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

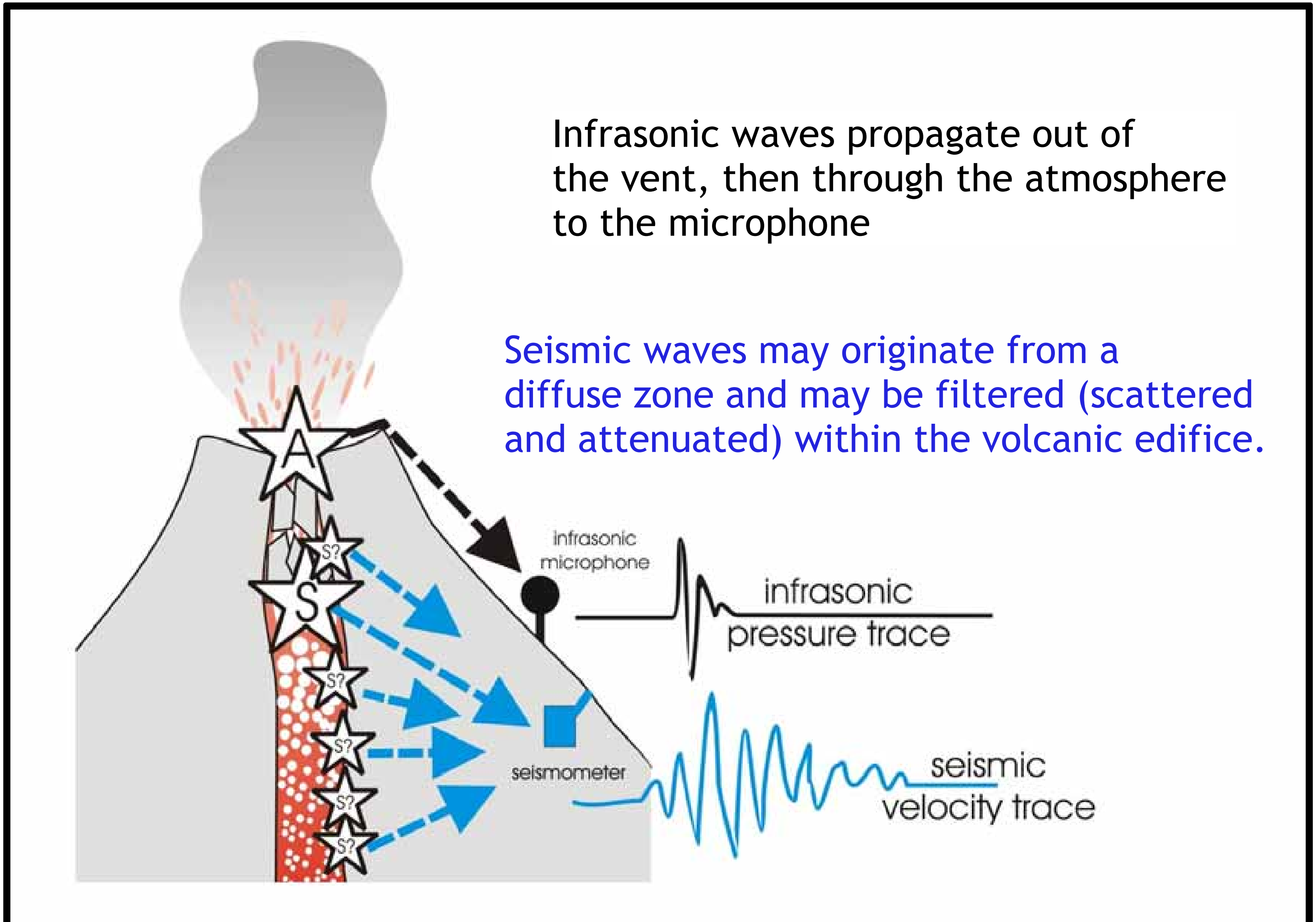
- Many challenges involved with deployment at remote site
- Software robustness is a major concern
- Postprocessing and analysis of data is as difficult as initial acquisition

Disclaimer

I A N A S*

* I am not a seismologist

Sensor Arrays for Volcanic Monitoring



Why do seismologists study volcanoes?

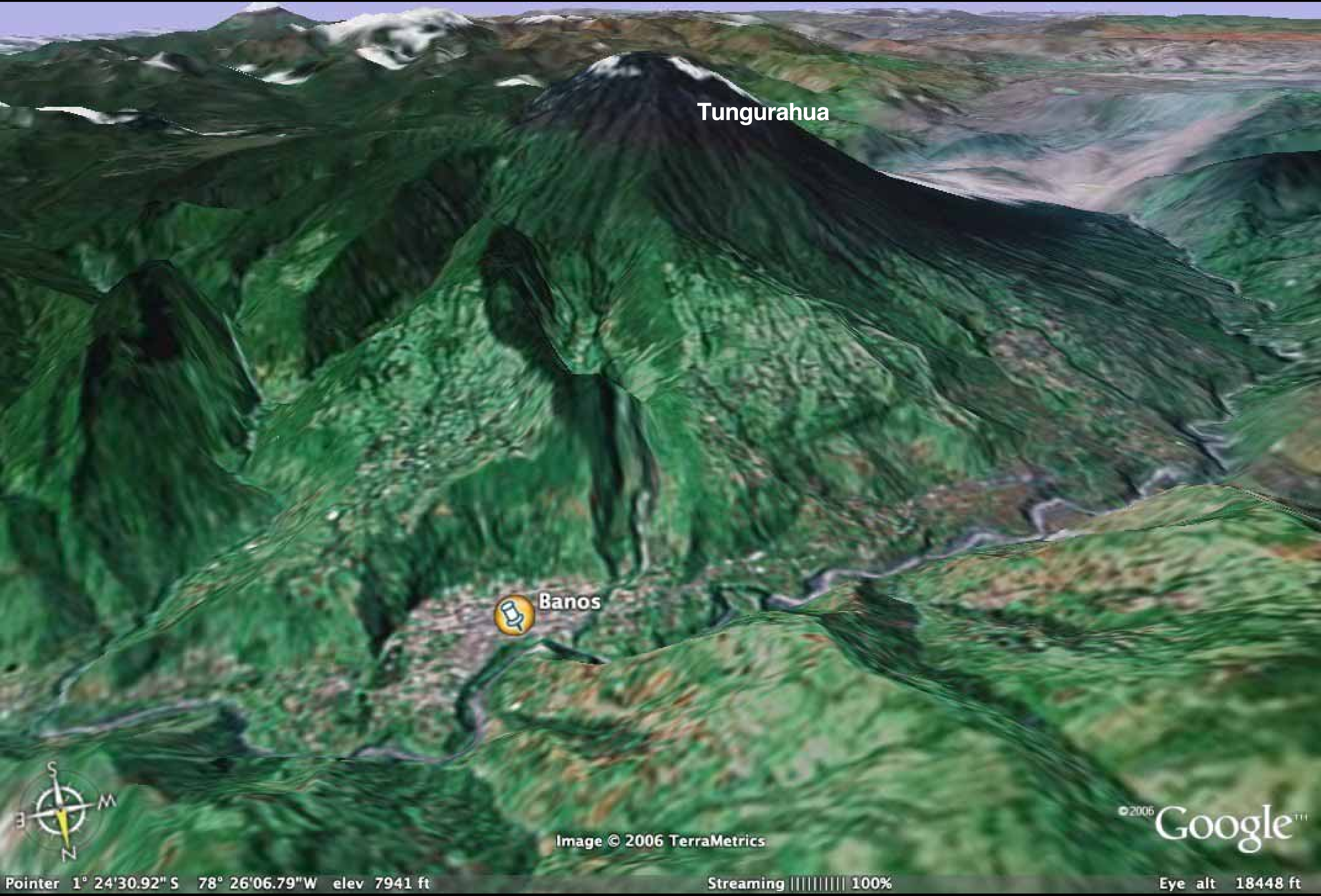
Two non-exclusive reasons:

Scientific study:

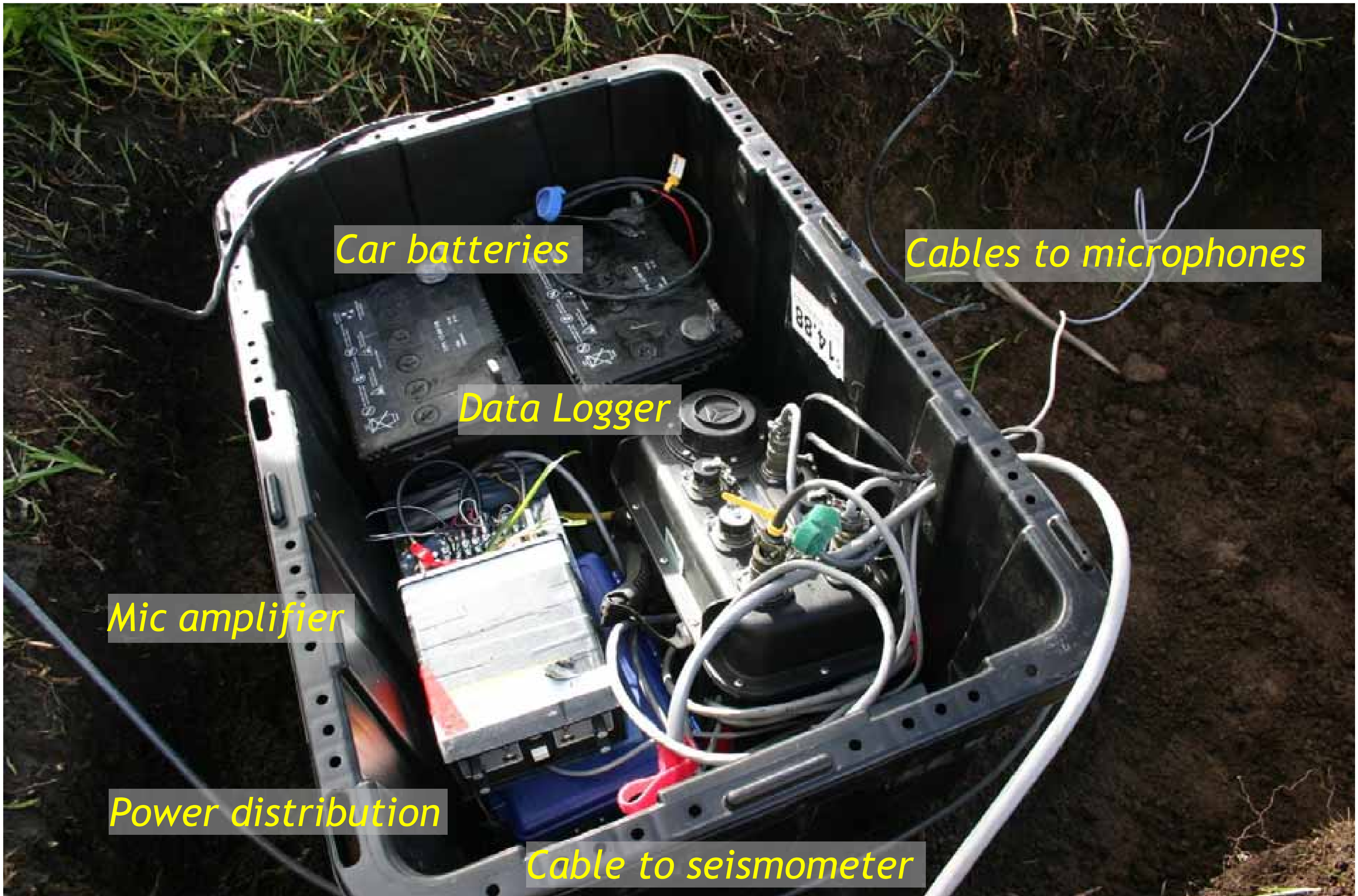
- Understand source processes – what's going on inside the volcano?
- Understand magma flow and gas expansion during eruptions
- Try to understand internal structures causing earthquakes
- What causes volcanoes to form and how do they evolve over time

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

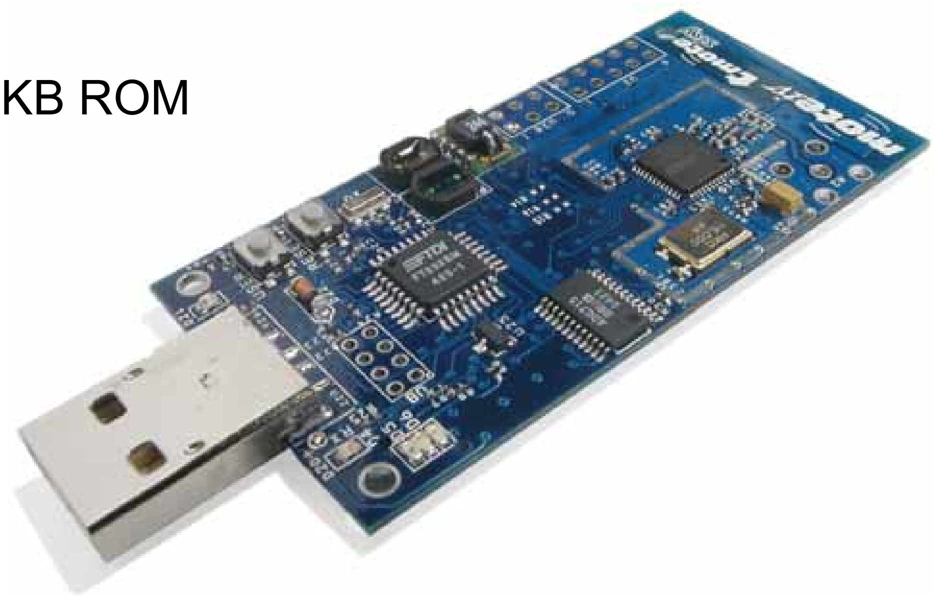
Existing Volcanic Sensor Station



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

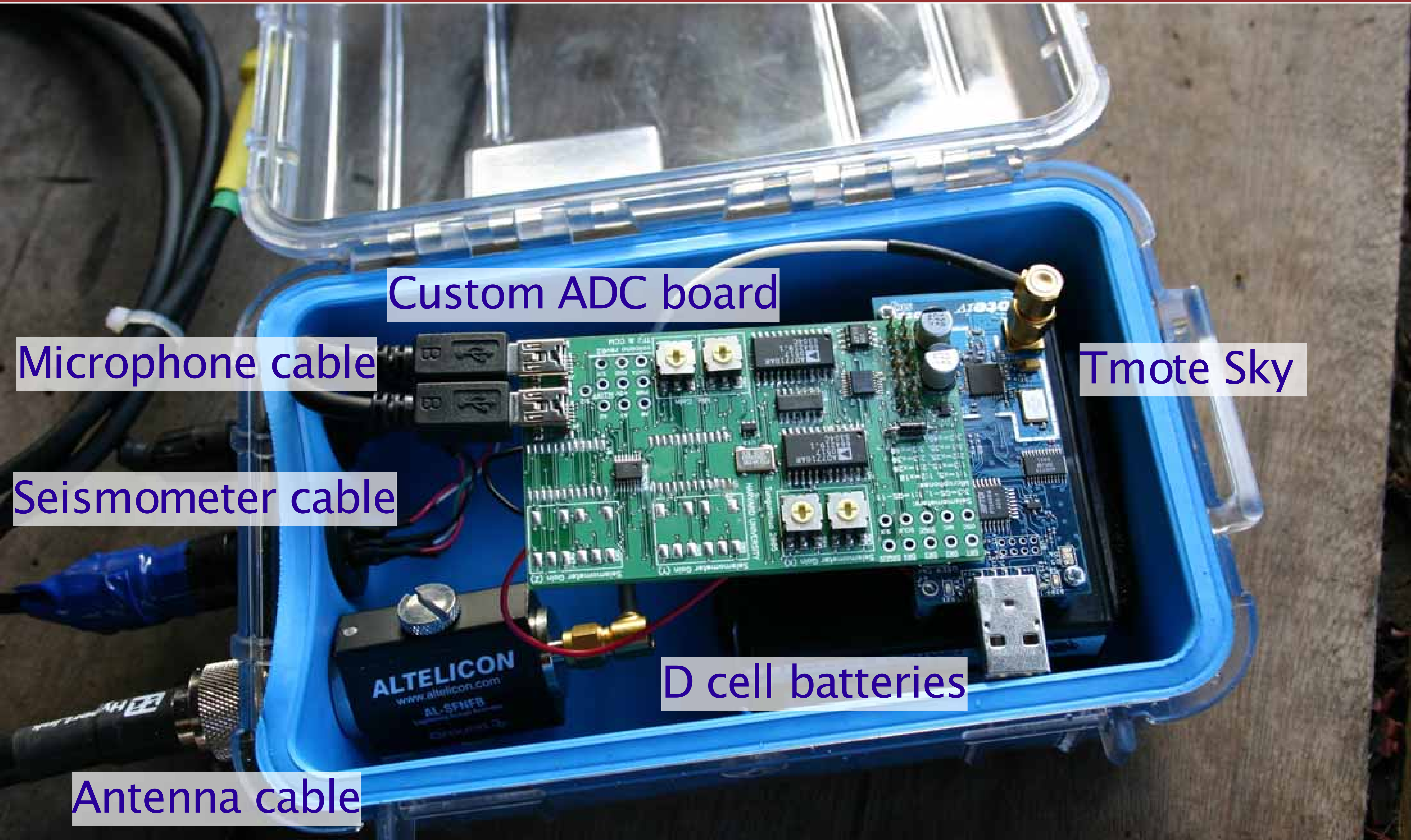
Can provide real time monitoring of volcanic activity

