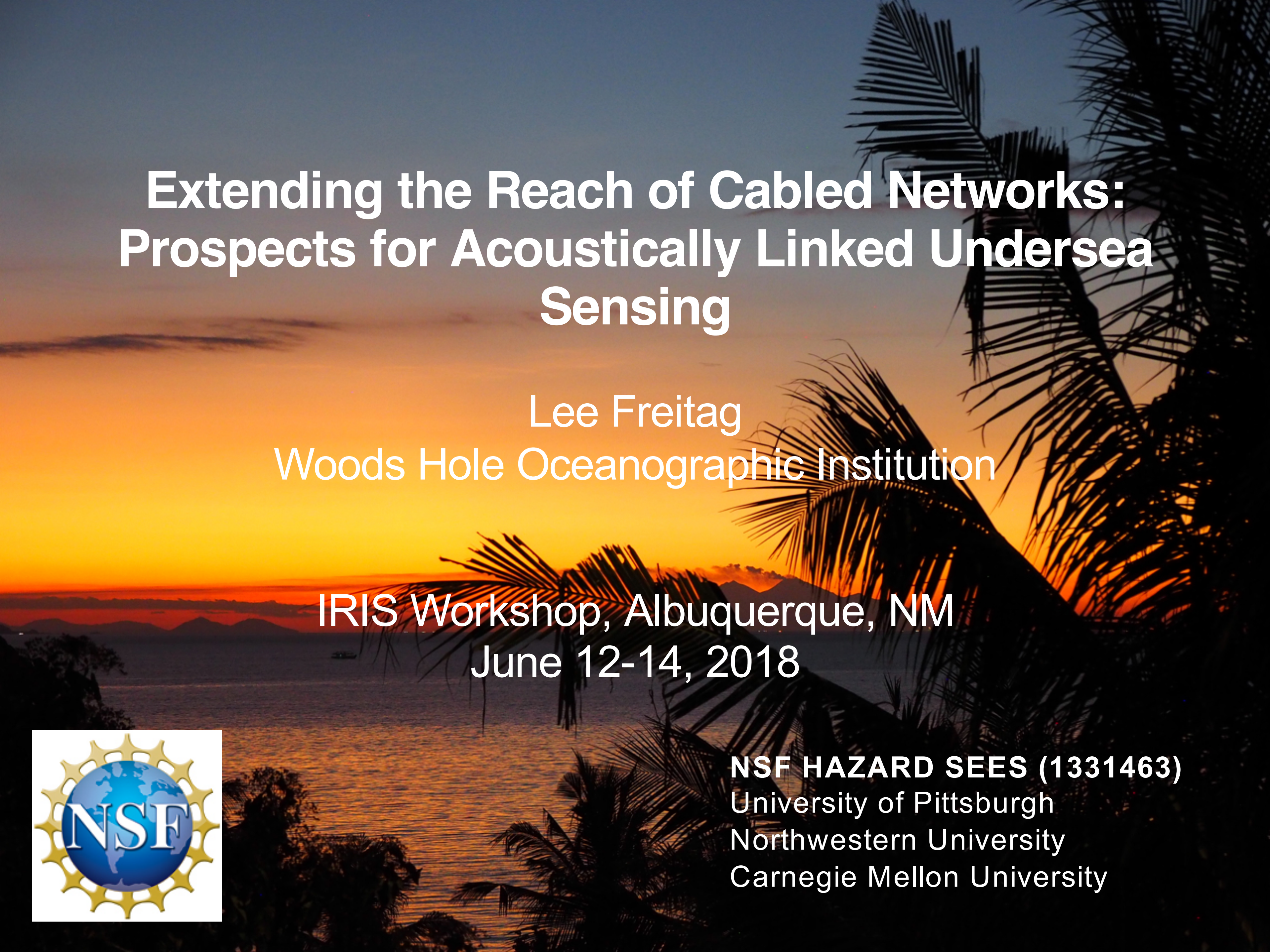


Extending the Reach of Cabled Networks: Prospects for Acoustically Linked Undersea Sensing

Lee Freitag
Woods Hole Oceanographic Institution

IRIS Workshop, Albuquerque, NM
June 12-14, 2018

NSF HAZARD SEES (1331463)
University of Pittsburgh
Northwestern University
Carnegie Mellon University

Wireless Undersea Sensing

Topics

1. Motivation for wireless
2. Other methods:
    - Buoys
    - Wave Glider
3. Observatory extensions
4. Proposed system for Indonesia
5. Field testing in Indonesia
6. Next steps and discussion

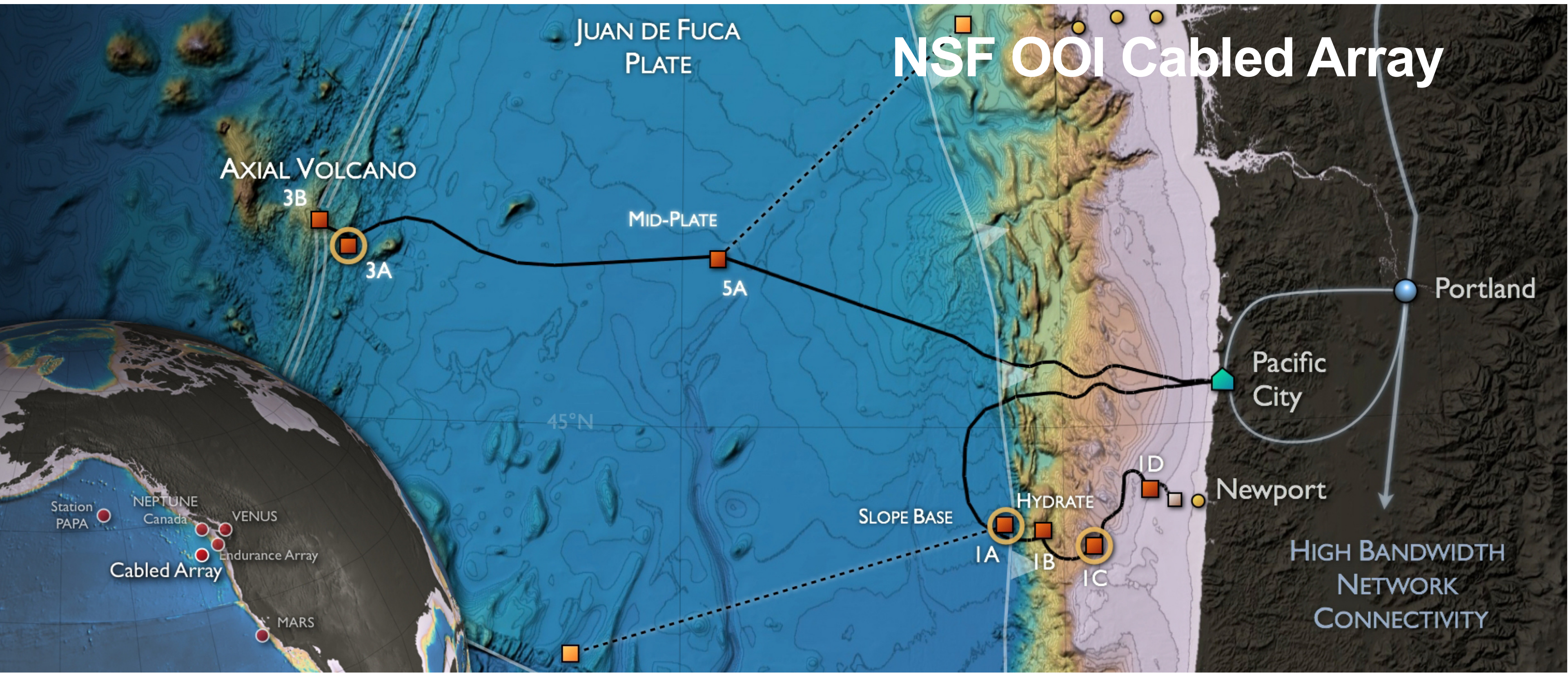
The work was funded by the National Science Foundation HAZARD SEES program as part of the project "Hazards SEES Type 2: From Sensors to Tweeters: A Sustainable Sociotechnical Approach for Detecting, Mitigating, and Building Resilience to Hazards" (Grant 1331463).

PI: Louise Comfort, *University of Pittsburgh*.

Seismologist: Emile Okal, *Northwestern University*

With additional material from two other NSF funded projects: acoustically-linked buoy observatory (2002-2006), and acoustic link for MARS observatory project (2004-2008).

NSF OOI Cabled Array



Motivation for Acoustic Connections:

- Leverage the investment in cables and seafloor nodes.
- Add new sensors without need for ROV operations.
- Extend reach at scales of several to tens of kilometers.

Obvious Limitations:

- Lower bandwidth.
- May require local clock.
- Cost is in energy (bits transmitted per Joule), longer range means lower efficiency.

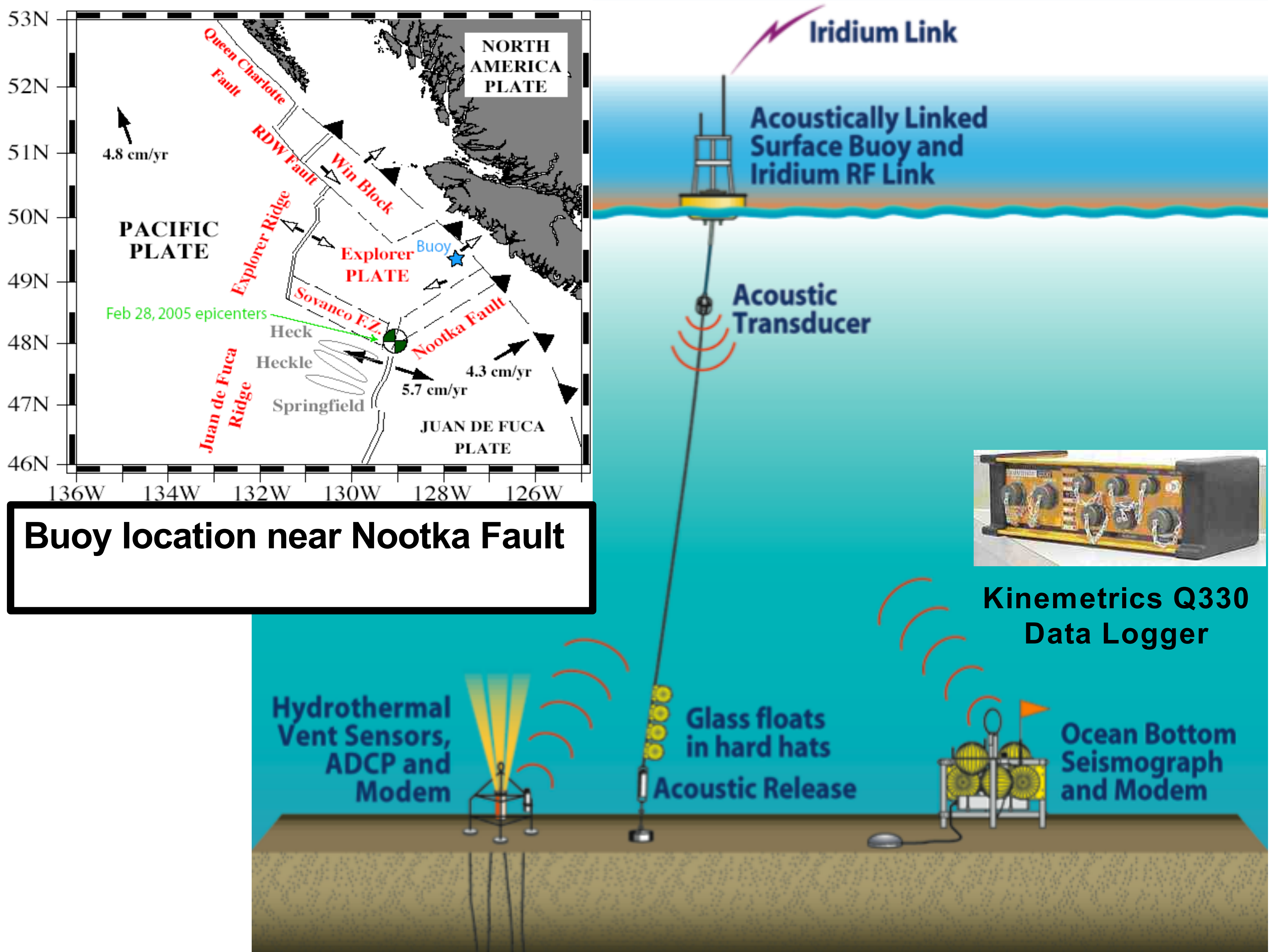
Advantages: increased sensor density, real-time data recovery.

Previous Work:

An Acoustically-Linked Deep-Ocean Observatory

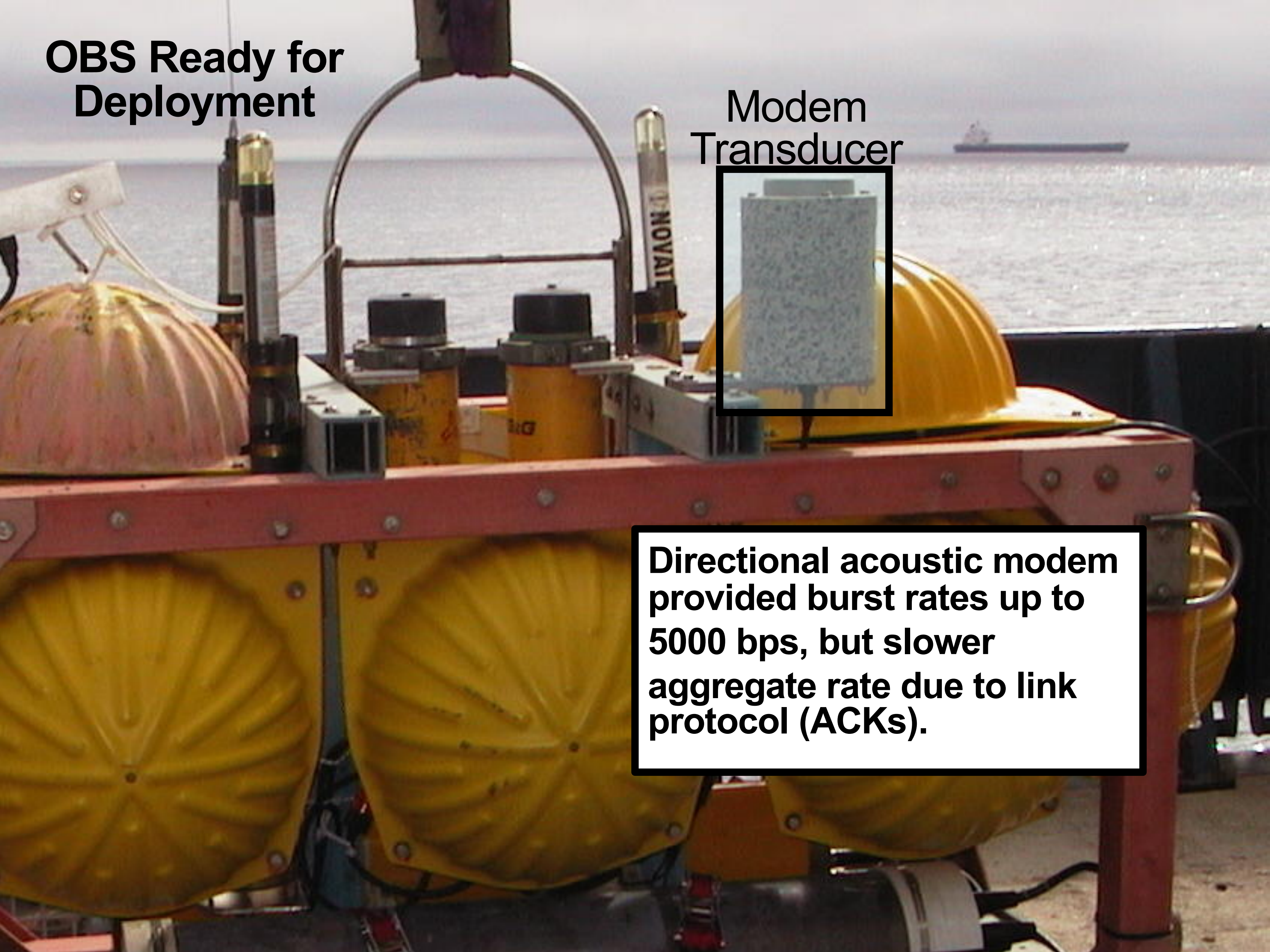
Woods Hole Oceanographic Institution

Additional sensors from APL-UW and SIO.



