Modeling of Tsunami Current Flows

Presenter: Dr. Don Barrick – President, CODAR Ocean Sensors
Coauthors: Dr. Belinda Lipa, Chad Whelan
RIAM Workshop on Oceanographic Radar

- **Tsunami capability of HF radar**
  - **Discovered, reported by Barrick in 1979 – ignored for 25 years**
  - **Interest again after 2004 Banda Aceh: CODAR simulations began**
  - **Real data first captured 2011 from strong Japanese tsunami: 16 SeaSondes as much as 8500 km apart**
  - **Further data from weak 2012 Indonesian tsunami that reached India, Indonesia, and Thailand**
  - **Provides data base for our software development/improvement**
- **Tsunamis are not observed via height – rather by orbital velocity from shallow-water wave physics**

Ultra-Compact New Tx/Rx Antenna

- We started in 1970 with large phased array antennas: 500 m long
- At NOAA, switched to compact two-unit antennas
- Reduced to single mast for higher bands
- Offers most security with minimal impact on coastal property

What Does It Look Like?

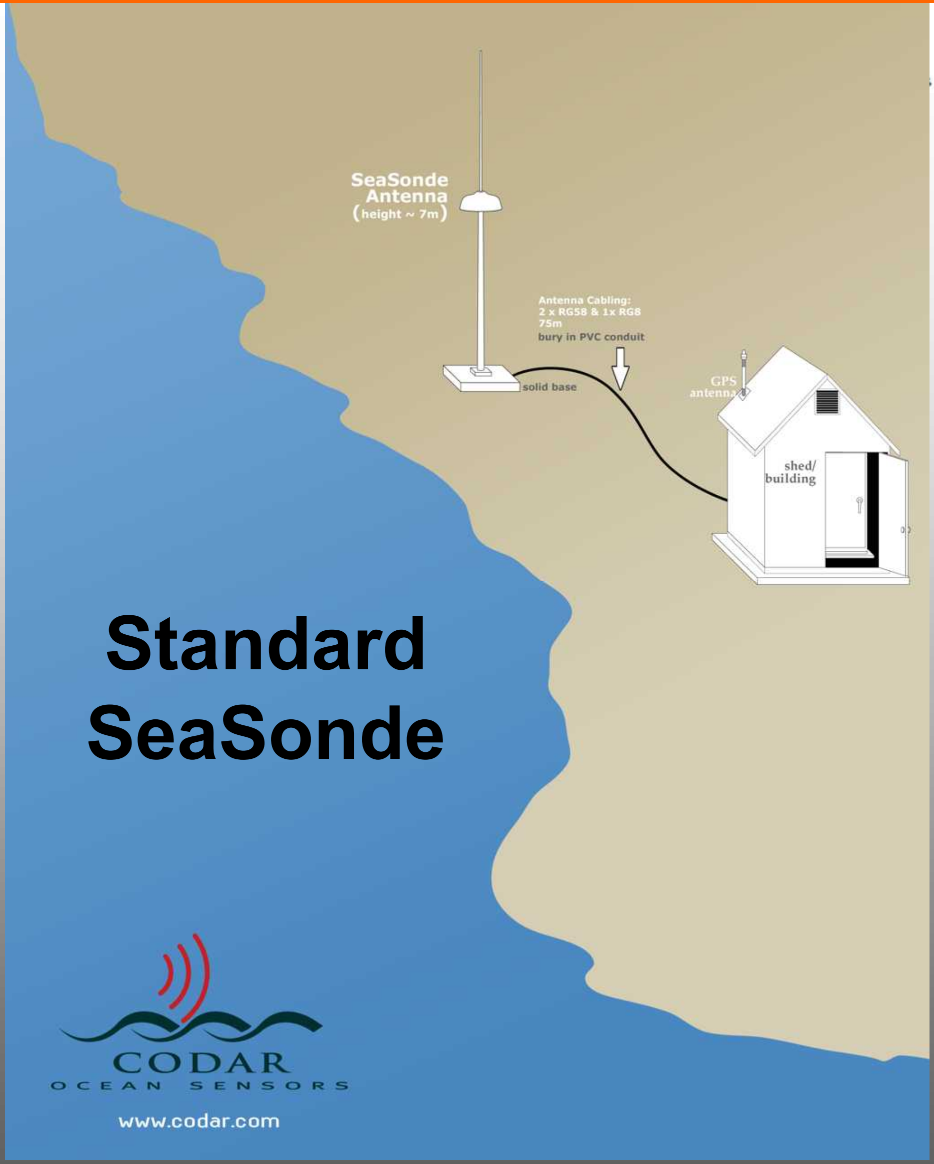
Environmental Enclosure:

1 m x 1 m x 0.5 m

+

Single-Mast

Tx/Rx Antenna



Standard SeaSonde

SeaSonde Tsunami Software Status & Future

- **Version 1: based on theory/simulations after 2004 event**
  - **Pattern recognition based on assumed idealized spatial pattern**
  - **Abandoned after real data captured in 2011 (too idealized)**
- **Version 2: based on recognizing expected temporal patterns in velocity time series, work of Belinda – preparing to install**
- **Version 3: site-specific spatial velocity patterns derived based on local bathymetry -- in progress**
- **Version 4: the ultimate -- combine temporal/spatial recognition**

Version 3: Understand Space-Time Tsunami Patterns Based on Bathymetry/Hydrodynamics

Underlying Equations and Resulting PDEs

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Work of Dr. Don Barrick

- **Navier-Stokes Dominant Terms** (Newton's force/acceleration terms)

$$\nabla \eta(x,y,t) = -\frac{1}{g}\frac{\partial \tilde{v}(x,y,t)}{\partial t}$$

- **Incompressibility of Water**

$$\nabla \cdot \left[\left(d(x,y)+\eta(x,y,t)\right)\tilde{v}(x,y,t)\right] = -\frac{\partial \eta(x,y,t)}{\partial t}$$

- **Resulting Time-Dependent Shallow-Water Hyperbolic PDE Wave Equations**

$$\nabla\nabla\cdot(d\tilde{v}) - \frac{1}{g}\frac{\partial^2 \tilde{v}}{\partial t^2} = \tilde{0}$$