- ... 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
Tungurahua
Galapagos Islands
100 Miles
100 Kilometers
Pacific Ocean
Pinta
Marchena
Genovesa
0° Equator
San Salvador
Baltra
Pinzón
Santa Cruz
San Cristóbal
Isabela
Santa Fe
Baquerizo Moreno
Villamil
Velasco Ibarra
Santa María
Española
Tumaco
Barbacoas
COLOMBIA
Florencia
PAN AMERICAN HIGHWAY
Cape Manglares
Bay of Sardinas
San Lorenzo
Valdez
Pasto
Túquerres
Tulcán
Ipiales
Mocoa
Rioverde
Esmeraldas
Point Galera
Muisne
Cojimíes
Rosa Zárate
El Ángel
San Gabriel
Atuntaqui
Ibarra
Otavalo
Cotacachi
Cayambe
Cayambe 18,996 ft. (5,790 m)
Puerto Asís
OIL FIELD
Nueva Loja
Shushufindi Central
ANDES MTS
CORDILLERA OCCIDENTAL
CORDILLERA ORIENTAL
Pichincha 15,696 ft. (4,784 m)
Quito
Santo Domingo
El Carmen
MONTAÑAS DE CONVENTO
Jama
Cape Pasado
Sangolquí
Baeza
Machachi
Antisana 18,714 ft. (5,704 m)
Sumaco 12,795 ft. (3,900 m)
Cotopaxi 19,347 ft. (5,897 m)
Bahía de Caráquez
Chone
Calceta
Bay of Manta
Manta
Montecristi
Rocafuerte
Portoviejo
Quevedo
Pujilí
Latacunga
Tena
Nuevo Rocafuerte
Cape San Lorenzo
Plata I.
North
San Miguel de Salcedo
Ambato
Píllaro
ECUADOR
Jipijapa
Santa Ana
Balzar
Chimborazo 20,561 ft. (6,267 m)
Baños
Puyo
Paján
López
Ventanas
Vinces
Guaranda
Guano
Riobamba
CERROS DE COLONCHE
Babahoyo
Daule
Samborondón
Manglaralto
Bay of Santa Elena
Guamote
Sangay 17,159 ft. (5,230 m)
Río Tigre
PERU
Point Santa Elena
Salinas
Santa Elena
La Libertad
Guayaquil
Yaguachi Nuevo
Eloy Alfaro
Milagro
Chunchi
Alausí
Macas
Sucúa
Río Corrientes
Playas
Gómez Rendón
Naranjal
Cañar
Patul 13,658 ft. (4,163 m)
Azogues
Méndez
Paute
Posorja
Puná I.
Cuenca
Gualaceo
General Leonidas Plaza Gutiérrez
Yaupi
Andoas
CORDILLERA DE CUTUCÚ
Pacific Ocean
Gulf of Guayaquil
Santa Clara I.
Santa Isabel
Sígsig
Machala
Pasaje
PAN AMERICAN HIGHWAY
Zarumilla
Tumbes
Santa Rosa
Arenillas
Piedras
Piñas
Zaruma
Saraguro
Gualaquiza
Veintimilla de Mayo
CORDILLERA DEL CÓNDOR
CERROS DE CAMPANAQUIZ
Máncora
Catacocha
Celica
Loja
Zamora
El Alto
CERROS DE LA BREA
Cariamanga
Macará
Amaluza
Borja
Talara
Point Pariñas
Negritos
Ayabaca
Viejo 12,907 ft. (3,934 m)
Zumba
Sullana
Bay of Paita
Paita
Chulucanas
PERU
Ecuador
International boundary
Road
Railroad
Oil pipeline
National capital
Provincial capital
Other city or town
Elevation above sea level

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

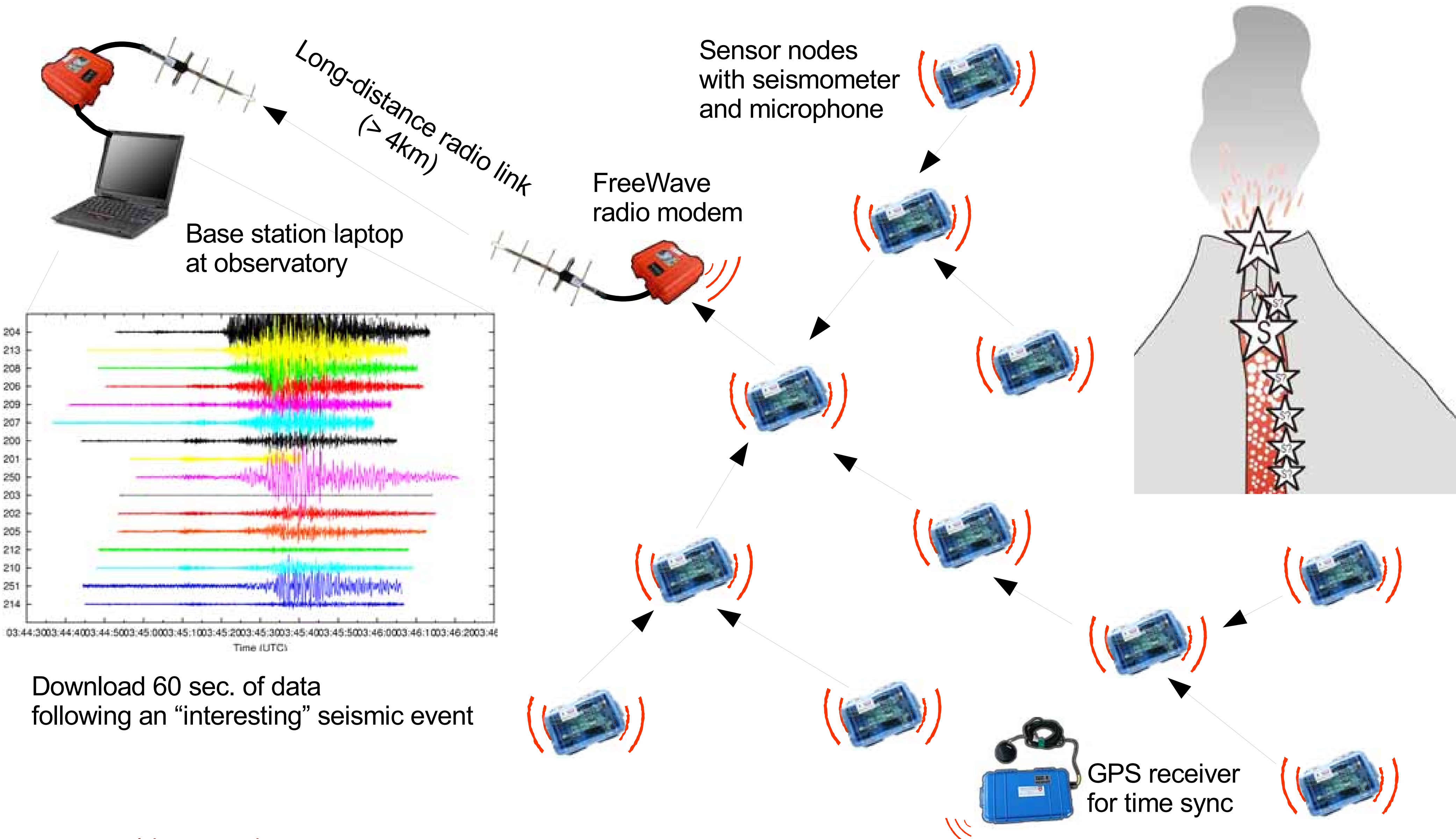
Recent activity (since November 2004)

- 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 decimted 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

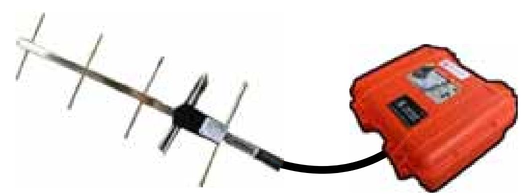
Motes sample data continuously and store to flash

- 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”

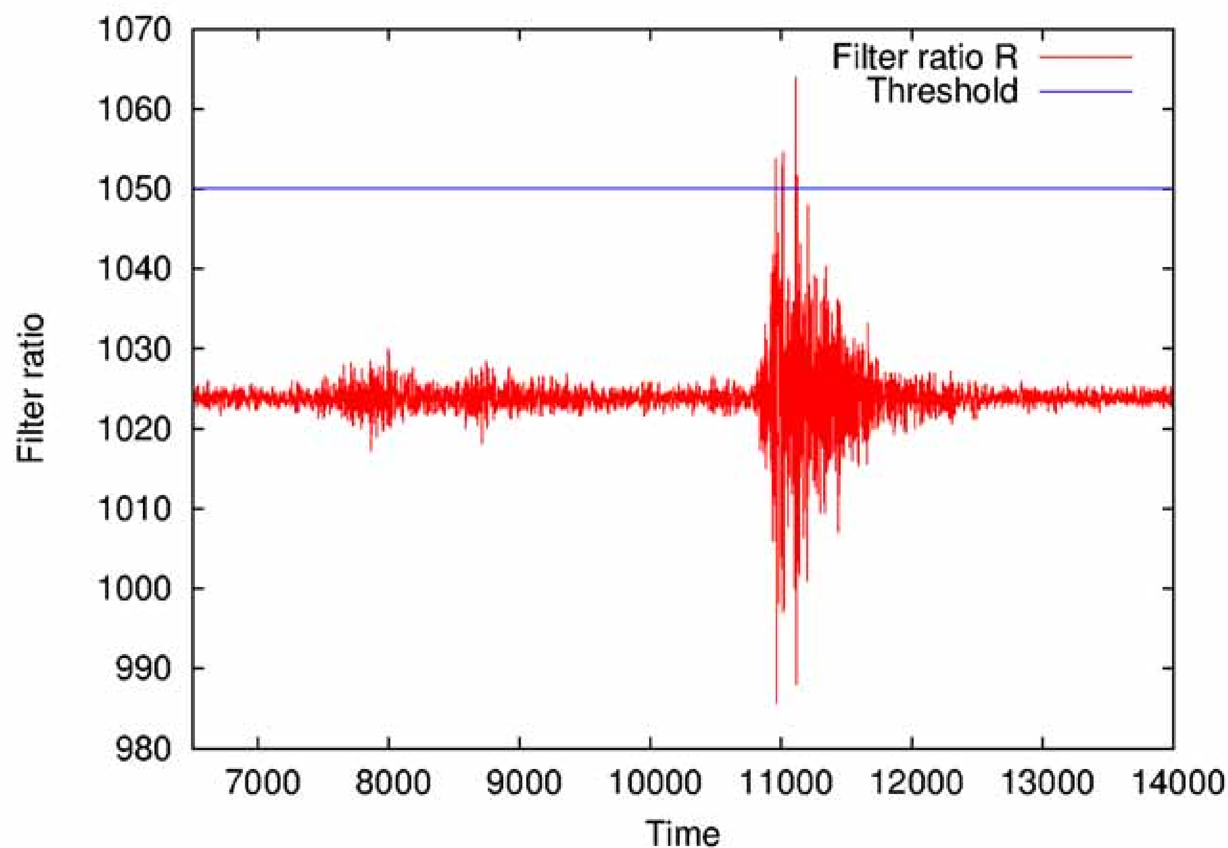
Eruption Detection Algorithm

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

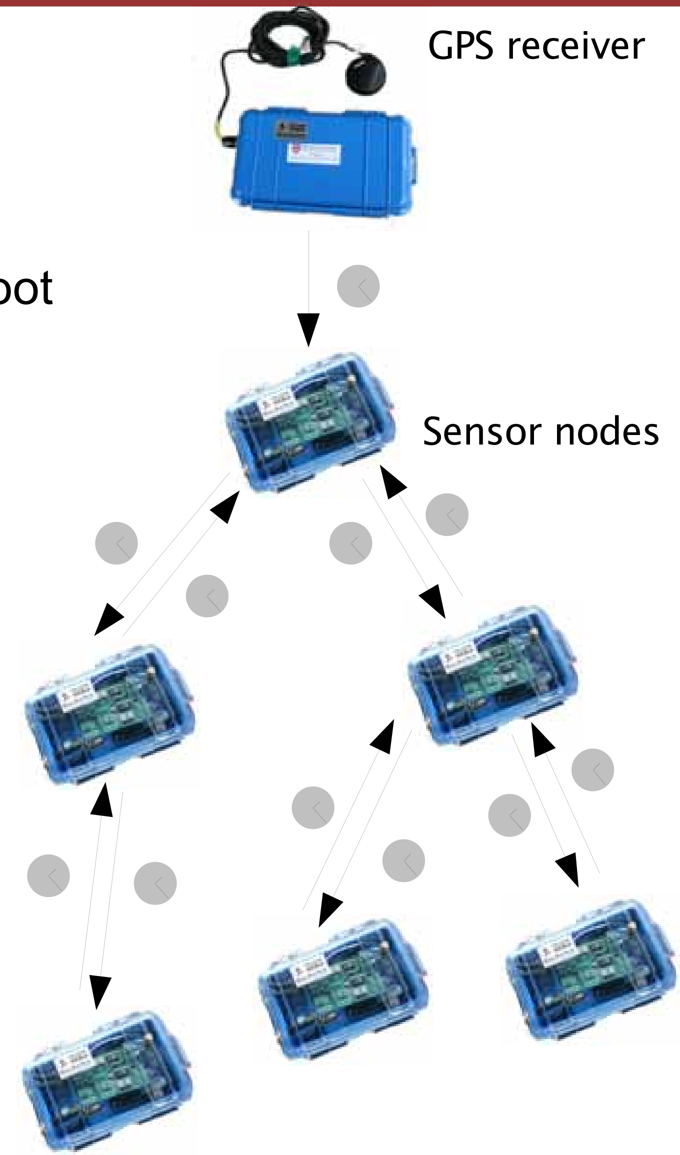
Each node broadcasts periodic *beacon* with global time of transmission