Buoy location near Nootka Fault

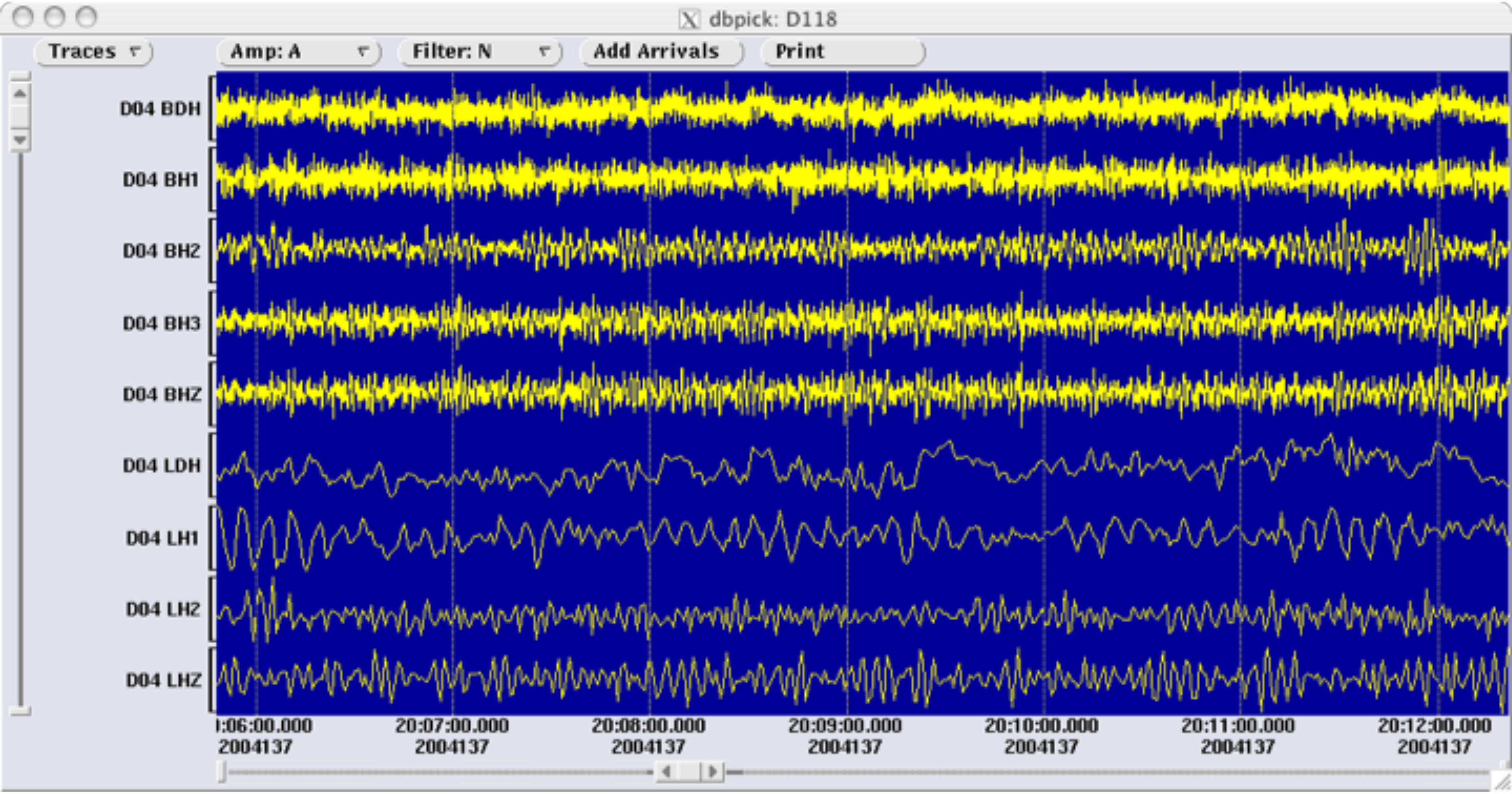
OBS Ready for Deployment



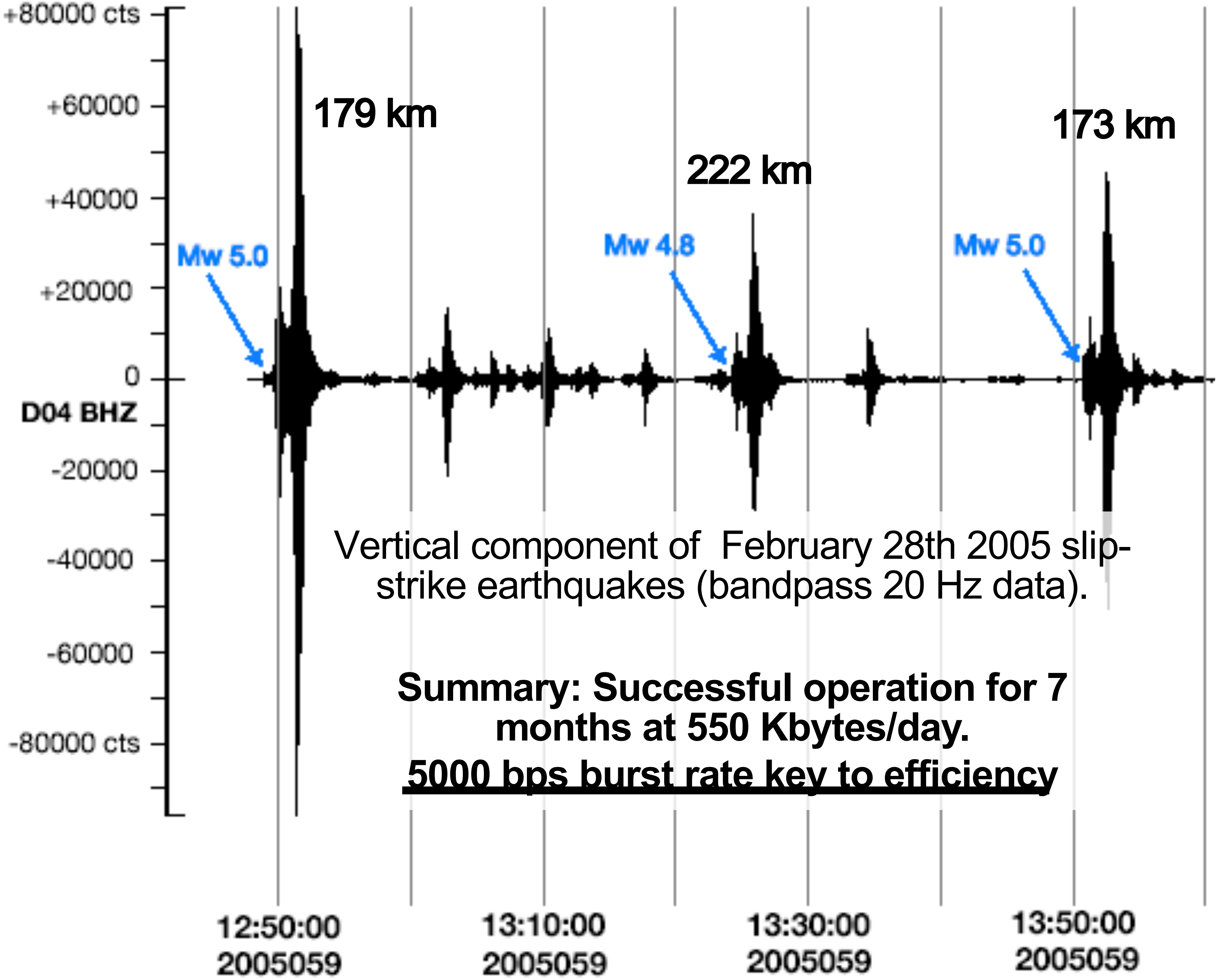
Modem Transducer

Directional acoustic modem provided burst rates up to 5000 bps, but slower aggregate rate due to link protocol (ACKs).

OBS Data Uploaded via Acoustic Link



BDH: 20 Hz Pressure, BH1/2/Z: 20 Hz Seismometer,
BH3: 40 Hz Vertical, LDH: 1 Hz Pressure (DPG),
LH1/2/Z 1 Hz Seismometer



Vertical component of February 28th 2005 slip-strike earthquakes (bandpass 20 Hz data).

Summary: Successful operation for 7 months at 550 Kbytes/day.

5000 bps burst rate key to efficiency

So what happened to the buoy-based acoustic observatory?

Two advancements:

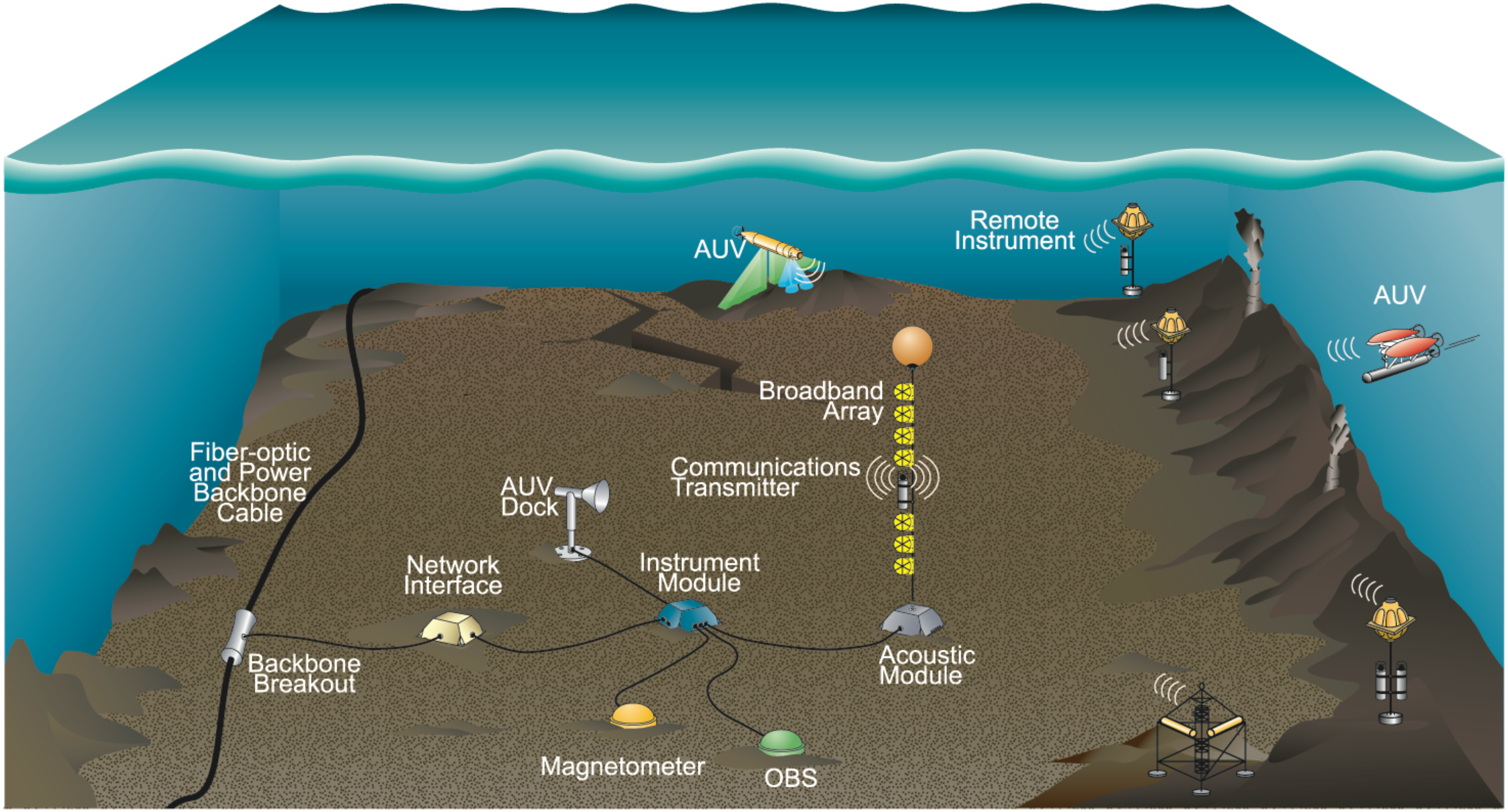
- Cabled observatories (MARS, then OOI)
- Liquid Robotics Wave Glider

Note: DART buoy is an operational example of a buoy-based seafloor system – and doing well (except in Indonesia).

Fixed Sea-Floor Network: Regional Cabled Observatory

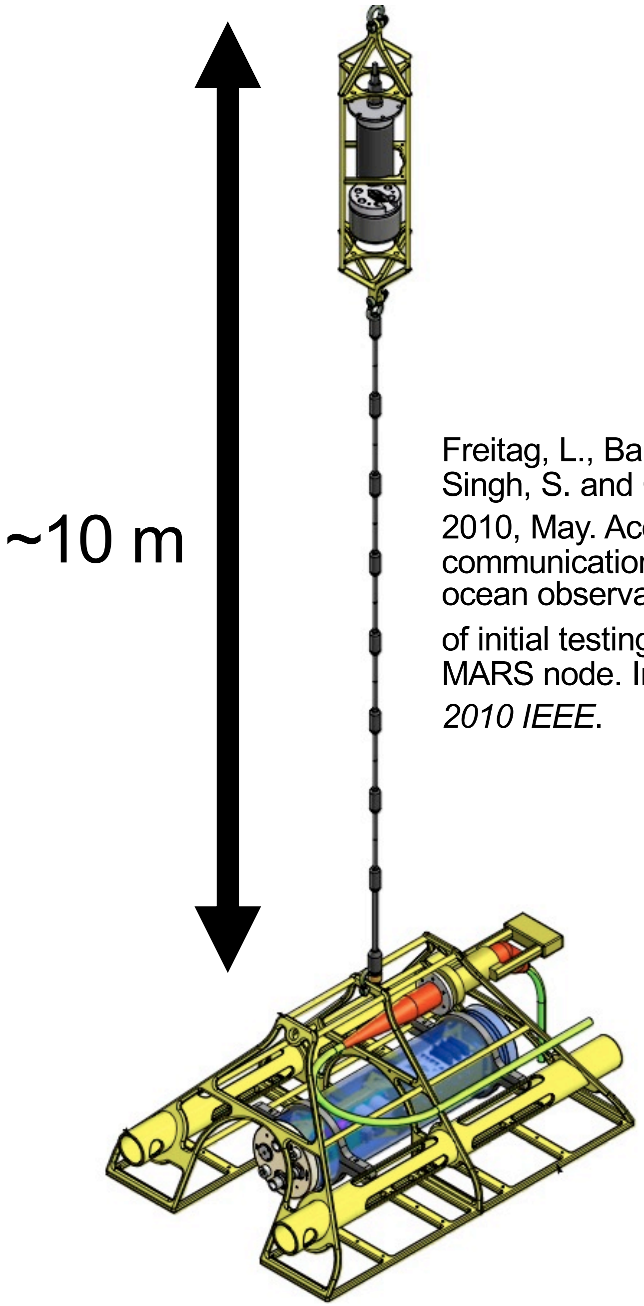
Provide drop-in instrument capability & AUV communication

