Observations of the March 11, 2011 Japan Tsunami Using HF Radars on Two Continents

Tsunamis & HF Radar

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Talk Outline

- Basic Principles
  - Evolution of Incoming Waves
  - Height vs. Velocity
- Detection Methods
  - Vector Current Maps
  - Radials From a Single Radar
  - Directly From the Bragg Spectrum
- Examples from Japan and America
- Issues Determining Warning Time

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Basic Principles

- Tsunamis are shallow water waves
- Signals are small in deep water, fast moving
- Currents increase faster than height for a wave entering shallow water

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

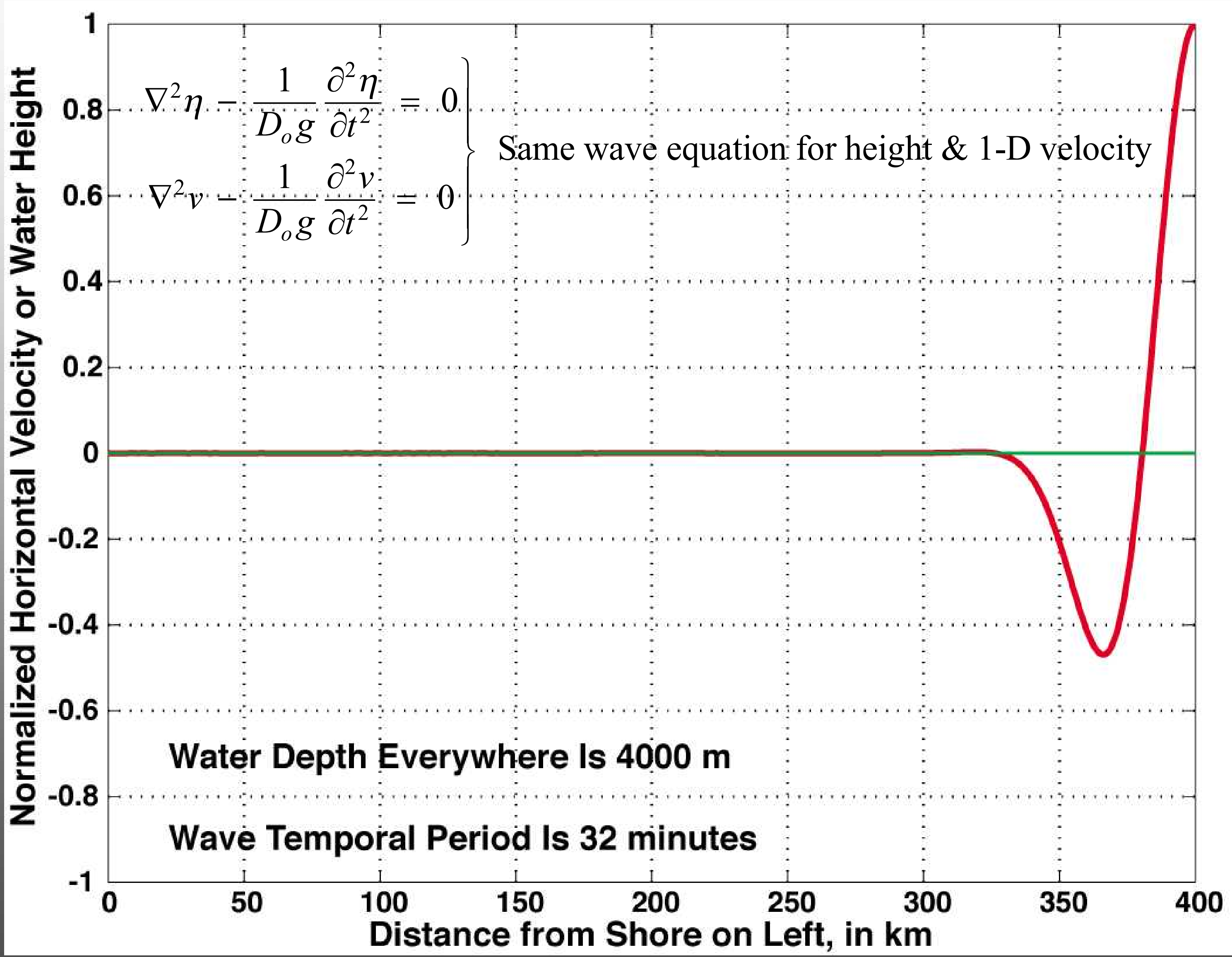
$$v_p(d) \propto hd^{-3/4}$$

- HF radars sense surface currents

Detection Methods

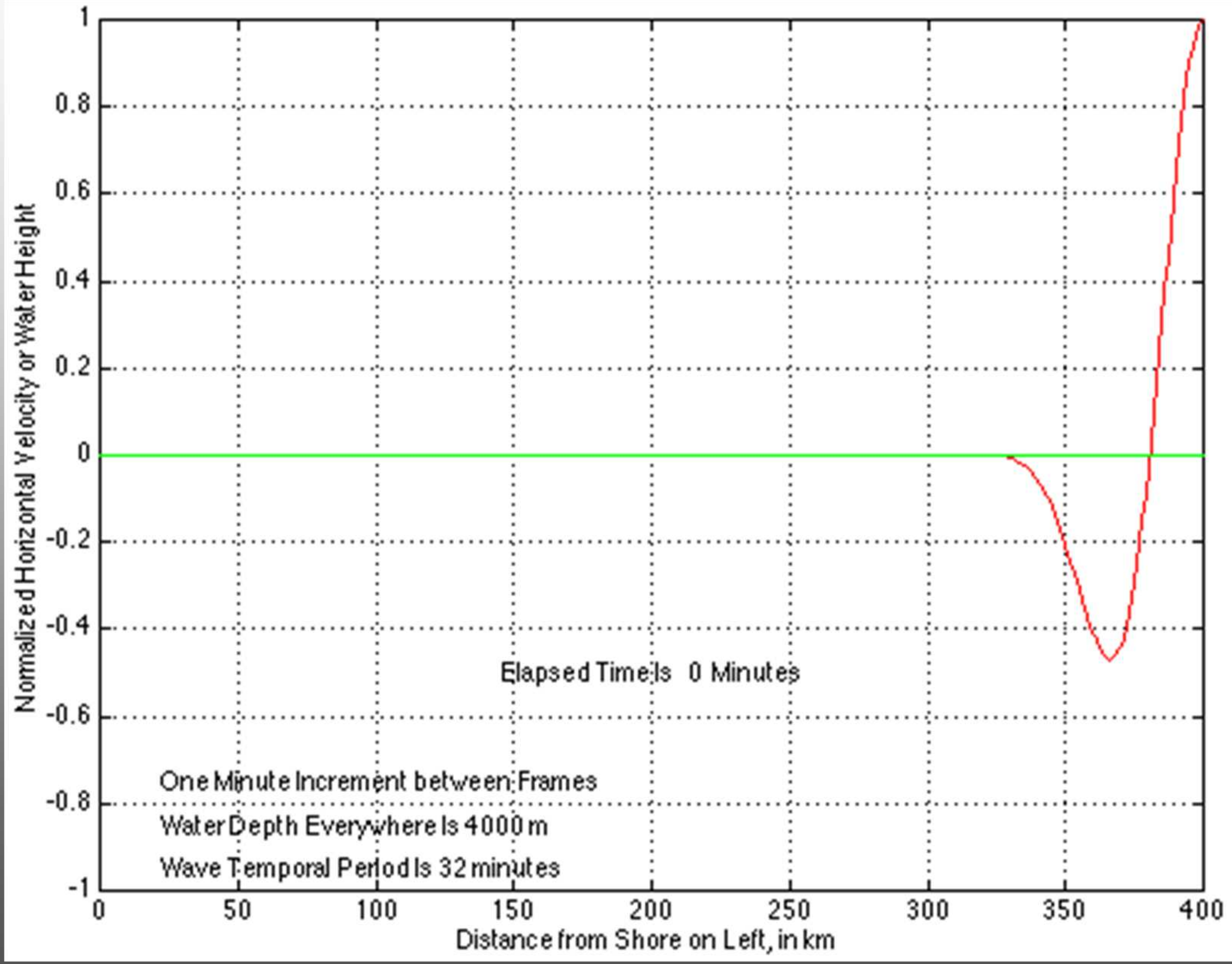
1. Direct observation of surface current vectors from two coastal HF radars
   – Use equations of motion to calculate height
2. Radial velocity from a single radar
   – Refraction drives wave to be perpendicular to the local depth contours
   – Radials resolved perpendicular to the local depth contours will see the wave
3. Directly from the Bragg backscatter spectrum
   – Frequency shifts
   – Peak width

