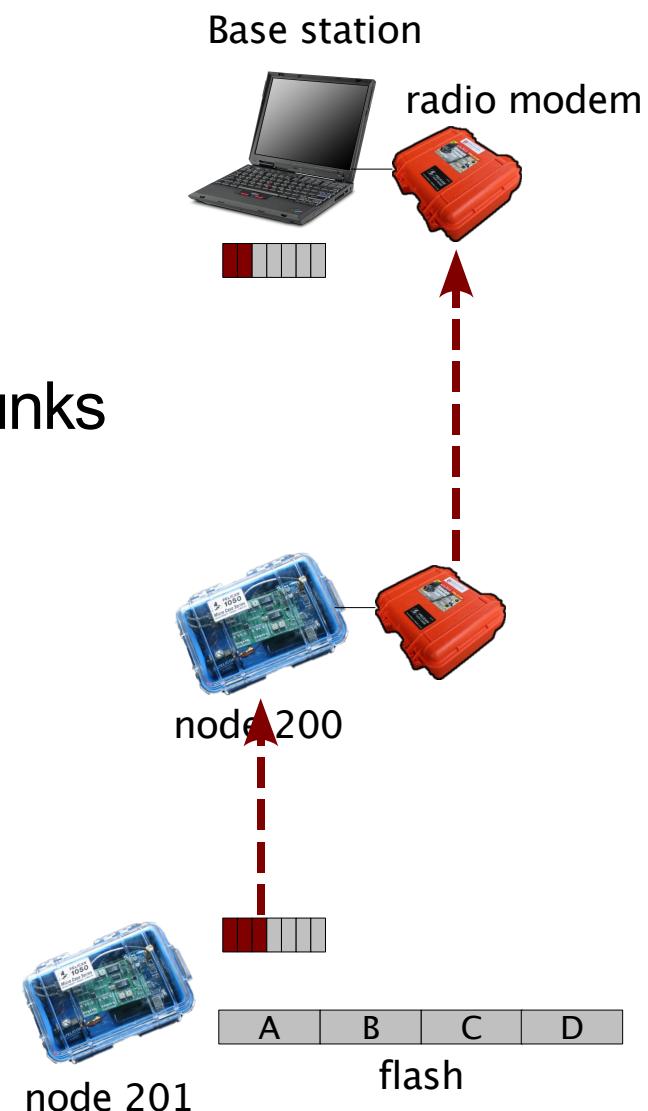
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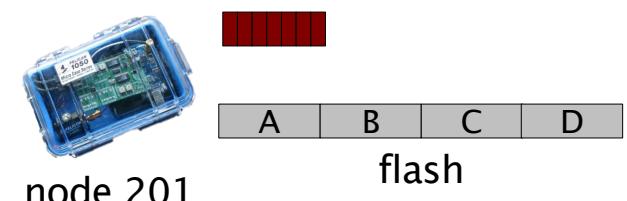
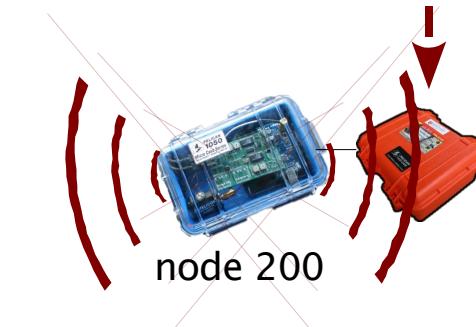
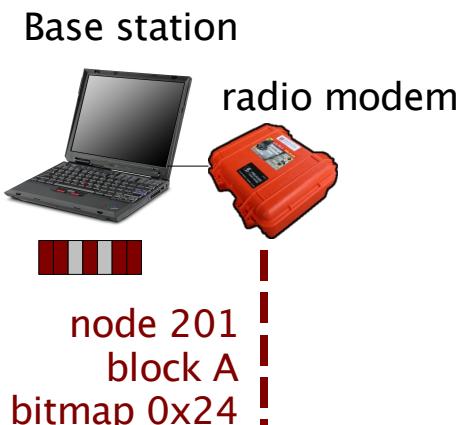
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Base requests missing chunks after timeout



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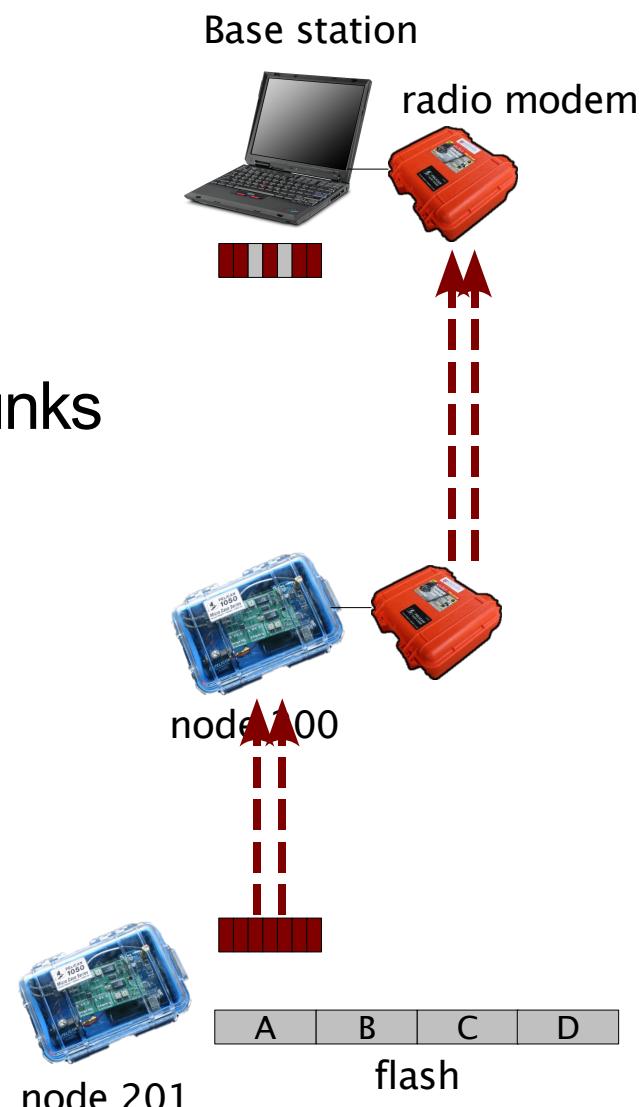
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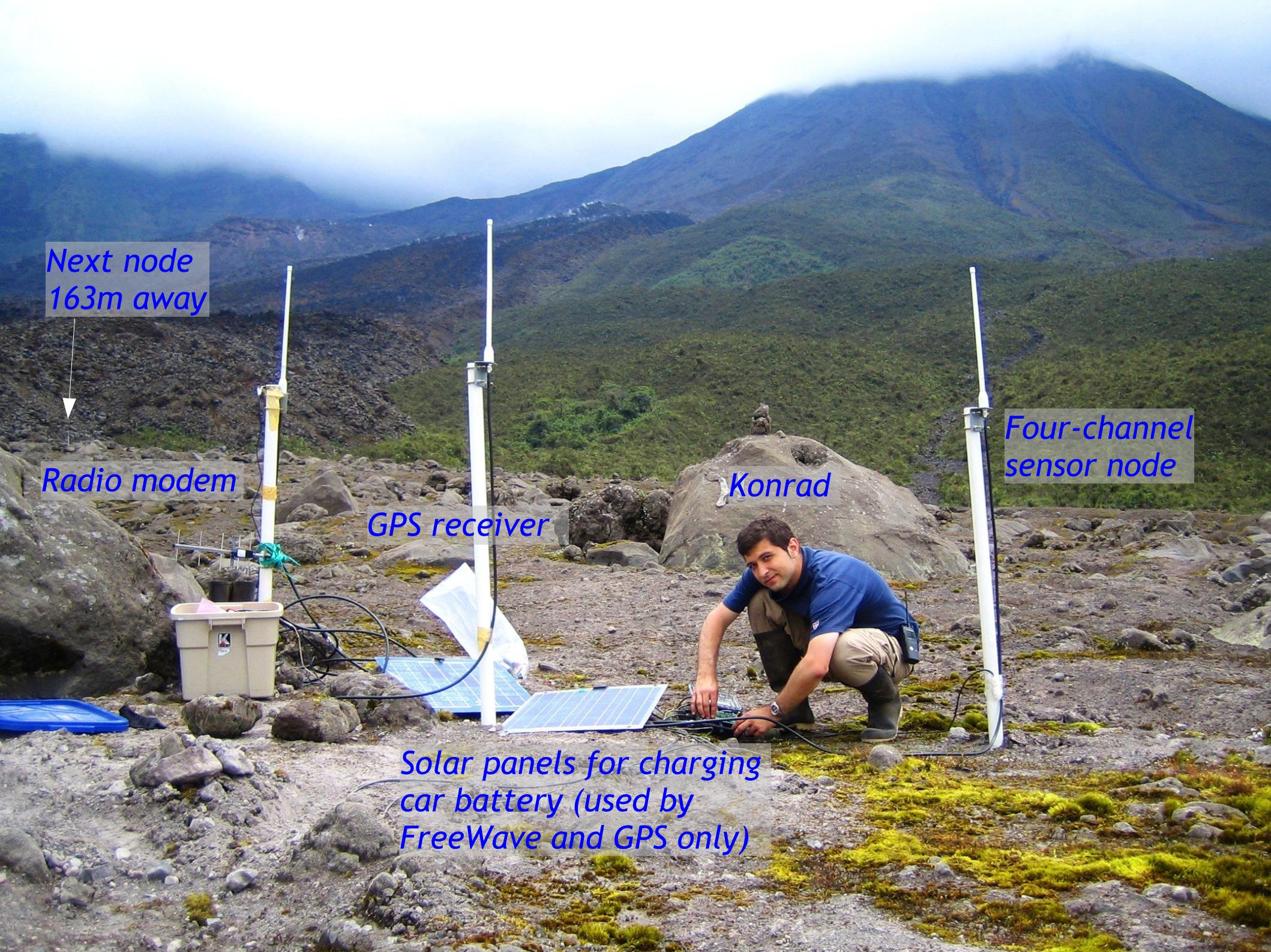
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- Route each chunk to base over multihop path