Wireless extension for subsea observatories

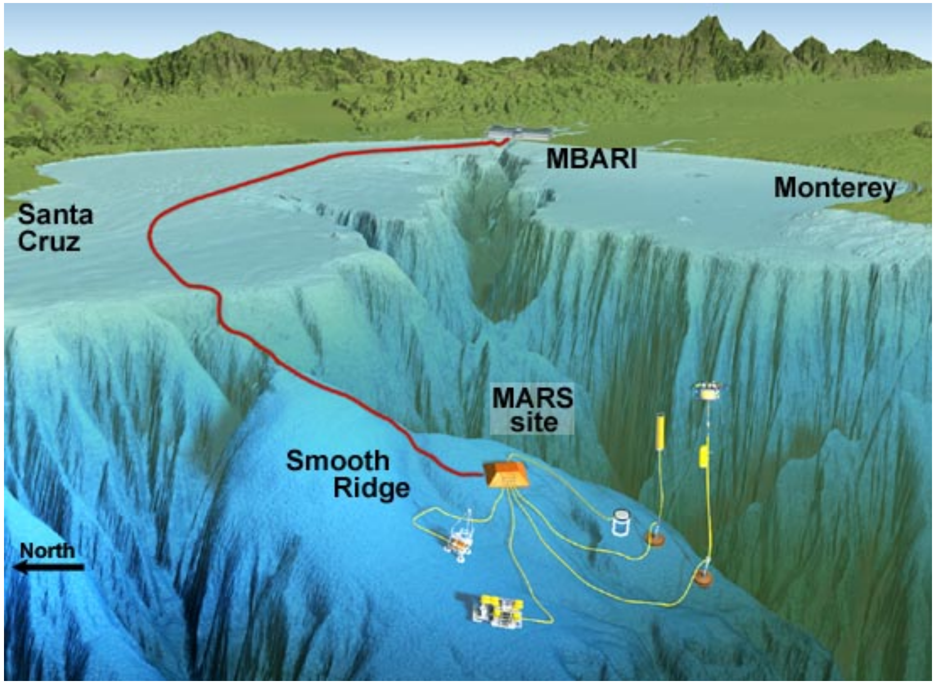


Deep-Sea Observatory with Acoustic Communications for AUVs and Instruments

Prototype Acoustic Modem Node for MARS Observatory

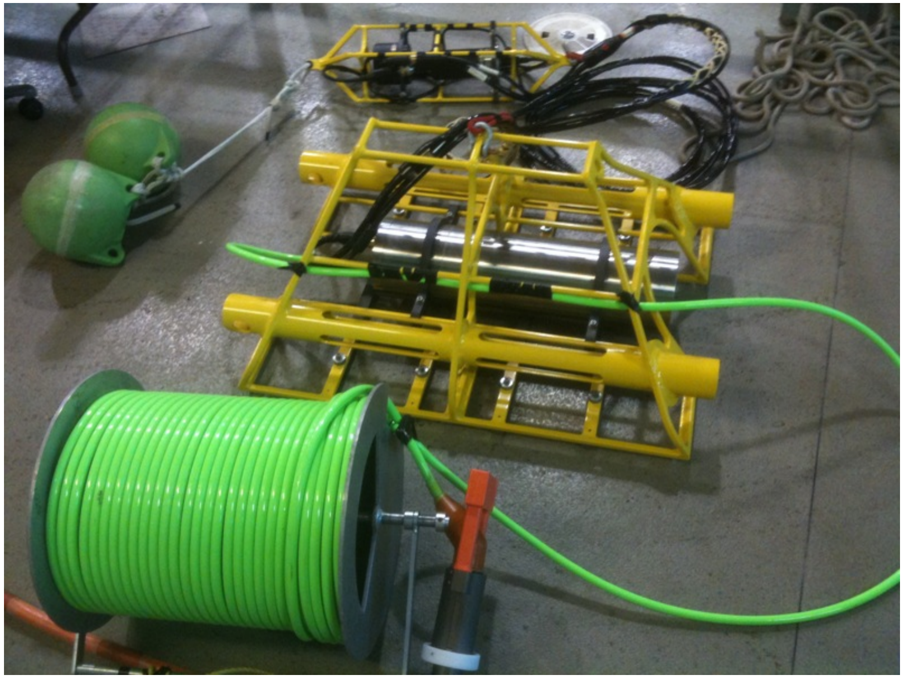


Freitag, L., Ball, K., Koski, P., Singh, S. and Gallimore, E., 2010, May. Acoustic communications for deep-ocean observatories: Results of initial testing at the MBARI MARS node. In *OCEANS 2010 IEEE*.




Todd Walsh (c) 2005 MBARI

Prototype Acoustic Modem Node for MARS Observatory

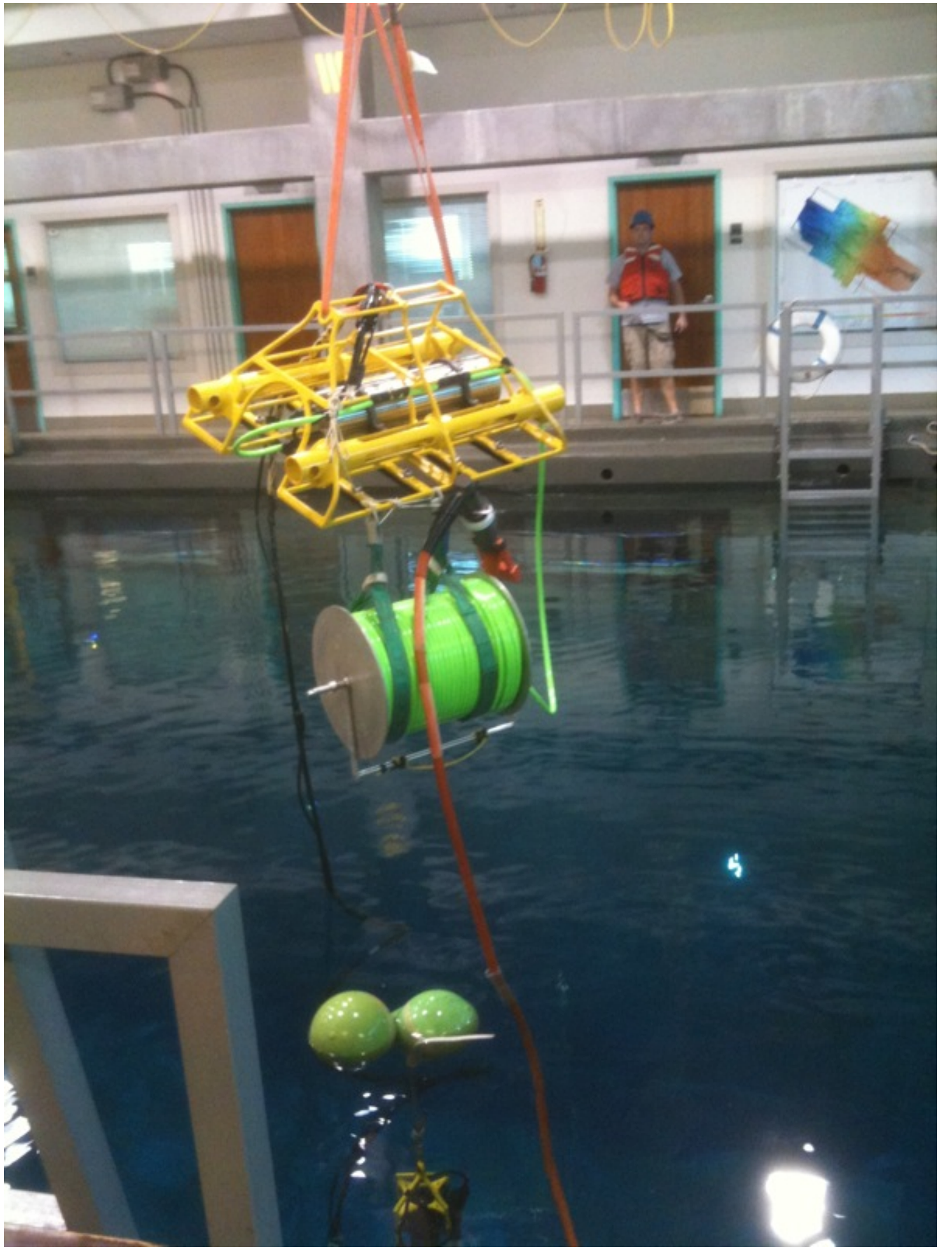


Node Features

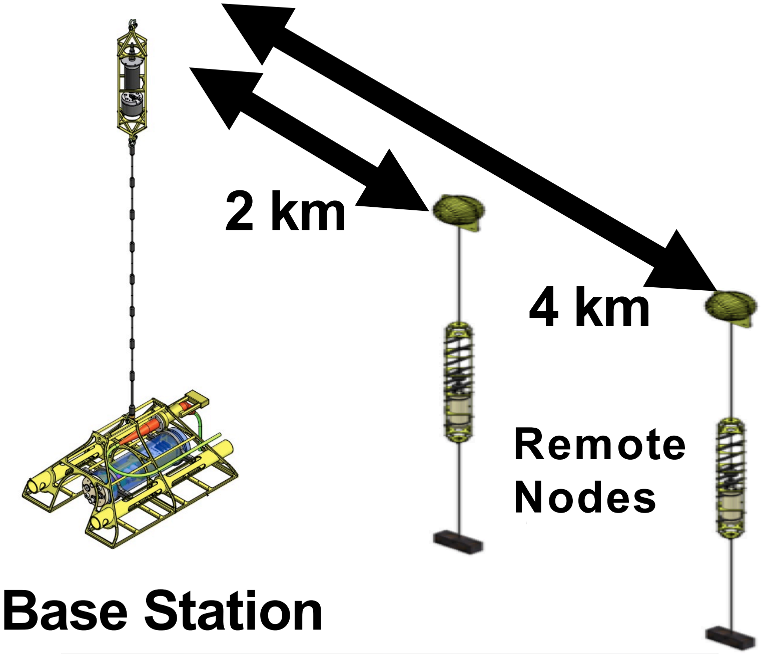
- Two bands 10 and 25 kHz
- Embedded Micro-Modems plus data acquisition system.

Prototype Testing

- 2 remote systems at 2 km
- 2 remote systems at 4 km



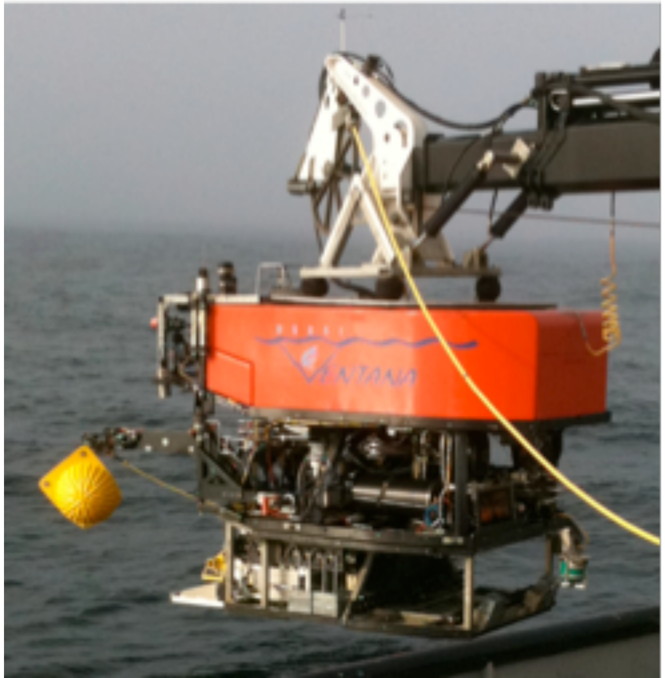
Results at the MARS Observatory



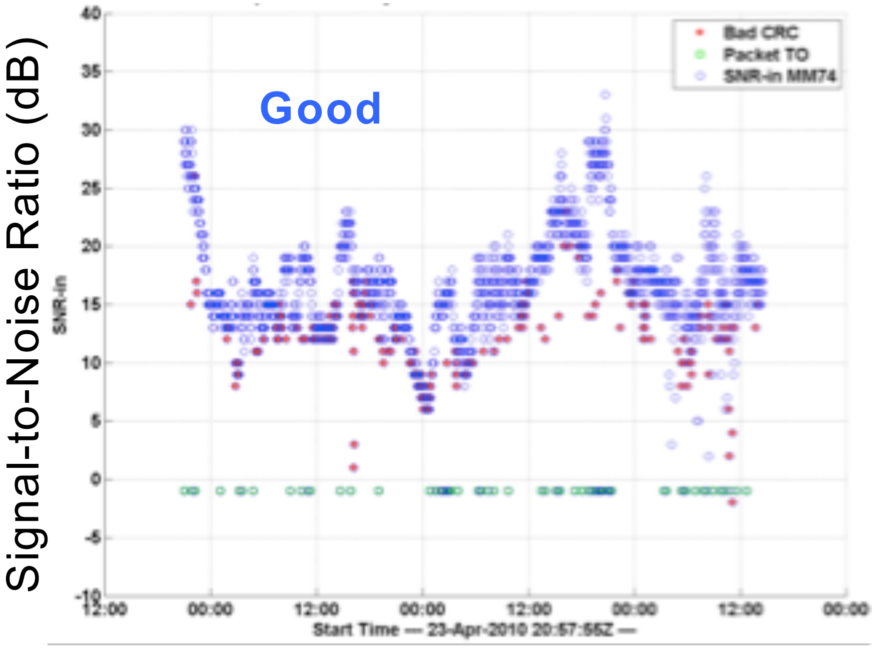
Remote Nodes

Observations:
- 2 km: >90% success rate (to 97% for some periods)
- 4 km: varied, depending on surface wave conditions (reflections)
- Noise from occasional ROV operations impacts reception.

Base Station



Link Statistics - Packet Success



Open Ocean Gateway: Wave Glider

- Wave Glider autonomous surface craft substitutes for moored buoy or ship.
- Excellent for deep-water data retrieval and monitoring.

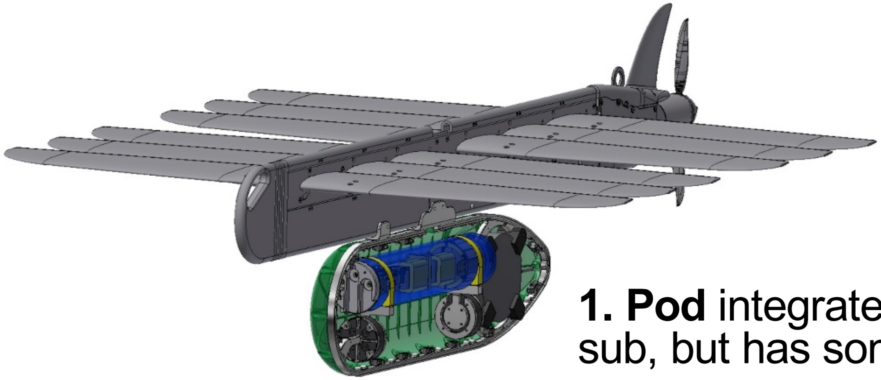
Wave Glider and Acoustic Communications

Main Challenge: Transducer integration

Mounting Options

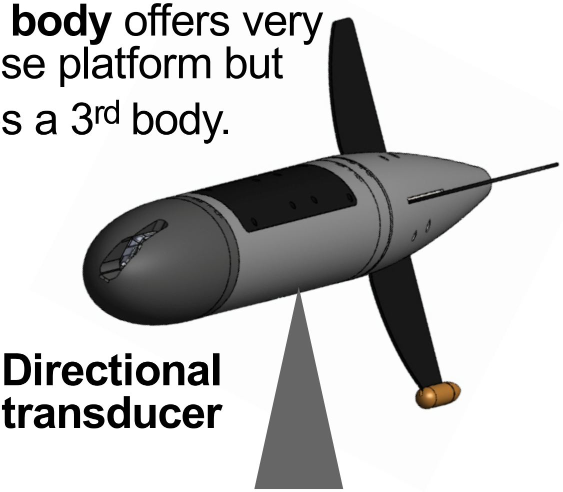
1. Sub-mounted modem.
2. Towed modem.

Acoustic modem on wave glider sub, but is near to mechanical noise sources. Achieved 1000 bps typical.