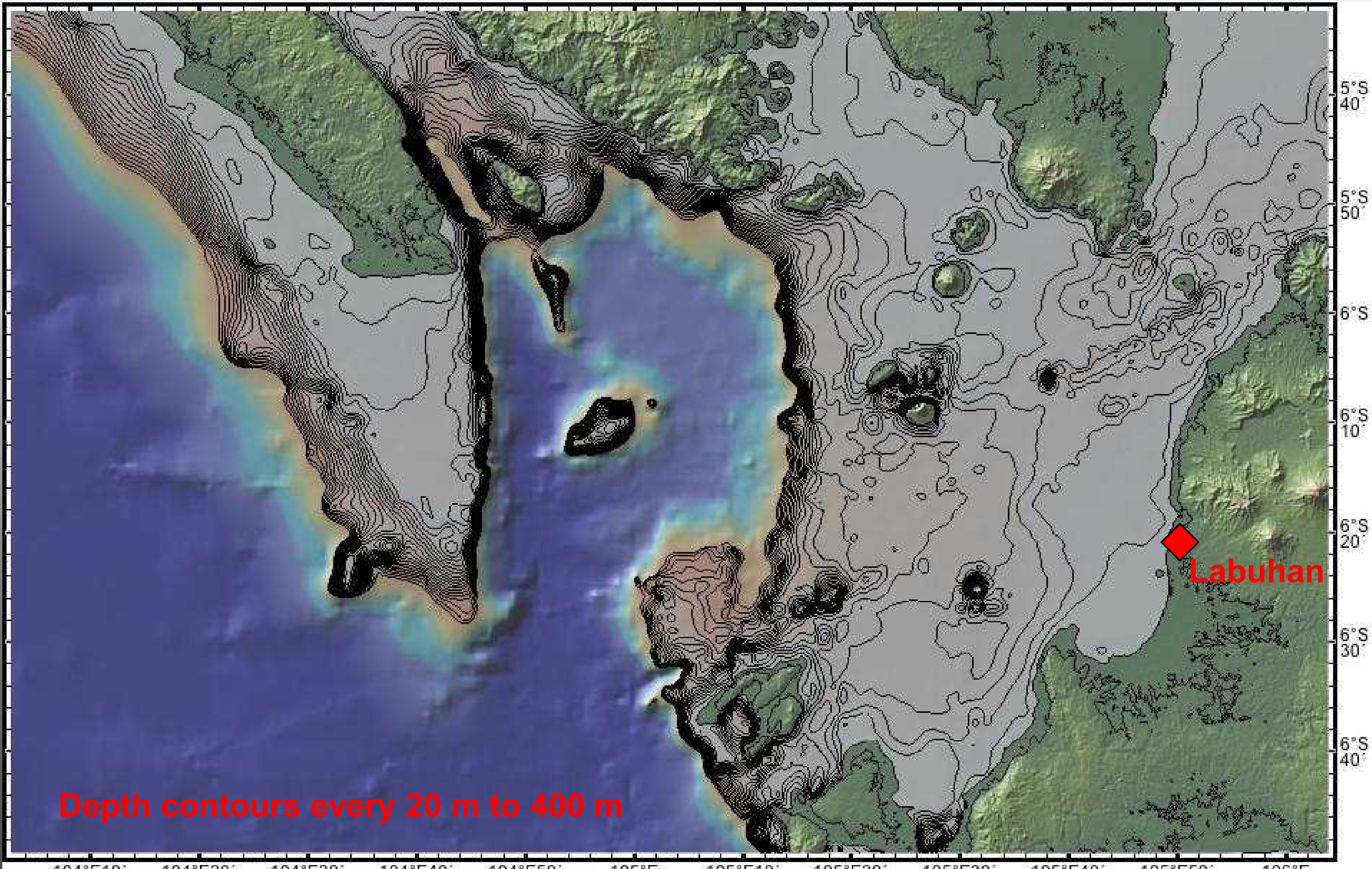
Vector Equation for Velocity

$$\nabla\cdot(d\nabla\eta) - \frac{1}{g}\frac{\partial^2 \eta}{\partial t^2} = 0$$

Scalar Equation for Height

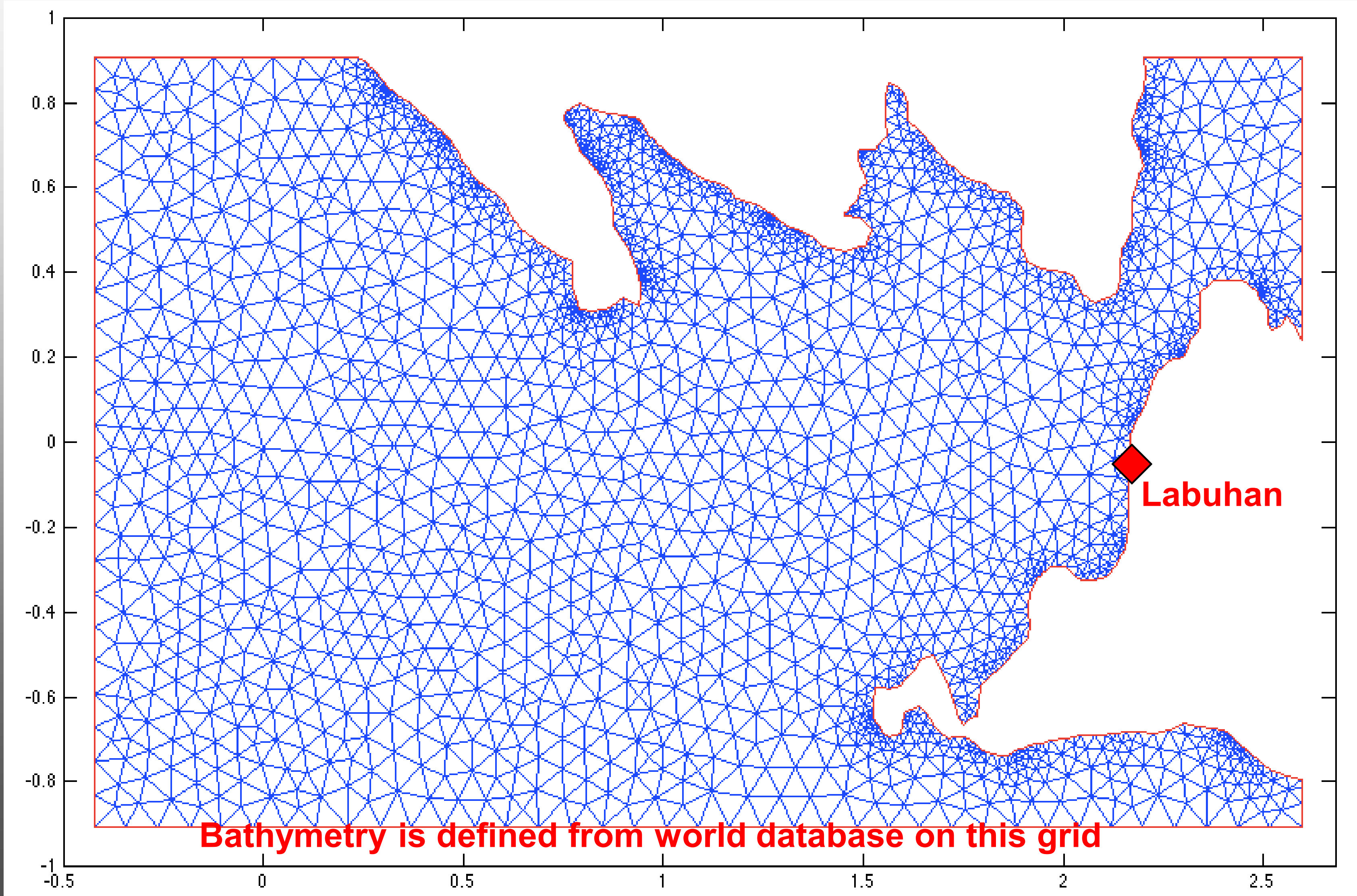
Application to Real Bathymetry in Sunda Strait
Area of Interest: Near Labuhan