- 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

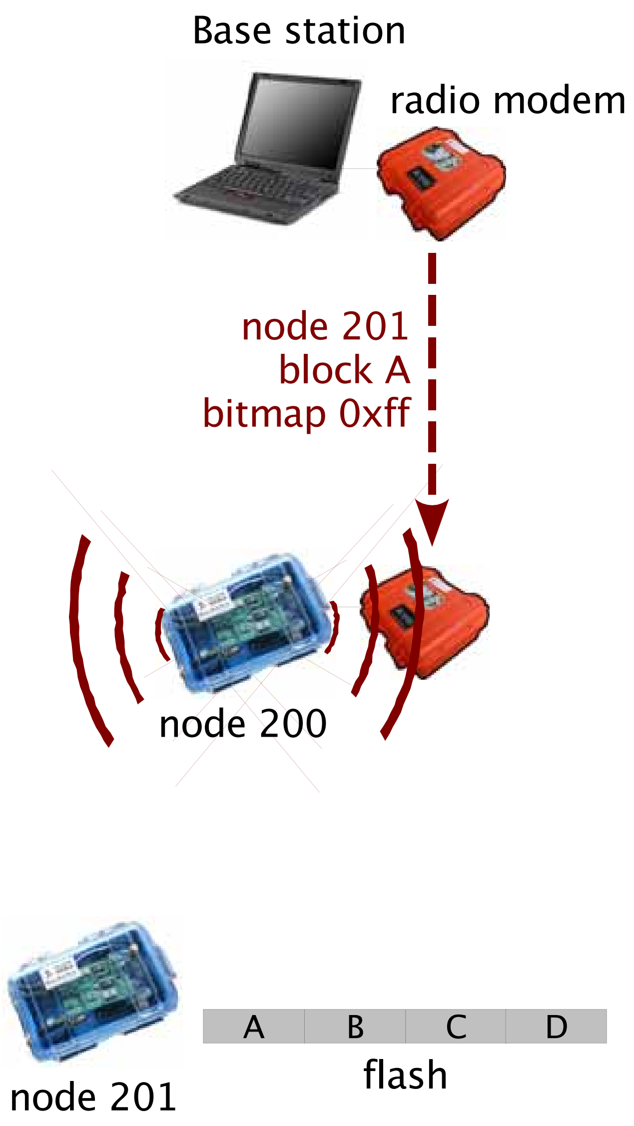
Fetch Reliable Transfer Protocol

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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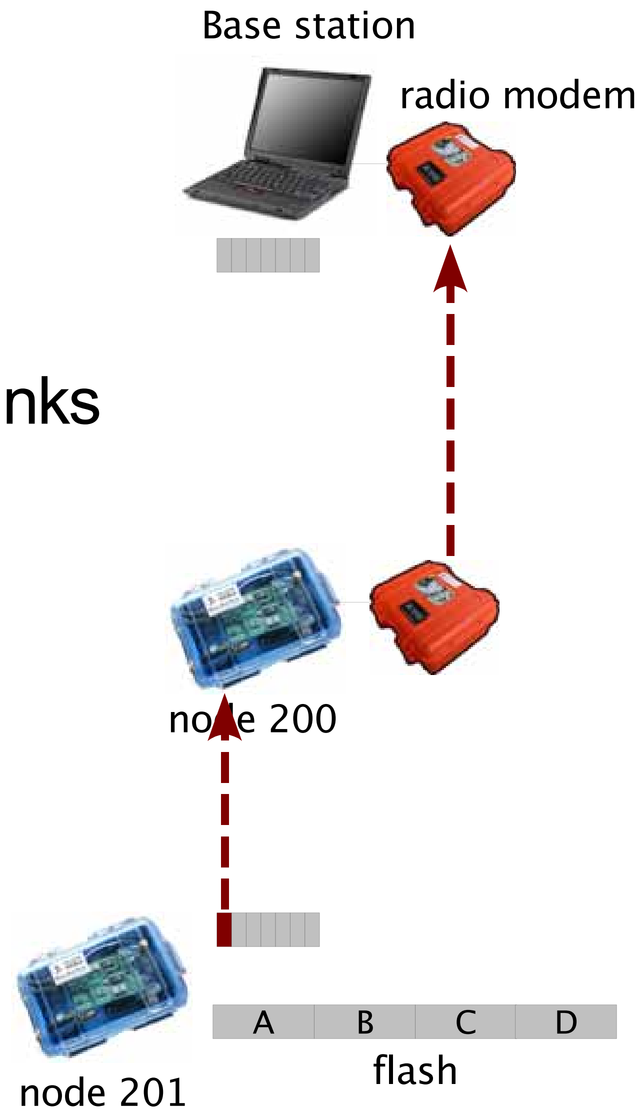
- Route each chunk to base over multihop path



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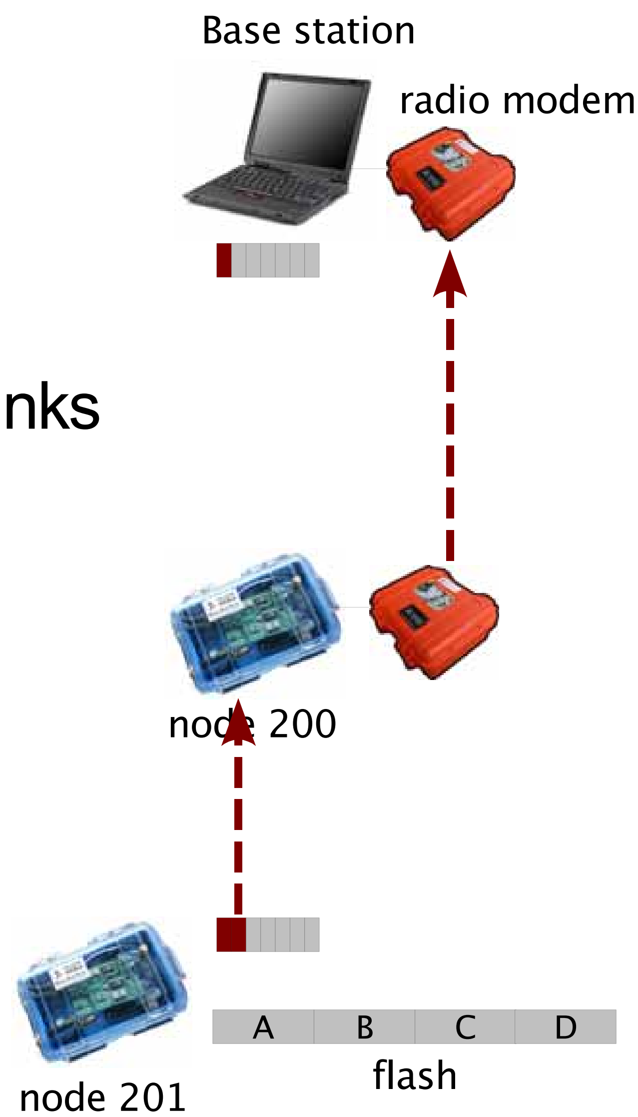

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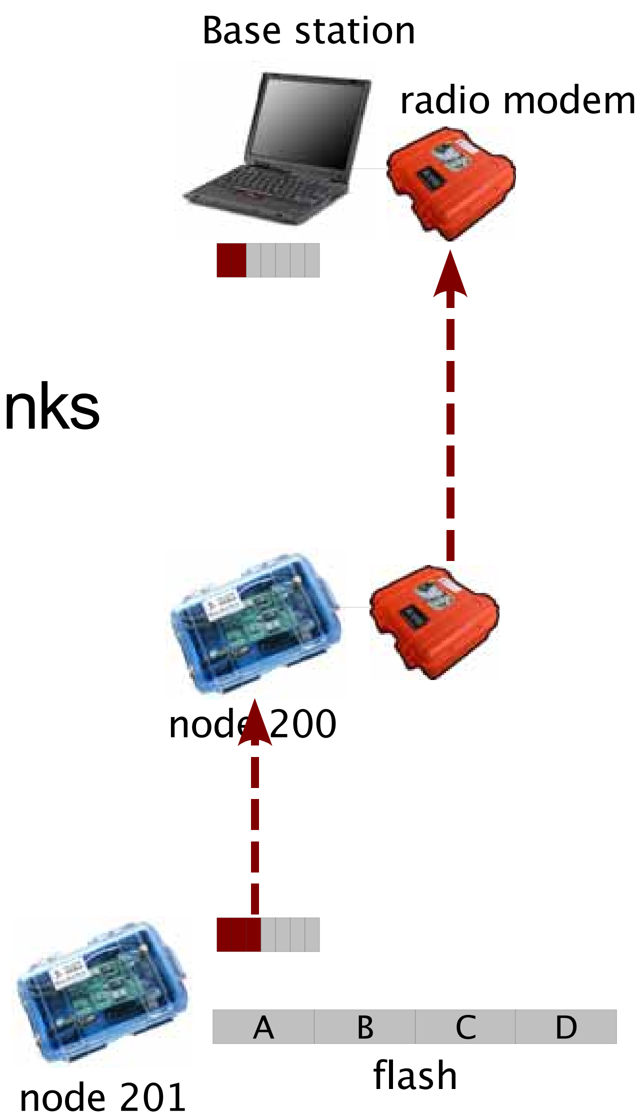

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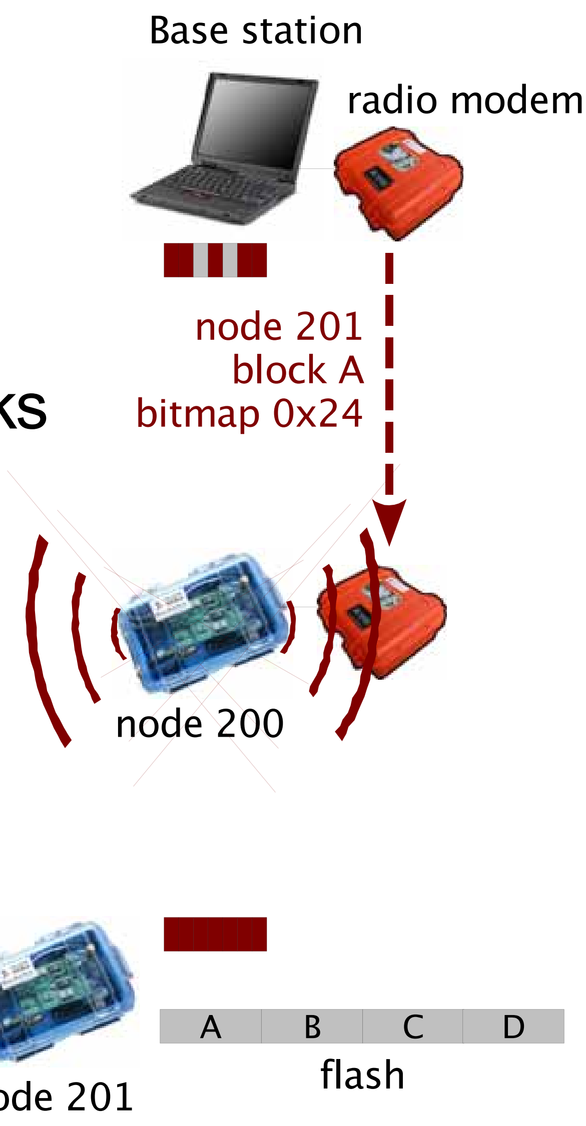
Base requests missing chunks after timeout



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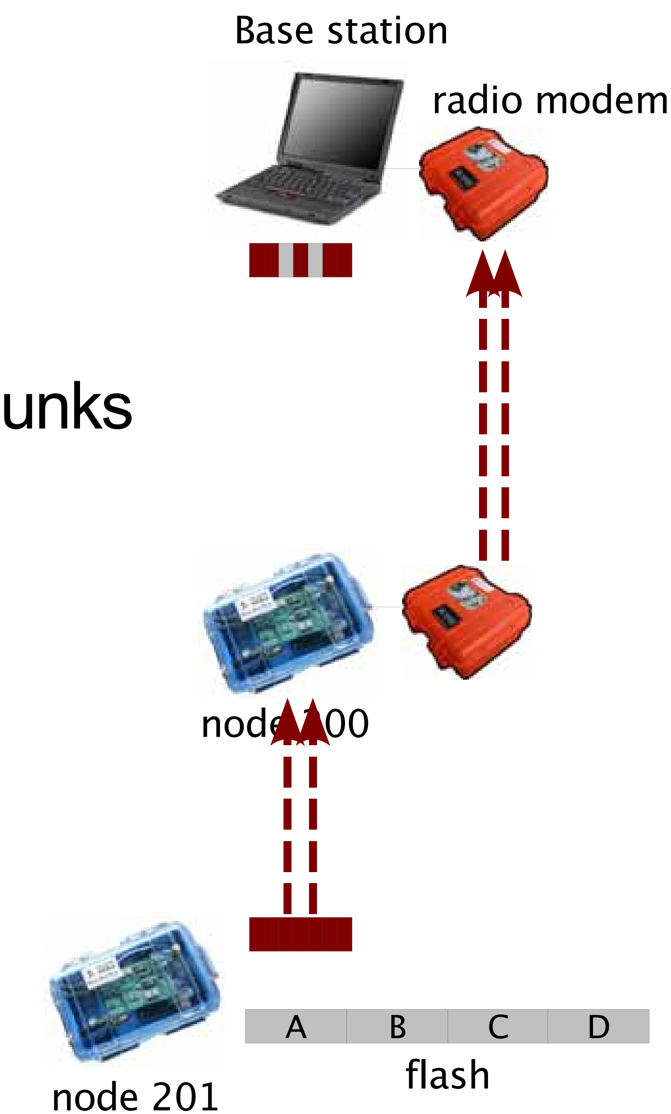
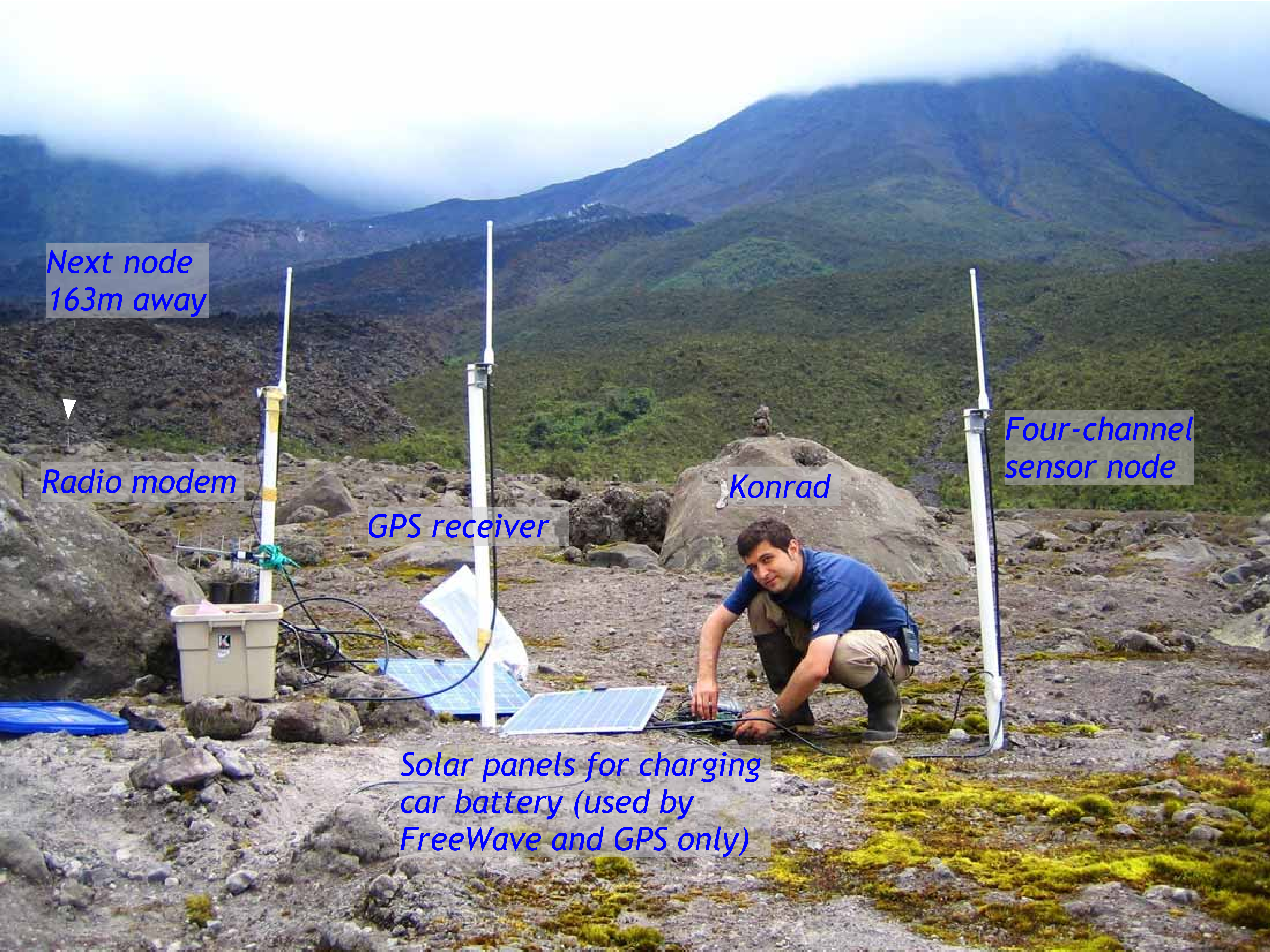
Base requests missing chunks after timeout

