HF Radar Near-Field Tsunami Observation Promise

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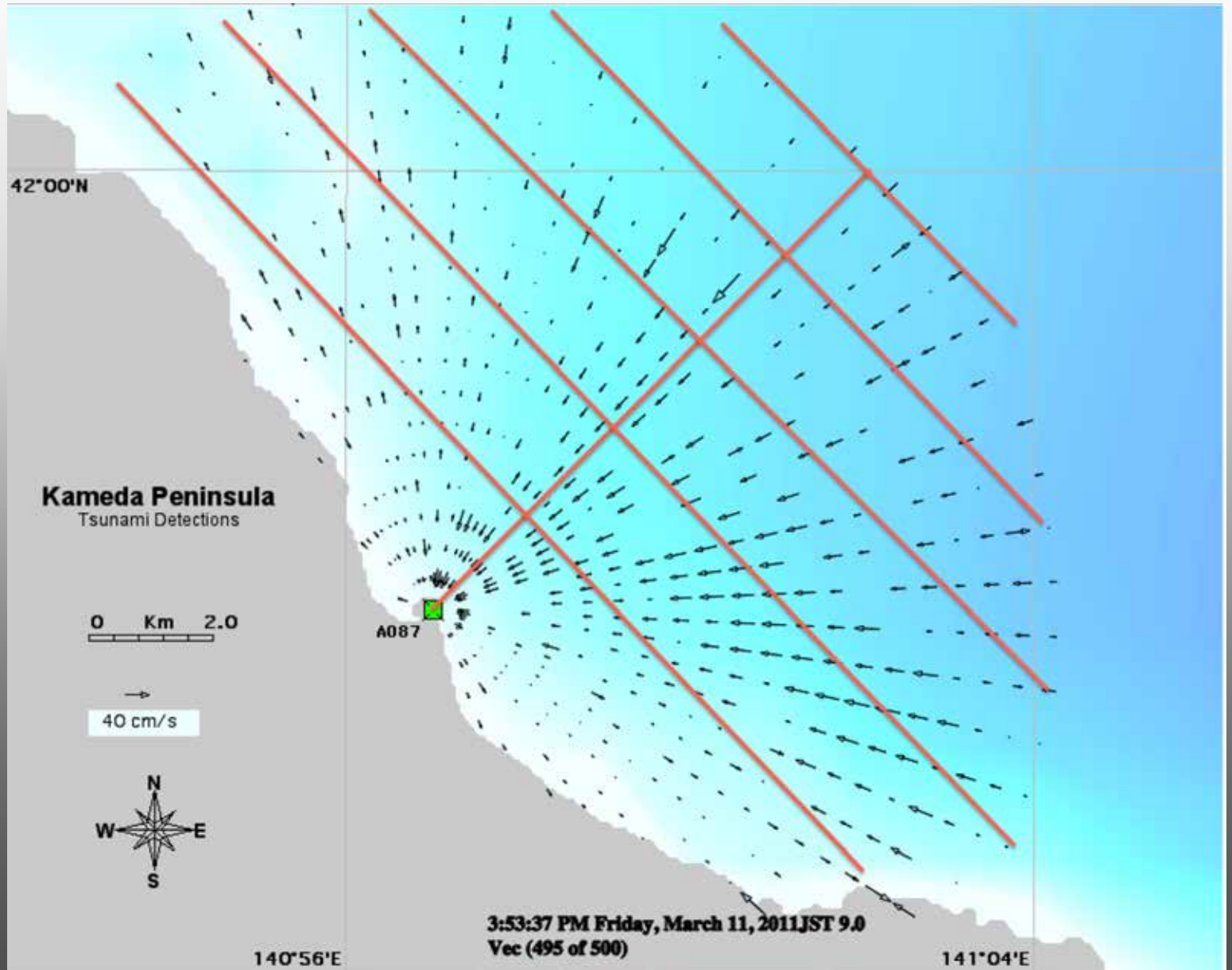
NTHMP Workshop -- February 10, 2015

- **Tsunami capability of CODAR HF radars**
  - **Discovered, reported by Barrick in 1979 – ignored for 36 years**
  - **Interest after 2004 Banda Aceh: CODAR simulations began**
  - **Real data first captured 2011 from strong Japanese tsunami: 18 SeaSondes as much as 8500 km apart**
  - **Further data from weak 2012 Indonesian tsunami that reached India, Indonesia, and Thailand**
  - **June 2013 U.S. East Coast Meteotsunami – 45-min warning**
  - **Provides data base for our software development/improvement**
- **Tsunamis are <u>not</u> observed via height – rather by orbital velocity from shallow-water wave physics**

$$v_p(d) \propto hd^{-3/4}$$

$$h_s(d) \propto hd^{-1/4}$$

Example for Hokkaido of Bands and Fitting of Radials from Single SeaSondes



Alert Software: Temporal Pattern Recognition Outputs a "Q-Factor" Trigger

Work of Dr. Belinda Lipa: 'Tsunami Arrival Detection with HF Radar', *Remote Sensing, 4*, 2012