- **Shallow bathymetry between Sumatra and Java gives longer observation times**



Differential Equations for Height and Velocity Are Solved on Finite Element Grid Below

- **Scalar height PDE solved on grid. From this the velocity is determined**
- **Solved in MATLAB on Macbook Air laptop**



Sunda Tsunami Height / Velocity Evolution

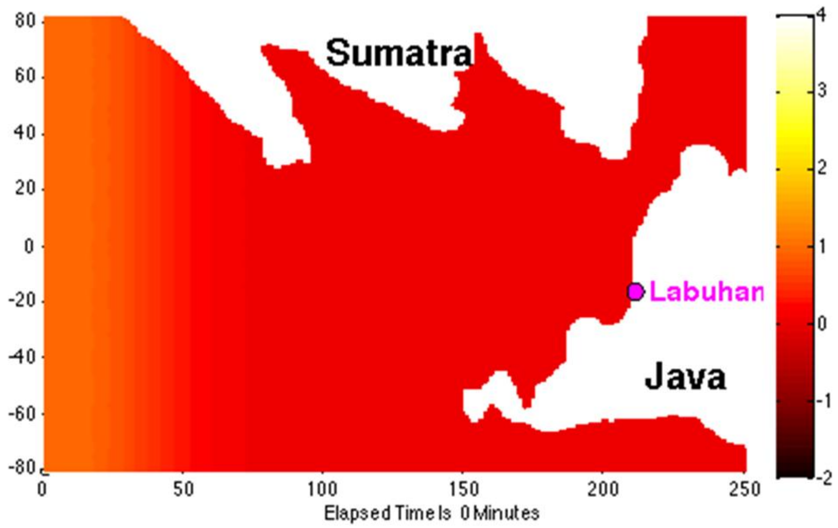
- Tsunami comes from West to East & refracts into Sunda Strait
- The radar measures the velocity (on the right)
- People care about the tsunami height (on the left)
- Go from radar-measured velocity to height through the equations