Modeled Example of Solitary Wave Feature Propagating Across Constant-Depth Bottom

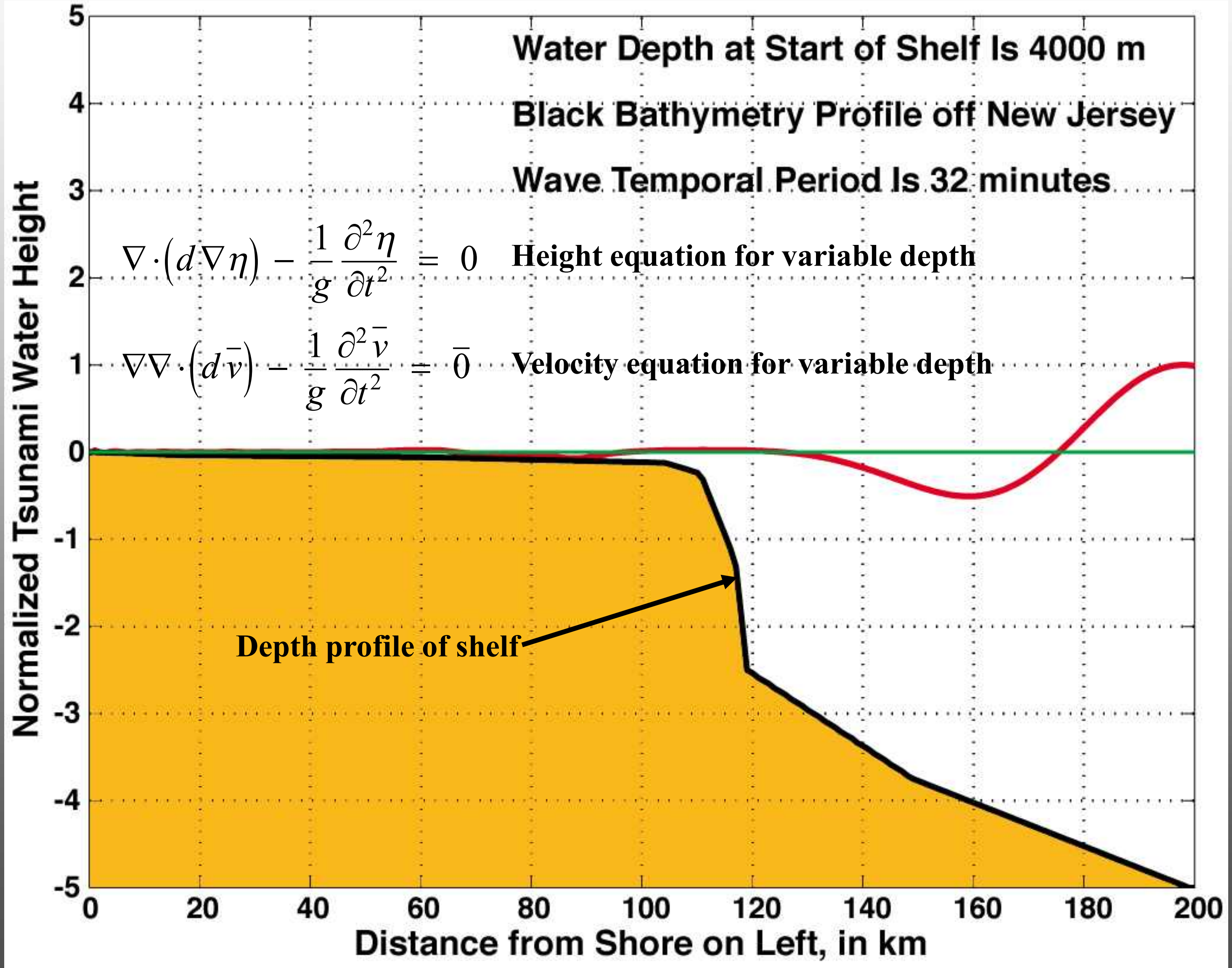


Animation: Tsunami Wave in Deep Water Depth = 4000 m

- Travels Fast!
- Non-Dispersive
- Typical amplitude: 10 - 100 cm
- Corresponding particle velocity: 2.5 cm/s
- Shape stays intact as wave propagates