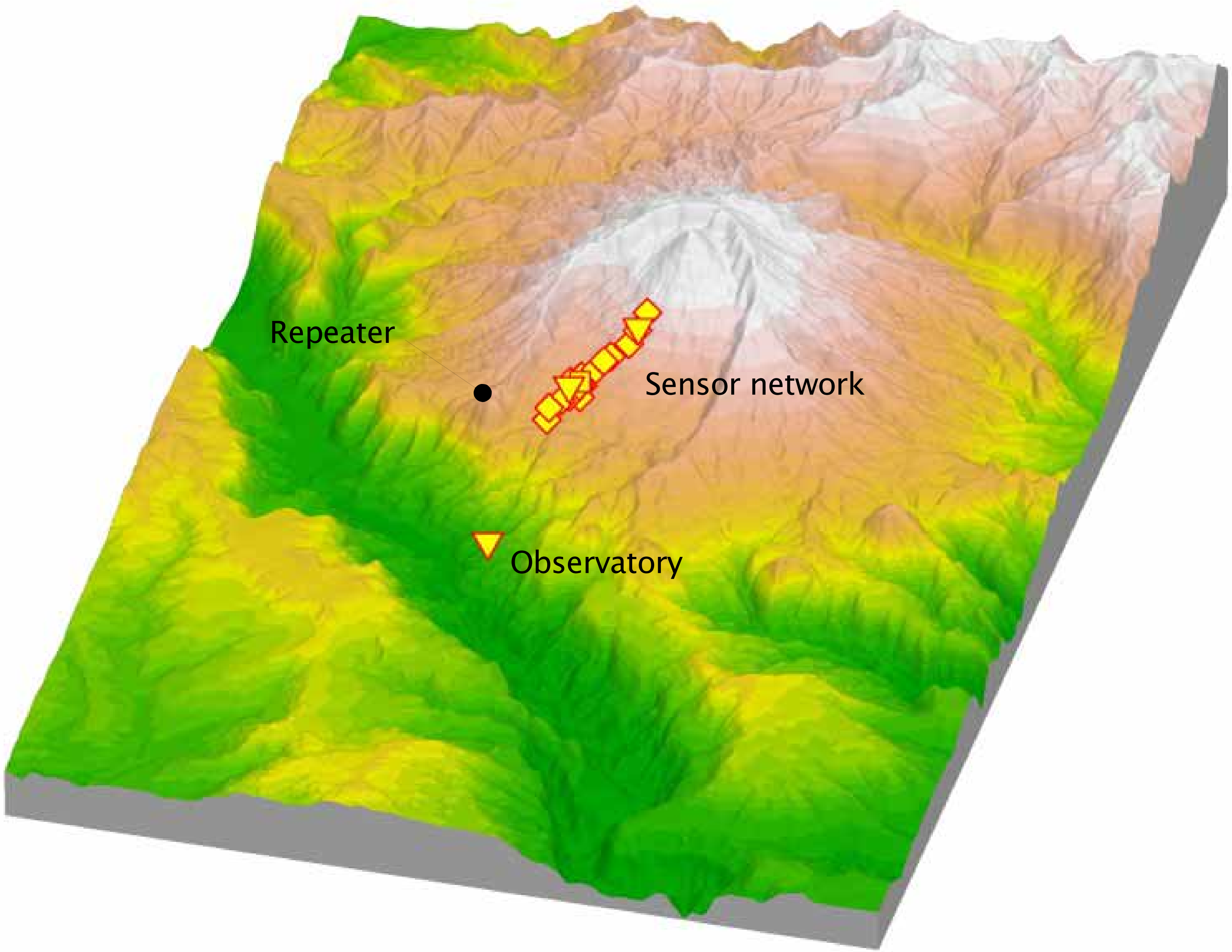
Node responds with missing data



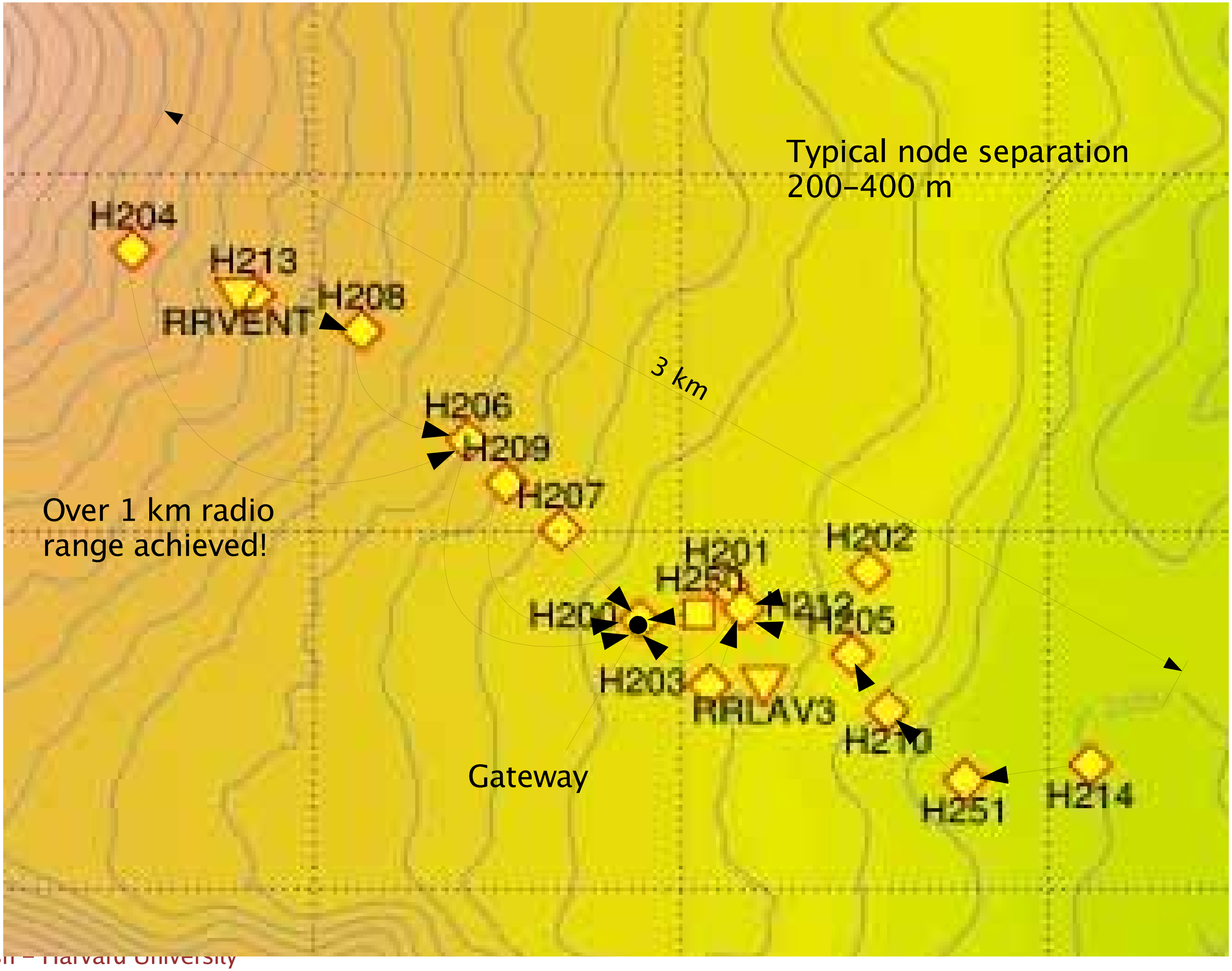


Next node
163m away
Radio modem
GPS receiver
Konrad
Four-channel
sensor node
Solar panels for charging
car battery (used by
FreeWave and GPS only)

Sensor Deployment Map



Network Topology



Event Collection Statistics

During the 19-day deployment...

... 272 events detected

... 230 events scheduled for download

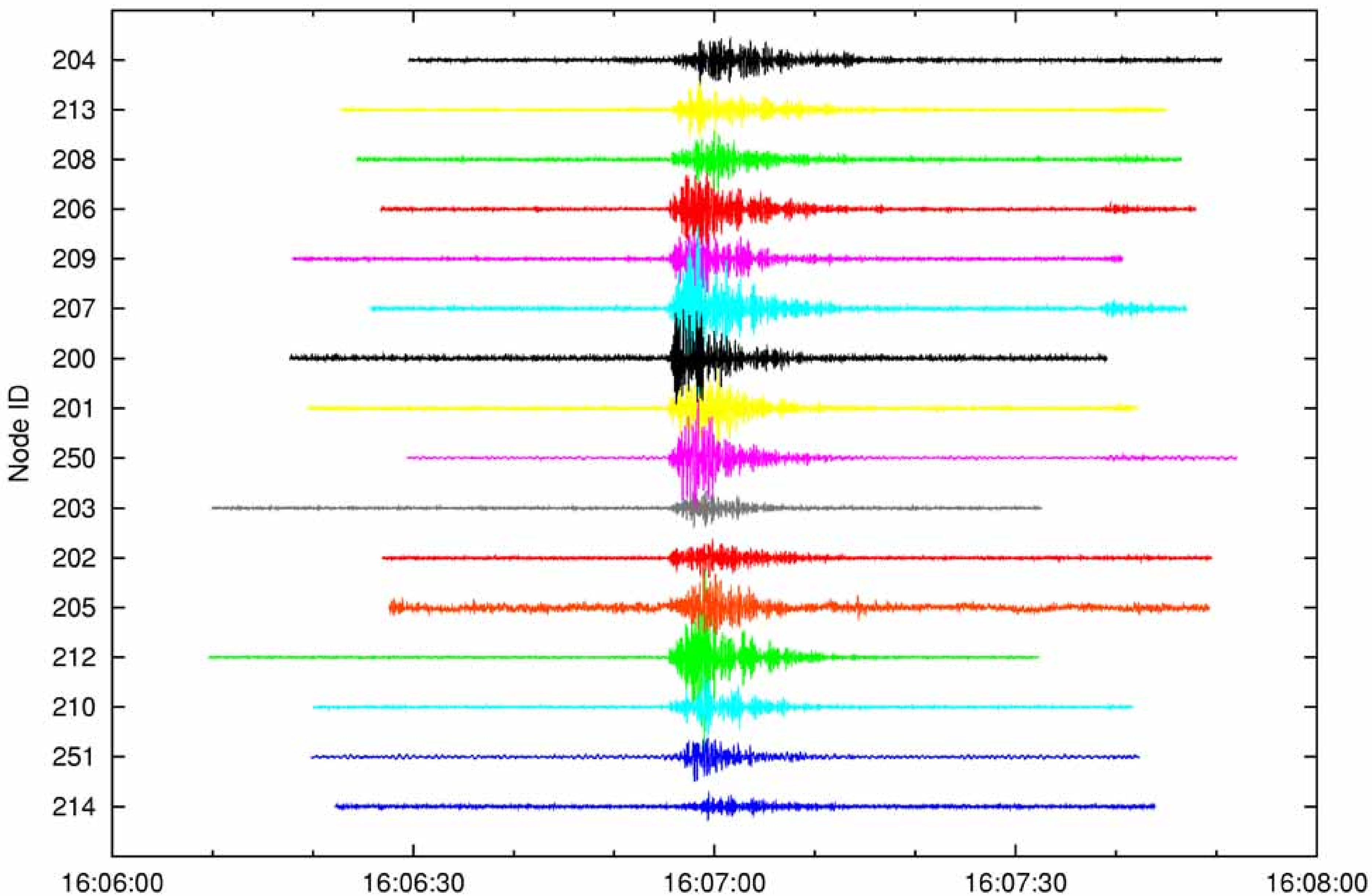
... Average yield of 8 nodes per event (50%)