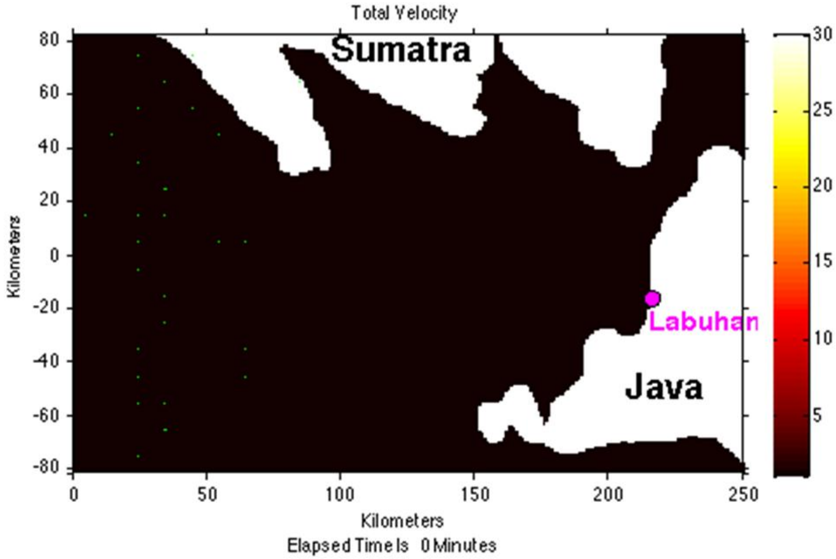
Tsunami Height Profile

- Normalized height scale on right

Tsunami Velocity Profile

- Absolute velocity color bar on right
- Velocity vectors/colors normalized





Radial Velocity Pattern Seen by Single Site

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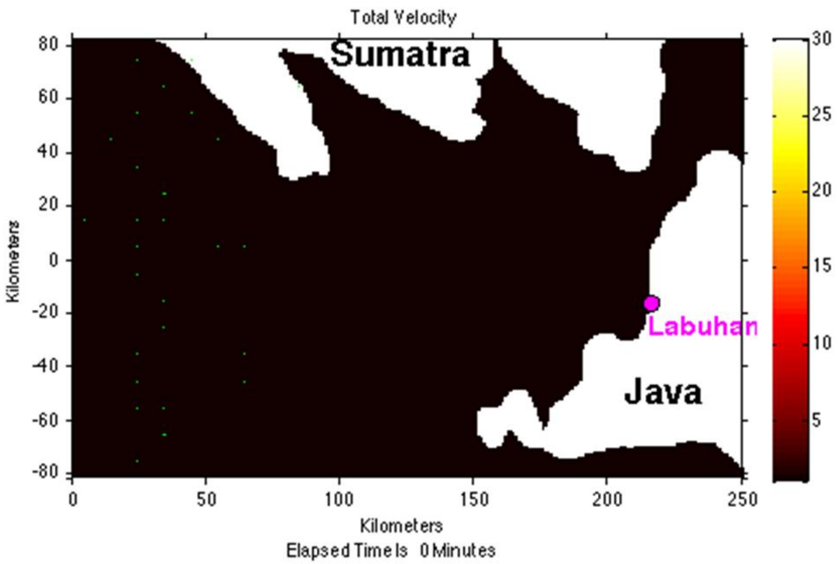
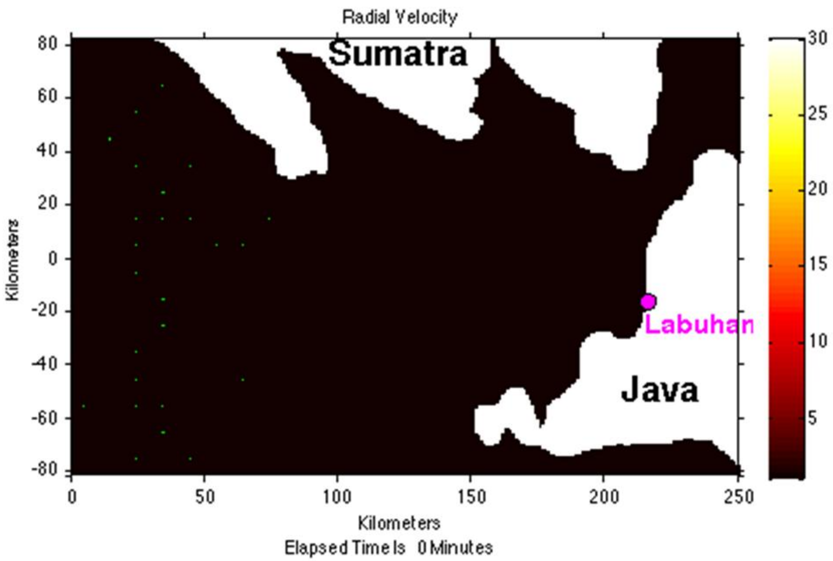
- **Greater utility and robustness if each radar observes tsunami independently**
- **Unique radial velocity pattern is seen, guided by bathymetry**
- **Total velocity & height to be reconstructed from radials via defining equations and bathymetry**

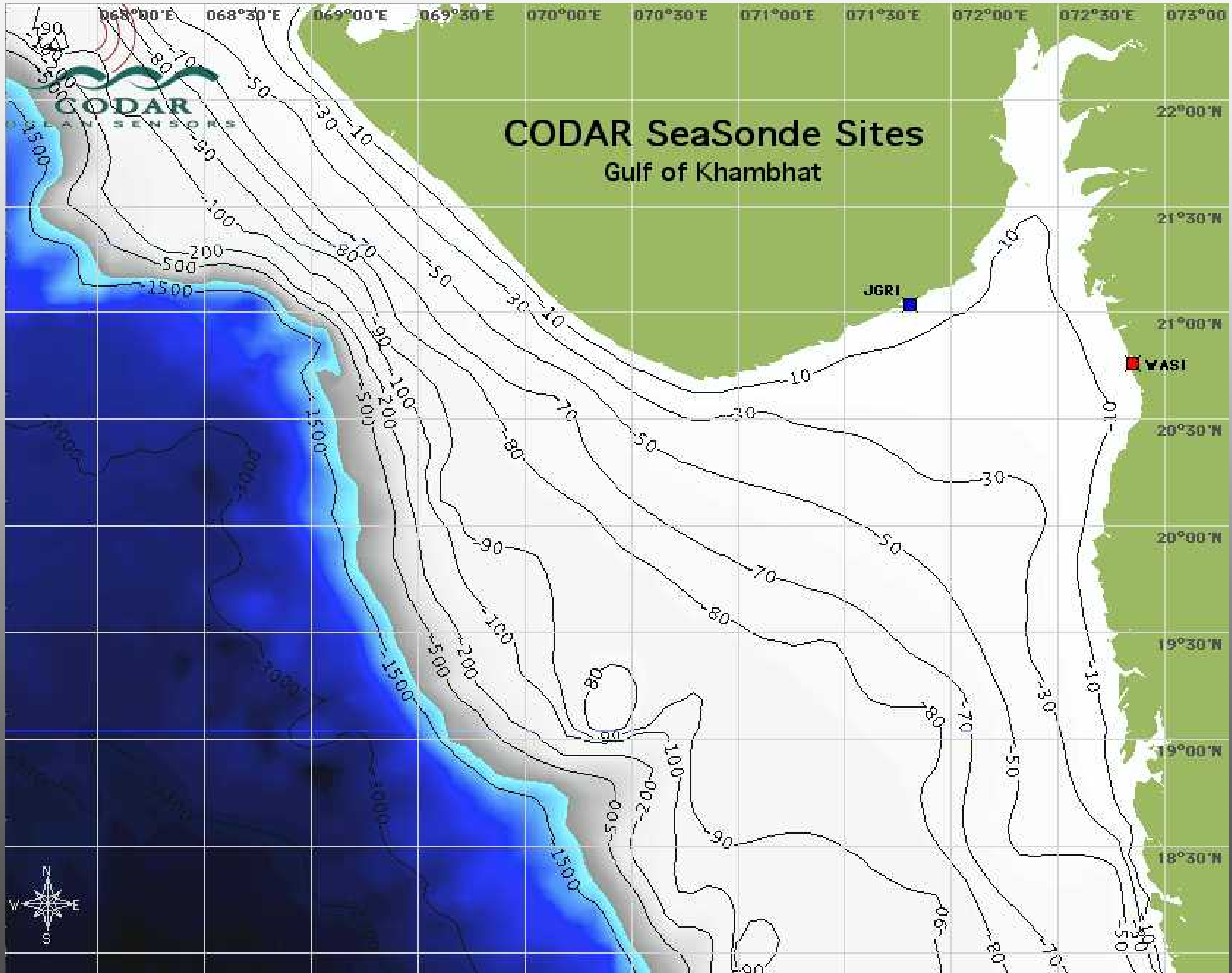
Total Velocity Profile **Radial Velocity Profile**





Application to Real Bathymetry: Gulf of Khambhat
Two SeaSonde Sites: Jegri & Wasi-Boursi