- **Several steps are inherent in algorithm**
- **Must separate distinctive but possibly weak tsunami pattern from stronger background currents**
- **Must minimize false alarm rate (P_{fa}) while maximizing detection probability (P_d)**
- **Tsunami detection "Q-Factor" is product of three functions based on known characteristics of tsunami velocity signals**

Objective: Increase P_d while decreasing P_{fa}

Tested with 14 SeaSondes in All 4 Frequency Bands That Saw 2011 Japan Tsunami

- Upper Table: Japan SeaSonde Observations
- Lower Table: U.S. West Coast SeaSonde Observations
- Latest Alert Software Installed in Asia
- Warning Alert Time Critically Depends on Offshore Bathymetry

Radar (XMTR Freq)	*Arrival time (JST)*	*Ground instrument*	*Arrival time (JST)*	*Water-level change*
A088 (42Mhz)	15: 49	Hakodate tide gauge	16:32	2.0m
A087 (42Mhz)	15: 54	Hakodate tide gauge	16:32	2.0m
TOKU* (25Mhz)	17:29	KO* wave gauge	17:24	0.5m
ANAN* (25Mhz)	17:25	KO* wave gauge	17:24	0.5m

Radar (XMTR Freq)	*Arrival time (UTC)*	*Tide gauge*	*Arrival time (UTC)*	*Water-level change*
STV2 (12Mhz)	15:32	Garibaldi	15:48	1.2m
SEA1 (12Mhz)	15:47	Garibaldi	15:48	1.2m
YHS2 (12Mhz)	15:45	South Beach	15:54	0.3m
TRIN (5Mhz)	15:34	Crescent City	15:48	0.5m
GCVE (14Mhz)	15:44	Pt. Reyes	16:00	0.5m
BML1 (12Mhz)	15:46	Pt. Reyes	16:00	0.5m
PREY (13Mhz)	15:49	Pt. Reyes	16:00	0.5m
COMM (13Mhz)	15:56	Fort Point	16:30	0.4m
ESTR (13Mhz)	16:04	Port San Luis	16:24	2.0m
LUIS (13Mhz)	16:05	Port San Luis	16:24	2.0m