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

... 226 MBytes of node statistics collected

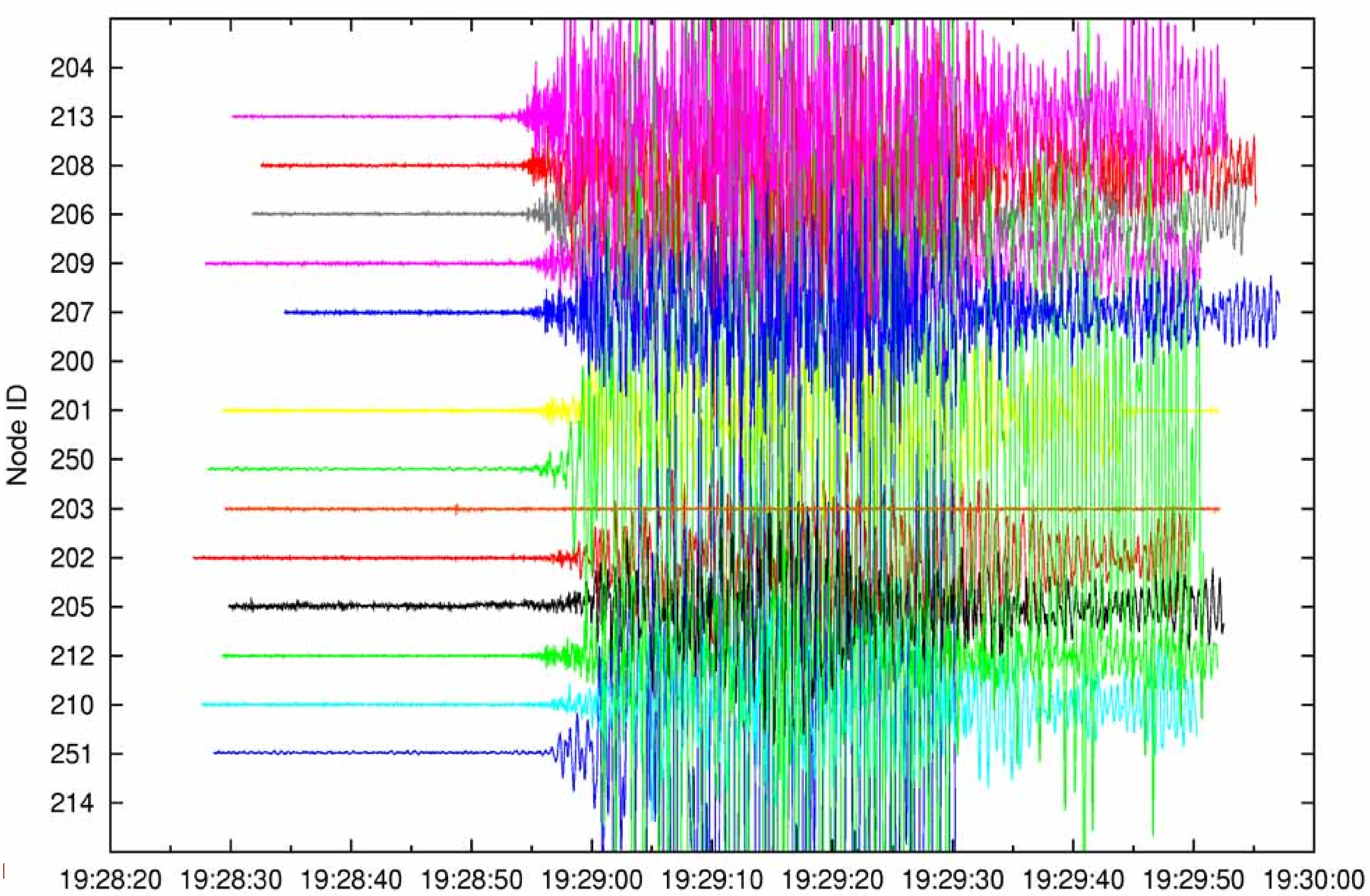
Some Representative Events

Volcano-Tectonic Earthquake

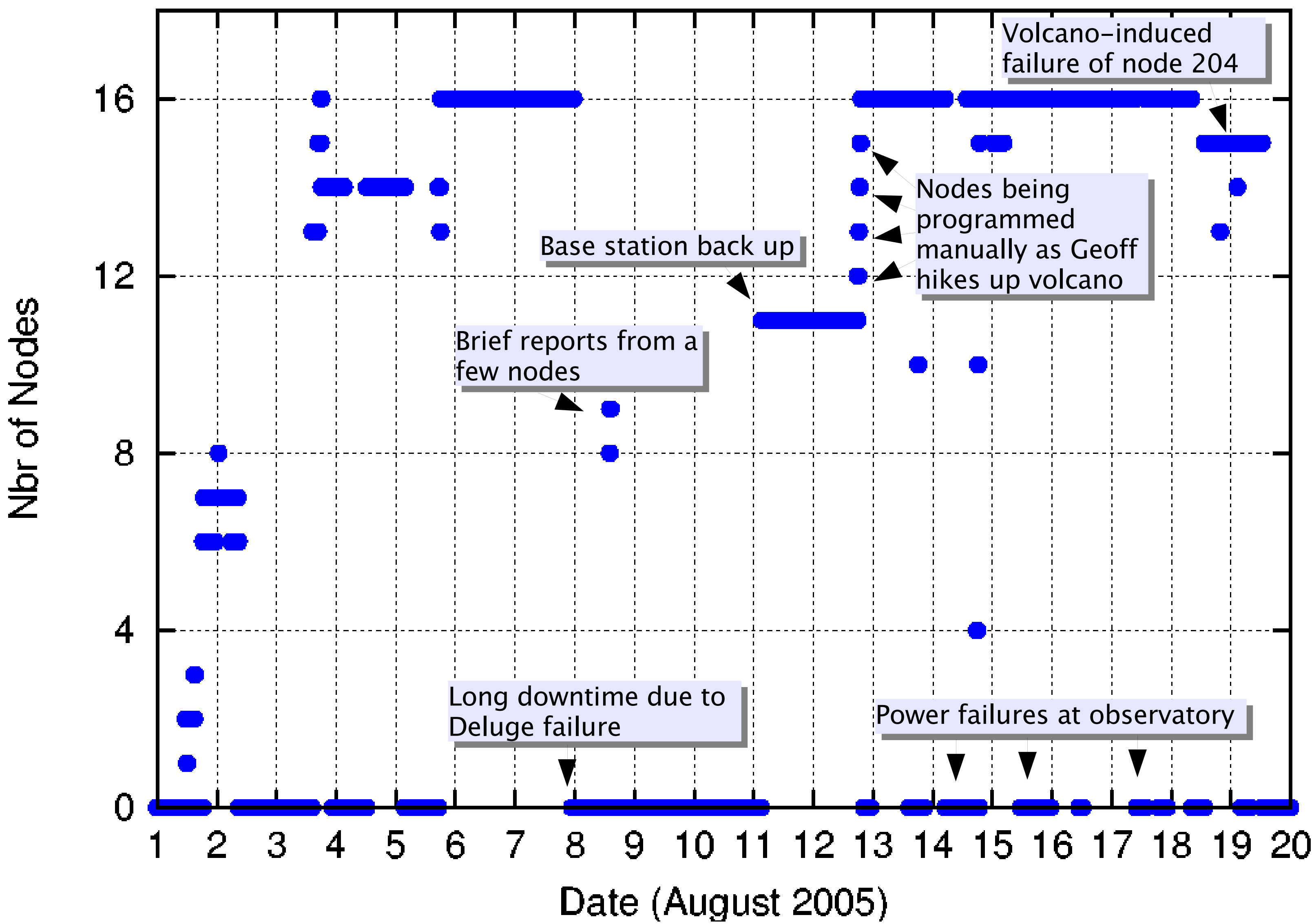


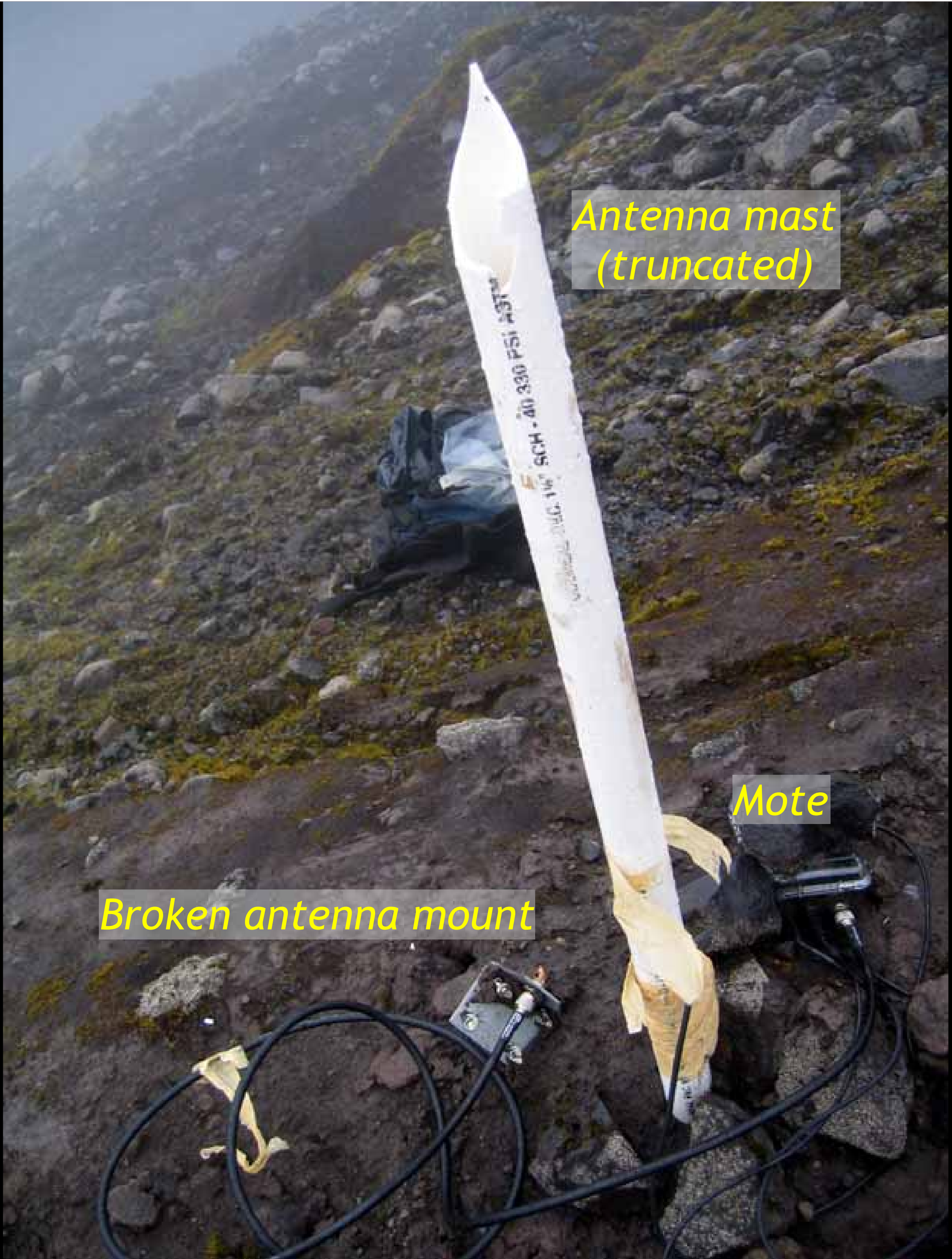
Some Representative Events

Explosion



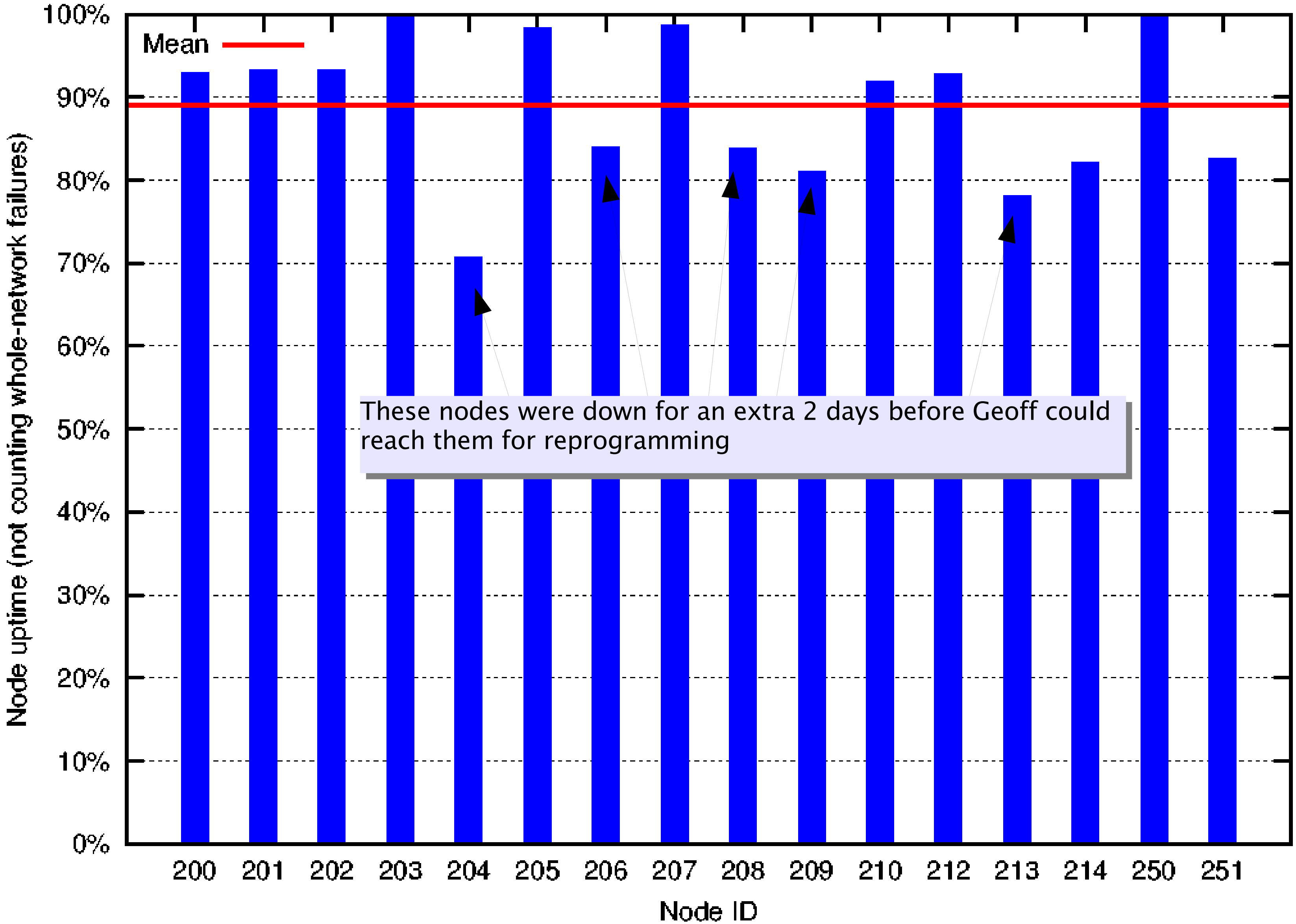
Node Reliability




Antenna mast
(truncated)
Mote
Broken antenna mount

Node reliability by node ID

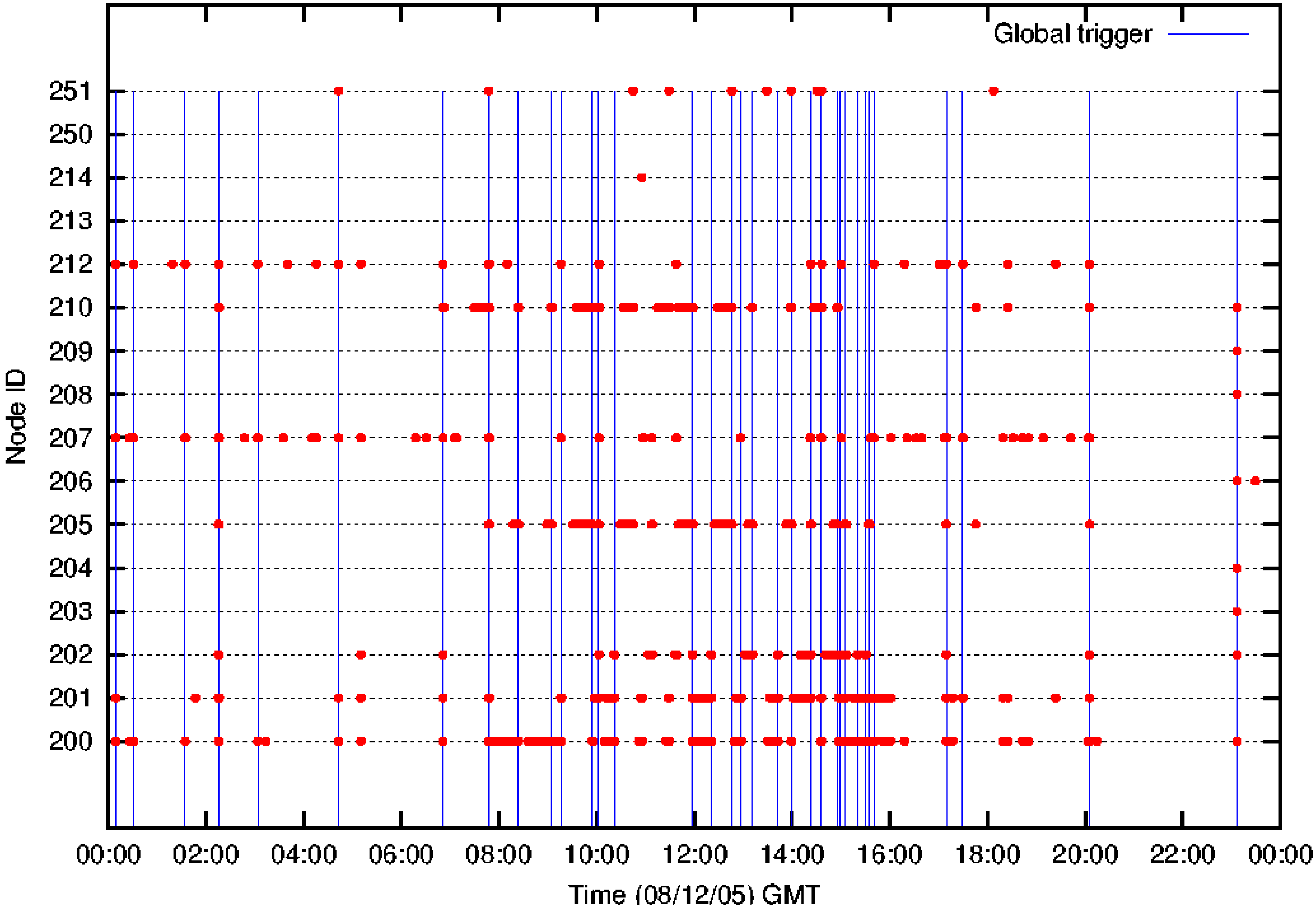
taken over 10-minute intervals



Mean node uptime **89%** (not counting infrastructure outages, 43% of total deployment)