- Very shallow water over all of Gulf: Much wider area than Sunda Strait

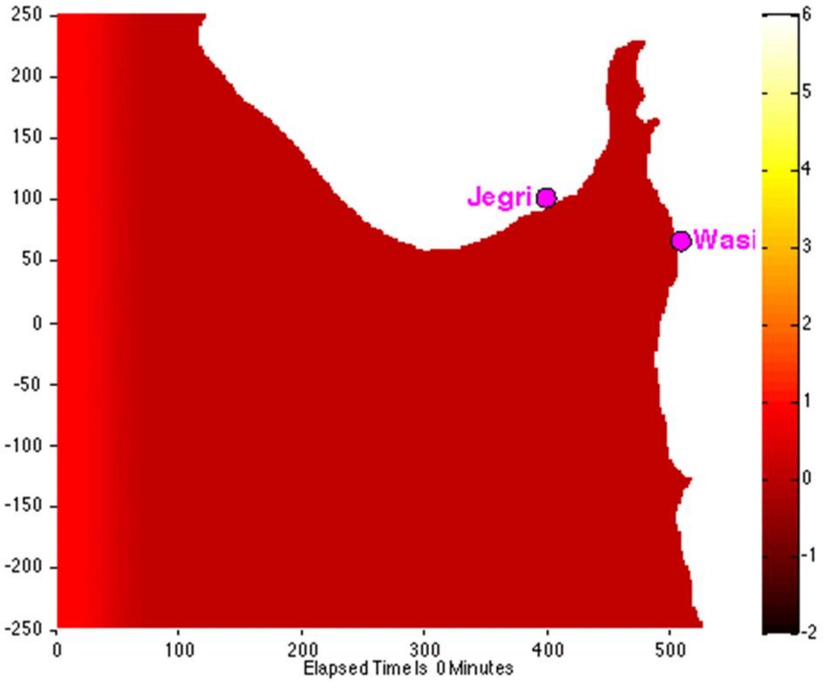


Khambhat Tsunami Height/Velocity Evolution

- Tsunami comes from West to East & refracts into Gulf
- The radar measures the velocity (on the right)
- People care about the tsunami height (on the left)
- Go from radar-measured velocity to height through the equations