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

Underlying Equations and Resulting PDEs

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**

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

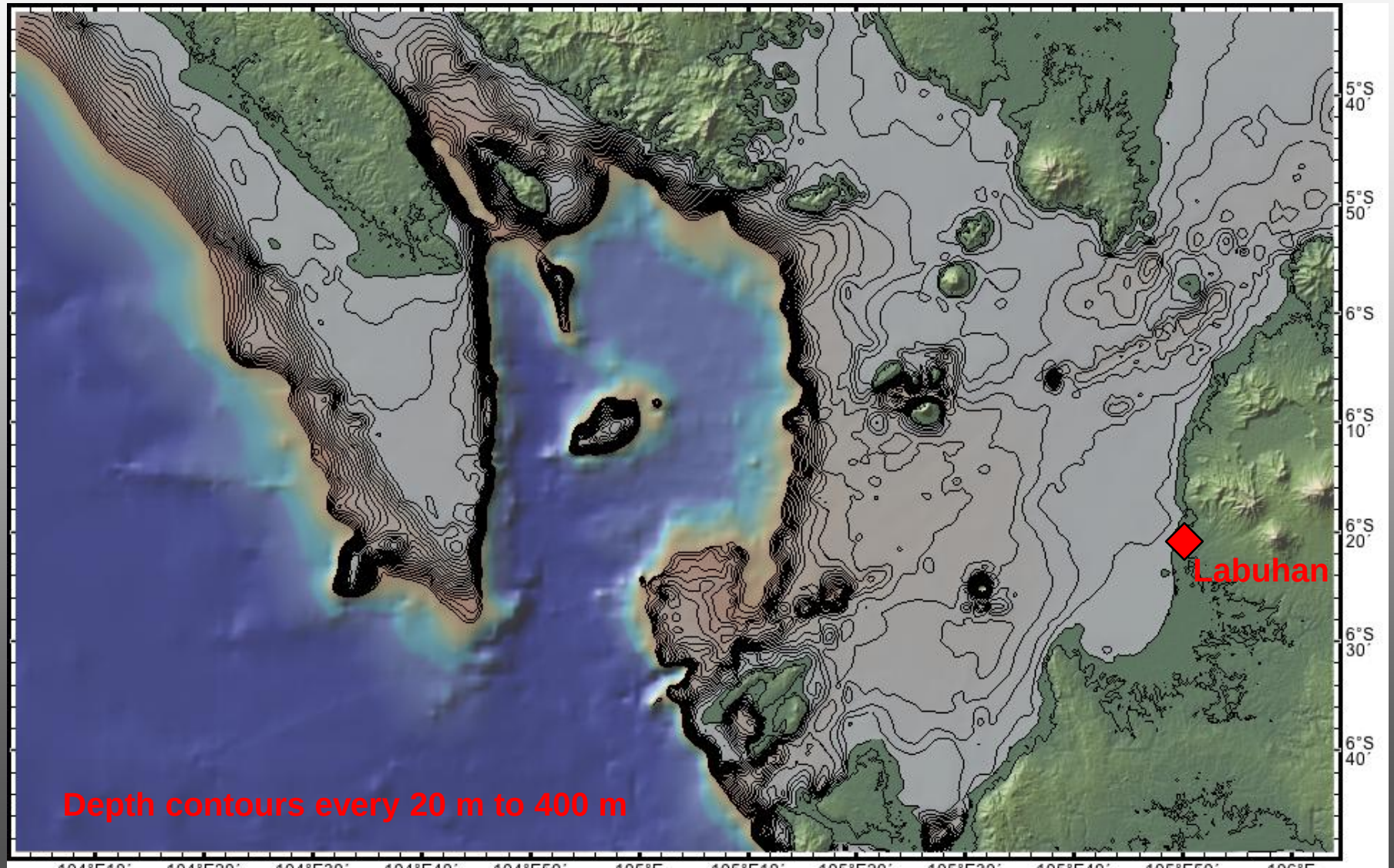
Vector Equation for Velocity

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

Scalar Equation for Height

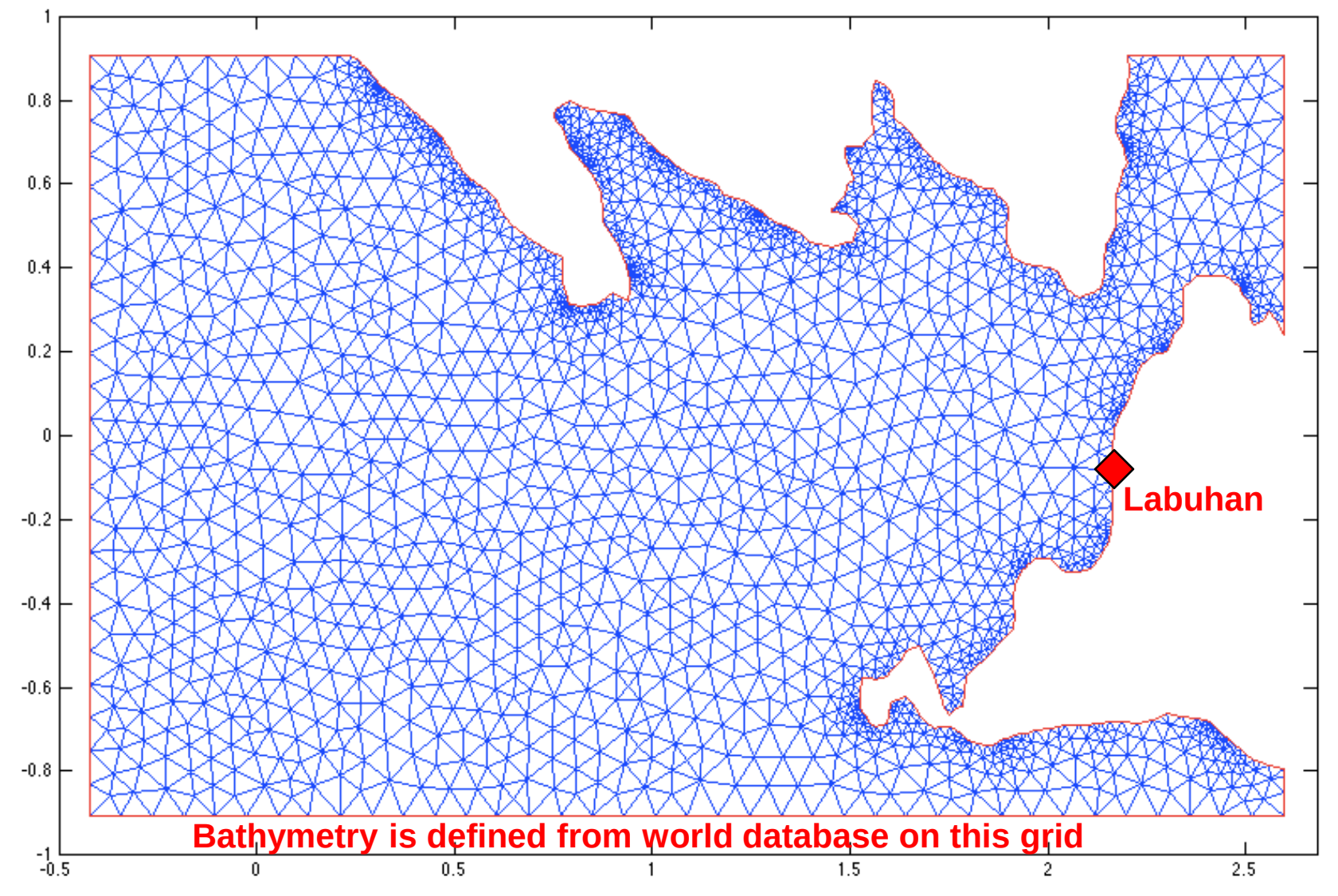
Application to Real Bathymetry in Sunda Strait
Area of Interest: Near Labuhan