Event Triggers

08/12/05



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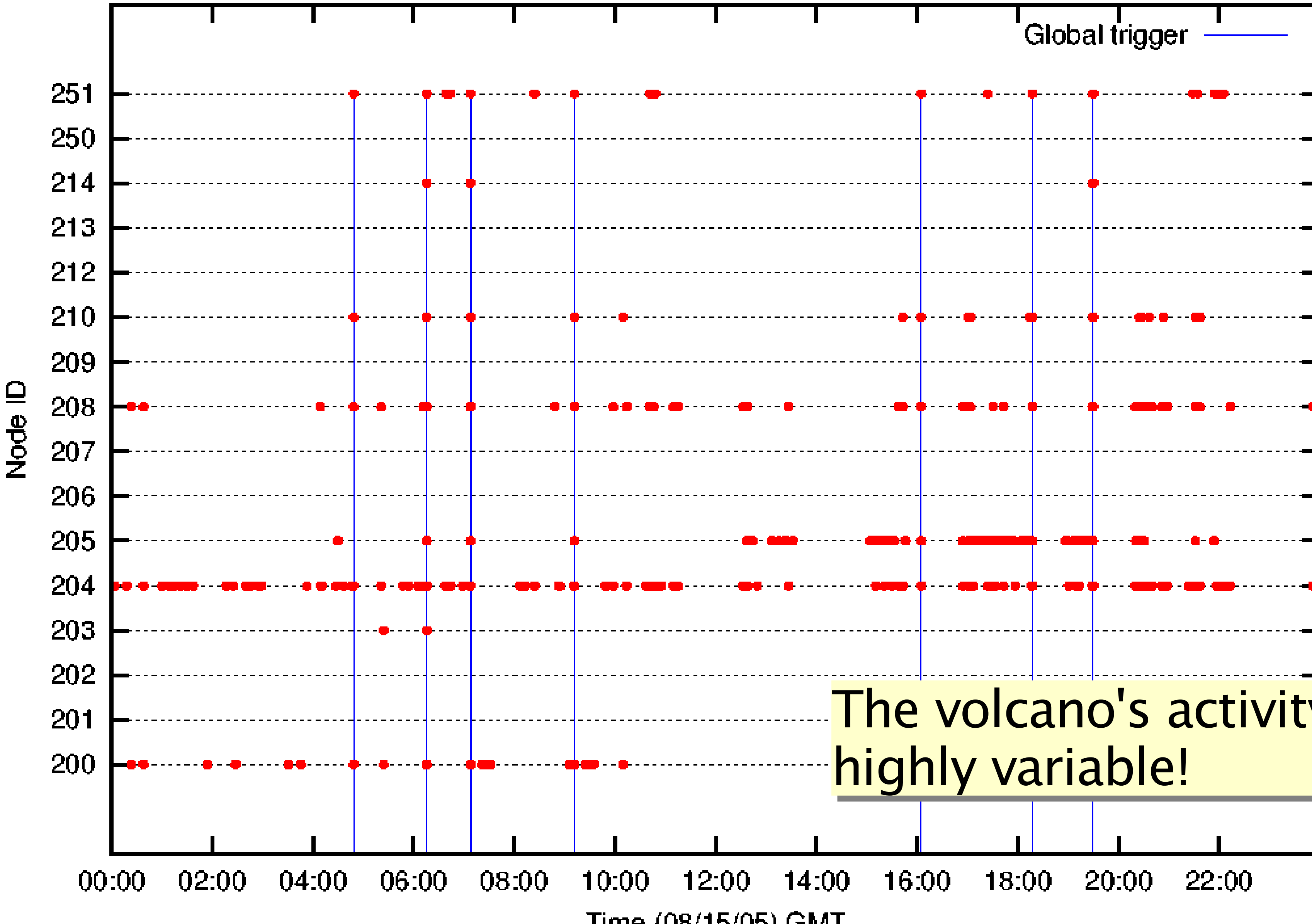
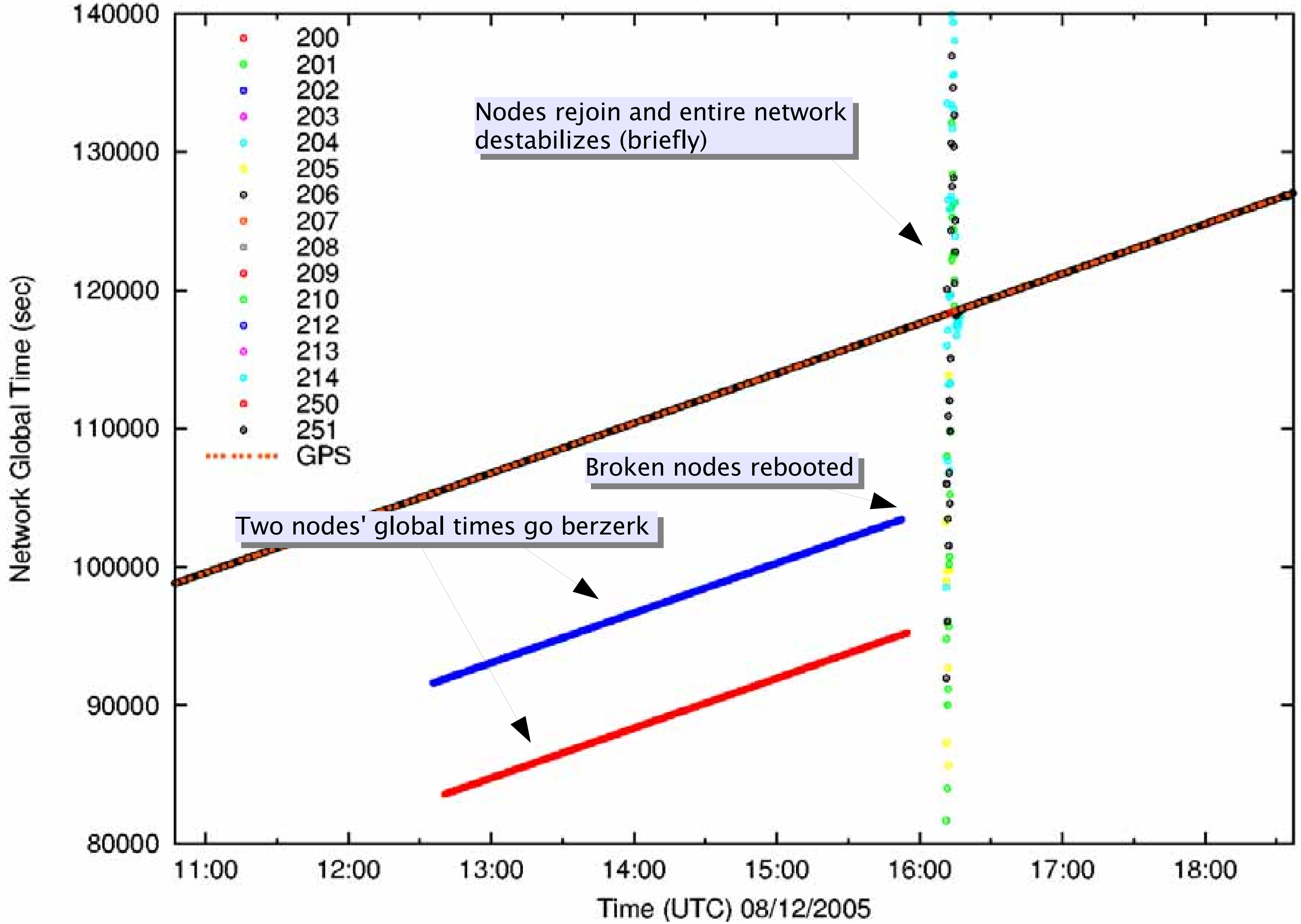
08/15/05



The volcano's activity is highly variable!

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

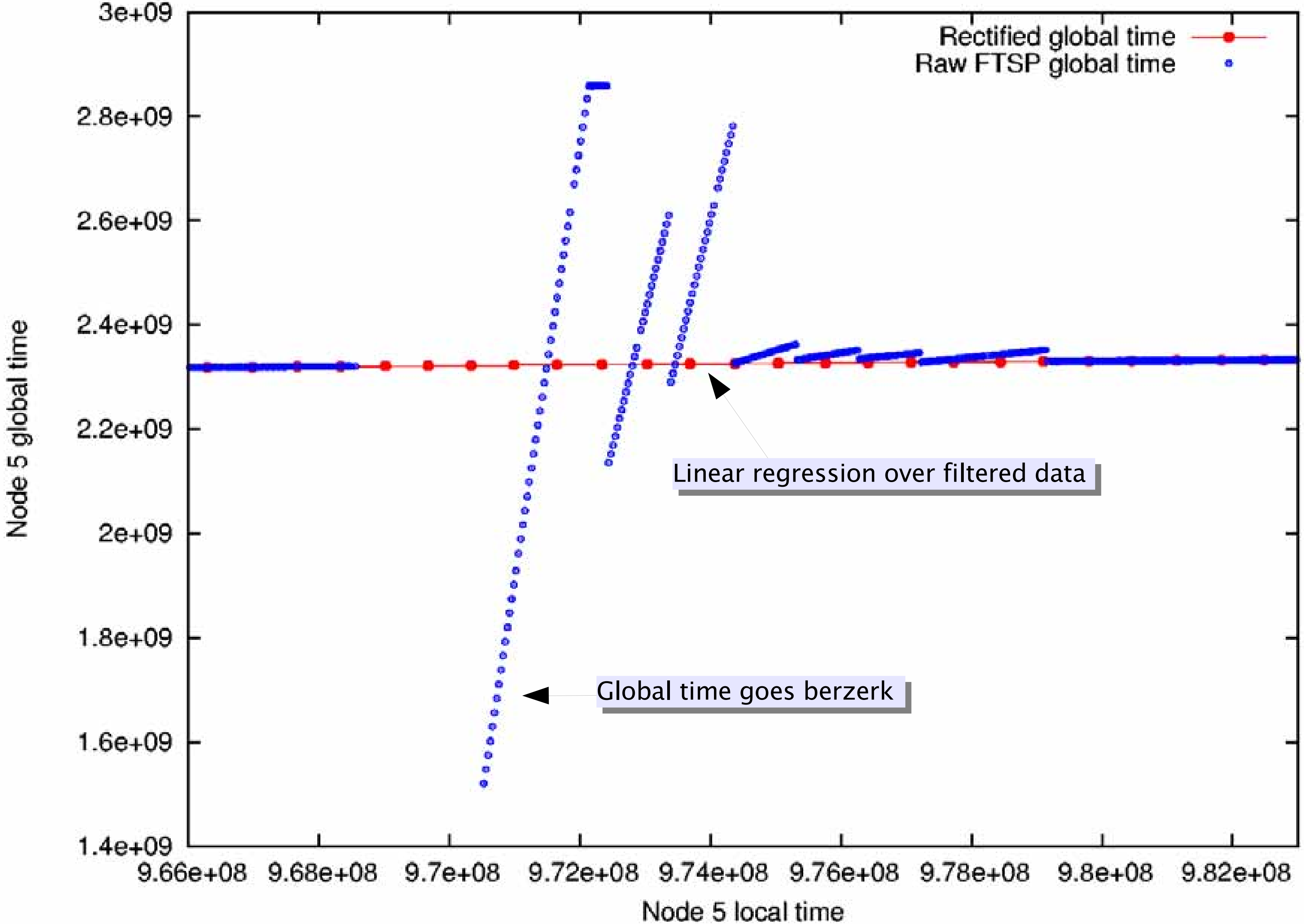
- e.g., Those that differ significantly from global time recorded by FTSP root
- Threshold used: 1 sec.

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



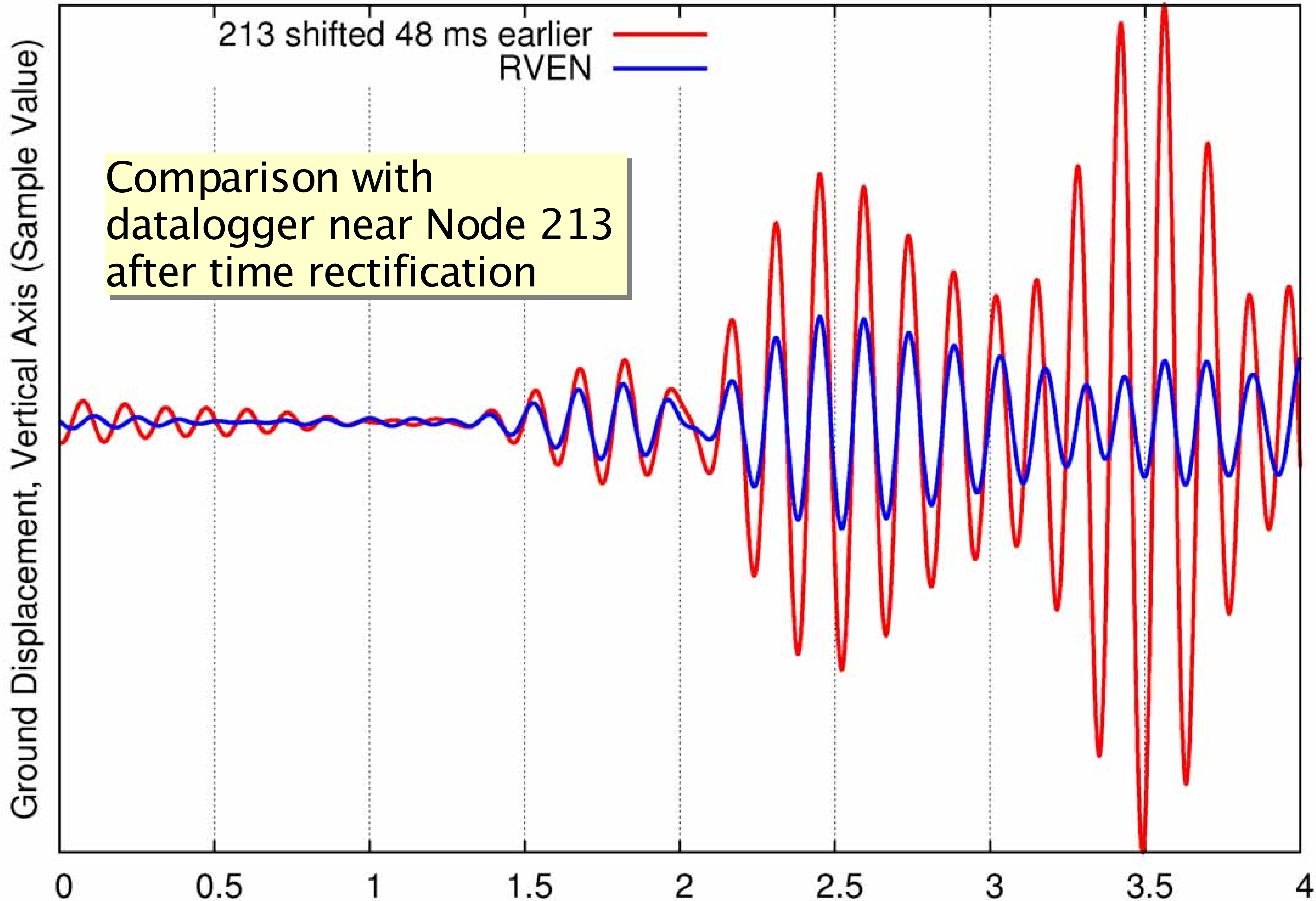
How do we know if we got the timing right?

Compare data captured by our mote to a datalogger nearby:

Node 213
(3 hops from FTSP root)

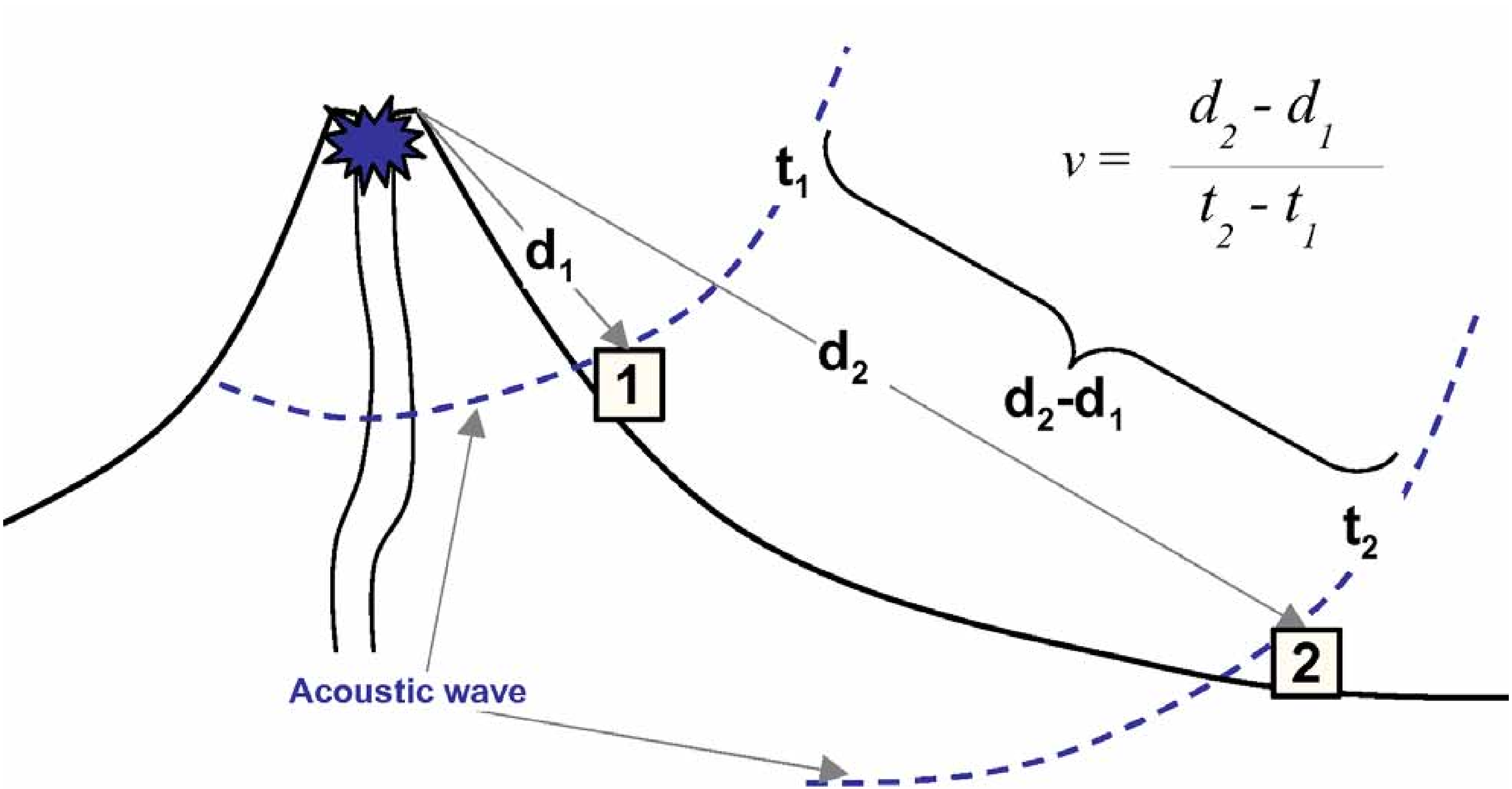
◄——— ~50 meters ———►

Reventador vent
(RVEN) station


213 shifted 48 ms earlier
RVEN
Comparison with datalogger near Node 213 after time rectification
Ground Displacement, Vertical Axis (Sample Value)
0
0.5
1
1.5
2
2.5
3
3.5
4