Base requests missing chunks after timeout

Node responds with missing data





Next node
163m away

Radio modem

GPS receiver

Konrad

Four-channel
sensor node

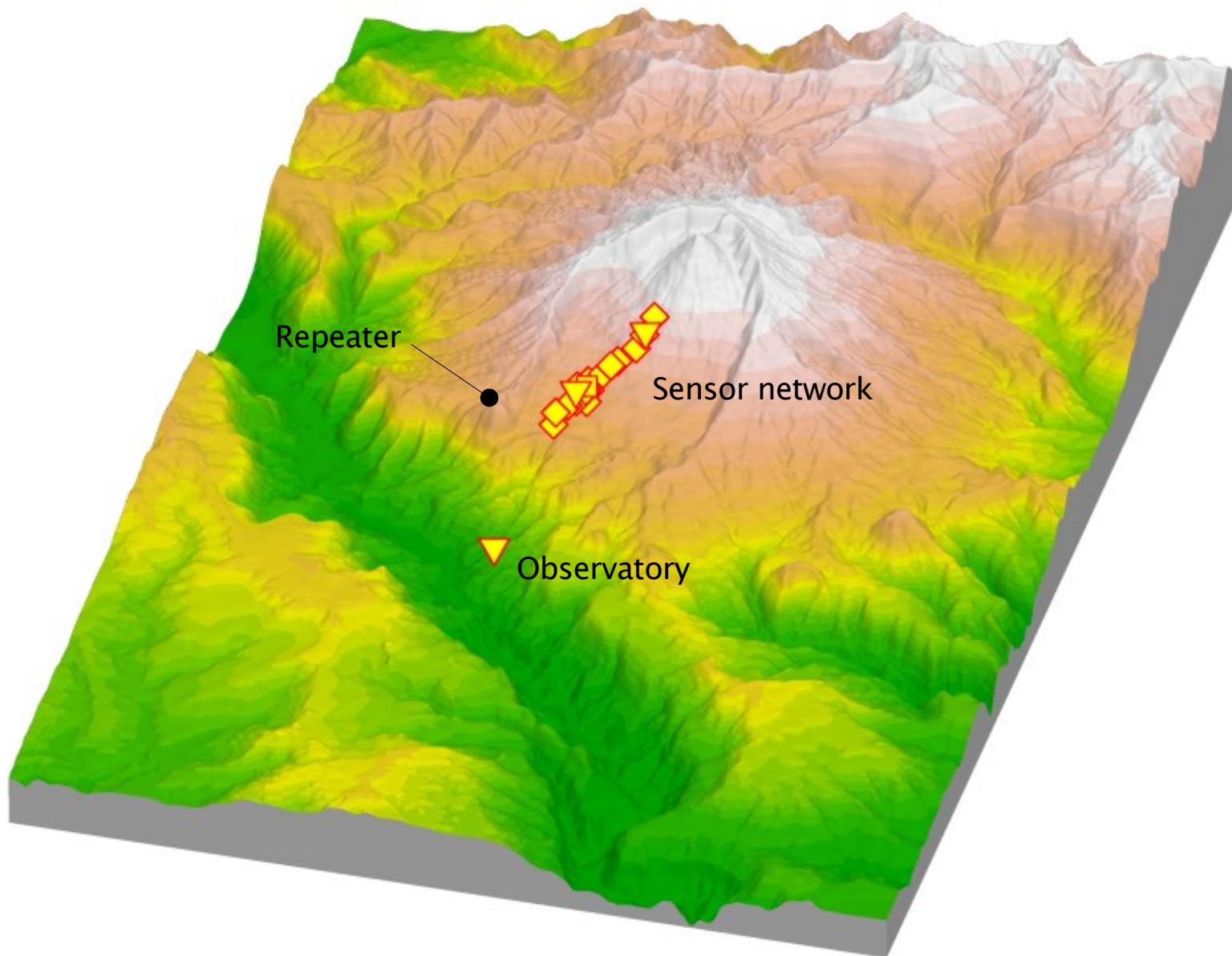
Solar panels for charging
car battery (used by
FreeWave and GPS only)



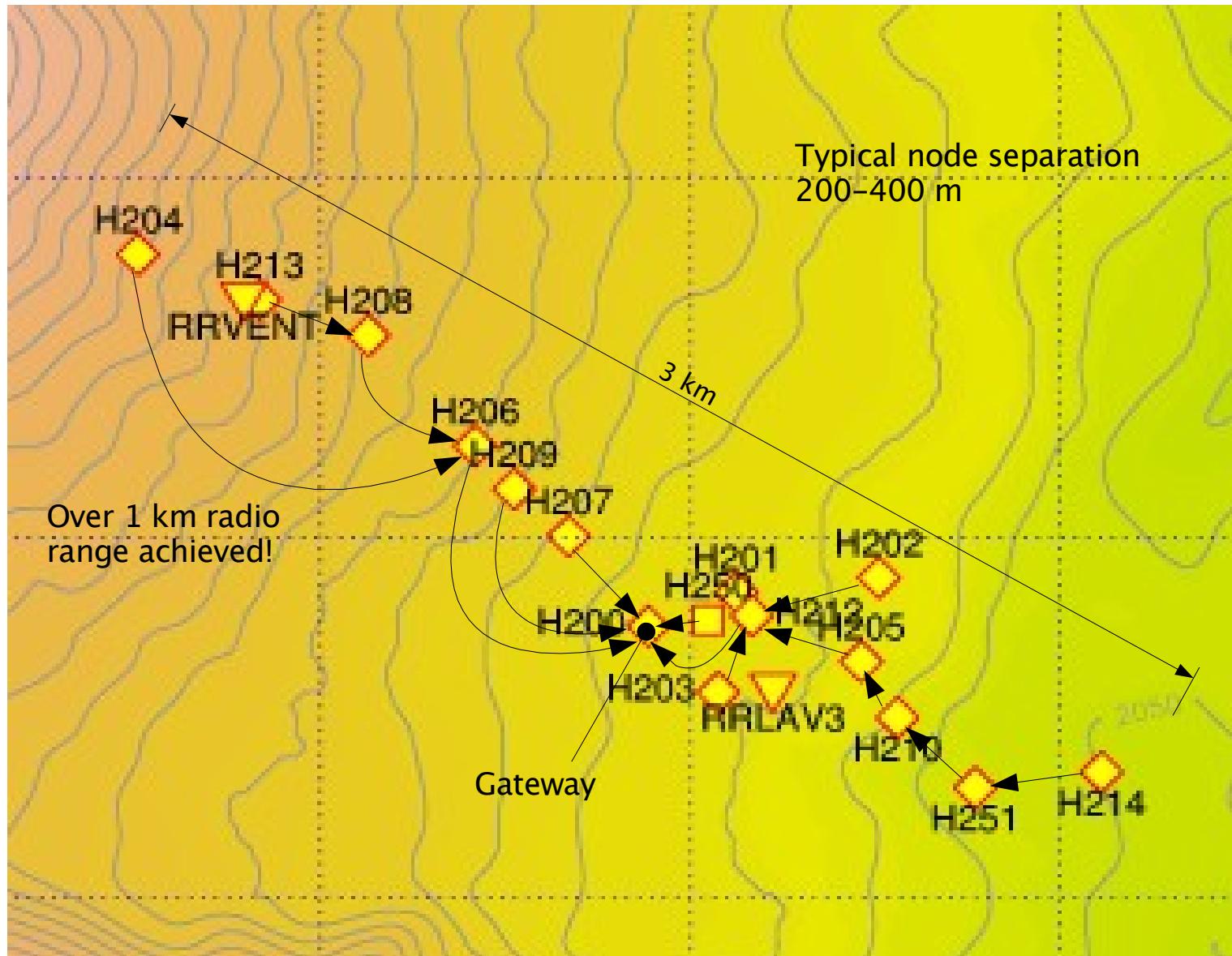




Sensor Deployment Map



Network Topology



Event Collection Statistics

During the 19-day deployment...

... 272 events detected

... 230 events scheduled for download

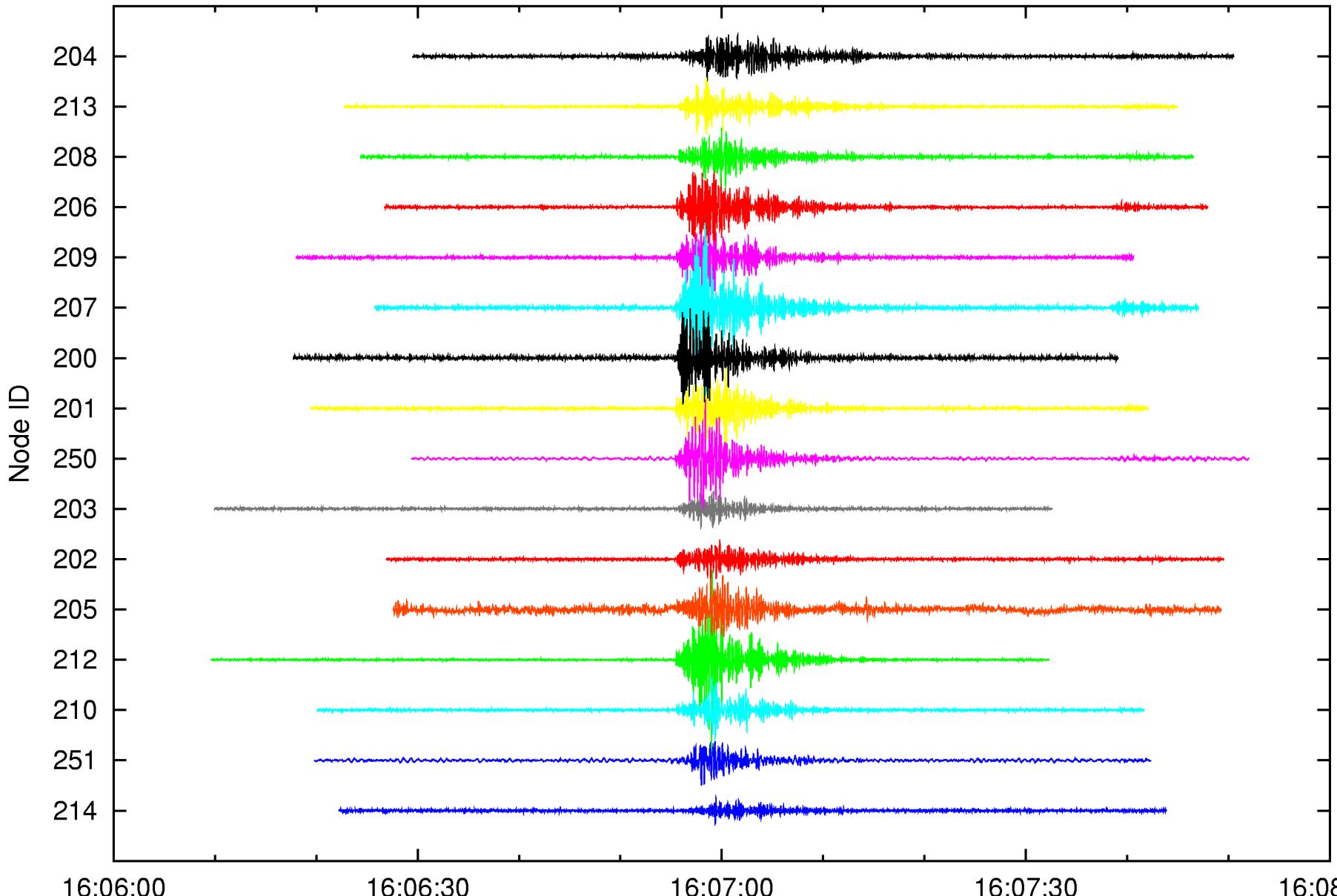
... Average yield of 8 nodes per event (50%)

... 538 MBytes of ASCII logged event data (roughly 64 MBytes raw)