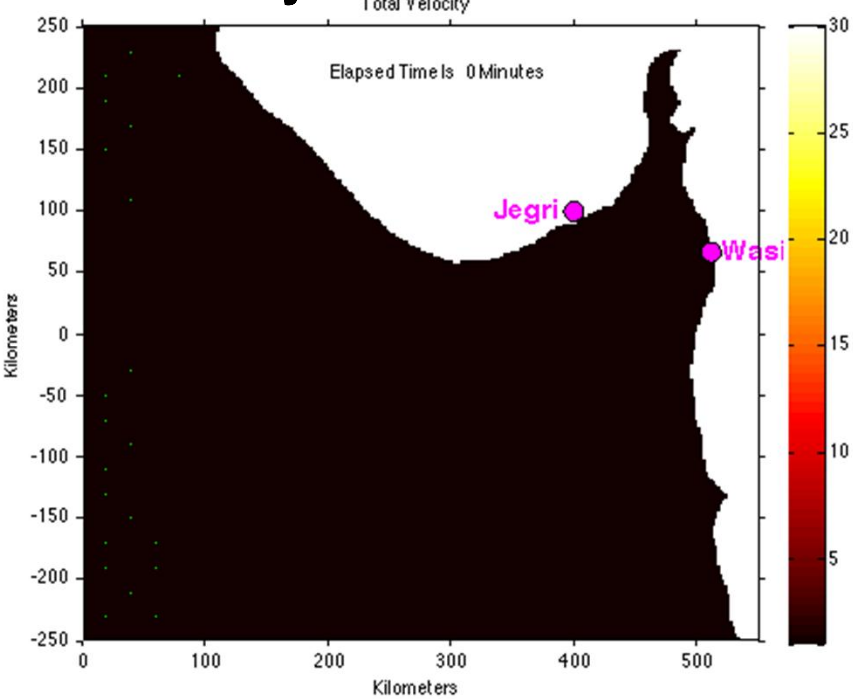
Tsunami Height Profile

- Normalized height scale on right



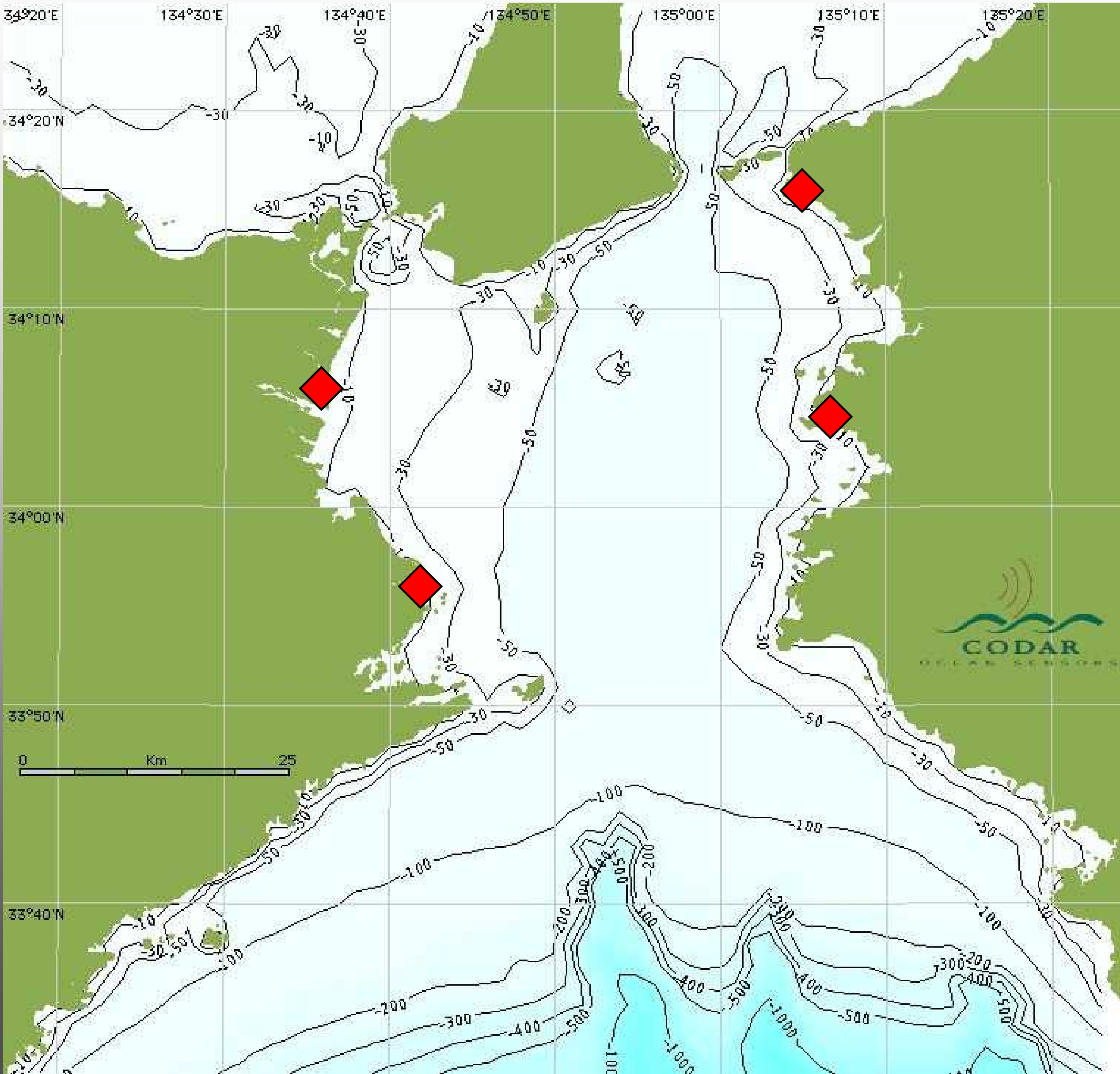
Tsunami Velocity Profile

- Absolute velocity color bar on right
- Velocity vectors/colors normalized



Application to Kii Channel, Japan: Two SeaSondes HF Radars in Place

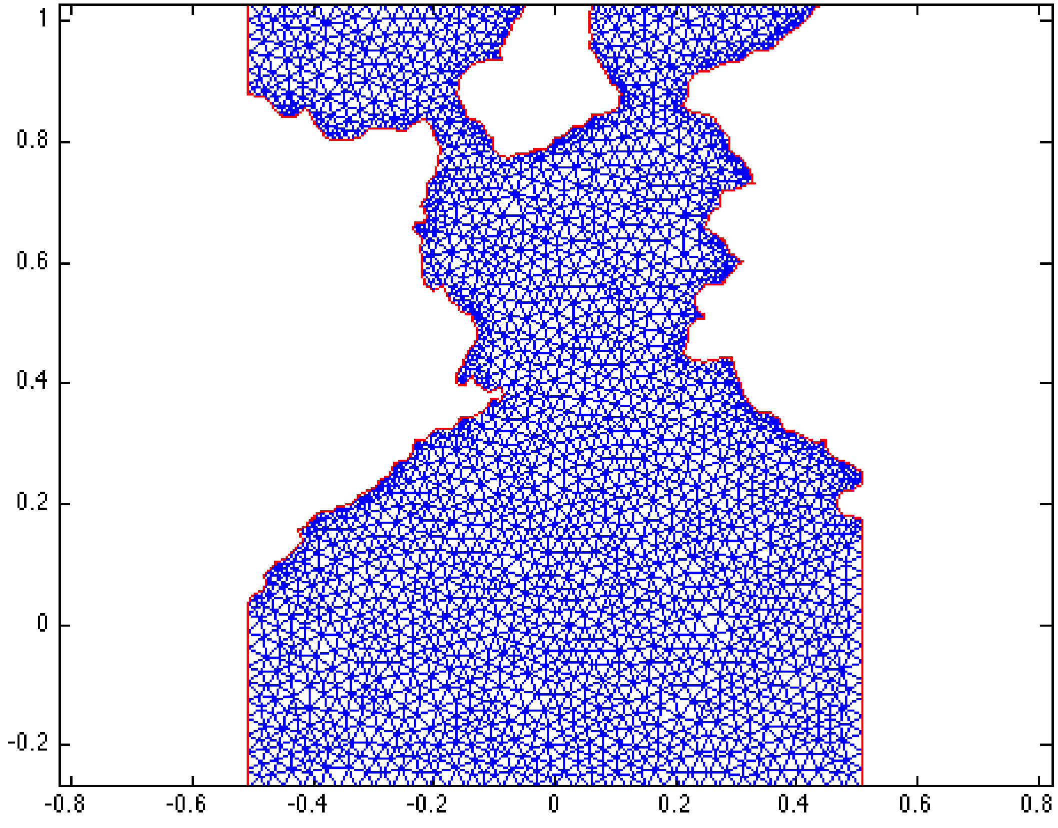
- **Tsunami approached from the South**
- **Coastal boundaries on three sides and shallow bathymetry gave rise to complex oscillatory behavior**
- **Radars on both sides observed the tsunami, confirmed by tide gages**
- **PDE modeling captures the complex behavior**



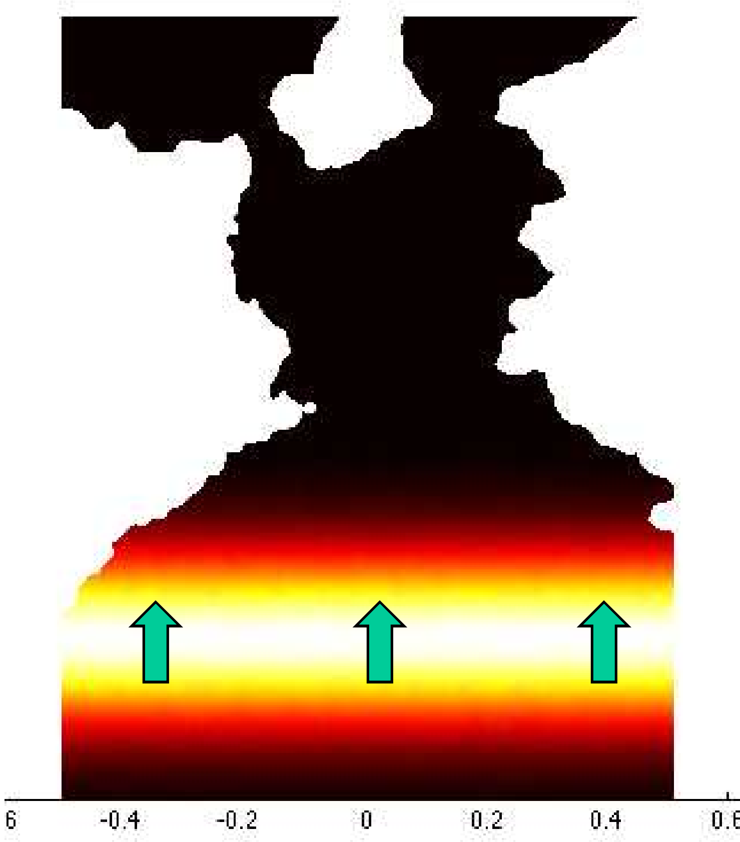
PDE Solution: FEM Grid and Initial Condition

- Single tsunami wave propagates into Channel from South
  - Green's function approach, i.e., "delta function" approximation