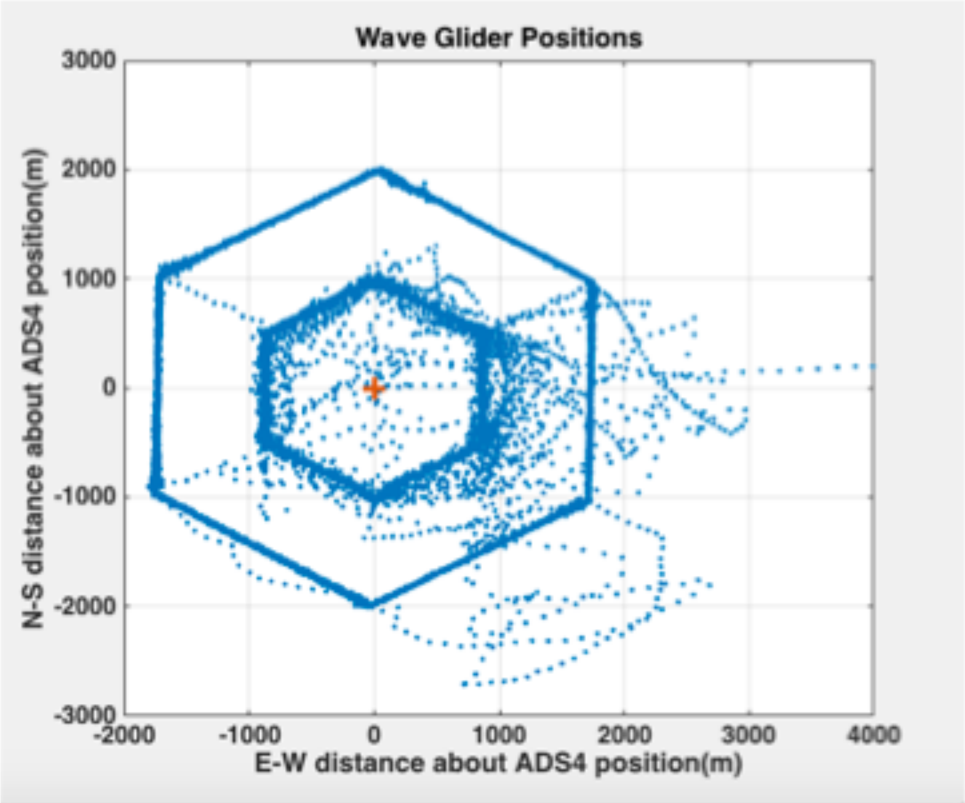
1. Pod integrates modem to sub, but has some noise from moving parts.

2. Tow body offers very low noise platform but requires a 3rd body.



Motion-decoupling tow cable

Acoustically-Linked OBS via Wave Glider



- Wave Glider removes need for large ship to deploy and recover buoy.
- Scripps approach includes dual wave gliders to maintain one on-site continuously.

Despite cost of Wave Glider, this may be the best approach for real-time OBS data access where no cable is available.

Scripps Wave Glider with WHOI Modem uploaded 1.3 MB/day from OBS in 2015.

See Poster HC4: John Orcutt, et. al.

Glider track holding demonstration, 70 days, 300 km offshore California.

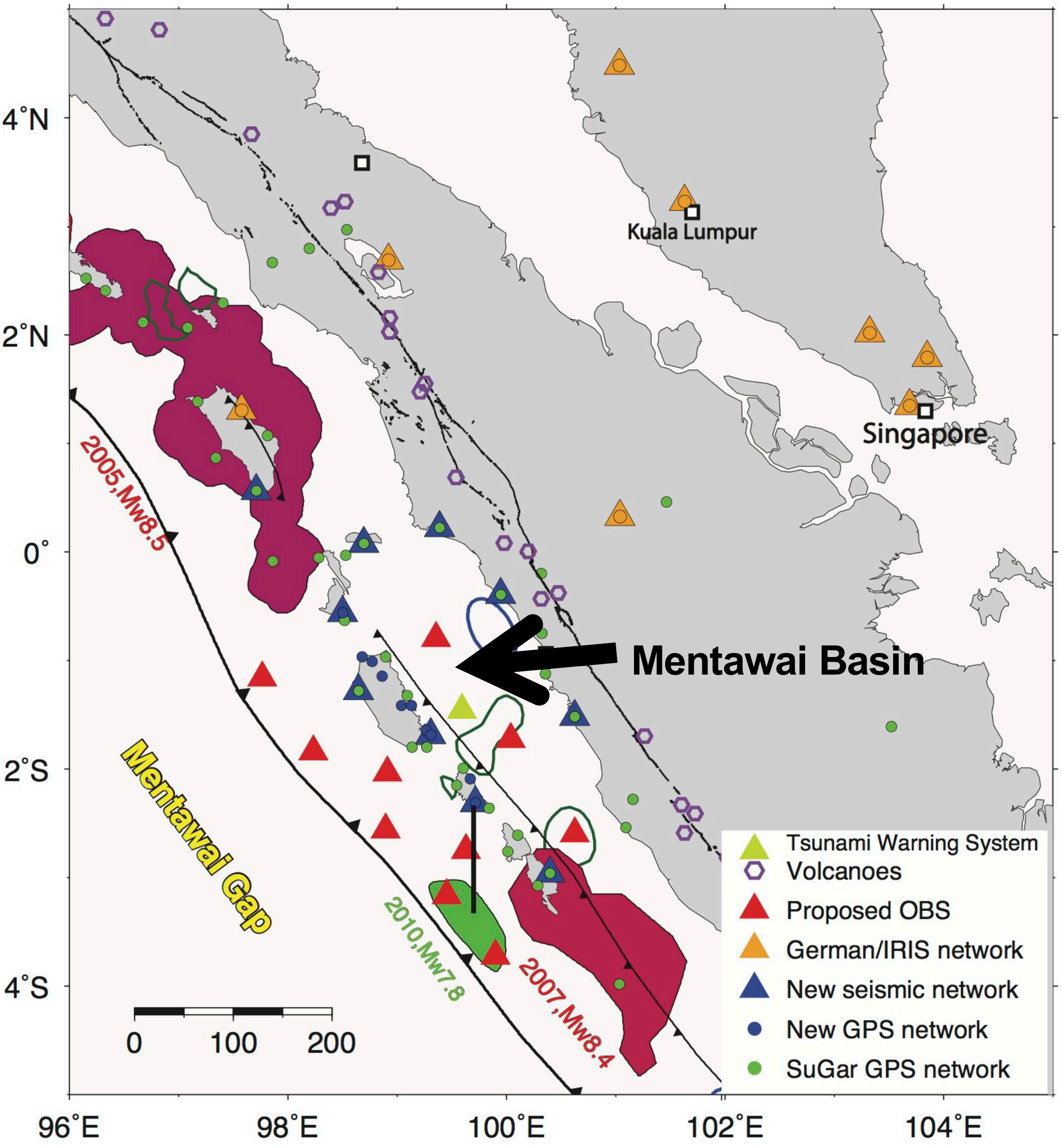
Indonesia Tsunami Threats

NSF HAZARD SEES (Science, Engineering, and Education for Sustainability) Project.

Multi-disciplinary approach to near-field tsunami hazard reduction.

Source: **Where the First Wave Arrives in Minutes** Indonesian Lessons on Surviving Tsunamis near Their Sources. United Nations Educational, Scientific and Cultural Organization Intergovernmental Oceanographic Commission. IOC Brochure 2010-4

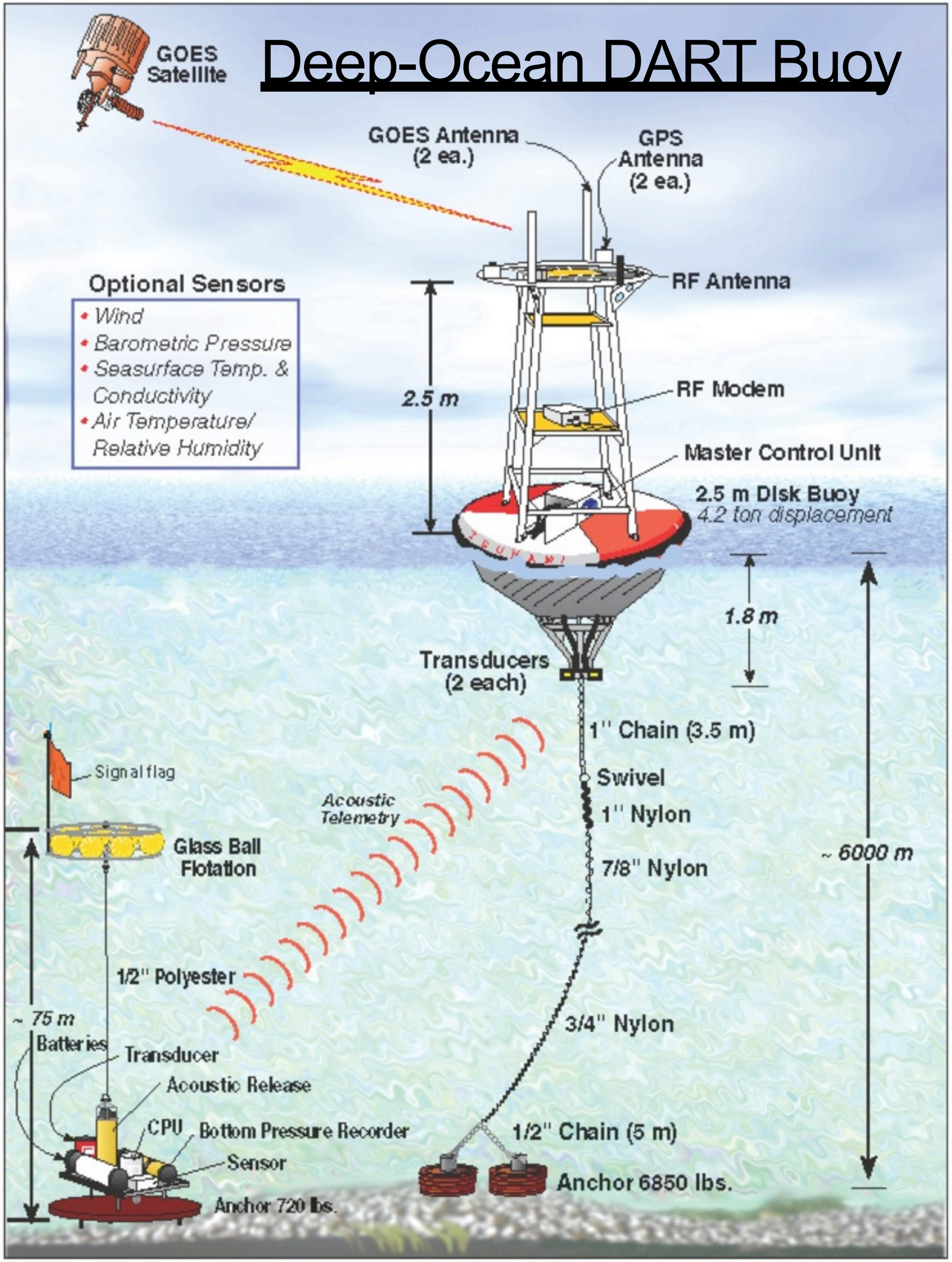
Sumatra Network



- Multiple threats, both offshore and within Mentawai basin.
- Need for OBS deployments to complement recent and new GPS stations on shore and islands.
- Near-field threat is focus of HAZARD SEES, but offshore important as well.

J. Mcguire (WHOI) with collaborators at EOS (S. Wei, K. Sieh), LIPI, BMKG, BPPT.

Deep-Ocean DART Buoy



Far-Field Tsunamis: DART Buoy is proven technology for detection. In Indonesia many have been vandalized. Near-field buoys will be even easier targets.

Figure 18. German GITEWS Tsunami Buoy – Stolen Superstructure and Buoy Payload

Figure 20. Indonesian Tsunami Buoy Recovery

Why a New Approach?

'No alert' in Indonesian tsunami

A crucial link in Indonesia's tsunami warning system was not working during Monday's tsunami because it had been vandalised, says an Indonesian official.

Hundreds of people were killed and many are missing as a result of the tsunami, which was generated by a magnitude 7.7 earthquake off the west coast of Sumatra.

The earthquake unleashed a 3m-high (10ft) wave that crashed into the remote Mentawai islands, levelling a number of villages.

Survivors have said no warning was given.

Ridwan Jamaluddin, of the Indonesian Agency for the Assessment and Application of Technology, told the BBC's Indonesian service that two buoys off the Mentawai islands were vandalised and so out of service.

"We don't say they are broken down but they were vandalised and the equipment is very expensive. It cost us five billion rupiah each (£353,000; $560,000).

Another official, from the Indonesian Climatology Agency told the BBC's Indonesian service that both tide gauges and buoys are used to detect a tsunami, but the buoys are more important to generating an early warning.

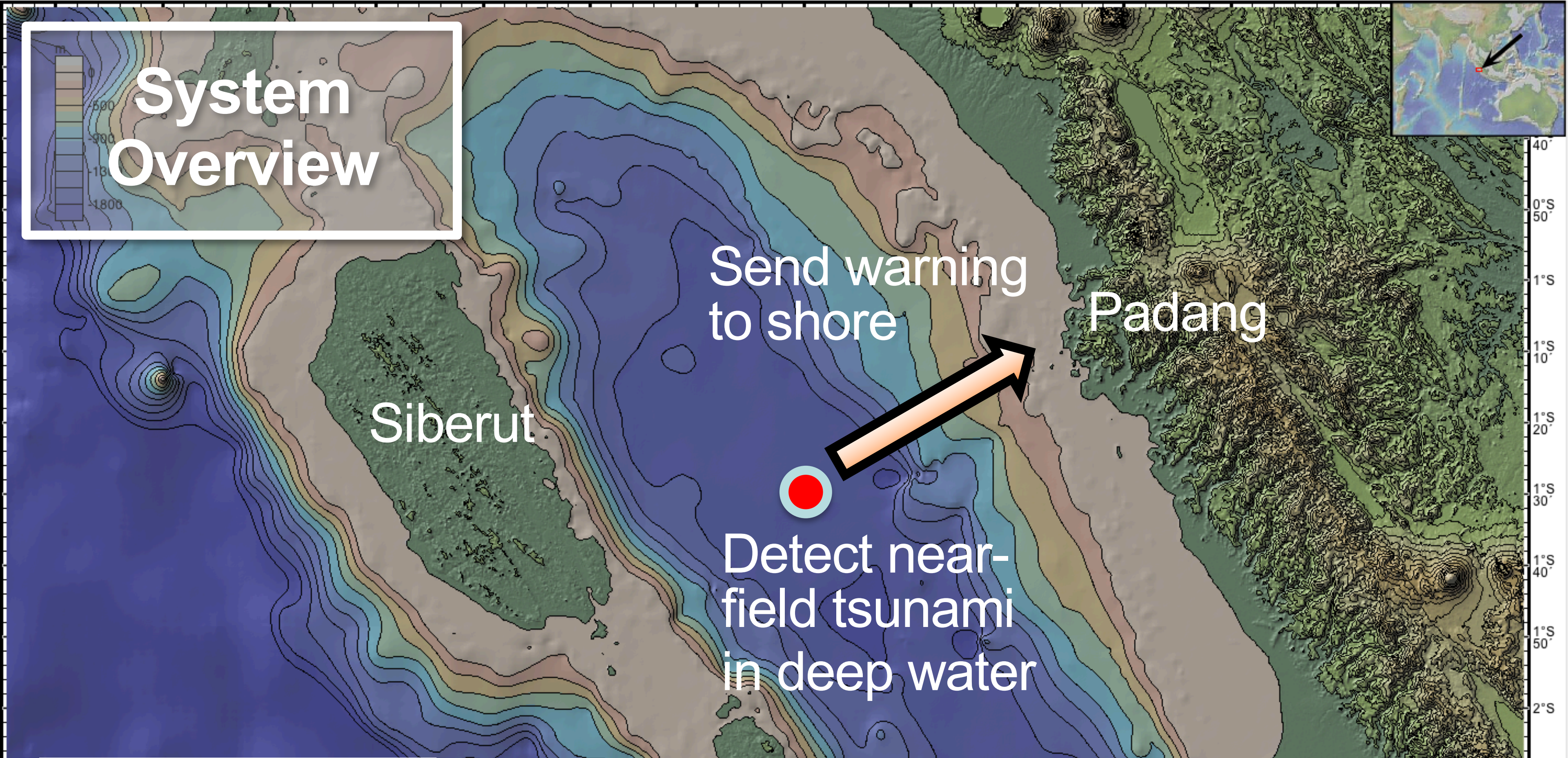
"To predict a tsunami, we need the data from the buoy and the tide gauge, which is located near the beach. The buoy is more important because it is on the sea, so it will record the wave much quicker that the tide gauge," said the official, named Fauzi.