... 226 MBytes of node statistics collected

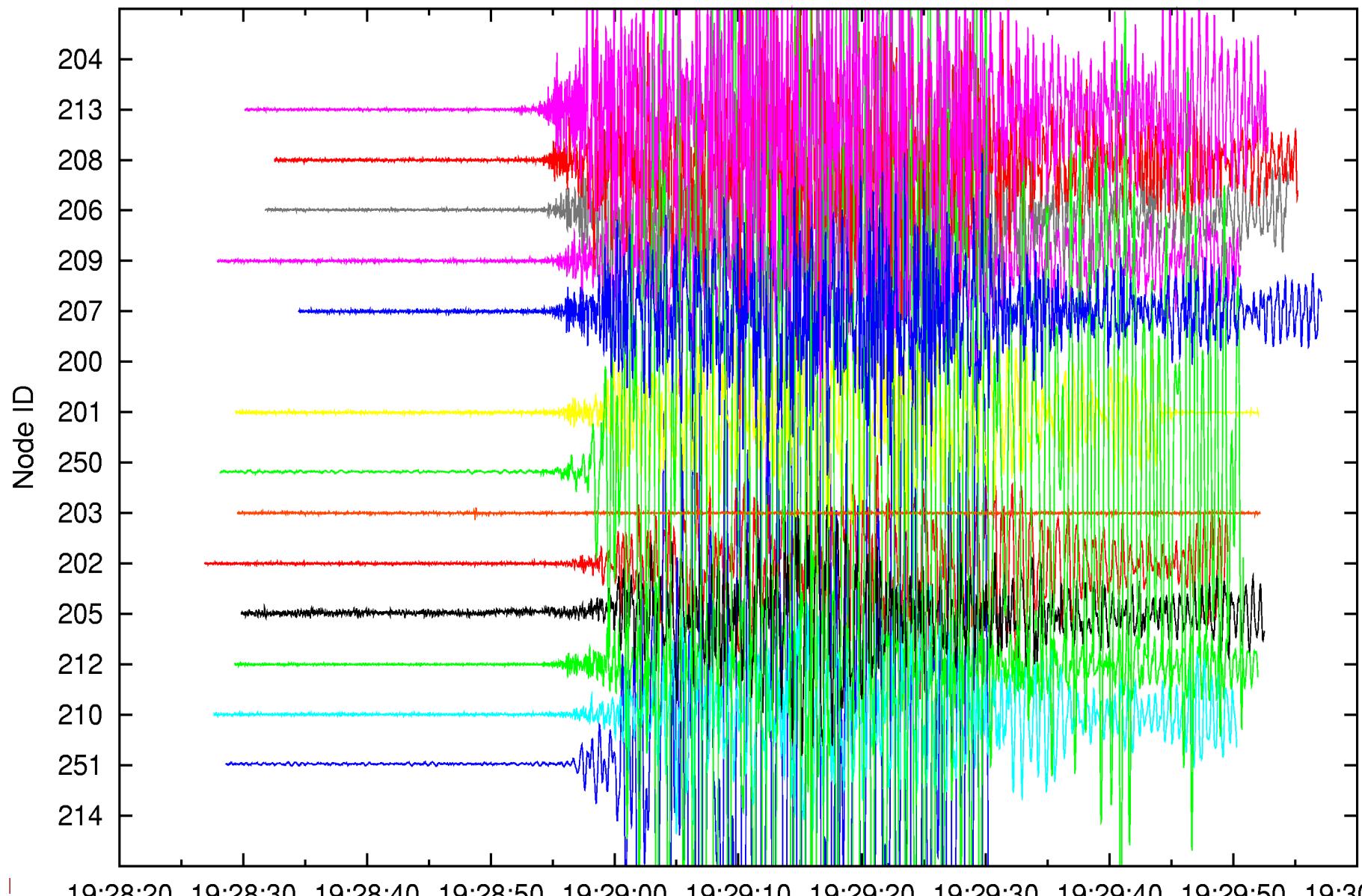
Some Representative Events

Volcano-Tectonic Earthquake

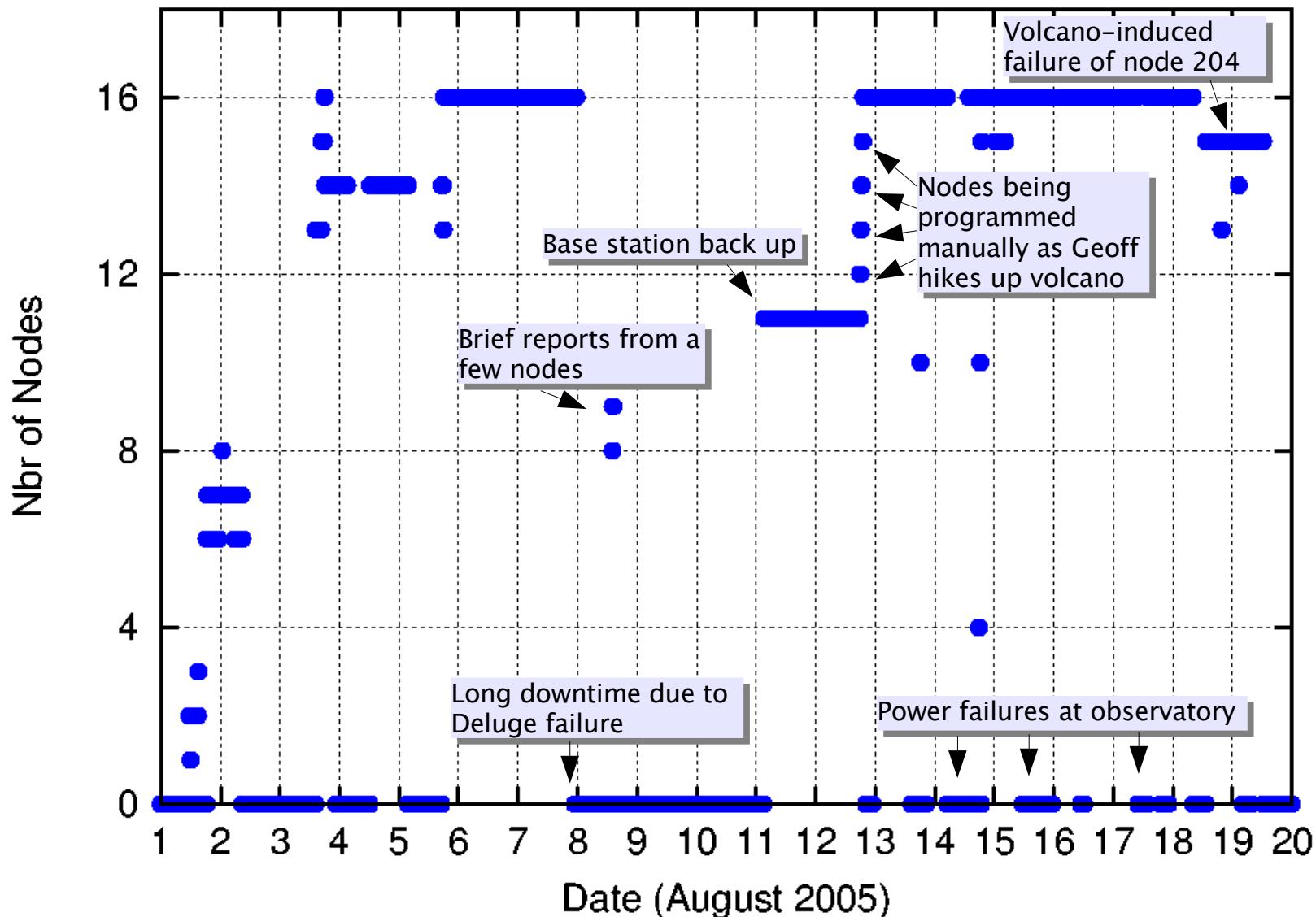


Some Representative Events

Explosion



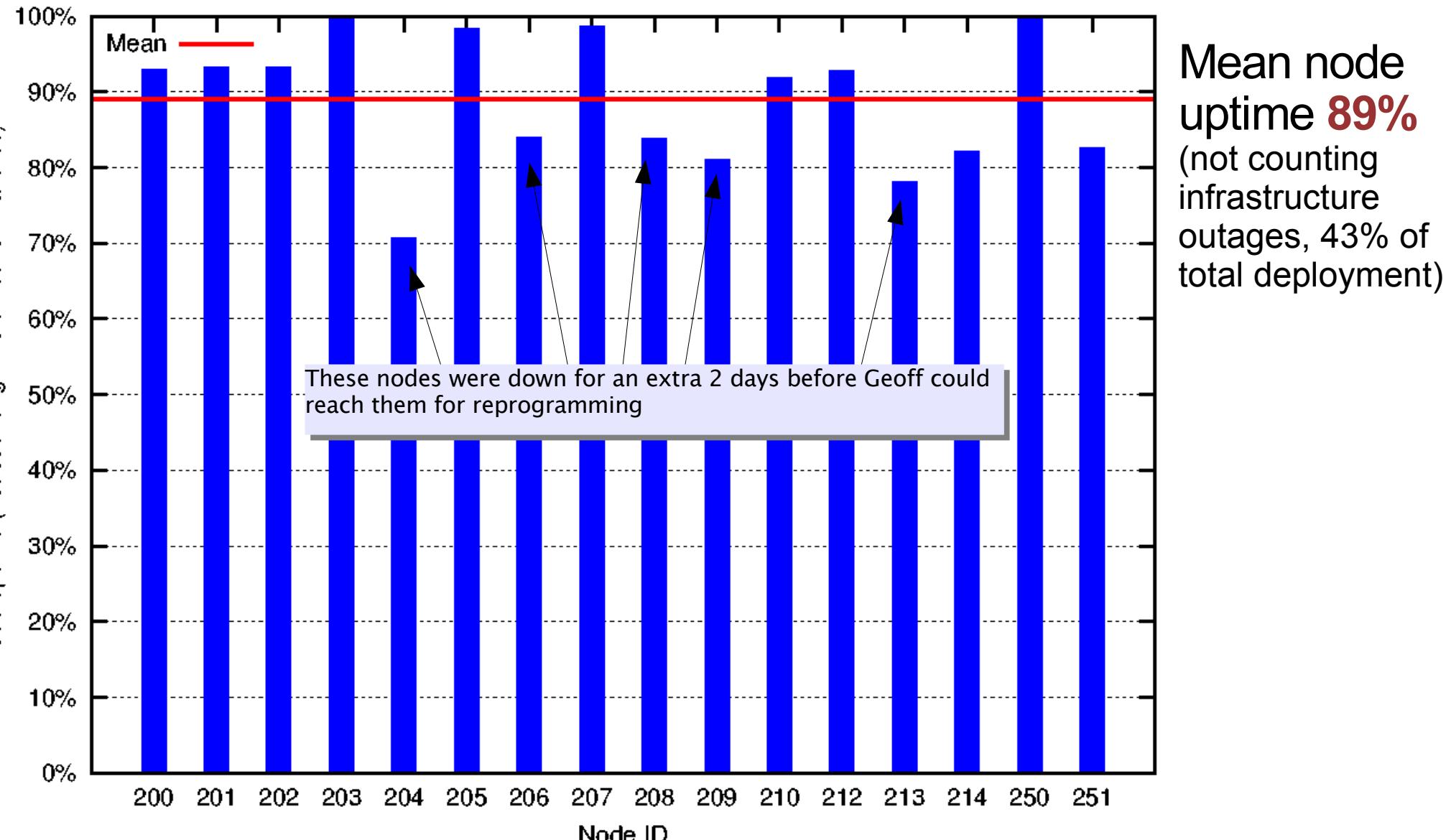
Node Reliability





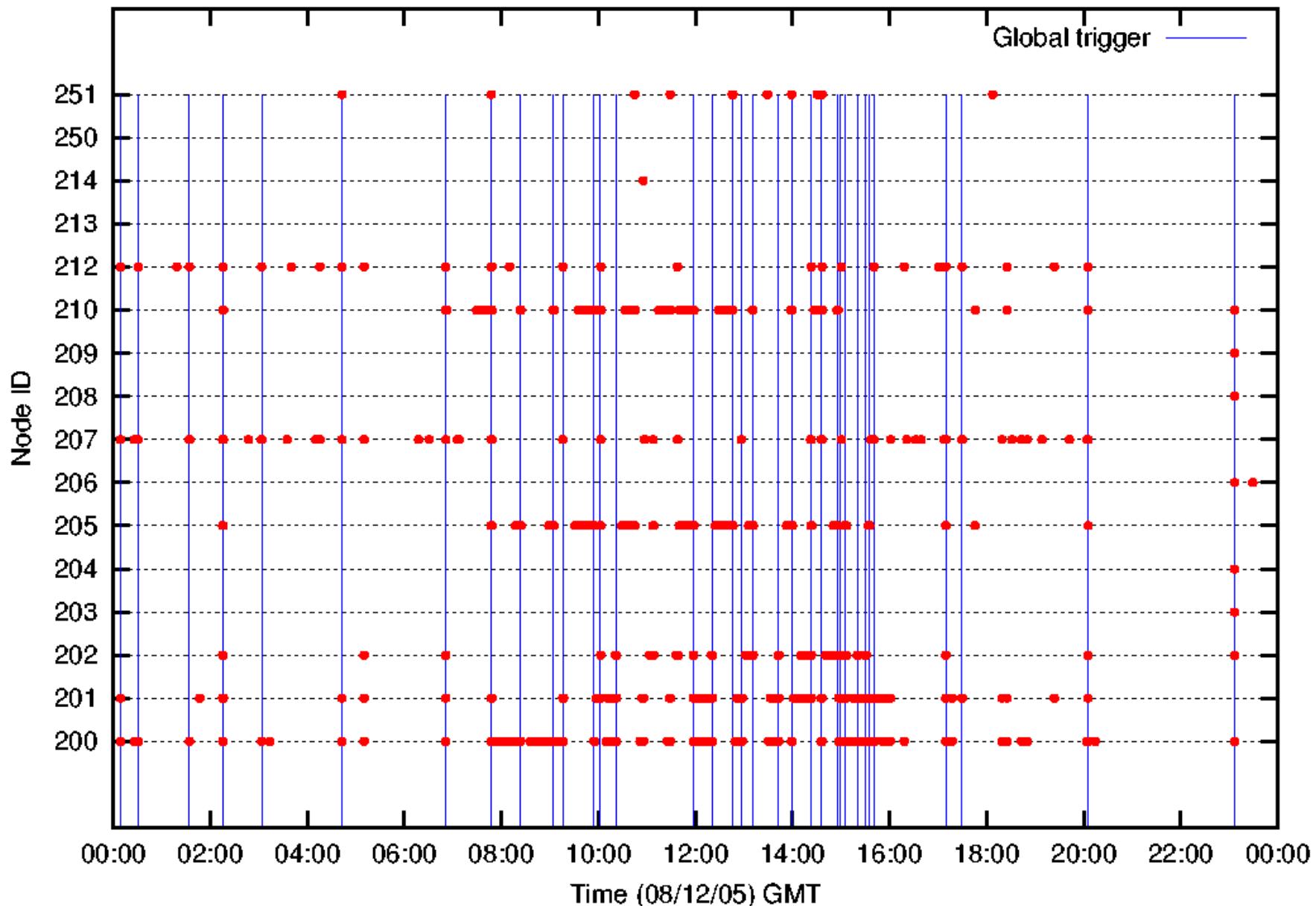
Node reliability by node ID

taken over 10-minute intervals



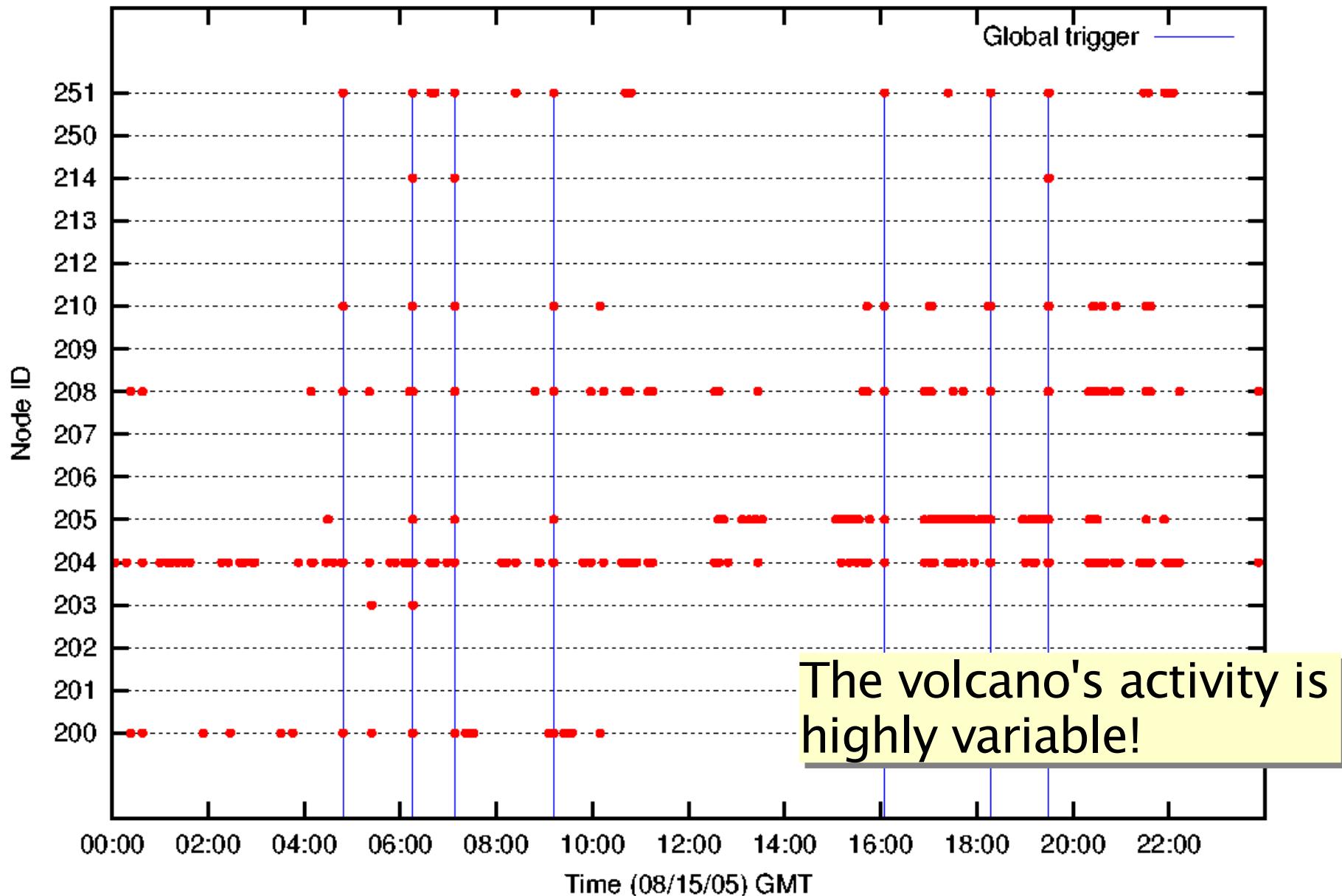
Event Triggers

08/12/05

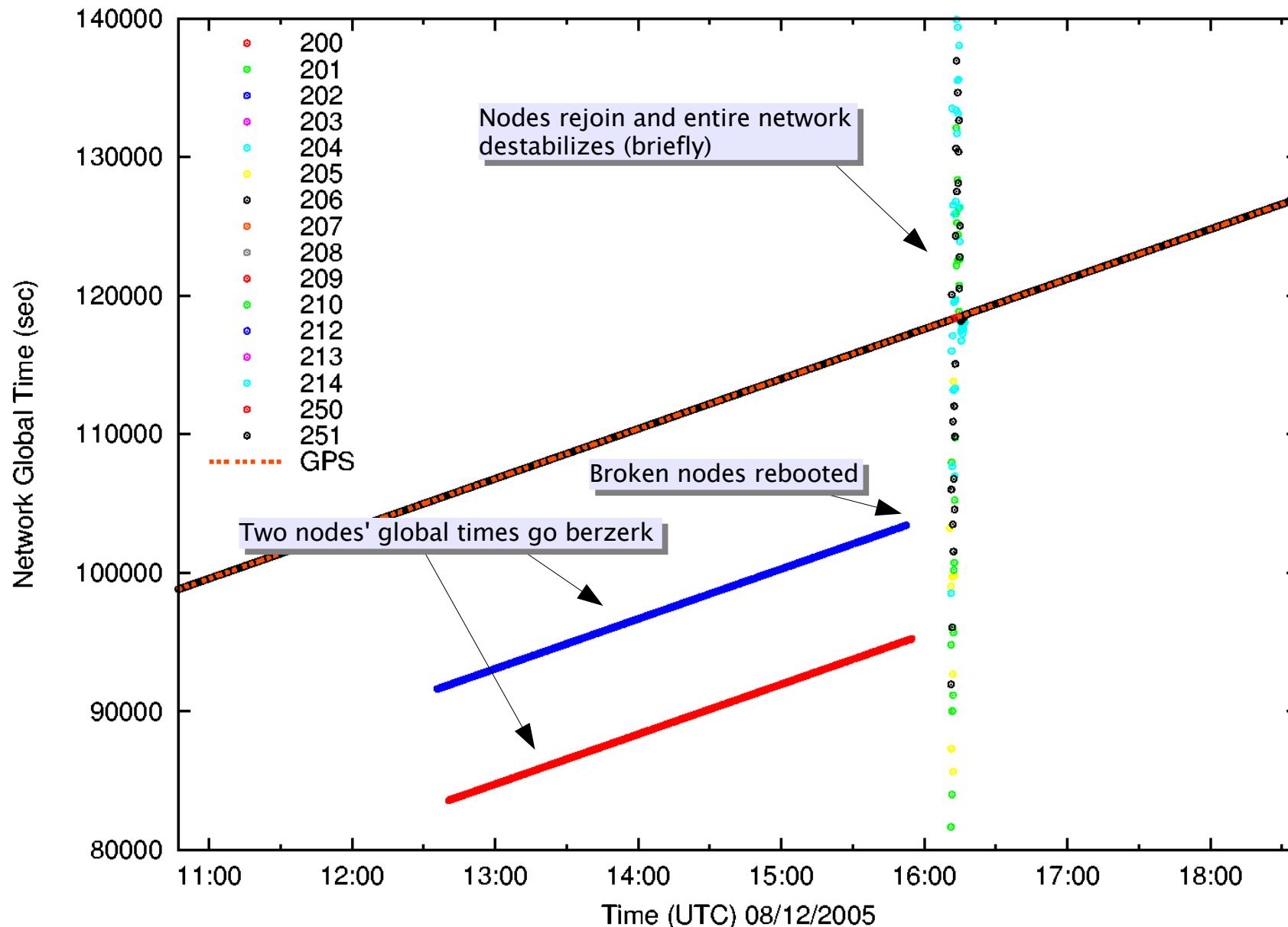


Event Triggers

08/15/05



FTSP stability issues



FTSP stability issues

In FTSP, nodes periodically exchange information on global timebase

- Each node sends heartbeat messages containing MAC-delay corrected global timestamp
- Nodes use this information to calculate local clock skew w.r.t. global clock

Problem: Nodes can receive *corrupted* FTSP messages

- Bug in MSP430 clock driver caused nodes to sometimes read wrong time.
- FTSP trusts this information and includes it in local skew/offset calculations
 - *Also, bad information can propagate throughout the network.*