- **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**



Sunda Tsunami Height / Velocity Evolution

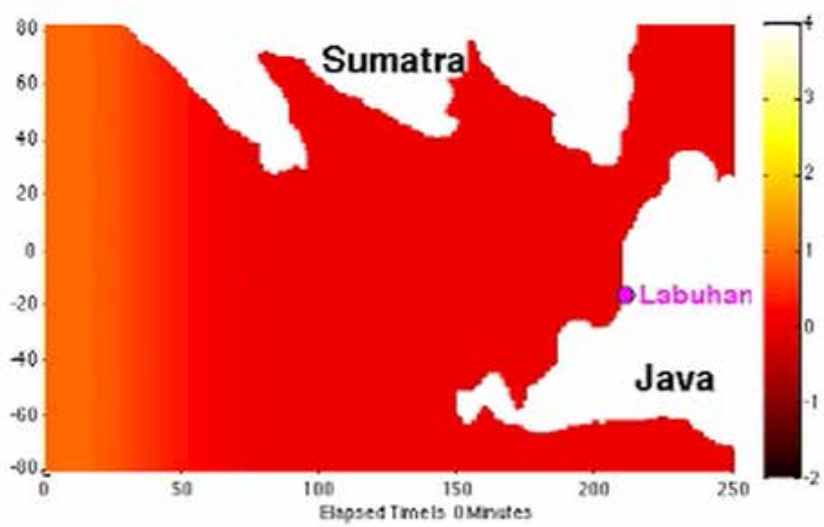
- Tsunami comes from West to East & refracts into Sunda Strait
- The radar measures the velocity (on the right)
- People care about the tsunami height (on the left)
- Go from radar-measured velocity to height through the equations

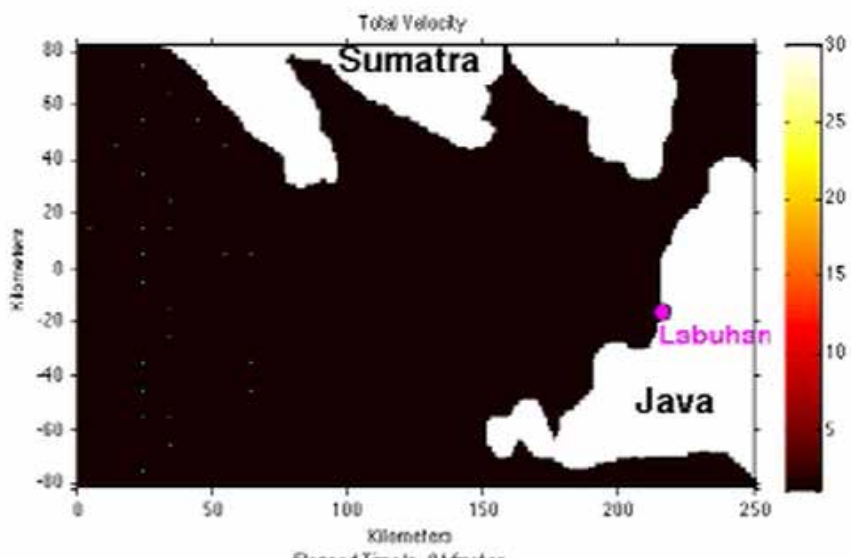
Tsunami Height Profile

- Normalized height scale on right

Tsunami Velocity Profile

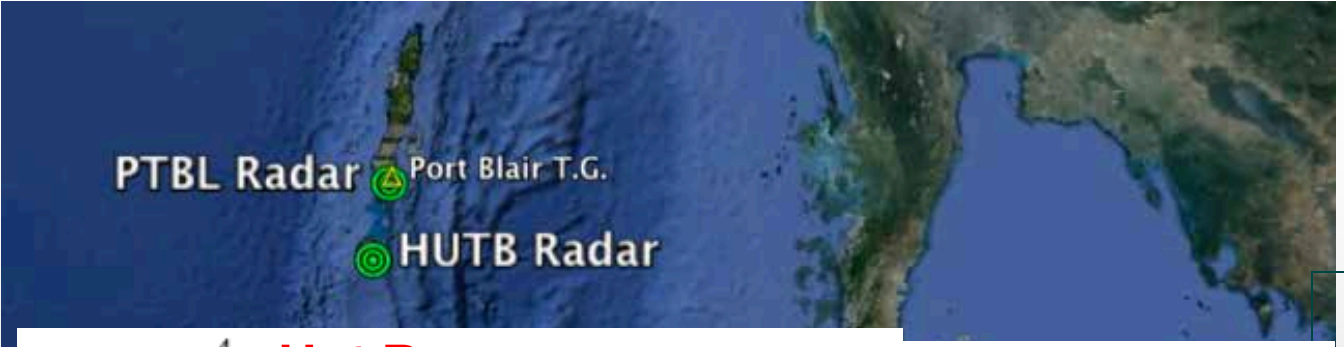
- Absolute velocity color bar on right
- Velocity vectors/colors normalized