Problem: Near-shore DART buoys that detect tsunami pressure signal have been vandalized.

Solution: Replace buoys with underwater acoustic network.

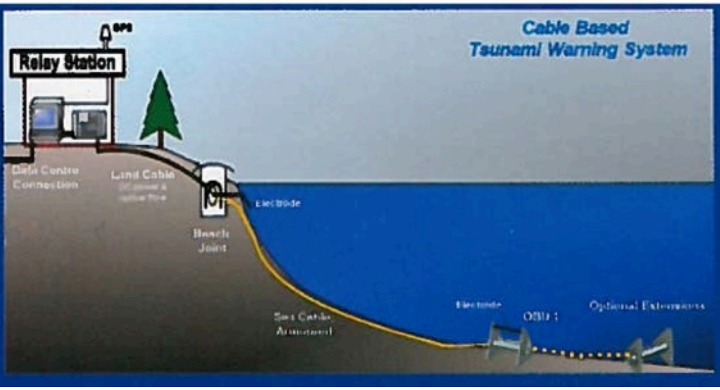
time”

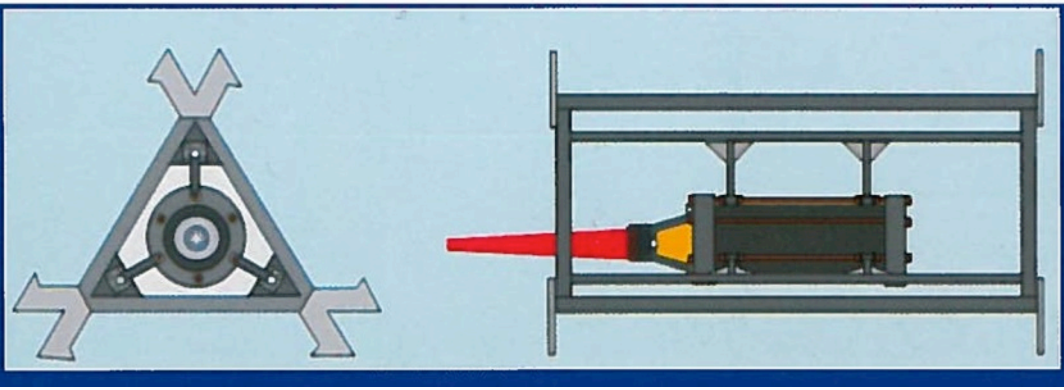
System Overview



Pressure sensor in Mentawai Basin

Proposed Solution:
No surface buoy.
Detect tsunami sub-sea, send data via acoustics to shore.





Cable-Based System

- BPPT is working on cable system with pressure sensor (tsunameter).
- Plan: add acoustic modem to end of cable to extend length of cable by 20-40 km.
- Acoustic network will increase warning time with no extra cost in cable.

Remote Sensor System

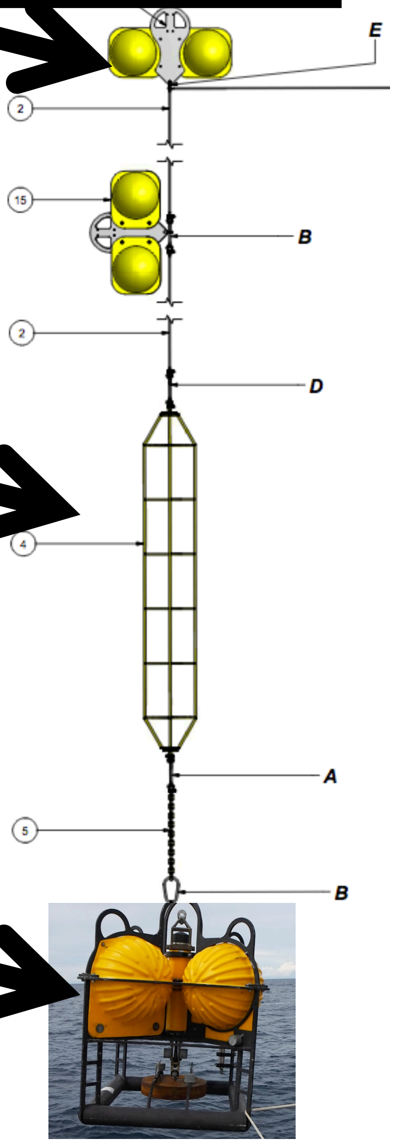
Remote Sensor Design

Design Goals & Constraints

- Pressure sensor on bottom, well-coupled to seafloor in “lander”.
- Acoustic modem above bottom to provide for best propagation to and from remote unit.
- Use existing lander (currently at Andalas University) and acoustic modem above lander as short mooring.
- Total system height constrained by deployment method and vessel size.

Risks

- Near-bottom currents can impart very small motions to array that can couple into pressure sensor. However, signal filtering can remove this noise.



Flotation

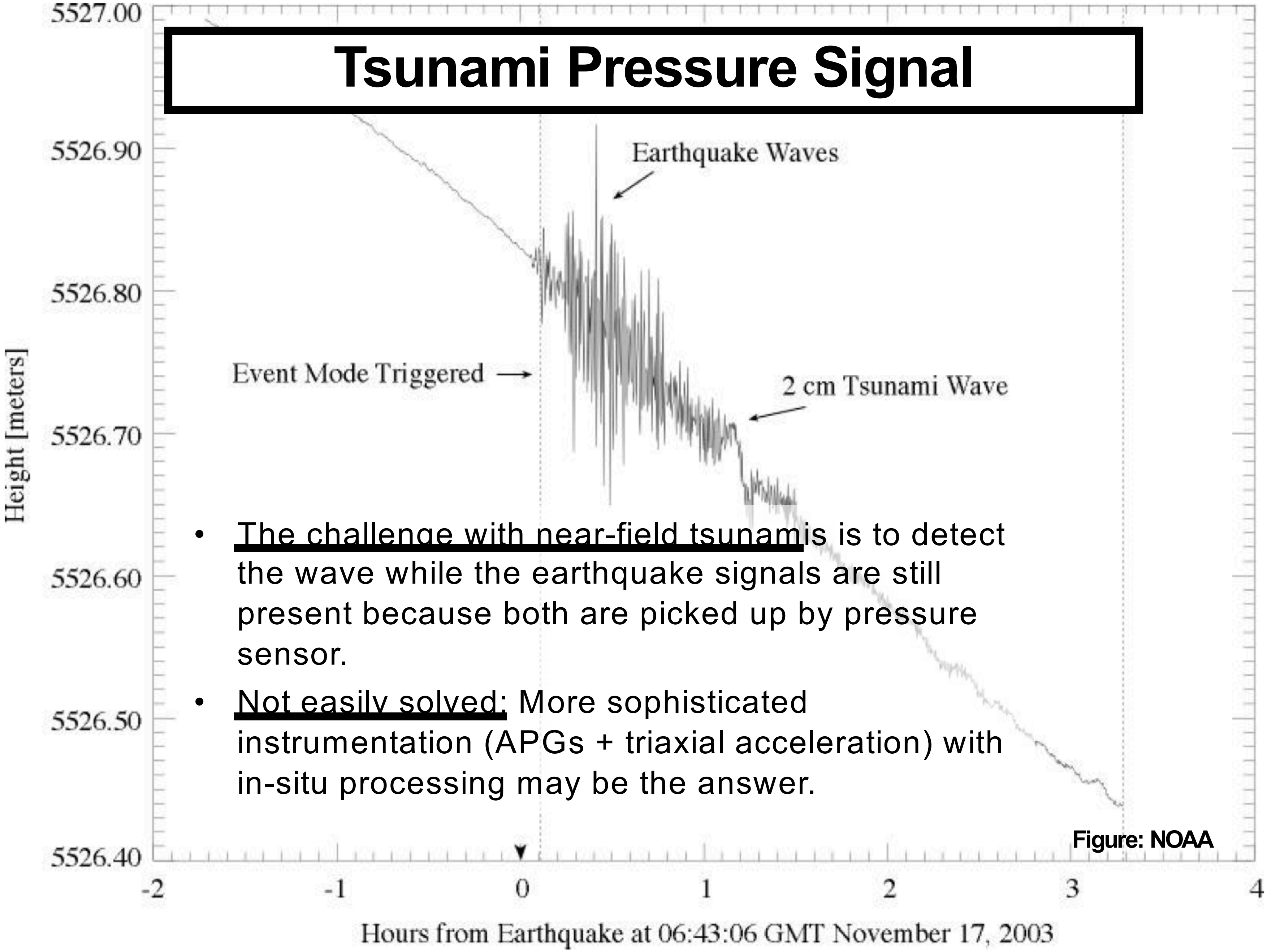
Acoustic Communications Subsystem

- Modem
- Transmit Transducer
- Receiver Array
- Battery Pack

Lander

- Pressure Sensor
- Battery Pack
- Detector Processor

Tsunami Pressure Signal

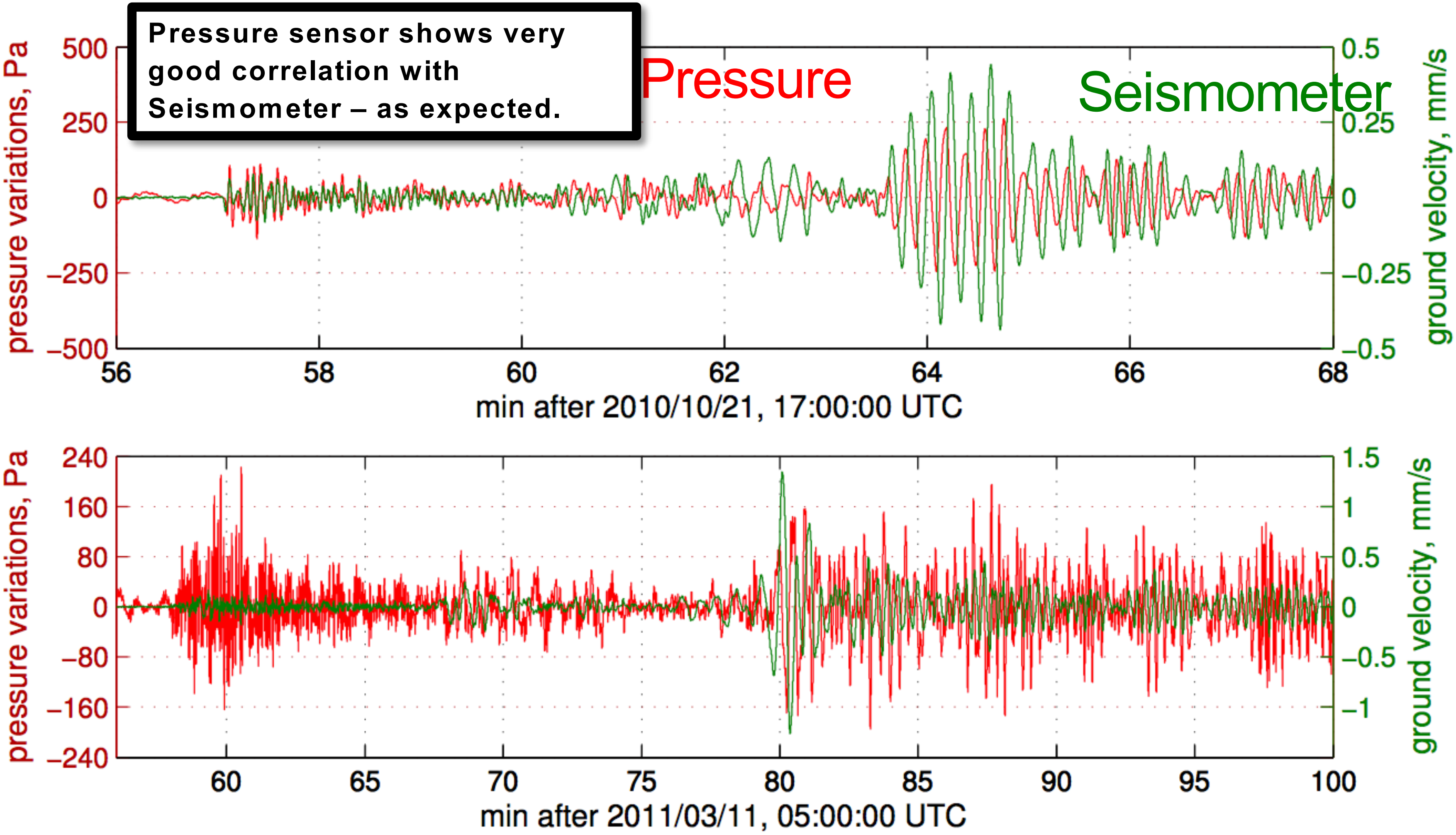


- The challenge with near-field tsunamis is to detect the wave while the earthquake signals are still present because both are picked up by pressure sensor.
- Not easily solved: More sophisticated instrumentation (APGs + triaxial acceleration) with in-situ processing may be the answer.

Figure: NOAA

Figure 2: Tsunami of November 17, 2003, as measured at the tsunameter located at 50 N 171 W.

Nano-Resolution Depth Sensor

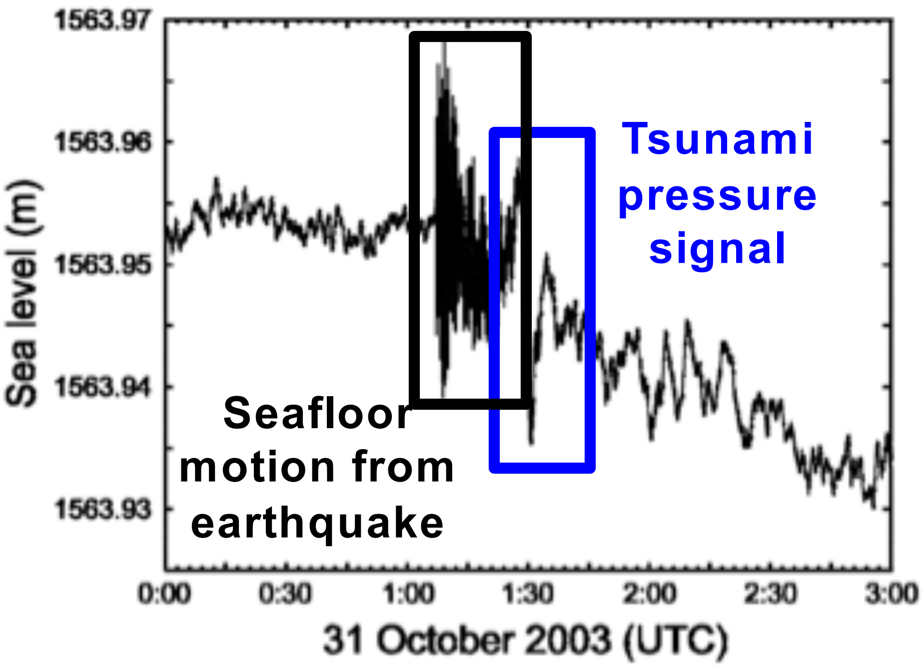


Pressure sensor shows very good correlation with Seismometer – as expected.

Figure 1: Records of the vertical component of the ground velocity and of the bottom pressure variations (HP filtered) upon seismic waves arrival at MARS after October 21, 2010, and March 11, 2011 earthquakes.

Figure 1 from: *Comparing the Nano-Resolution Depth Sensor to the Co-located Ocean Bottom Seismometer at MARS by* Elena Tolkova and Theo Schaad, (NorthWest Research Associates and Paroscientific, Inc.)