Lesson: FTSP should perform internal consistency checks

- e.g., Avoid radically updating local phase/skew if well-synchronized already

Post hoc time rectification

Must correct global timestamps in recorded data set

1) Filter out obviously wrong global timestamps

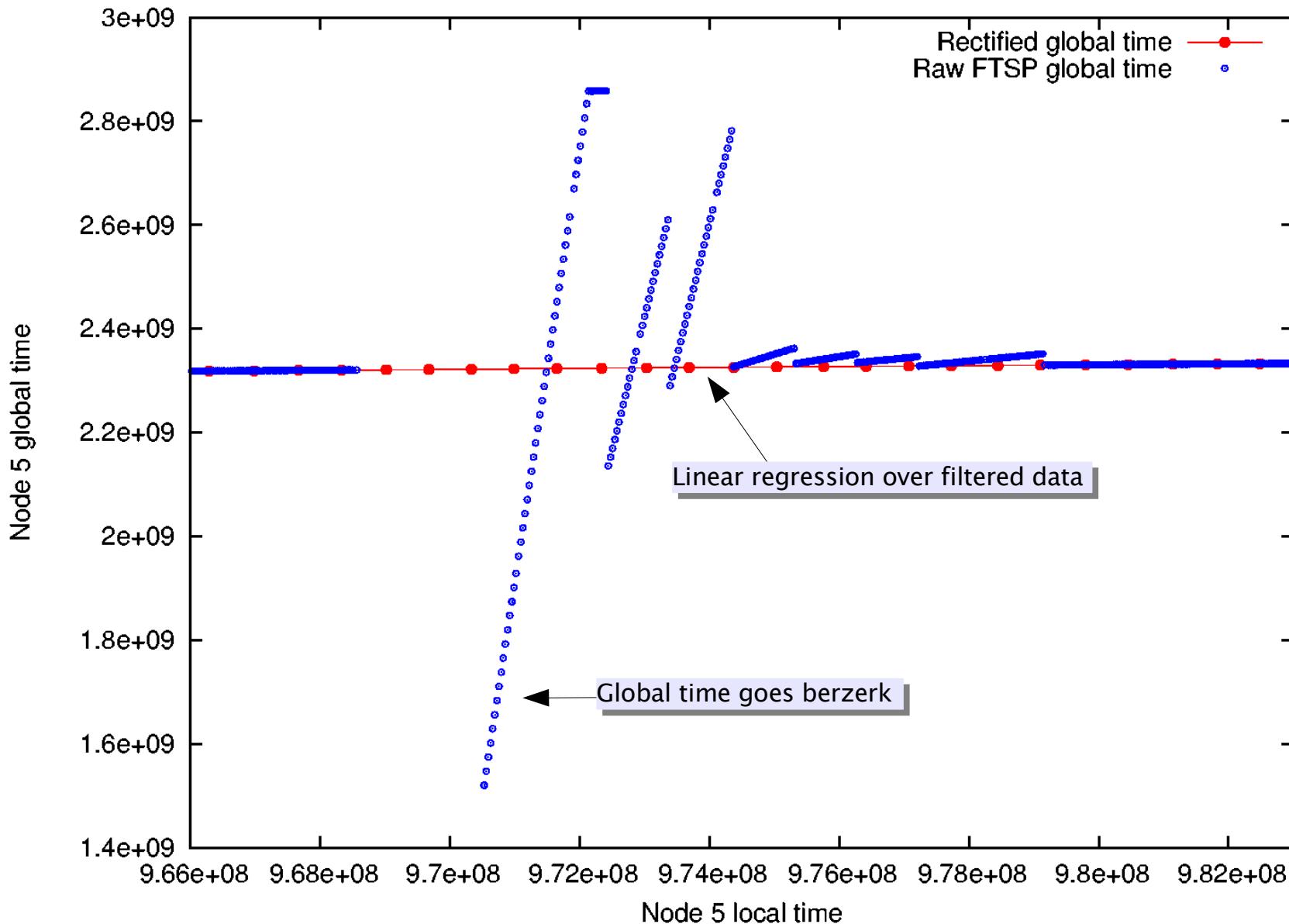
- e.g., Those that differ significantly from global time recorded by FTSP root
- Threshold used: 1 sec.

2) Perform piecewise linear regression on remaining data set

- Produce a mapping from node's local time to "correct" global time
- Linear regression extends for no more than 30 minutes
- Check that clock skew produced by model is sane (within error tolerance of crystal frequency)

3) Apply this mapping to the recorded data for all events

Time rectification example



How do we know if we got the timing right?

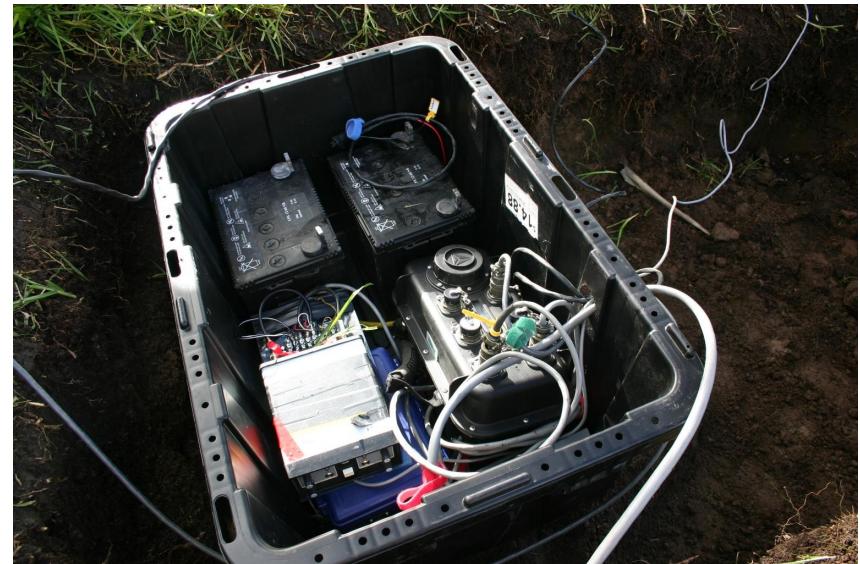
Compare data captured by our mote to a datalogger nearby:



↔

~50 meters

Node 213
(3 hops from FTSP root)