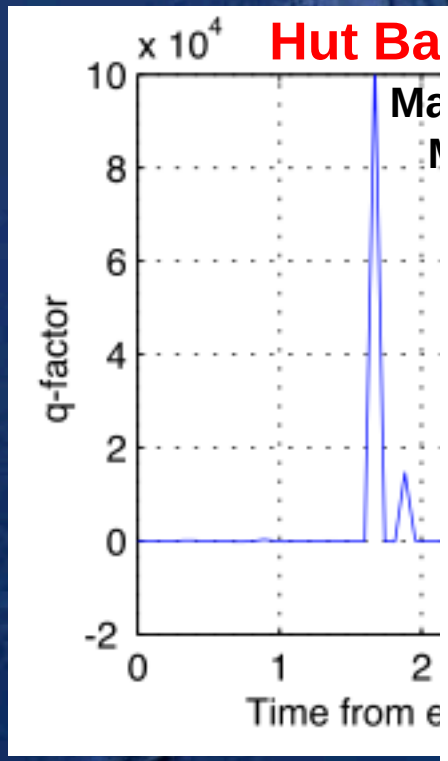


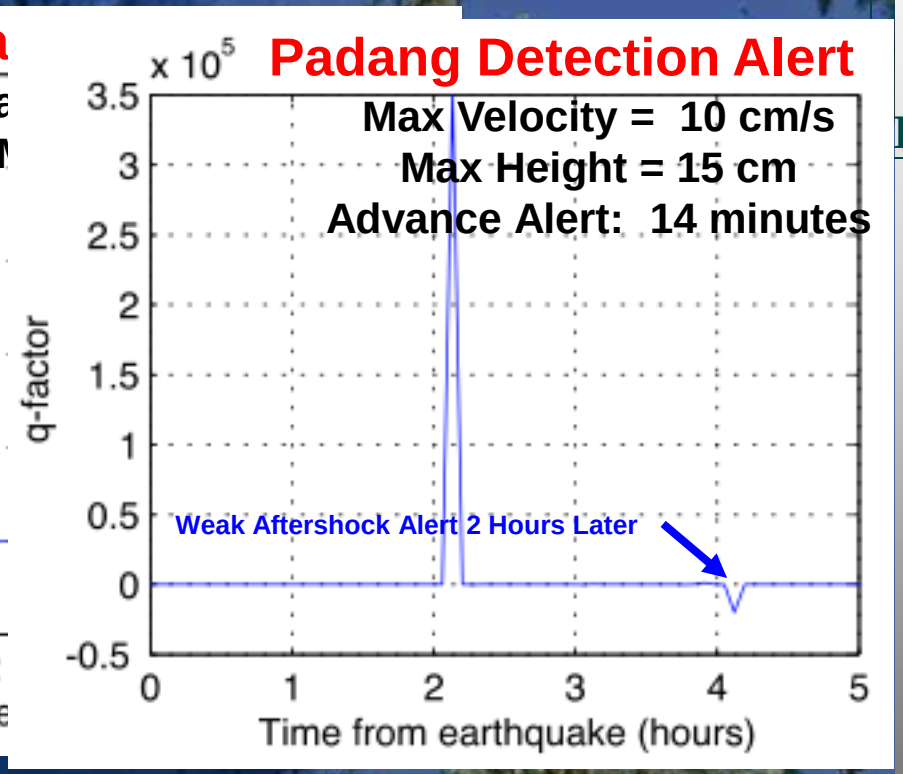


SeaSonde Detections of Weak Tsunamis:

Indian Ocean April 11, 2012



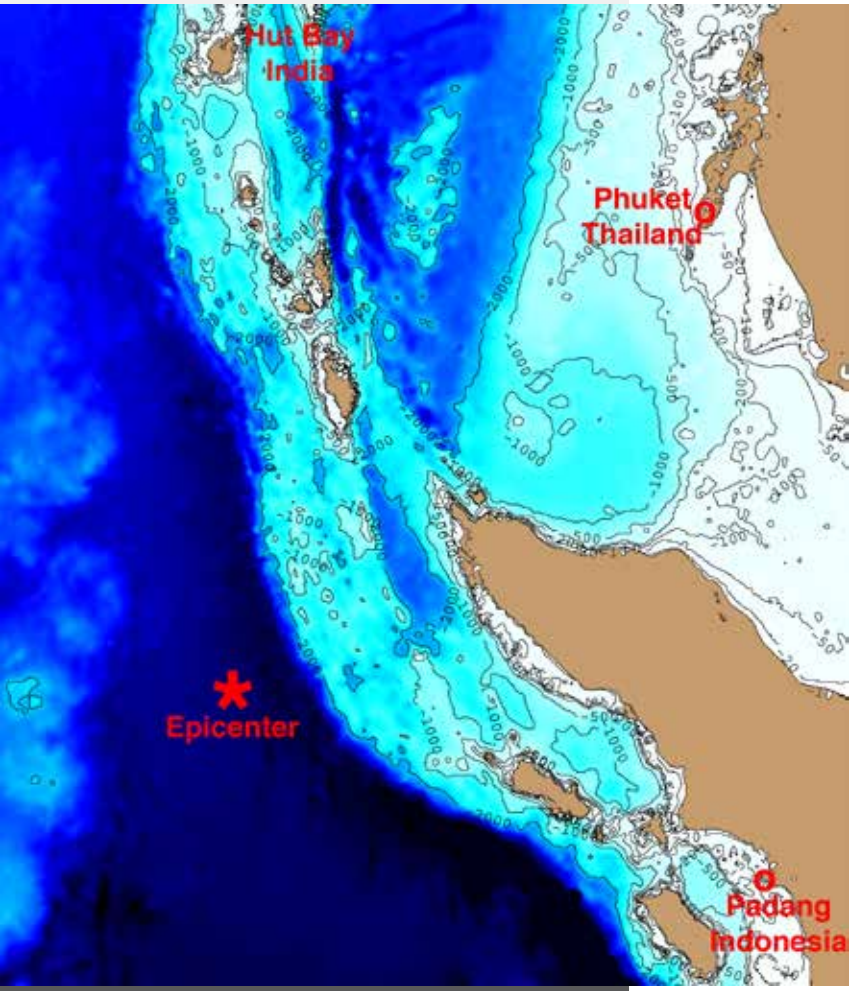


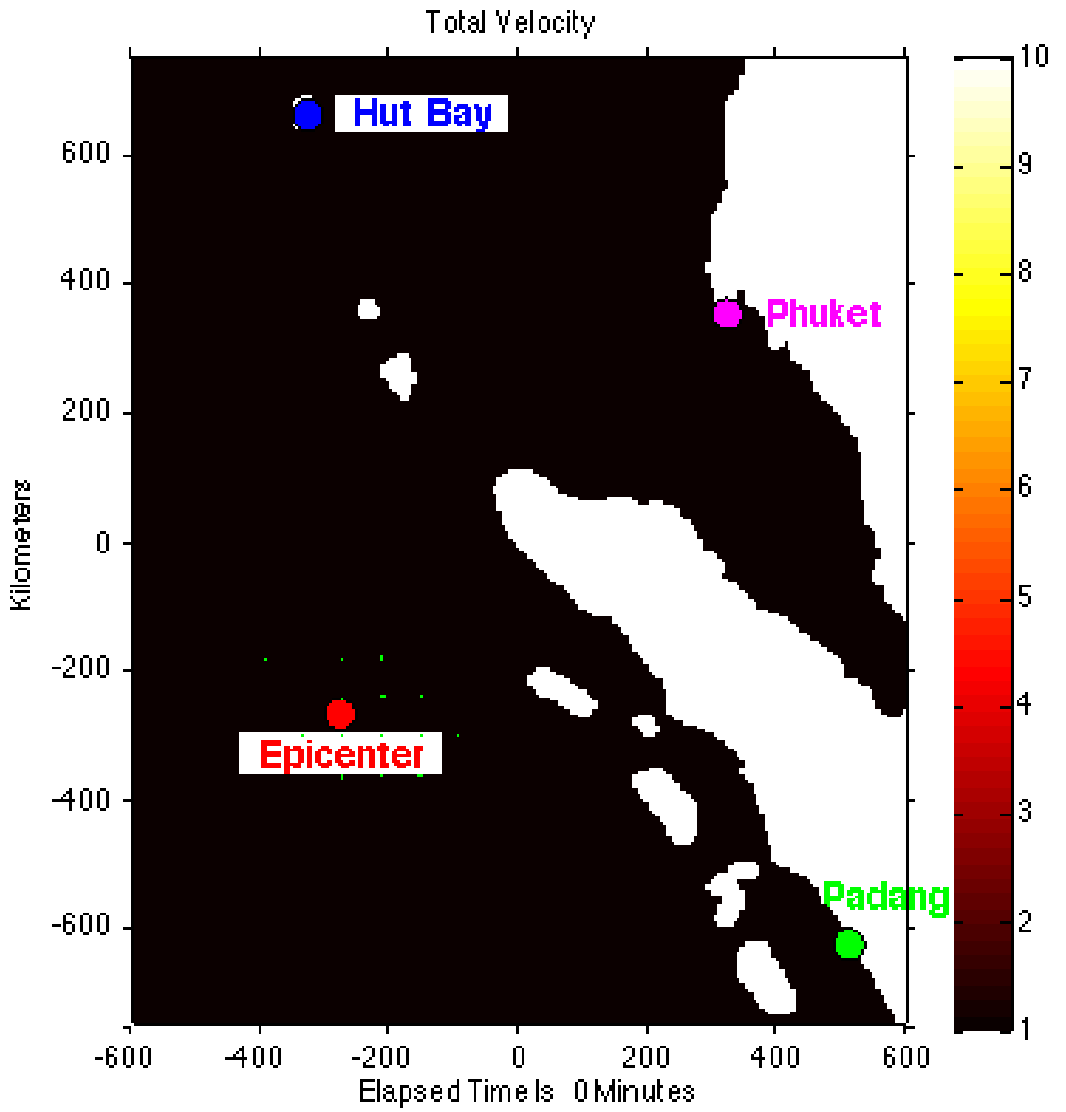


Q-Factor Algorithm Detects Tsunami Arrival by Single Radar after Earthquake