Near-Term Approach to Near-Field Detection: Filter and Threshold

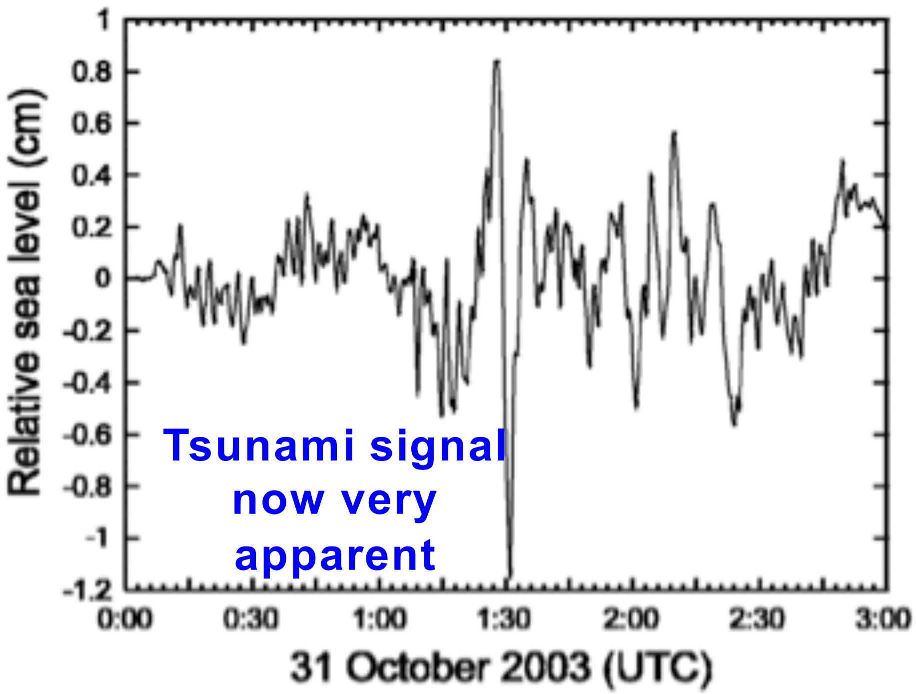


Tsunami pressure signal

Seafloor motion from earthquake

Raw Pressure Record

- 0.5 mm resolution, Fs=10 Hz.
- 60 sec moving average filter
- Contamination from motion is high frequency.



Tsunami signal now very apparent

Filtered Pressure Record

- Ocean tides removed
- High-pass filter.

Near-field tsunami forecasting from cabled ocean bottom pressure data, Hiroaki Tsushima, Ryota Hino, Hiromi Fujimoto, Yuichiro Tanioka, and Fumihiko Imamura, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, 2009.

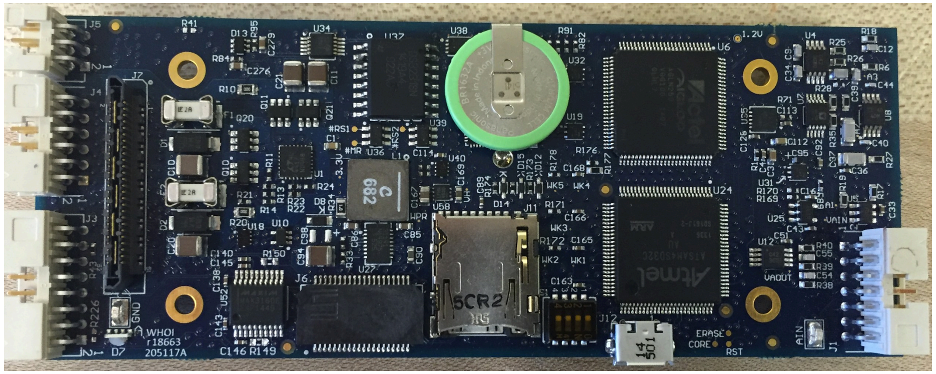
Real-Time Detector Notes

Real-Time Detector:

- Runs continuously at 1 Hz sample rate.
- Filters for signal in tsunami band.
- Check level against threshold.
- When detection occurs: Wake-up modem and transmit filtered signal to shore.

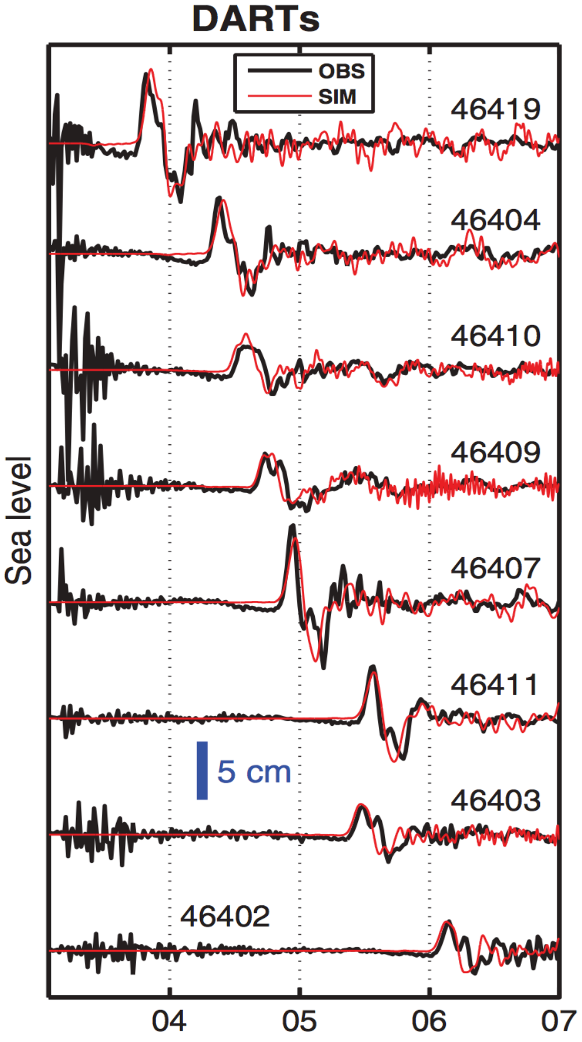
Key points:

- Sensor does not detect tsunami, it reports pressure level over a pre-set threshold for interpretation on shore.



Low-power real-time processor board (ARM-based CPU).

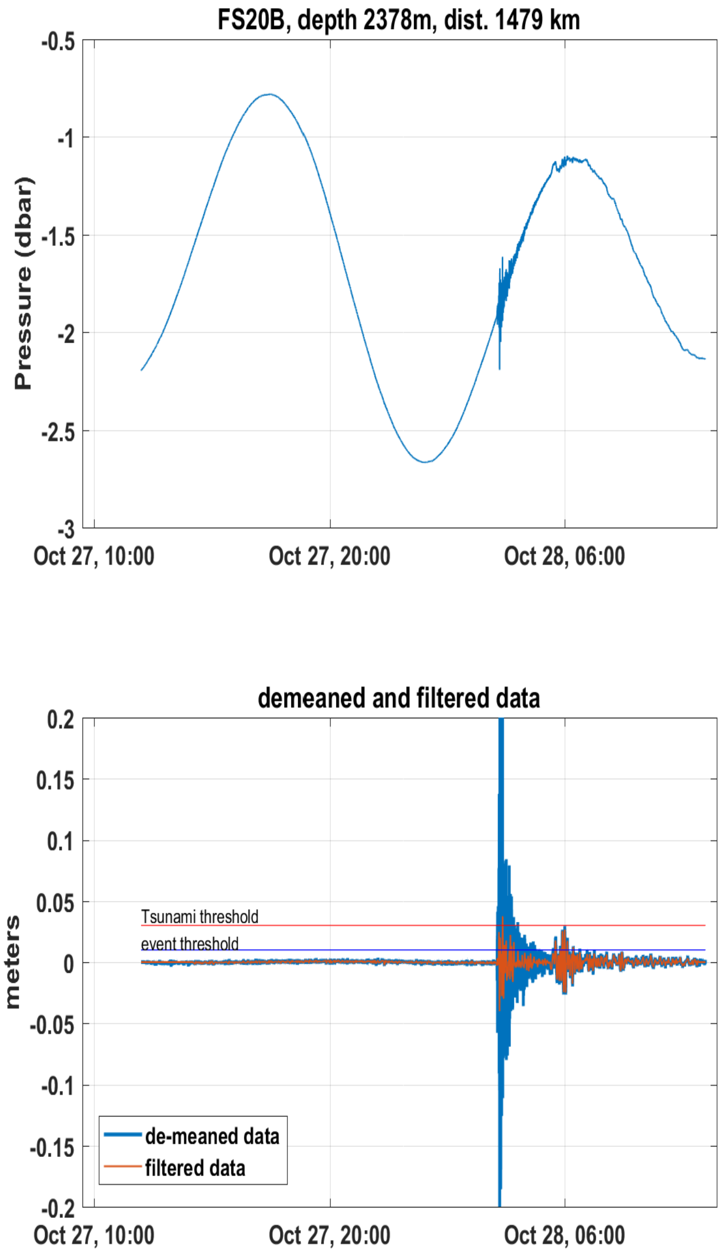
Example pressure data from 2012 Haida-Gwaii being used for validation



Detector Development: Use of data from 2012 Haida Gwaii Earthquake, BC

Proposed Data Processing

- Decimate to 0.1 Hz
- Remove one hour moving mean to take out tide
- Tsunami band filter (2 to 90 minutes), adds up to 3 minutes or more of delay (red line in graph shows filtered data)
- Apply ‘event threshold’ set at 1 cm to zero-mean data
- Apply ‘tsunami threshold’ set at 3 cm, to filtered data



Paroscientific APG pressure data
Sample rate, 125 Hz

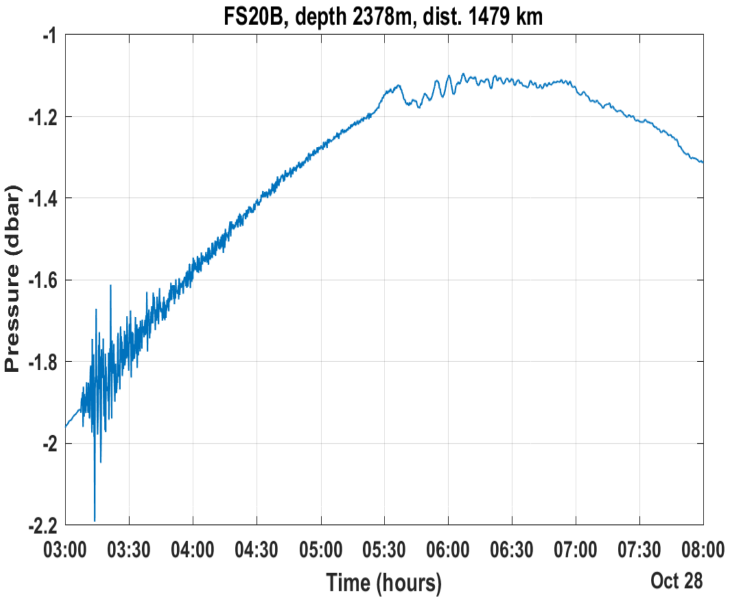
Sheehan AF, Gusman AR, Heidarzadeh M, Satake K. Array observations of the 2012 Haida Gwaii tsunami using Cascadia Initiative absolute and differential seafloor pressure gauges. Seismological Research Letters. 2015 Aug 19;86(5):1278-86.

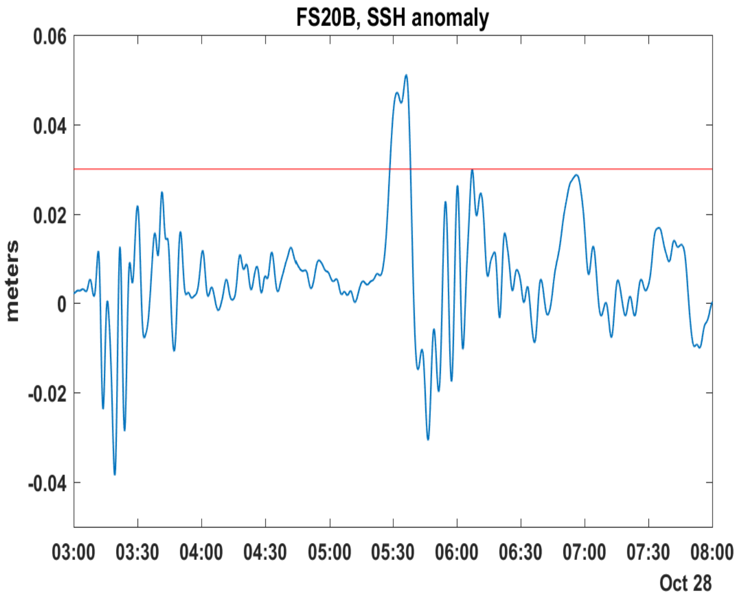
Haida Gwaii earthquake and tsunami signal from sensor FS20B

Processing as described in previous slide:

1. Remove mean.
2. Bandpass filter in 200-5000 second band (assumed tsunami signal band).

Total delay through filters is 3 minutes.


FS20B, depth 2378m, dist. 1479 km


FS20B, SSH anomaly

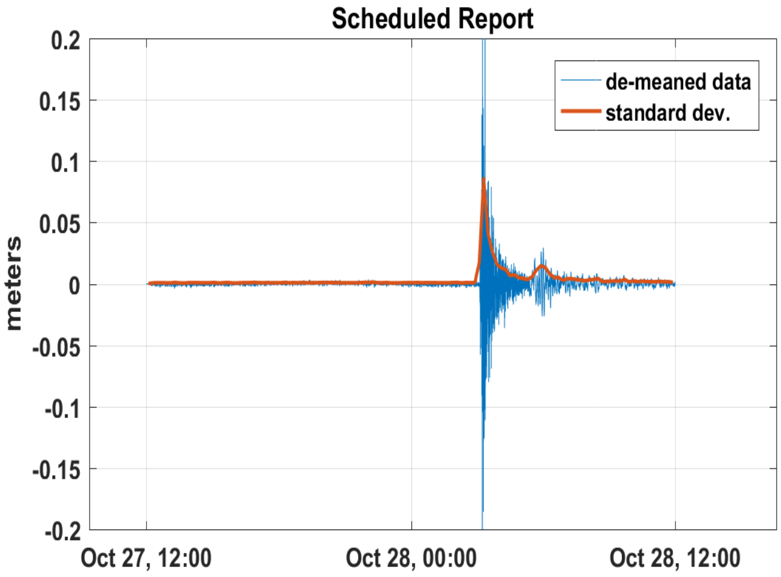
Example of detector processing for event with separated ground motion and pressure wave signals.

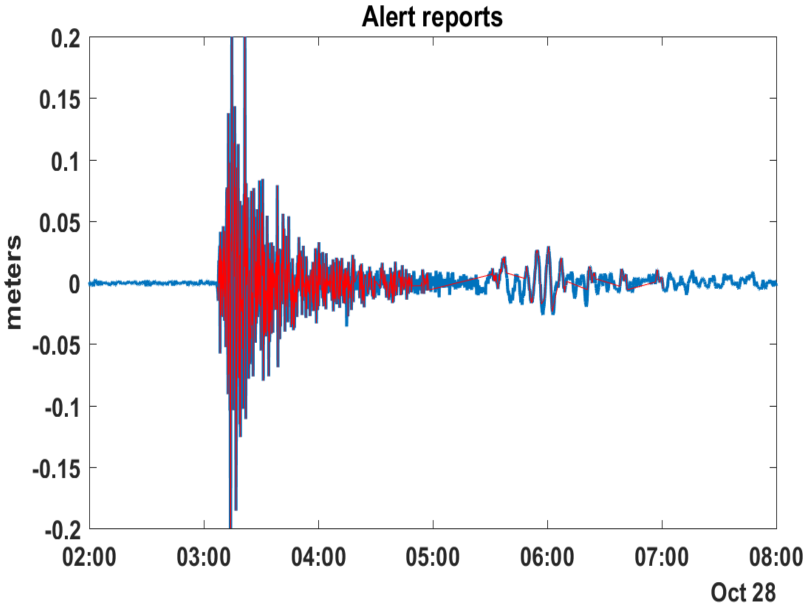
Ground motion signal is still clearly evident in waveform, though human observer can see differences between residual from motion in tsunami band, and the tsunami signal itself.