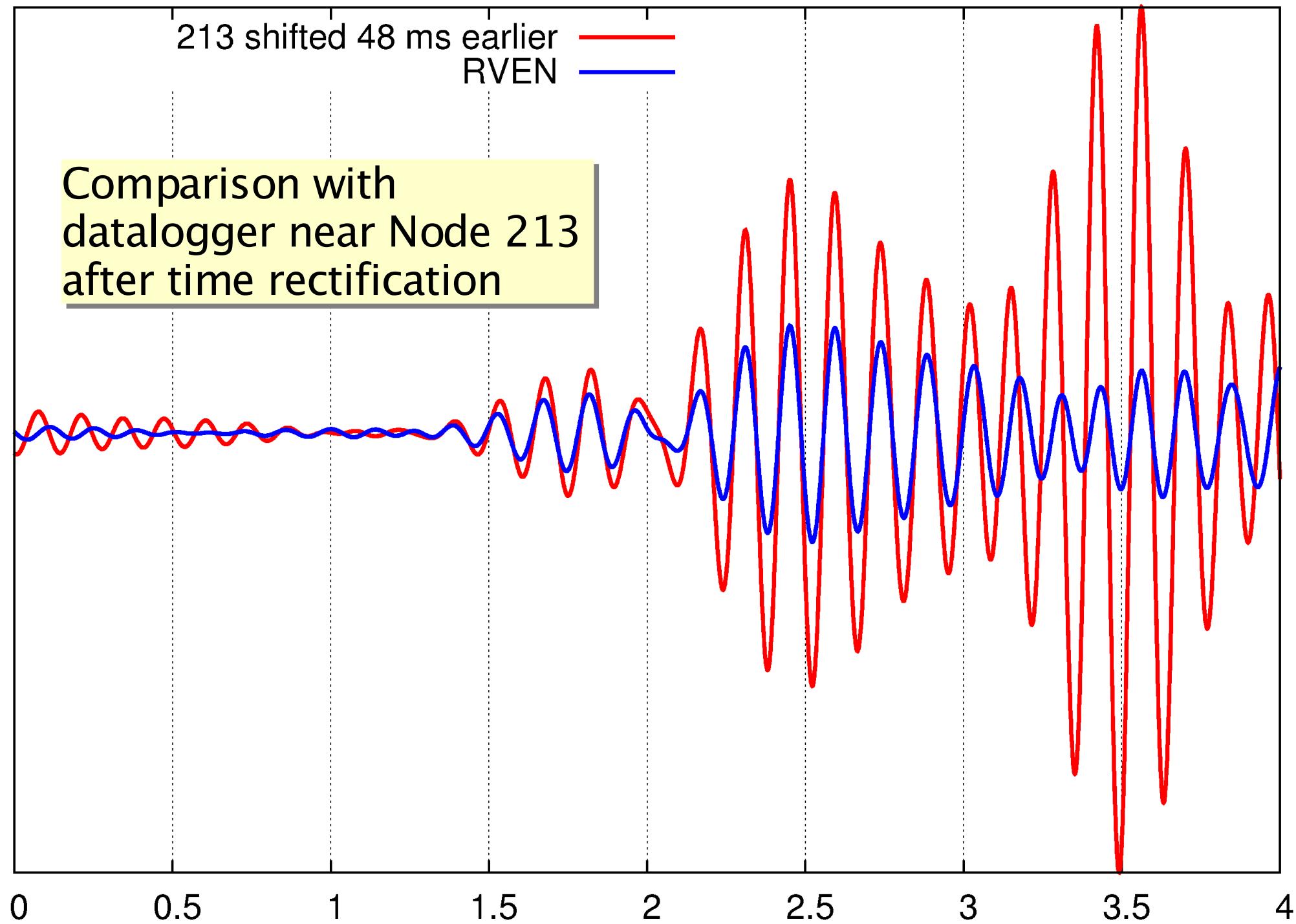


Reventador vent
(RVEN) station

213 shifted 48 ms earlier
RVEN

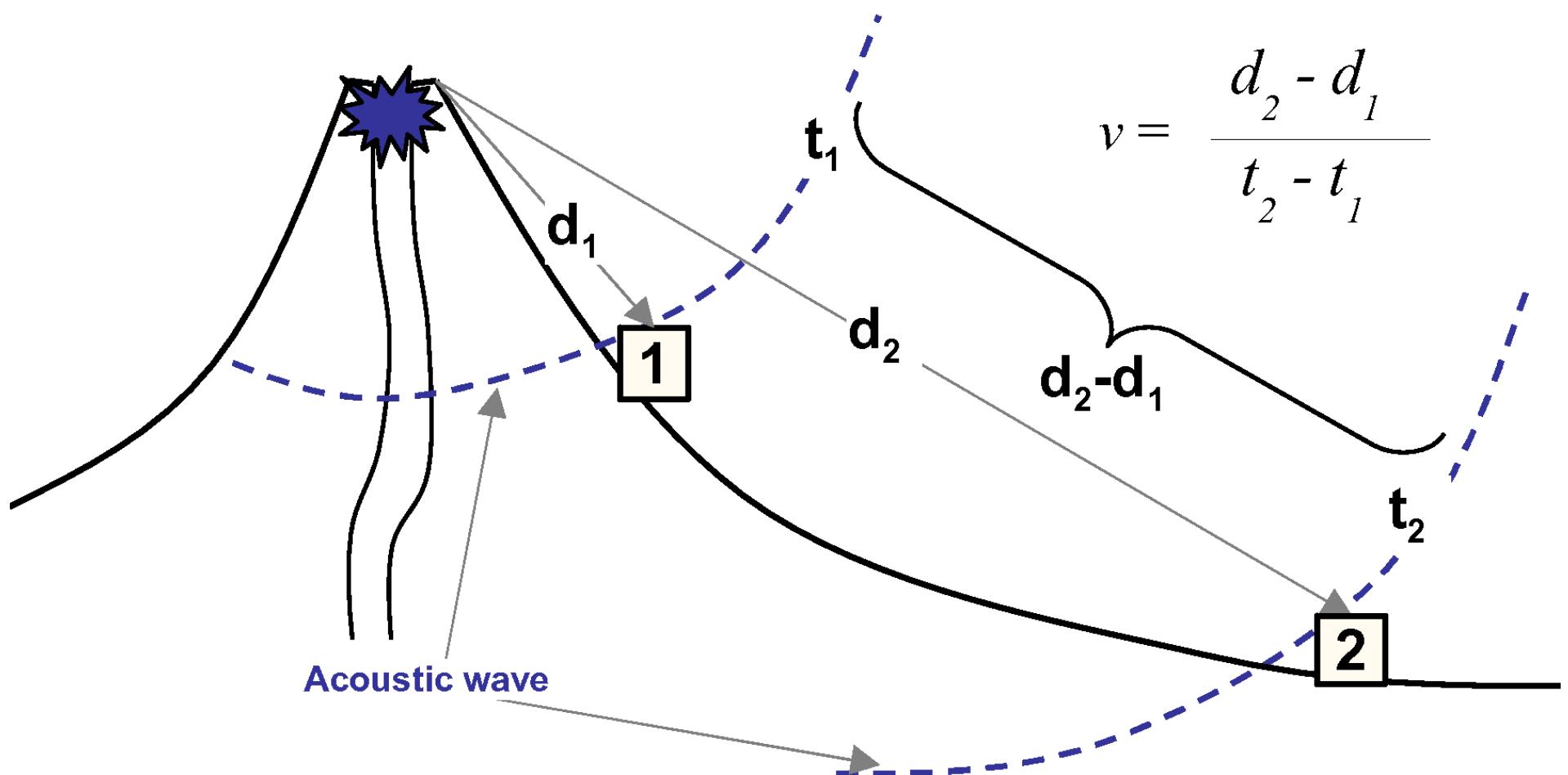
Ground Displacement, Vertical Axis (Sample Value)

Comparison with
datalogger near Node 213
after time rectification



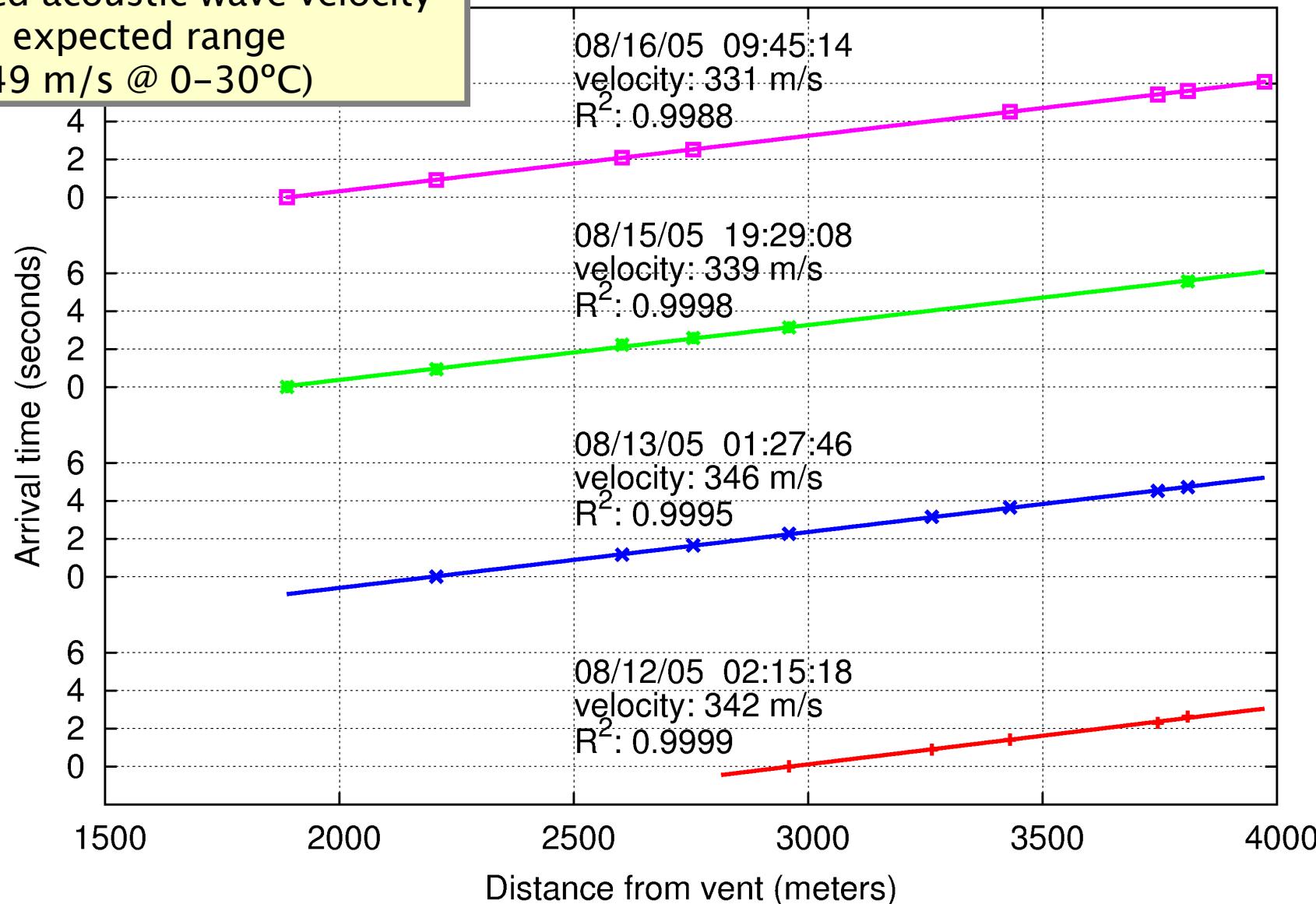
Data validation: Acoustic wave traversal

Check the speed of acoustic waves propagating across the array!

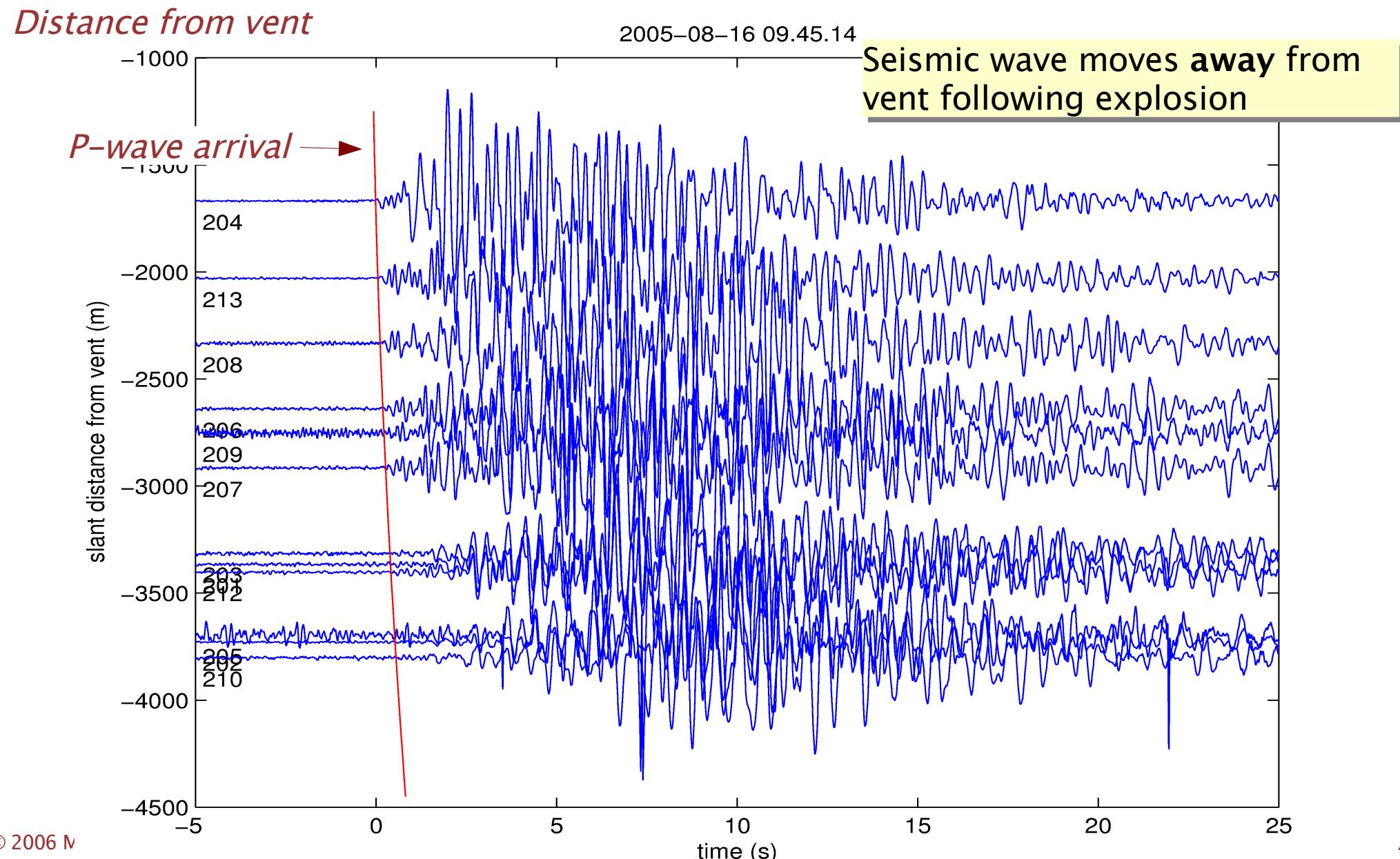


Data validation: Acoustic wave traversal

Measured acoustic wave velocity
is in the expected range
(331–349 m/s @ 0–30°C)