Weak April 2012 Indonesia Tsunami Evolution

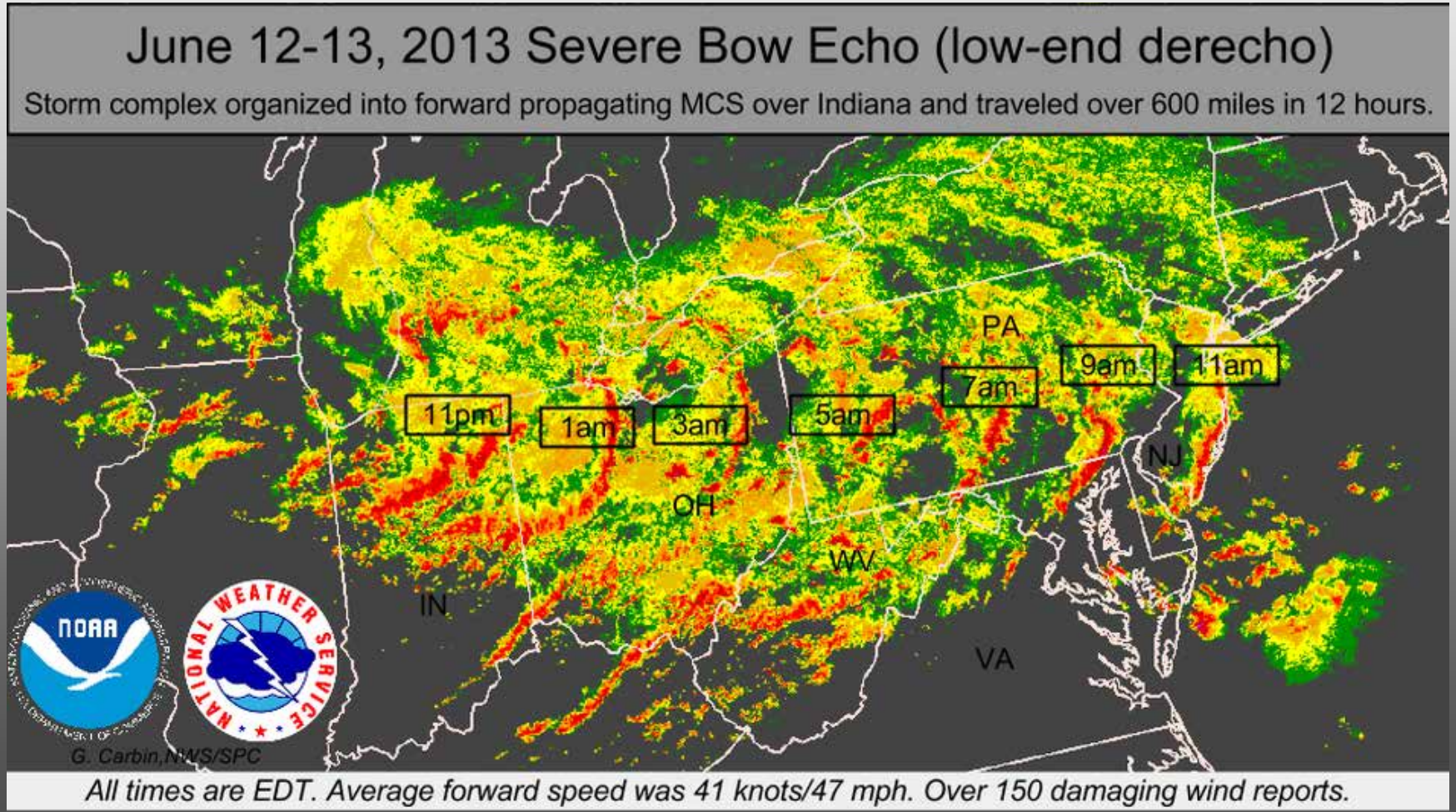
- Propagation & arrival depends on bathymetry (depth)
- Movie shown is velocity, calculated from model equation used by all