Finite-Element Solution Grid



Height Initial Condition

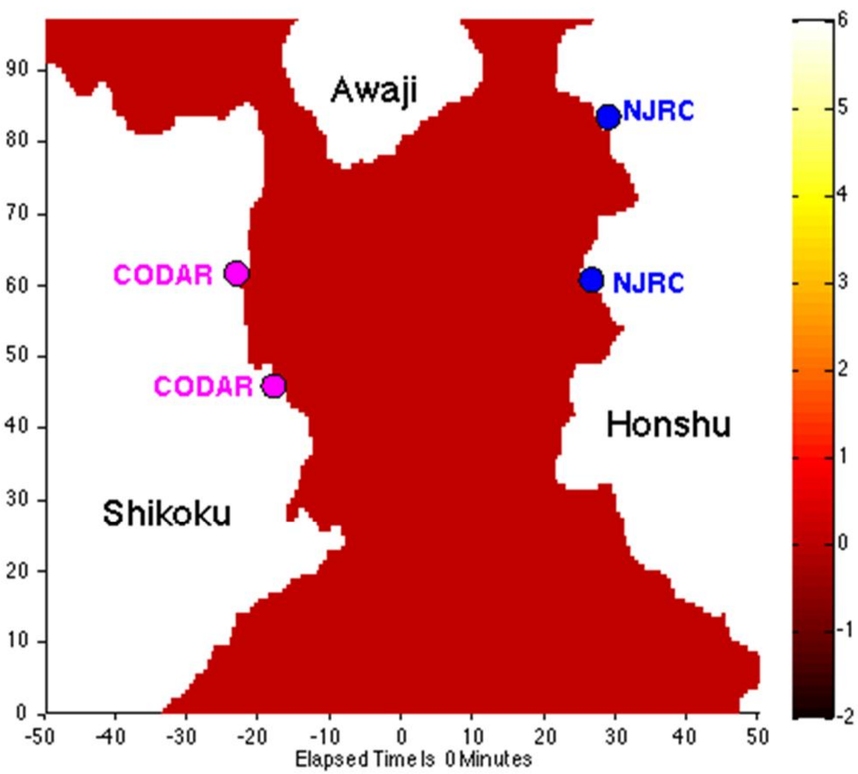


Kii Channel Tsunami Height/Velocity Evolution

- Tsunami comes from South, refracts, slows by shallow bathymetry
- Reflections from coasts, Awaji Isl, and steep bathymetry slope