Changing bandwidth could help improve difference, but still will not be unequivocal.

Approach for acoustically transmitted data:

(1) provide regular status to show system is functional and 'noise' level.





(2) Provide alert when signal exceeds threshold

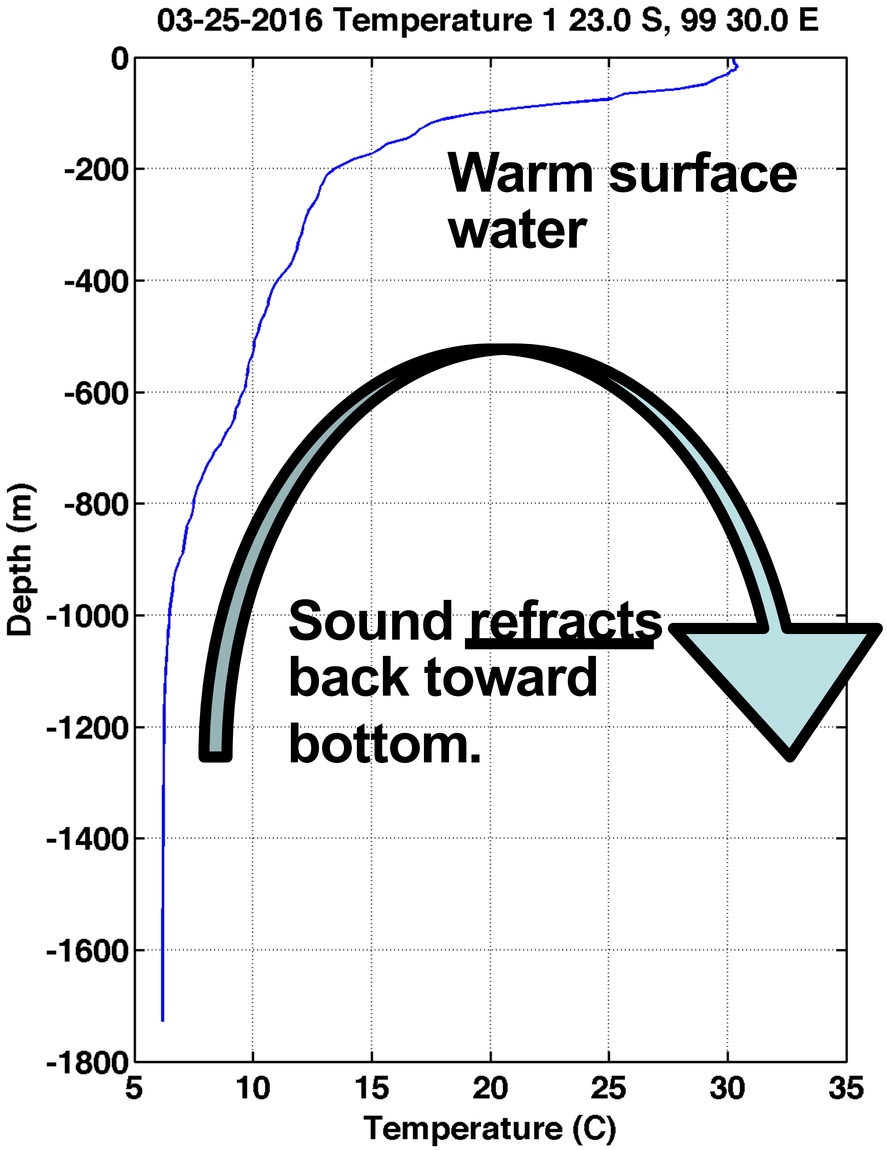
An **alert report** will go out immediately (filter delay may be present) if the 'Tsunami threshold' is exceeded.

The alert reports will have only 1 or two samples of post-threshold data, the rest will be past history. Alerts will continue for at least 10 minutes.

Field Testing in Indonesia – Mentawai Basin, near Padang, Sumatra


ARAH
EVAKUASI
EVACUATION
ROUTE

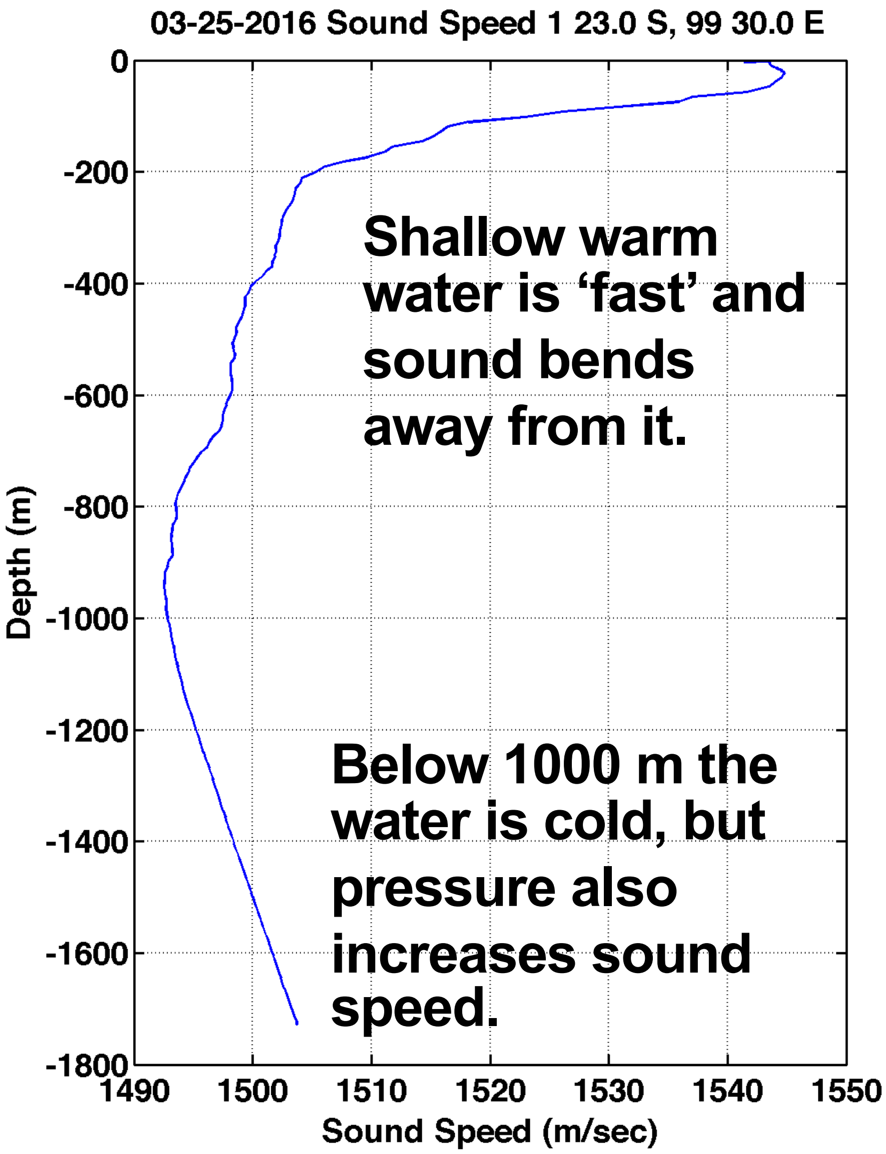
Results: Measured Temperature from CTD and Computed Sound Speed



03-25-2016 Temperature 1 23.0 S, 99 30.0 E

Warm surface water

Sound refracts back toward bottom.

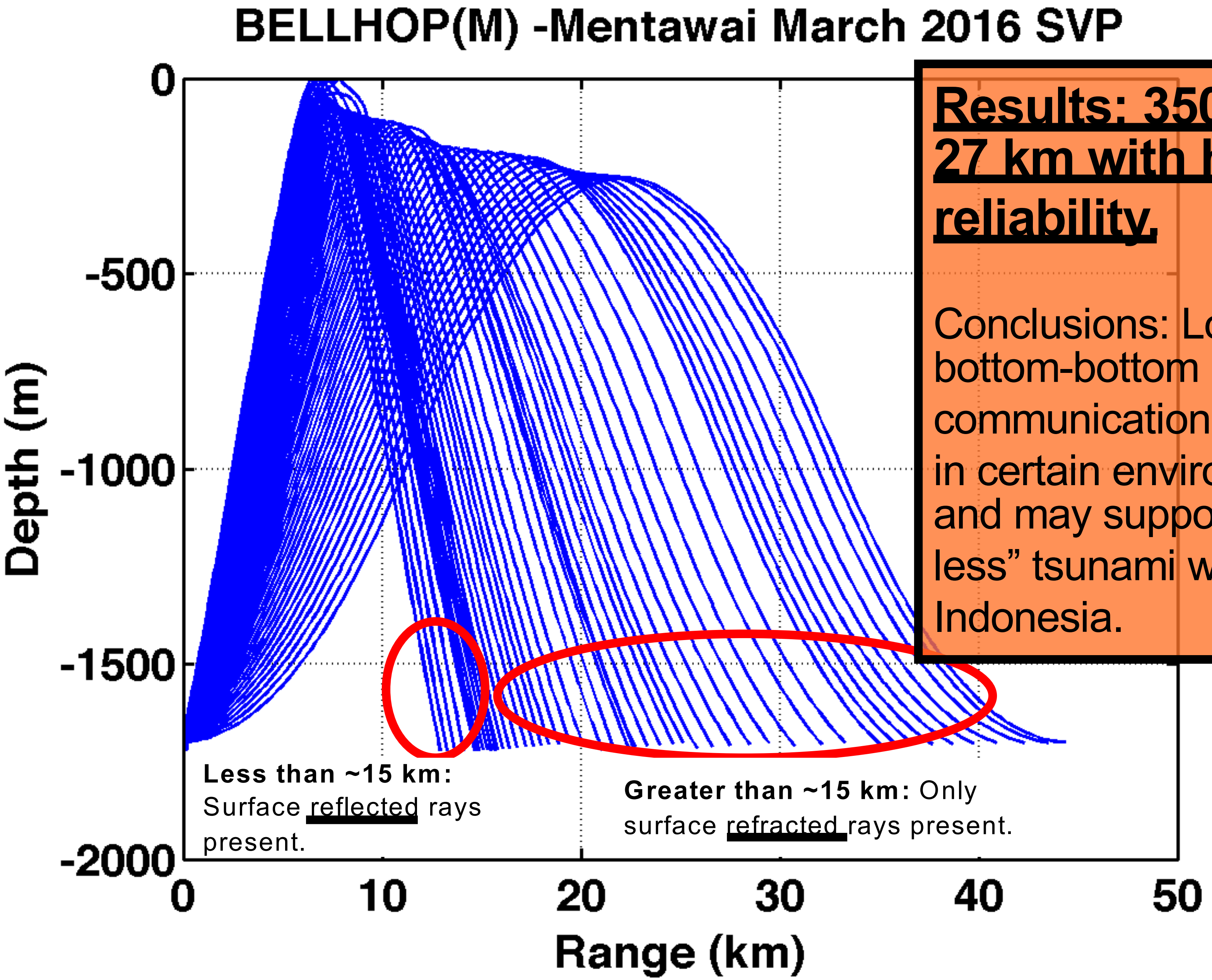


03-25-2016 Sound Speed 1 23.0 S, 99 30.0 E

Shallow warm water is ‘fast’ and sound bends away from it.

Below 1000 m the water is cold, but pressure also increases sound speed.

Acoustic Propagation In Mentawai Basin



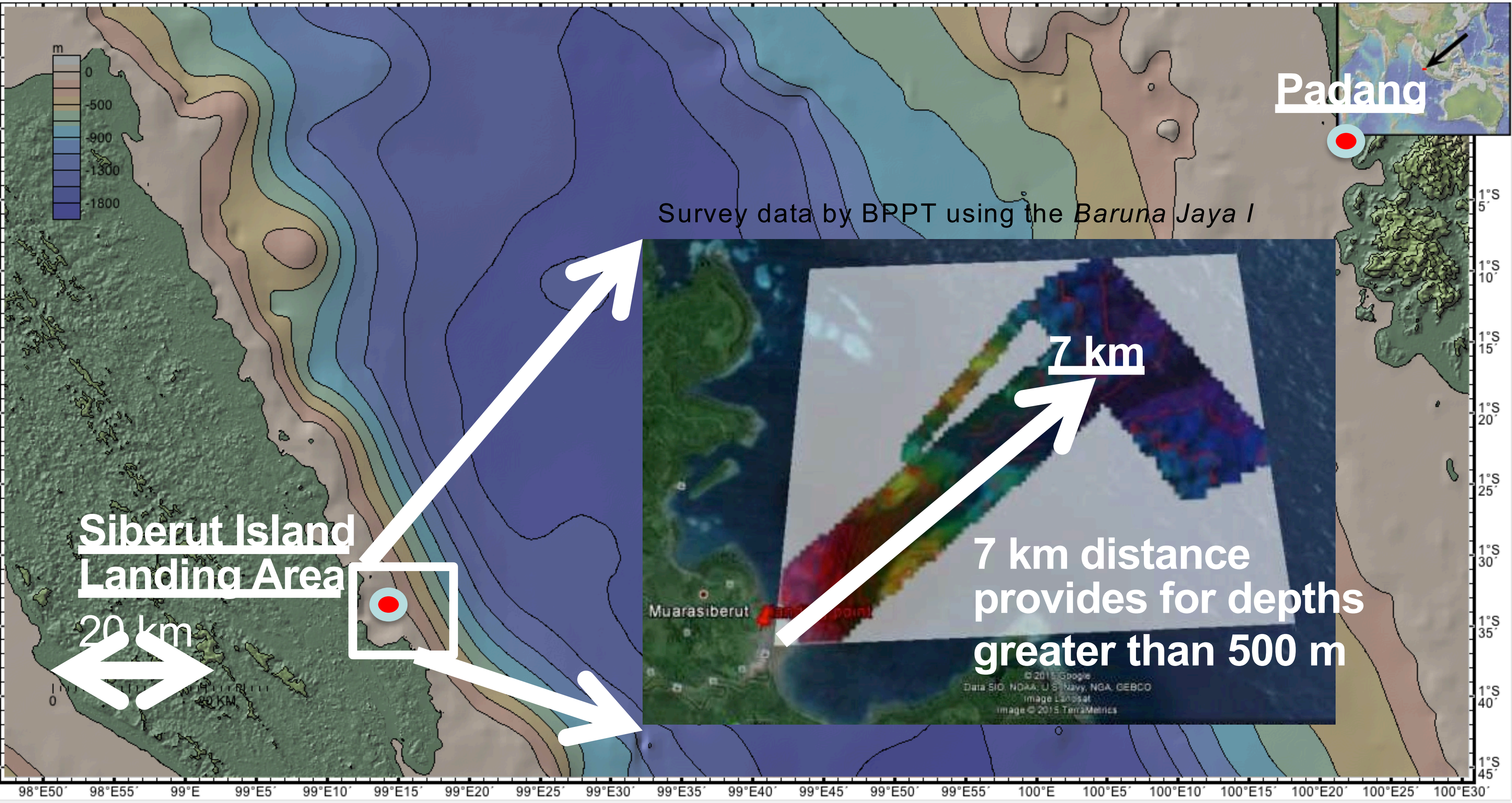
Less than ~15 km: Surface reflected rays present.

Greater than ~15 km: Only surface refracted rays present.

Results: 350 bps at 27 km with high reliability.

Conclusions: Long-range bottom-bottom horizontal communications is feasible in certain environments, and may support “buoy-less” tsunami warning in Indonesia.