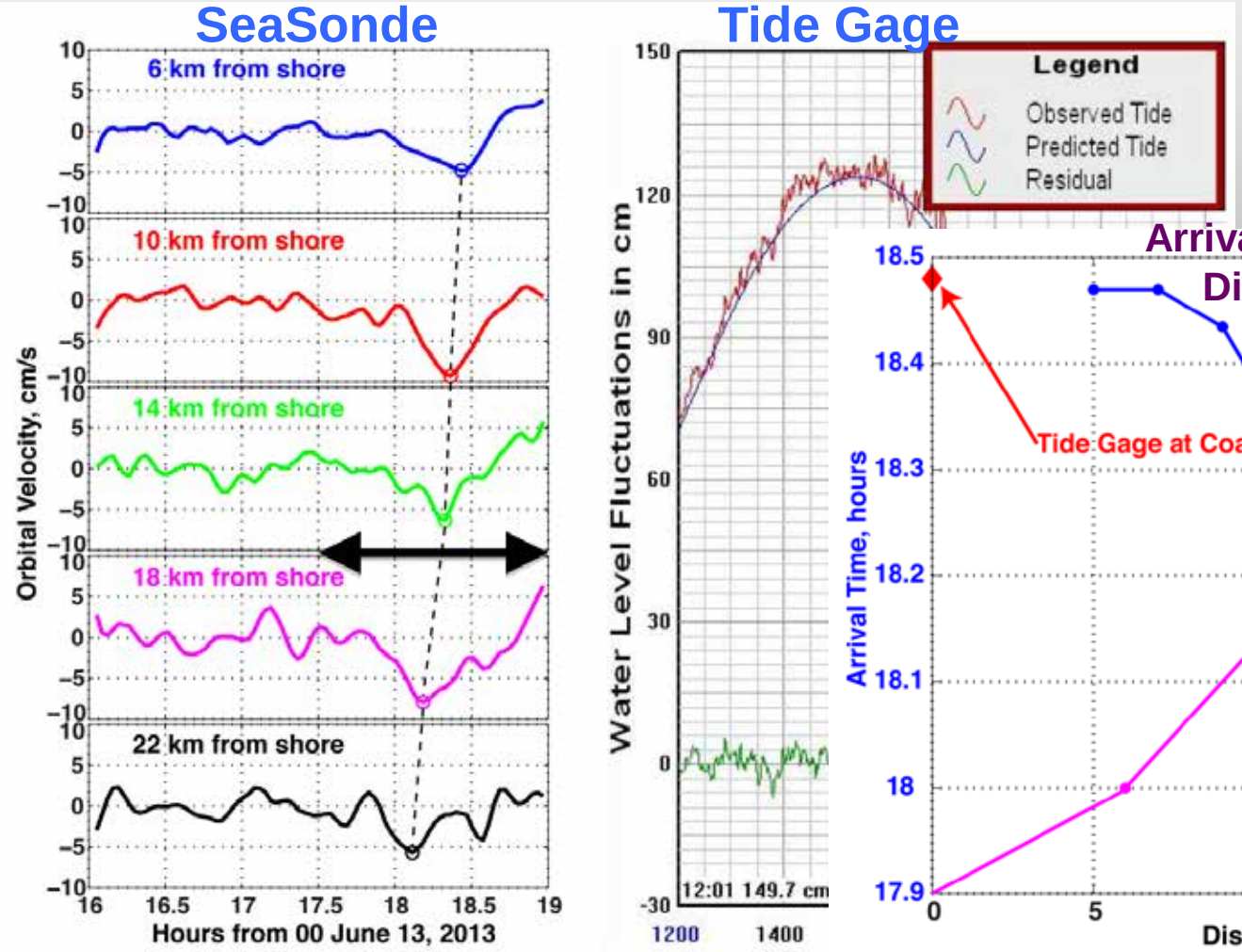


Weak June 13, 2013 MeteoTsunami off East U.S. Coast Observed/Confirmed

- **Meteotsunami is produced by fast moving atmospheric storm**
- **First ever event seen by SeaSondes, Tide Gages, DART Buoy**



- **Wave generated traveled Eastward offshore**
- **Strong reflection from shelf edge comes back, hits shore**
- **SeaSonde saw the event 43 minutes before coastal arrival**
- **Solid black arrows show period of tsunami event**



How to Use SeaSonde HF Radar Near-Field Tsunami Velocity Observations

- Use q-Factor Pattern Recognizer to Detect Onset of Tsunami Velocity Peaks
- Based on Near-Shore Bathymetry and Model, Forecast Arrival Time at Coast
- Using Equations from PDE Model, Relate Velocity to Height and Provide This to Tunami Centers