Data validation: Acoustic wave traversal

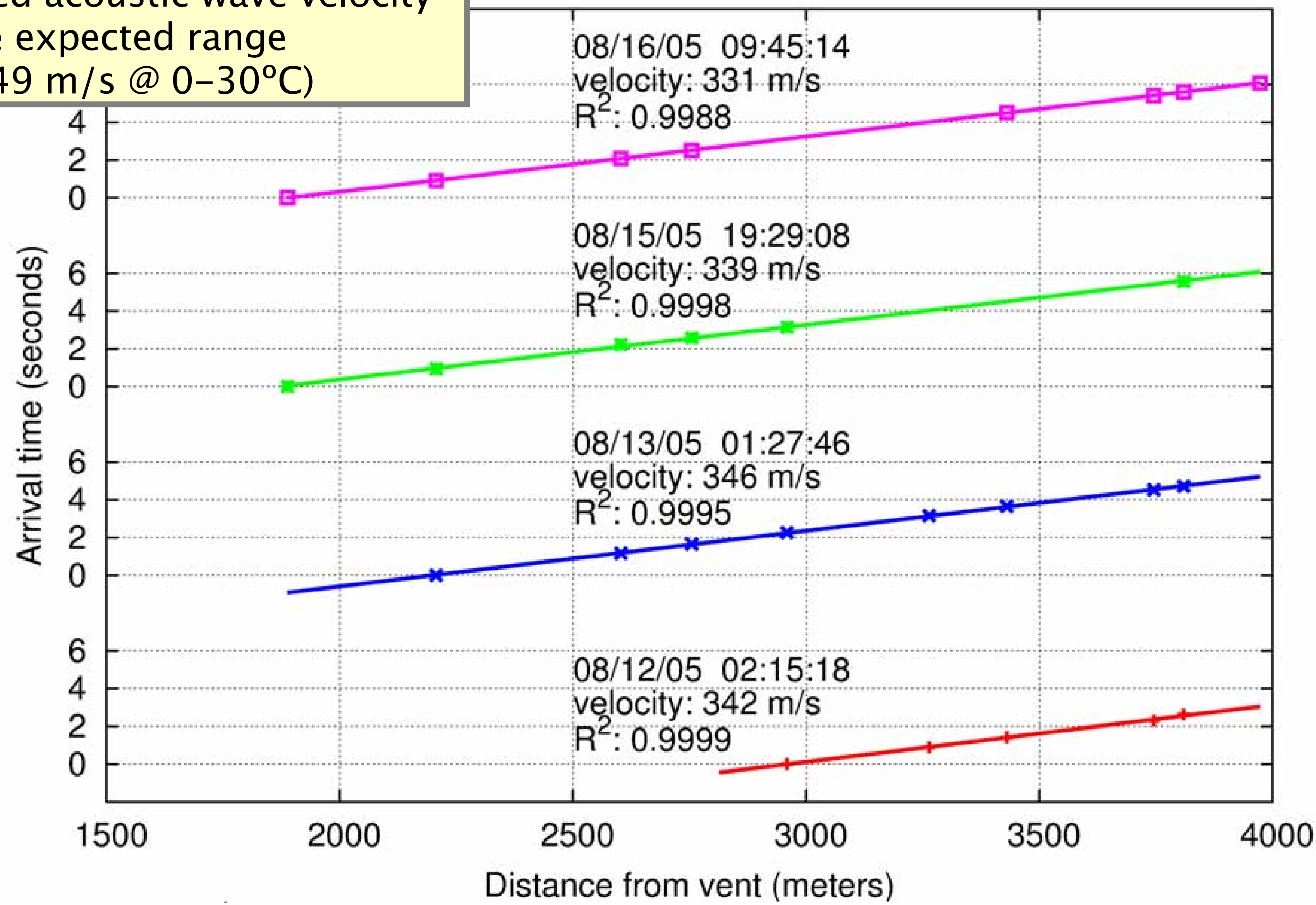
Check the speed of acoustic waves propagating across the array!



$$v = \frac{d_2 - d_1}{t_2 - t_1}$$

Data validation: Acoustic wave traversal

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

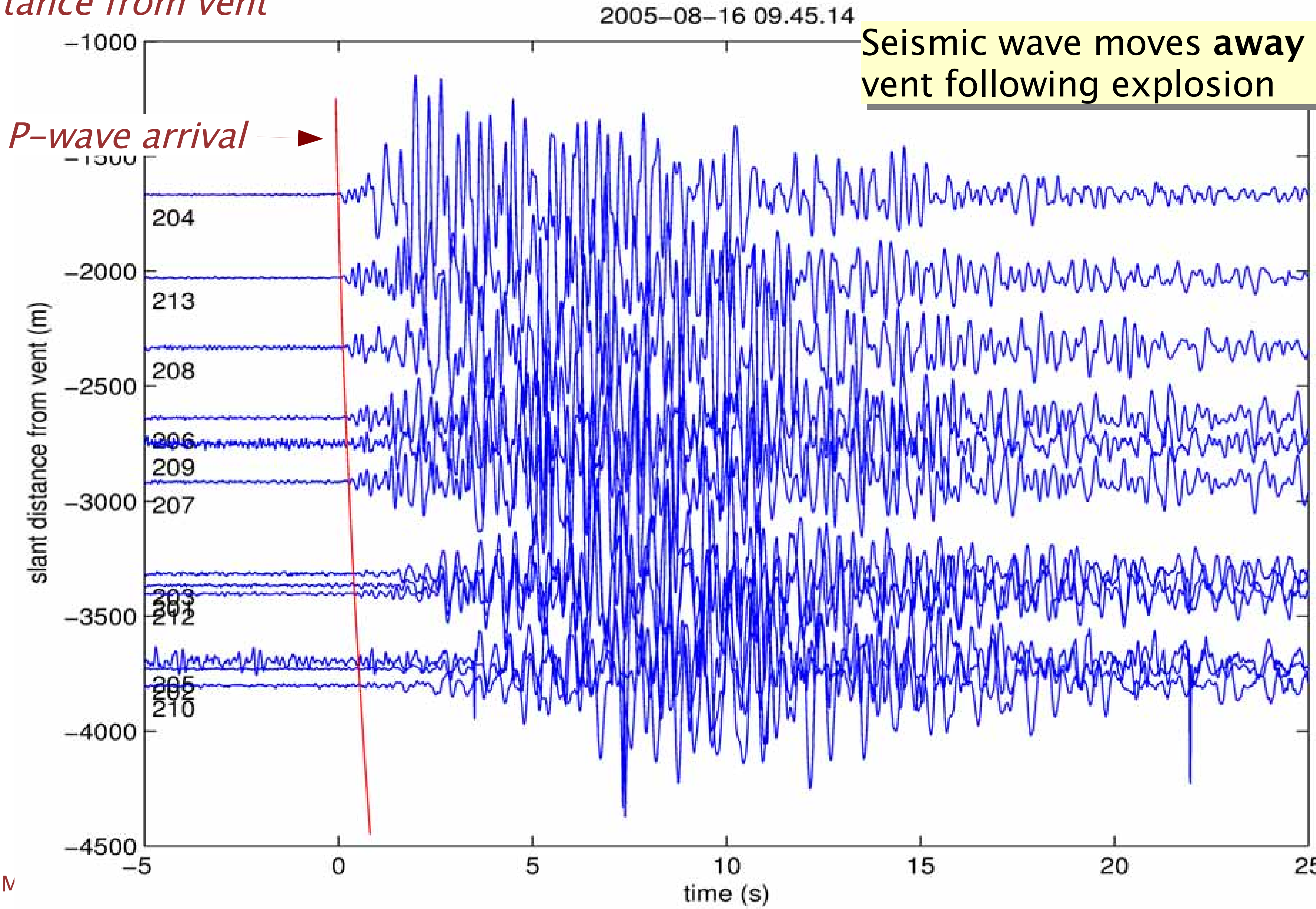


Data validation: Seismic wave traversal

Distance from vent

P-wave arrival

Seismic wave moves **away** from vent following explosion



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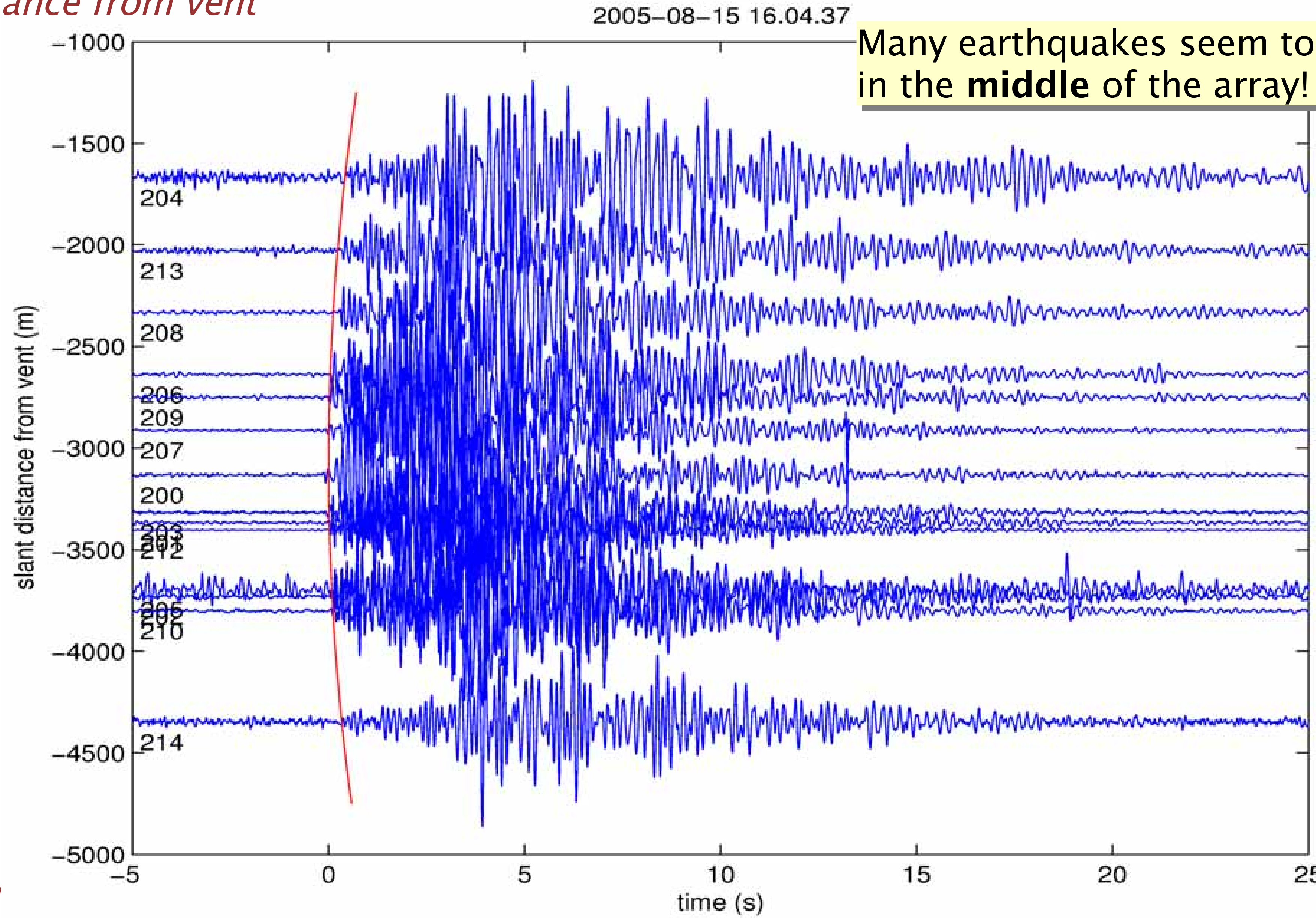
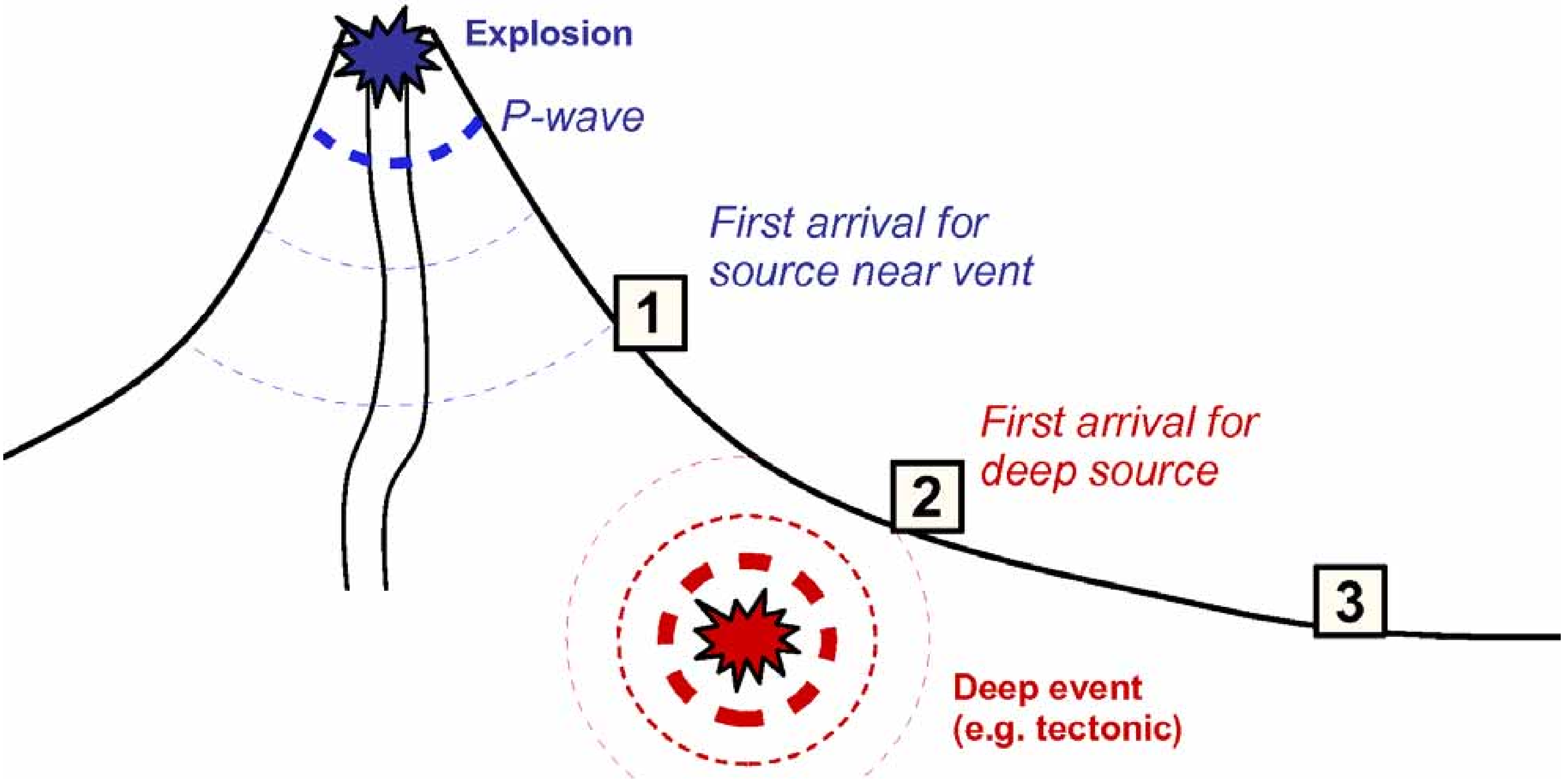
Distance from vent



Many earthquakes seem to start in the **middle** of the array!