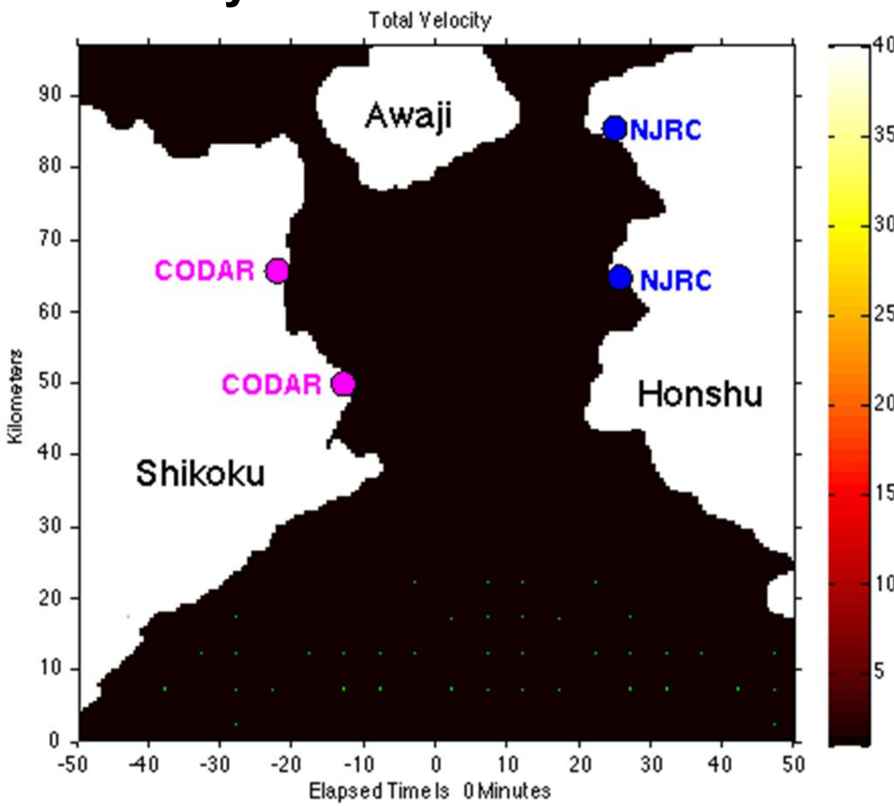
Tsunami Height Profile

- Normalized height scale on right



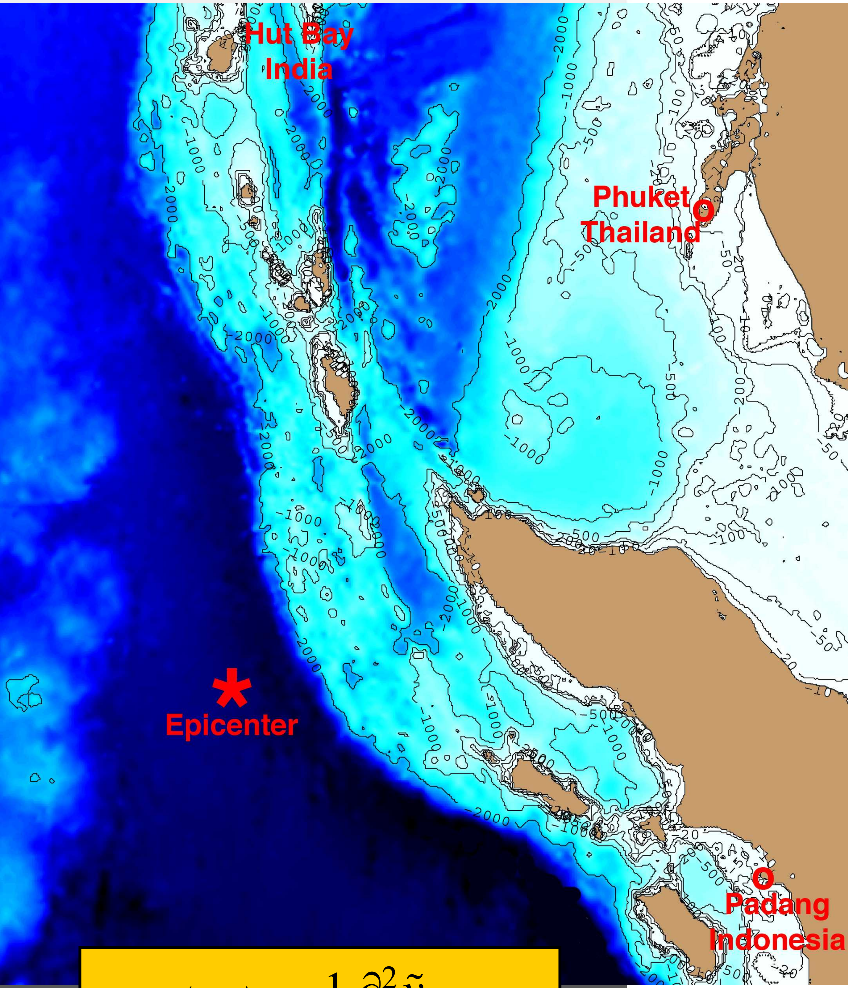
Tsunami Velocity Profile

- Velocity strength color bar on right
- Velocity vectors/colors normalized

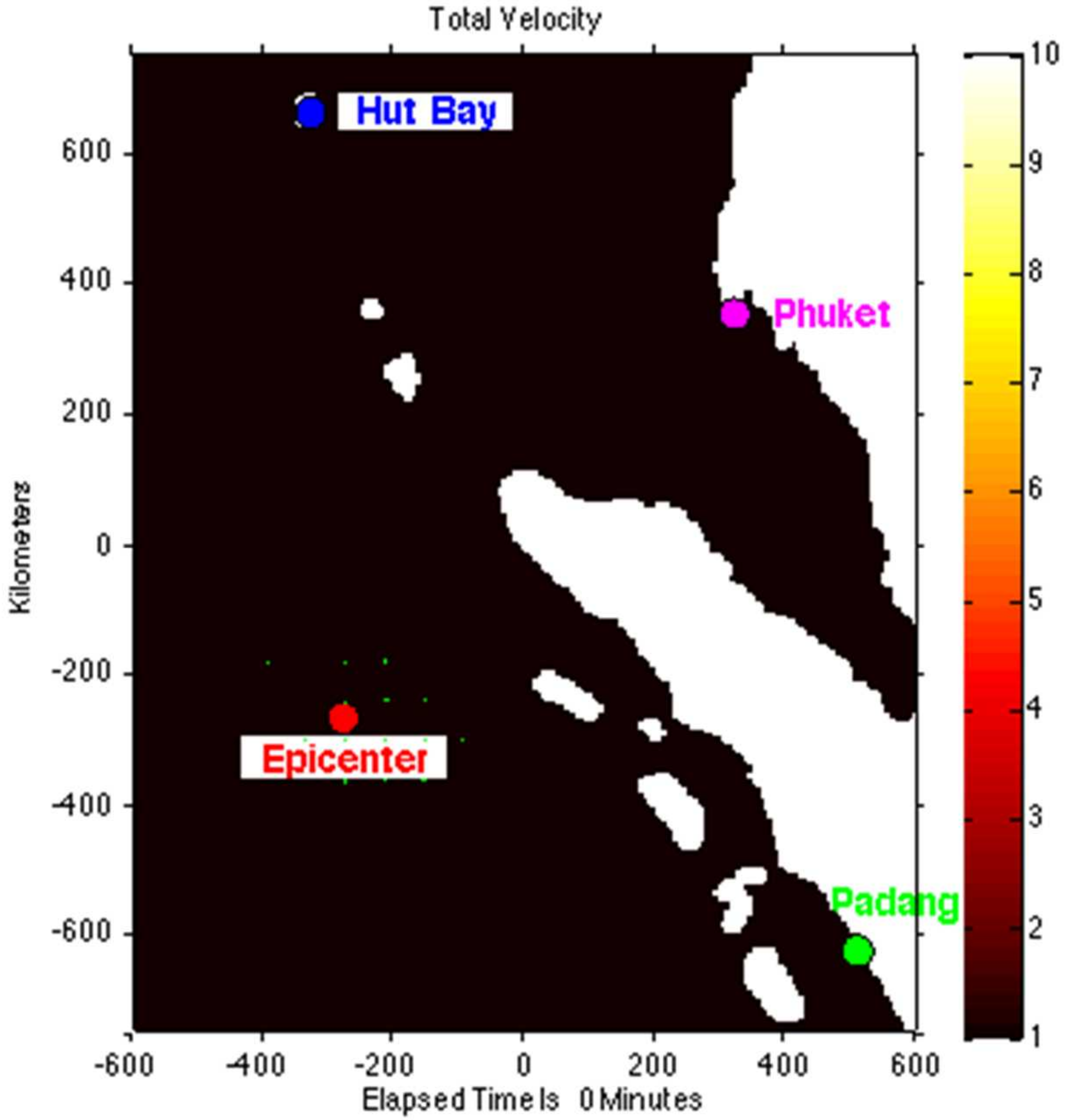


8.6 April 2012 Indonesia Event & Weak Tsunami

- **Propagation & arrival depends on bathymetry (depth)**
- **Movie shown is velocity, calculated from model equation used by all**



$$\nabla\nabla\cdot\left(d\tilde{v}\right) - \frac{1}{g}\frac{\partial^2 \tilde{v}}{\partial t^2} = \tilde{0}$$



What Does SeaSonde Contribute to Tsunami Management/Mitigation?

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- Should it be considered a "stand-alone" warning system? No!
- Seismic warning is first signal – however this does not indicate strength of tsunami
- "Far-Field" (deep-ocean-basin) measurements are next, where possible: bottom pressure sensors and satellite altimetry
- The above are integrated into models that provide coarse warning
- "Near-Field" (coastal) sensors are final important observations:
  - HF radars (SeaSondes) and tide gages
  - These provide local expected variations before final impact/runup
- Reduce false alarm rates and increase accuracy among all sensors
- These must be integrated/coordinated in national warning center

Improvements Needed and Underway in CODAR's Q-Factor Tsunami Algorithms

- **Integrate our spatial propagation/evolution models into Q-Factor time-detection algorithm for better warning**
- **Predict impact time at local radar coastal region from offshore advance SeaSonde velocity observations**
- **Predict expected local heights from radar velocity observations**
- **Decrease false alarm rate and spurious information from radar and other sensor inputs**

CODAR's Two-Pronged Approach to Tsunami Software for HF Radar

- **Provide alert to warning center before first arrival of waves at the coast (Belinda Lipa's algorithms)**

- **Develop longer-term PDE model applied to data to explain spatial-temporal evolution after first arrival, i.e., resonance & interaction of incoming/reflected waves (Don Barrick's algorithms)**