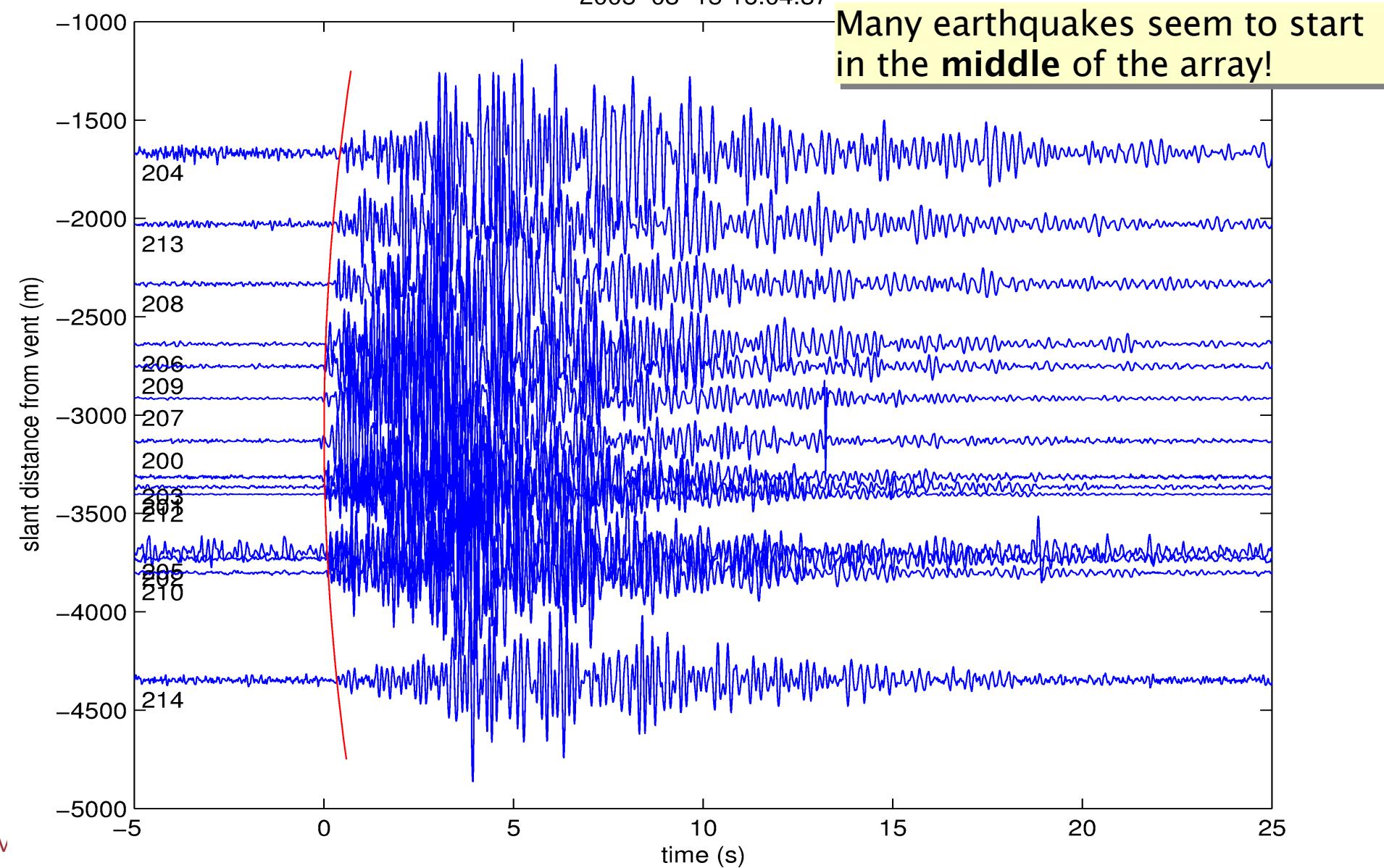
Data validation: Seismic wave traversal



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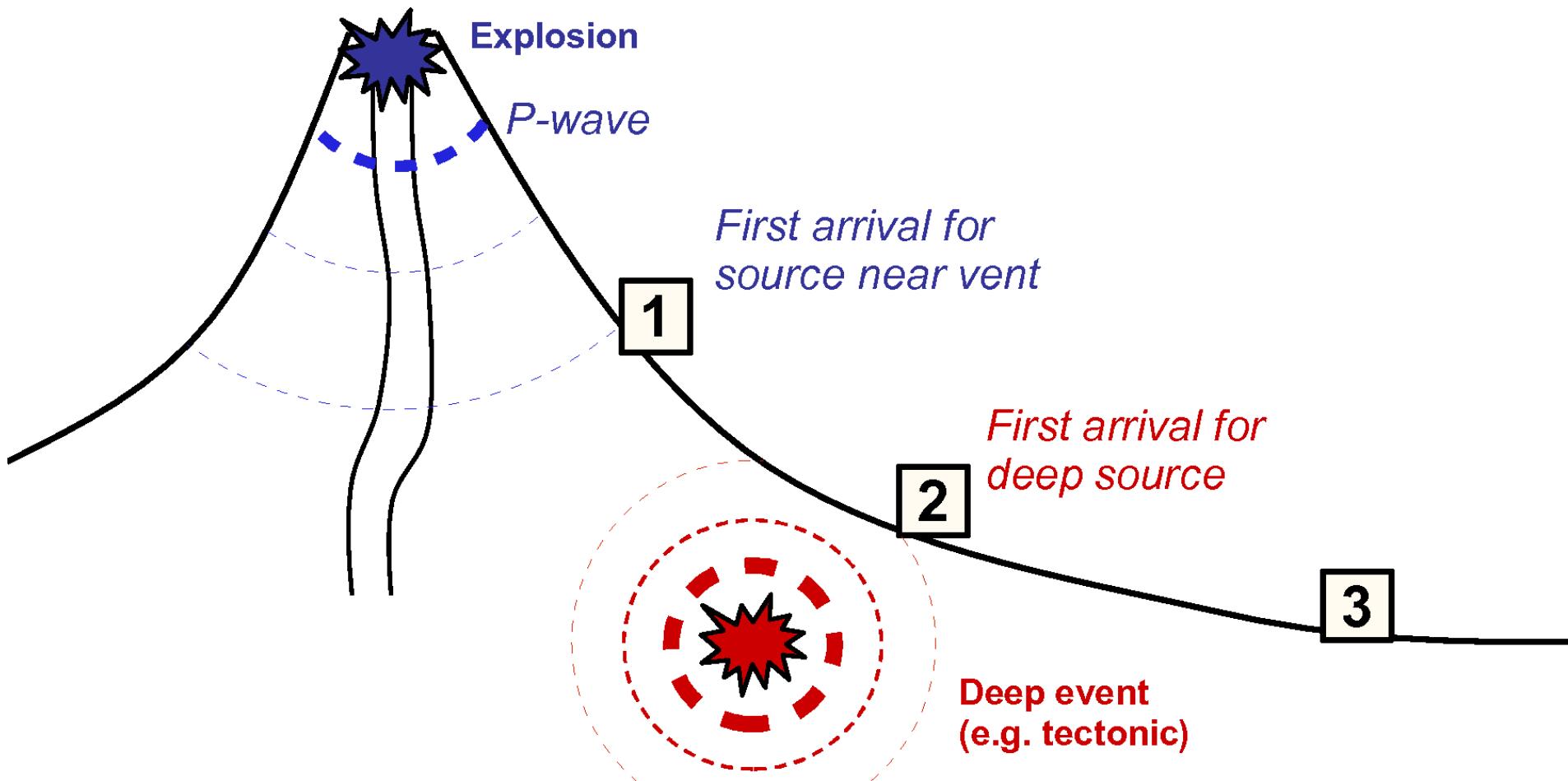
Distance from vent

2005-08-15 16.04.37



What's going on here?

Many earthquakes at Reventador seem to originate from a **deep source** --- an interesting scientific finding.



What did we learn?

Lesson #1: Extracting accurate timing is *hard!*

- More than 6 months of work after returning from the deployment
- FTSP worked very well in the lab – not so in the real world

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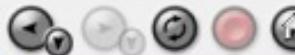
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Lesson #4: Build in self-validation mechanisms early on

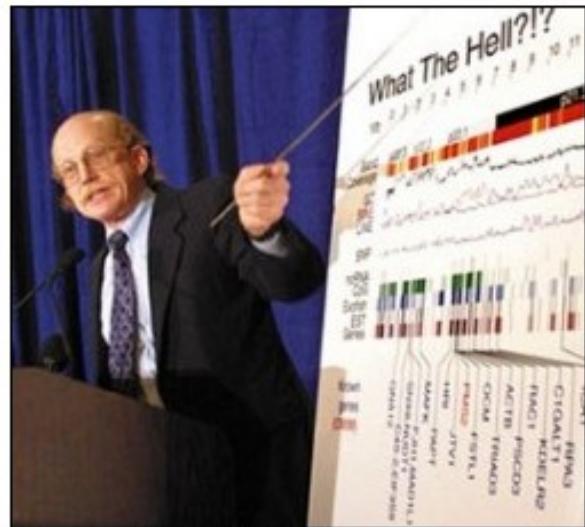
- We did not build in enough cross-checking for things like FTSP errors
- Did not colocate enough motes with broadband stations for later verification



National Science Foundation: Science Hard

June 5, 2002 | Issue 38•21

INDIANAPOLIS—The National Science Foundation's annual symposium concluded Monday, with the 1,500 scientists in attendance reaching the consensus that science is hard.



Farian explains the NSF findings.

"For centuries, we have embraced the pursuit of scientific knowledge as one of the noblest and worthiest of human endeavors, one leading to the enrichment of mankind both today and for future generations," said keynote speaker and NSF chairman Louis Farian. "However, a breakthrough discovery is challenging our long-held perceptions about our discipline—the discovery that science is really, really hard."

"My area of expertise is the totally impossible science of particle physics," Farian continued, "but, indeed, this newly discovered 'Law of Difficulty' holds true for all branches of science, from astronomy to molecular biology and everything in between."

The science-is-hard theorem, first posited by a team of MIT professors in 1990, was slow to gain acceptance within the science community. It gathered momentum following the 1997 publication of physicist Stephen Hawking's breakthrough paper, "Lorentz Variation And Gravitation Is Just About The Hardest Friggin' Thing In The Known Universe."

This weekend's conference, featuring symposia on how hard the Earth sciences are, how confusing medical science is, and how ridiculously un-gettable quantum physics is, represented a major step forward for the science-is-hard theorem.

Next Steps...

Can we perform extensive signal processing ***within the network?***

- Greatly reduce bandwidth and energy requirements

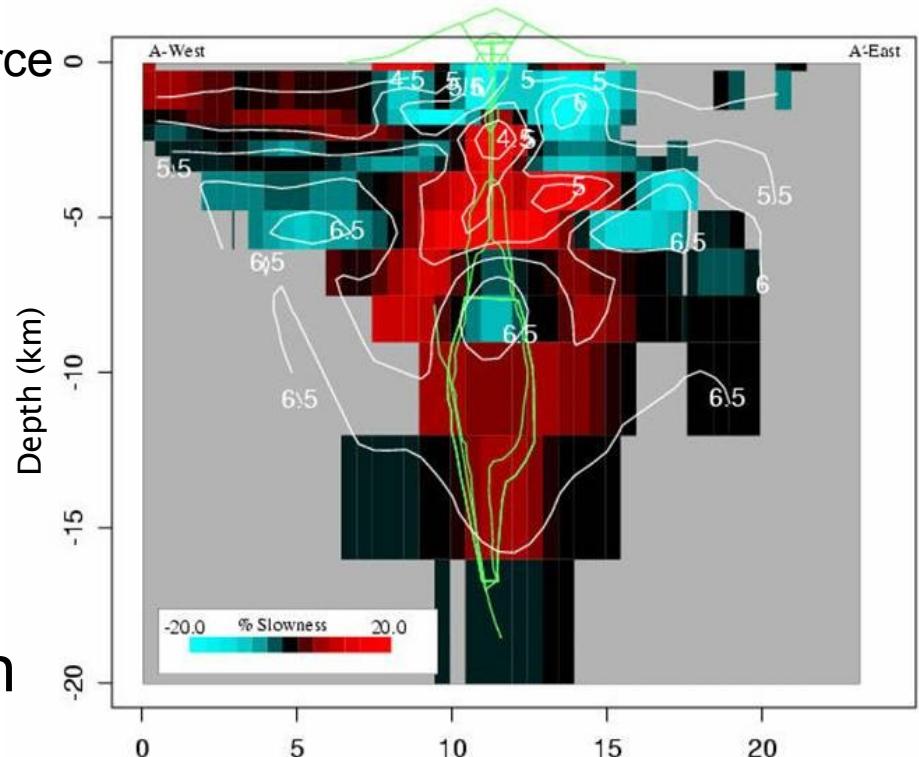
Earthquake localization

- Sensor nodes can coordinate to localize source 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)