What's going on here?

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



What did we learn?

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

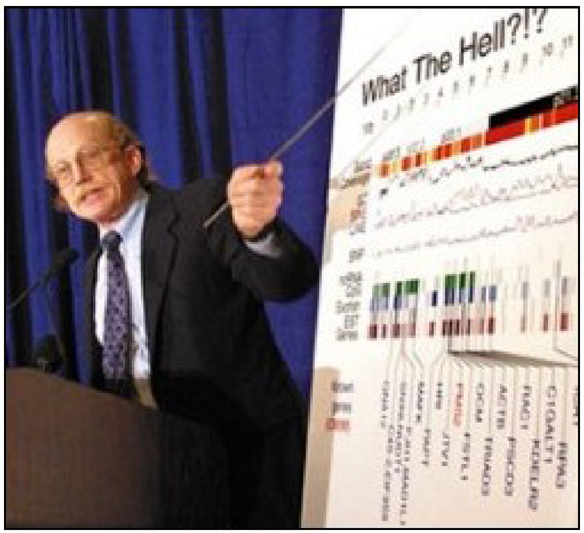
- We did not build in enough cross-checking for things like FTSP errors
- Did not colocate enough motes with broadband stations for later verification

the ONION

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

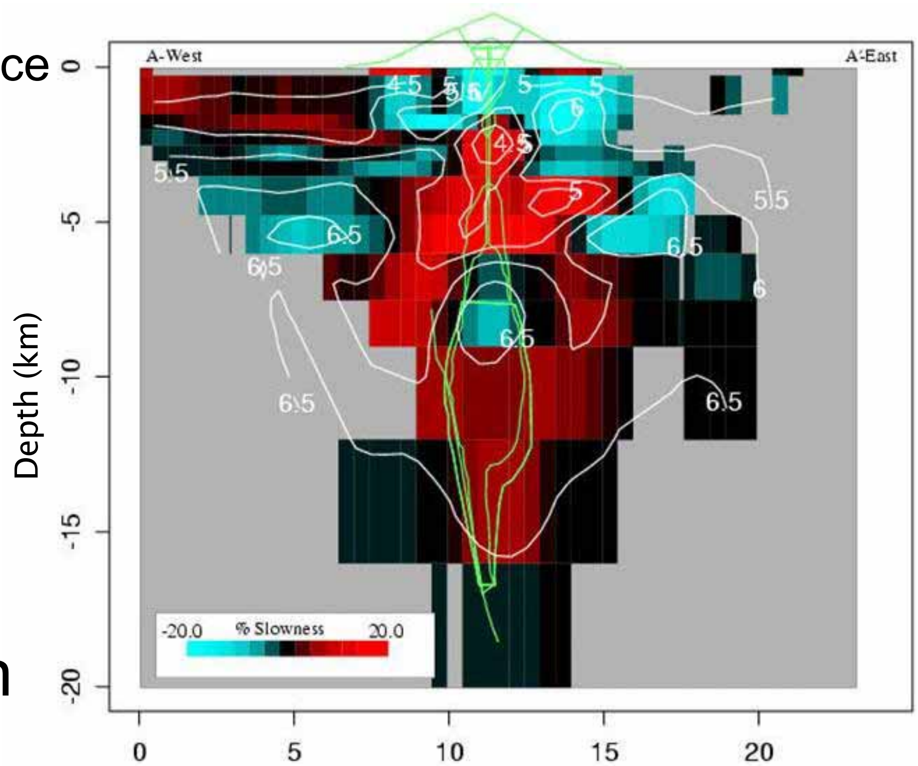
Earthquake localization

- 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)

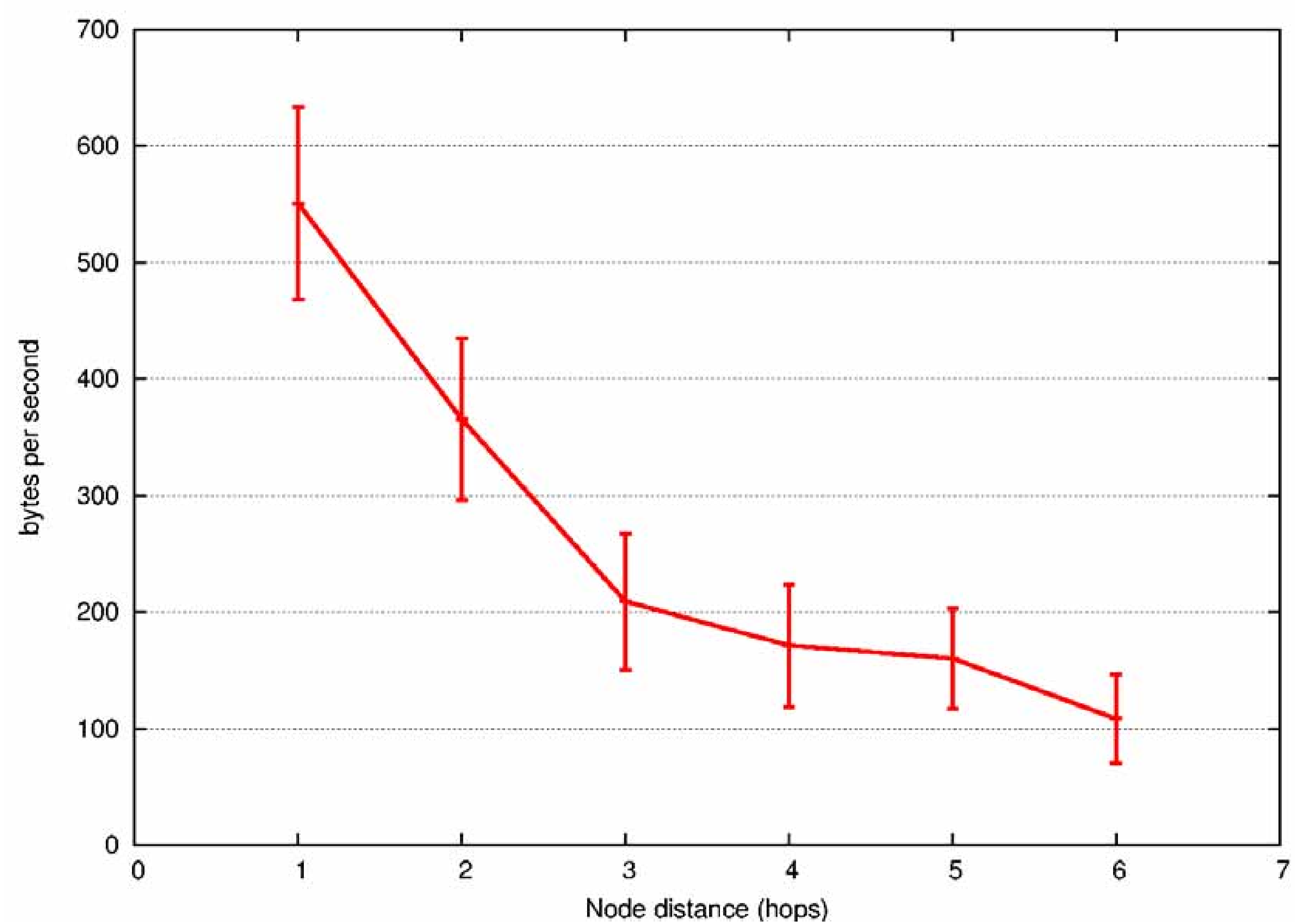
Exciting opportunity: Source localization and tomography in ***real time***



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

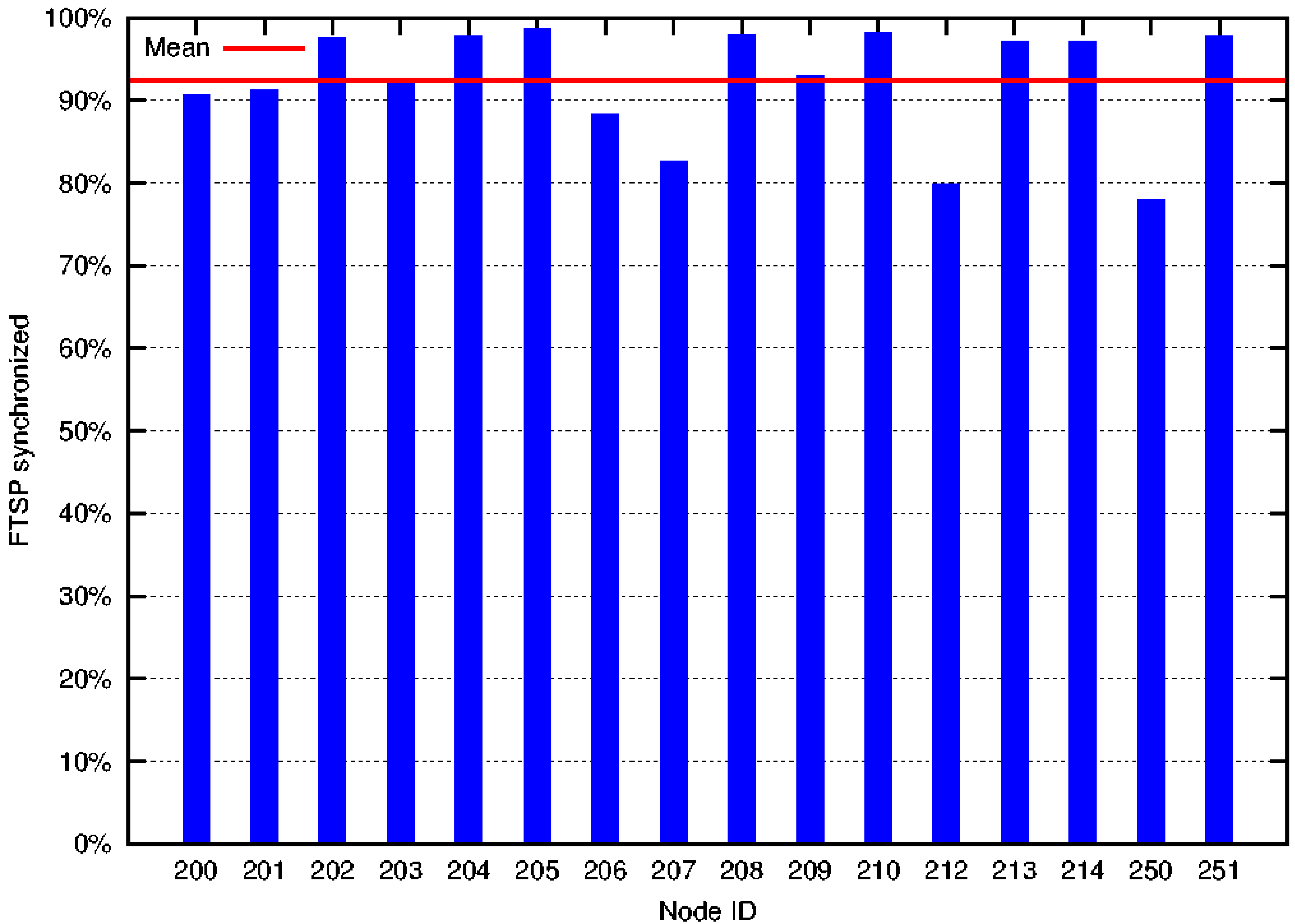

Thank you!
http://www.eecs.harvard.edu/~mdw/proj/volcano

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

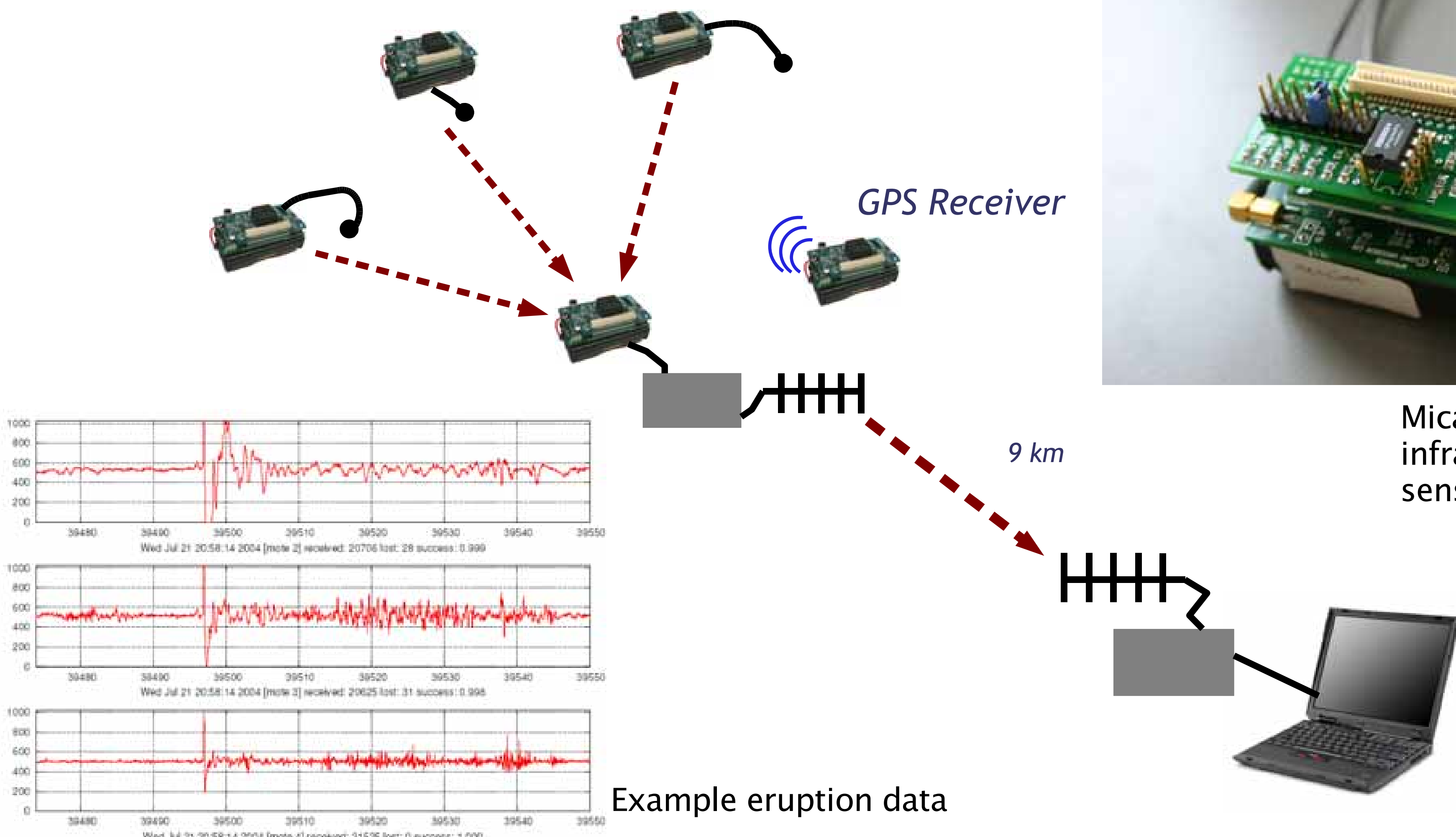
Pelican weatherproof case

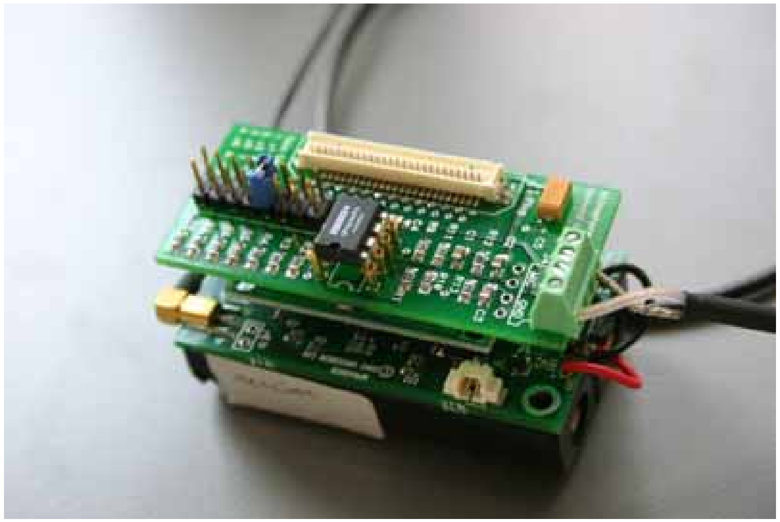
- External environmental connectors to sensors

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