Siberut Island Cable Landing Site, Deployment Planned for Late 2018



Survey data by BPPT using the *Baruna Jaya I*

Padang

Siberut Island Landing Area

20 km

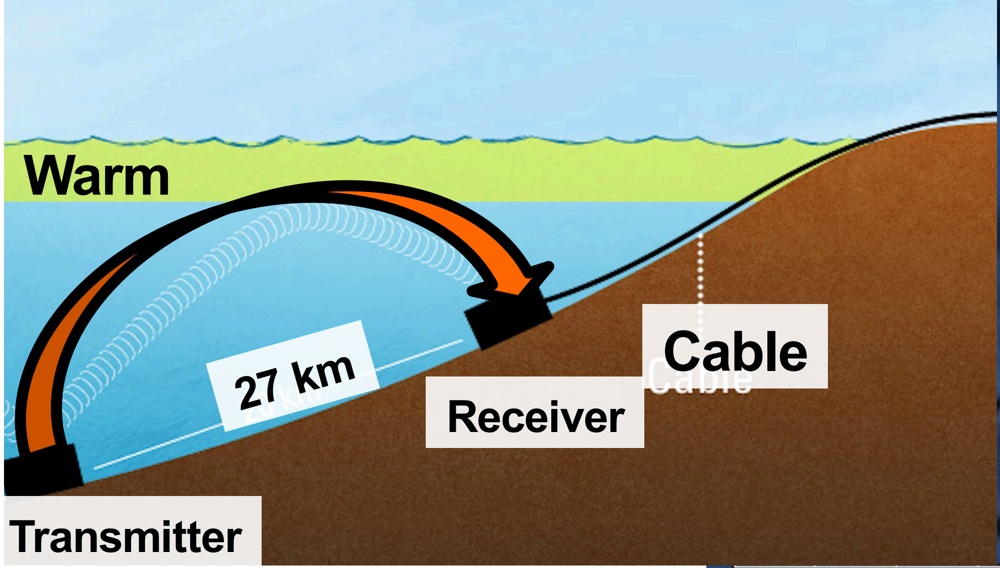
7 km

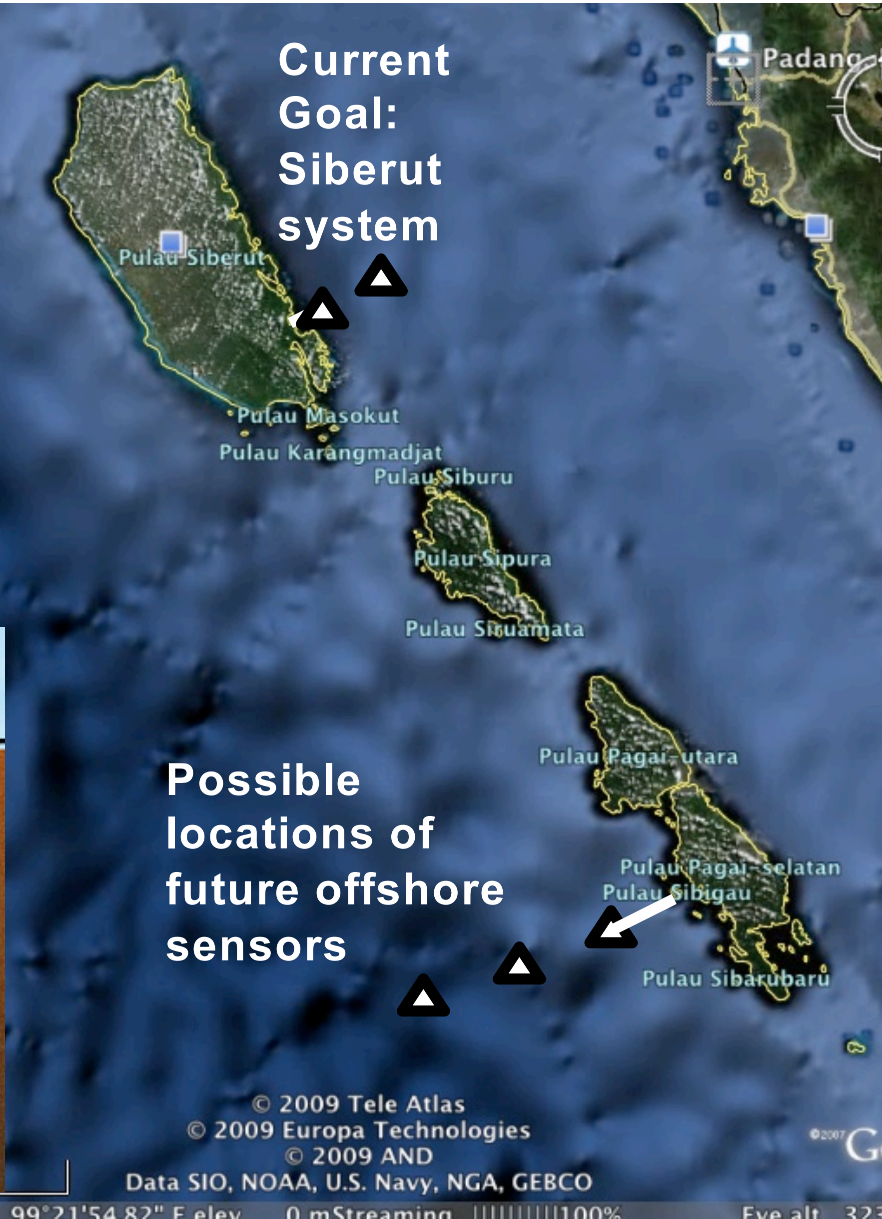
7 km distance provides for depths greater than 500 m

Future Options for Indonesia

Future Plans

- When proven, the concept for short cables (5-10 km) and wireless acoustics (25-50 km) may provide for tsunami detection outside the Mentawai Islands.





Current Goal: Siberut system

Possible locations of future offshore sensors

© 2009 Tele Atlas
© 2009 Europa Technologies
© 2009 AND
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Conclusions: Back to the Feasibility of Acoustically–Linked Cabled System

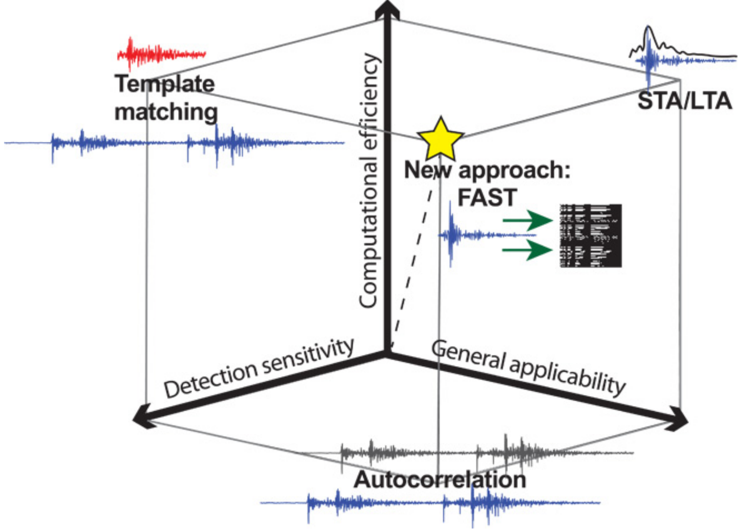
What makes a low bandwidth (100 bps) connection feasible?

1. Emerging methods in automated detection.
2. Data compression, e.g. wavelet-based methods.
3. Low power processing is advancing to enable deep learning on mobile devices.

What about the energy cost?

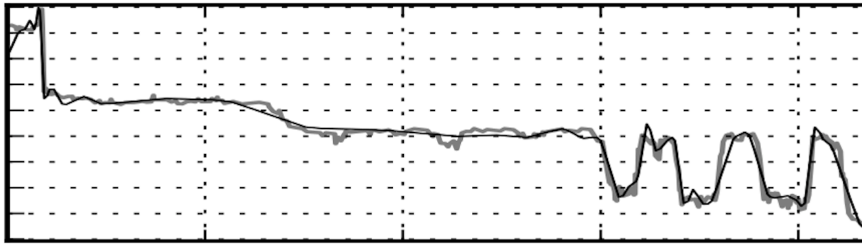
Example: 10 minutes of 1 Hz data compressed to 1byte/sample at 100 bps is <1 minute transmission time. In battery cost: <$1.

Automated Earthquake Detection



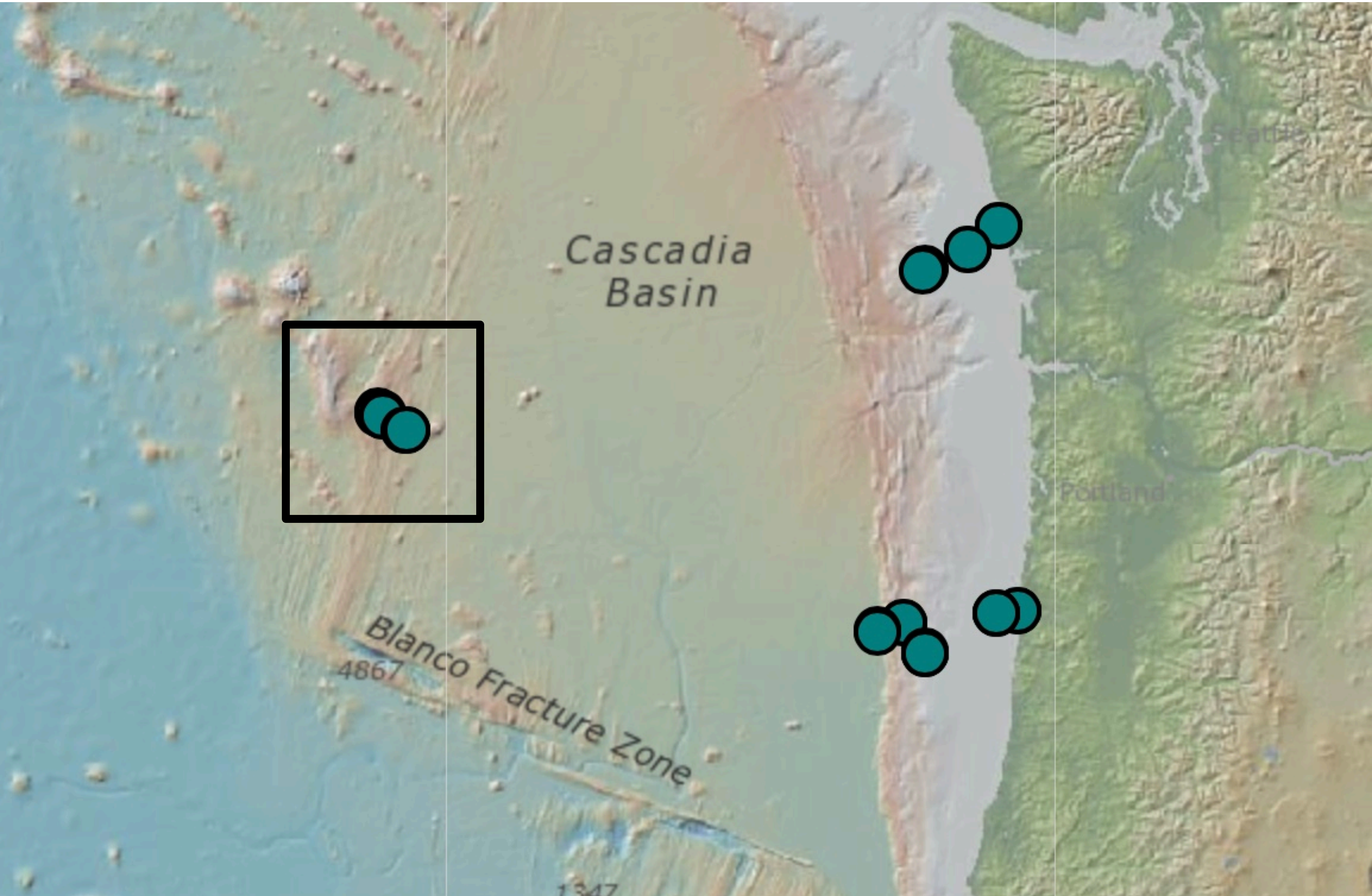
Yoon, C.E., O'Reilly, O., Bergen, K.J. & Beroza, G.C., Sci Adv 2015;1:e1501057

Wavelet Encoding for Compression

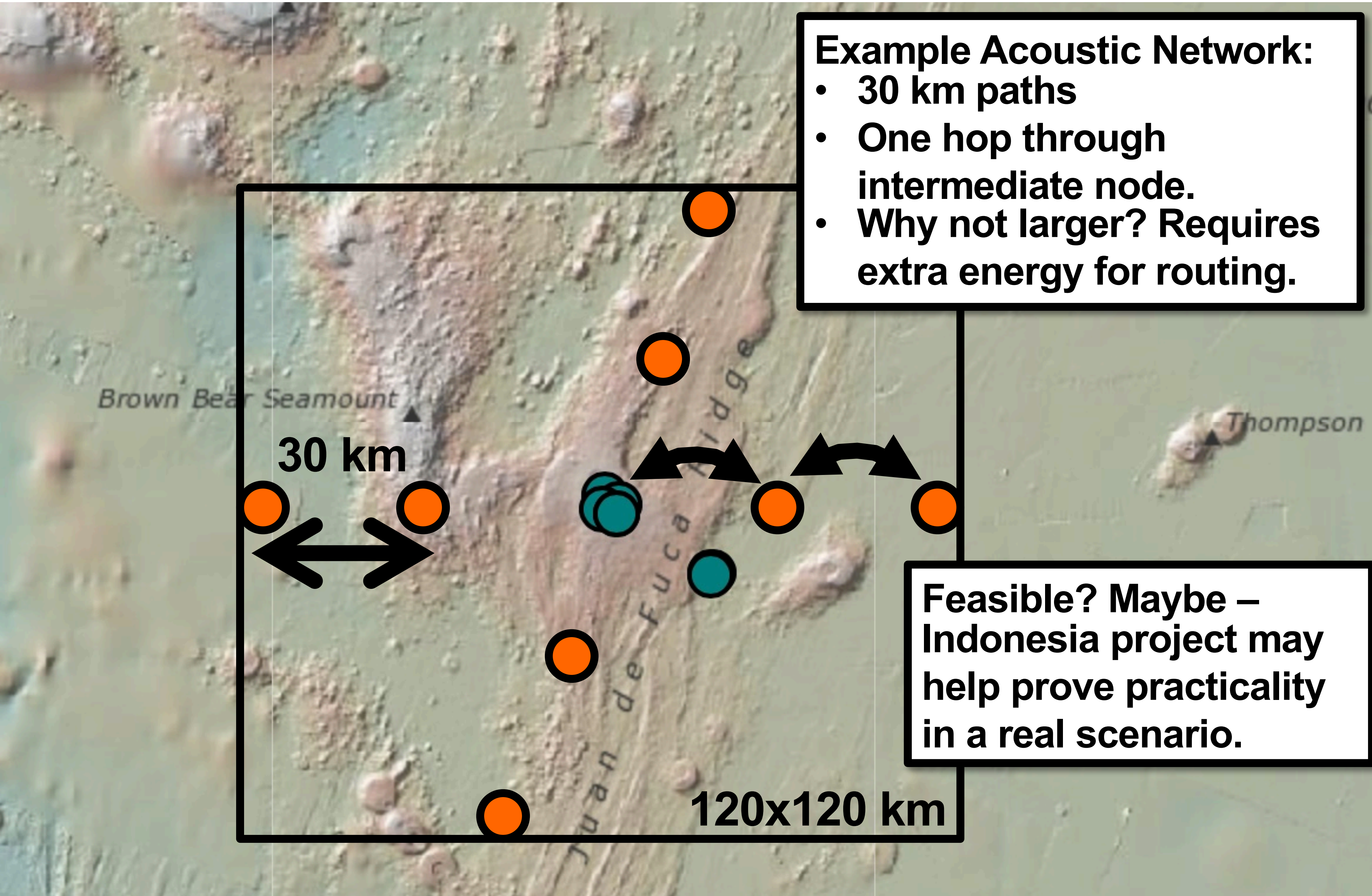


Method from A. Said and W. Pearlman, "A new, fast, and efficient image codec based on set partitioning in hierarchical trees. Circuits and Systems for Video Technology, IEEE Transactions on, 6(3):243–250, Jun 1996.

OOI Cabled Observatory: Cascadia



Acoustic Extensions at OOI Axial Site



Example Acoustic Network:

- 30 km paths
- One hop through intermediate node.
- Why not larger? Requires extra energy for routing.

Feasible? Maybe – Indonesia project may help prove practicality in a real scenario.