Exciting opportunity: Source localization and tomography in ***real time***



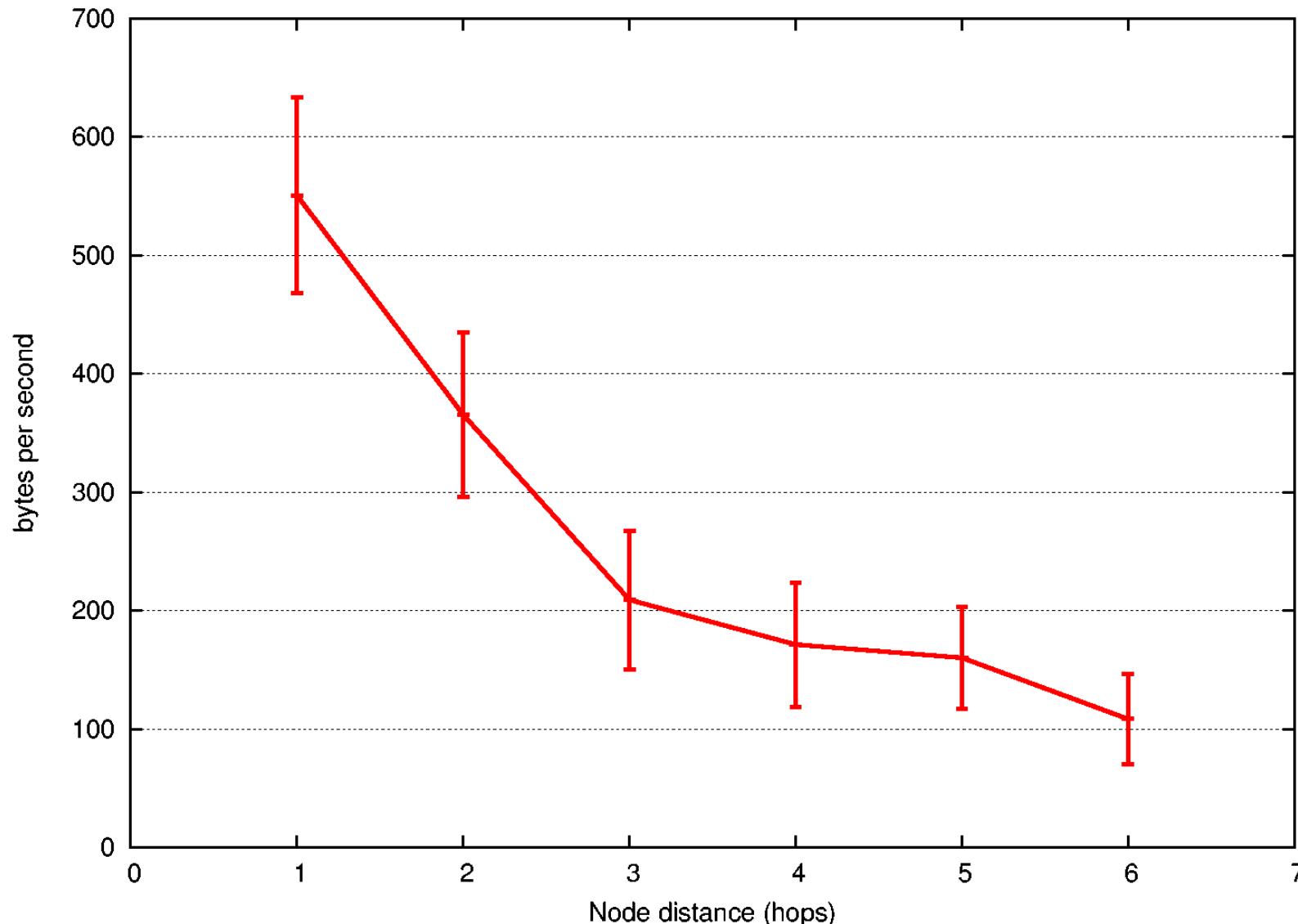
Vertical cross-section of tomographic inversion of Mt. St Helens (J. Lees, UNC)

Thank you!



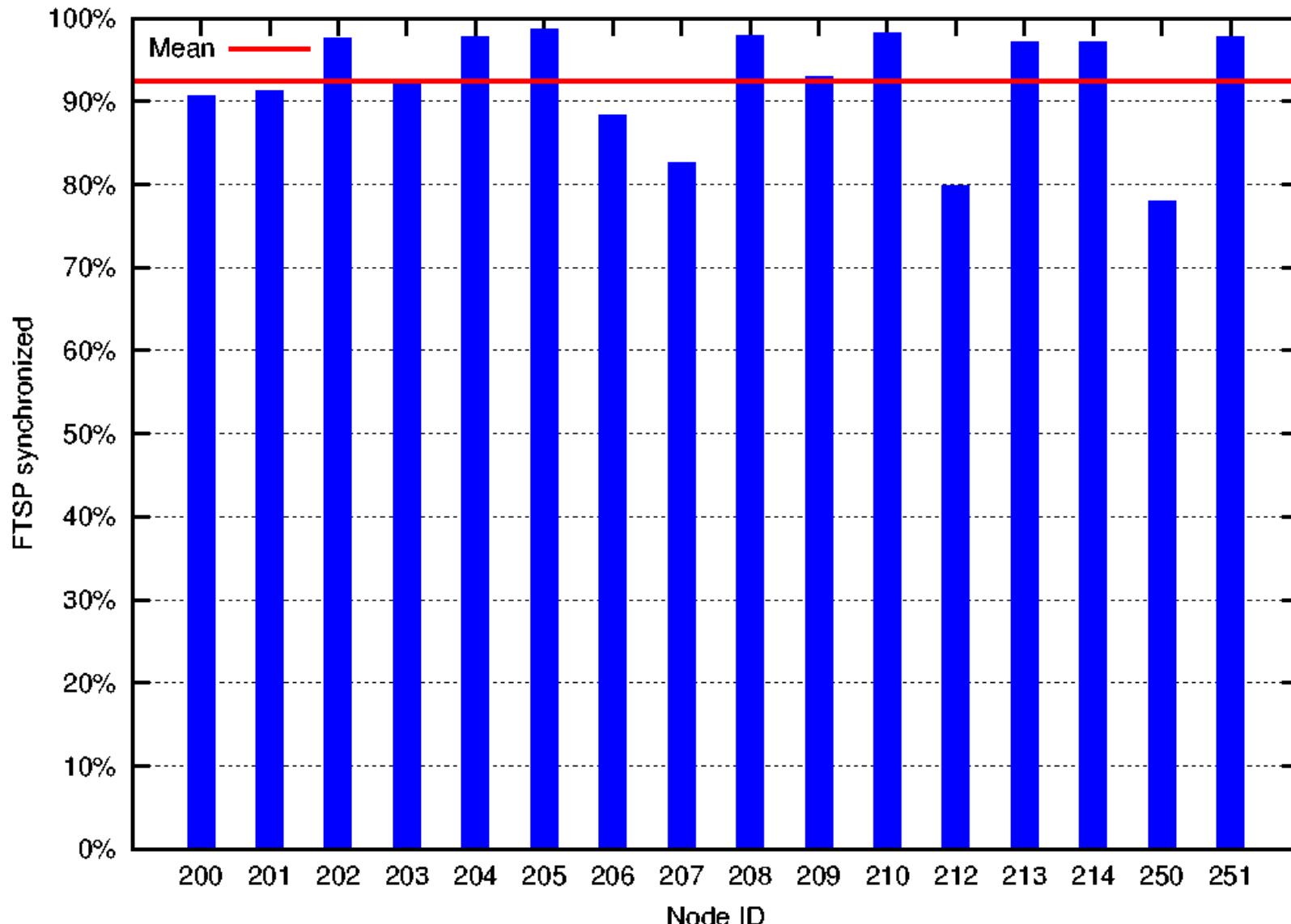
<http://www.eecs.harvard.edu/~mdw/proj/volcano>

Fetch download speed by hopcount



FTSP Stability

08/12/05 to 08/19/05



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

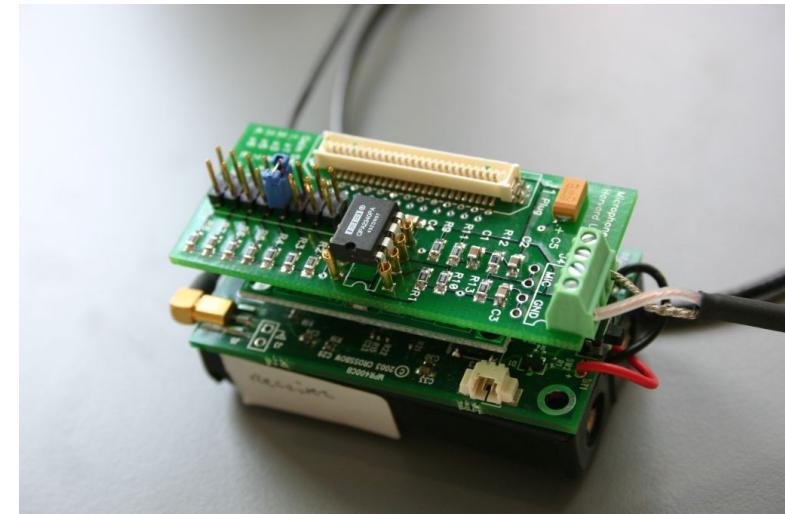
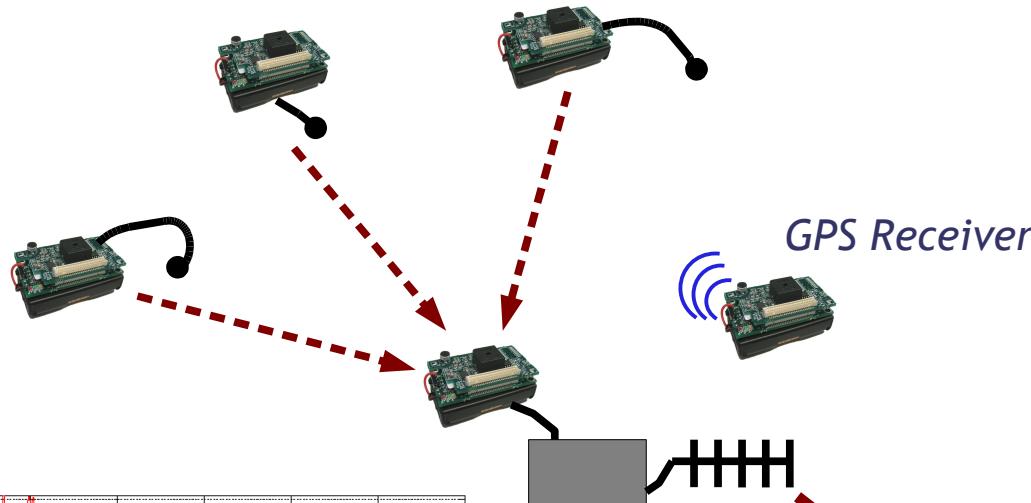
- External environmental connectors to sensors



First Deployment: 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