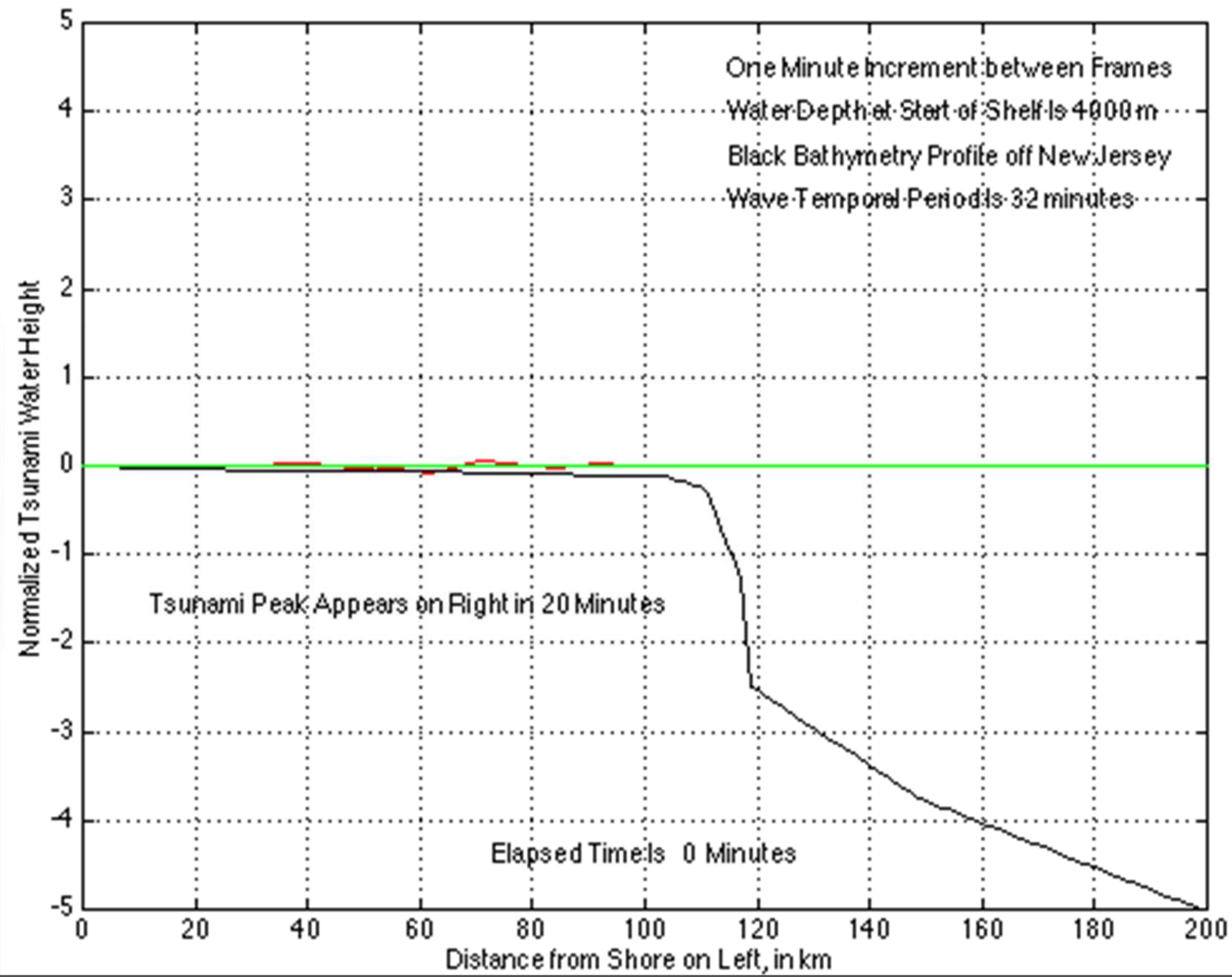


Example: Propagation on New Jersey Shelf



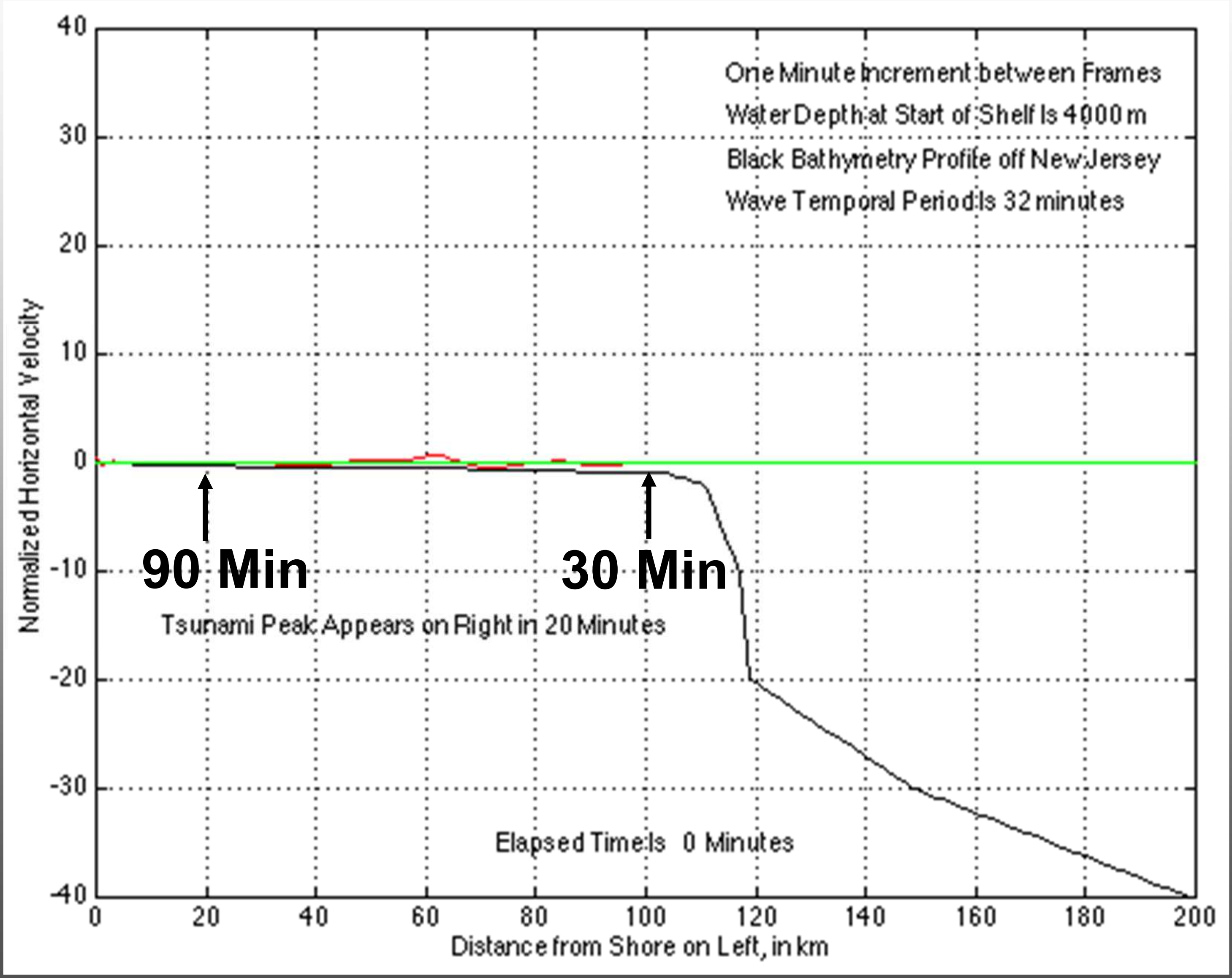
Animation: Tsunami ELEVATION across NJ Shelf

- **Feature speed decreases**
- **Height increases as inverse 1/4 power of depth**
- **Shape compresses as depth decreases so temporal nature remains intact**

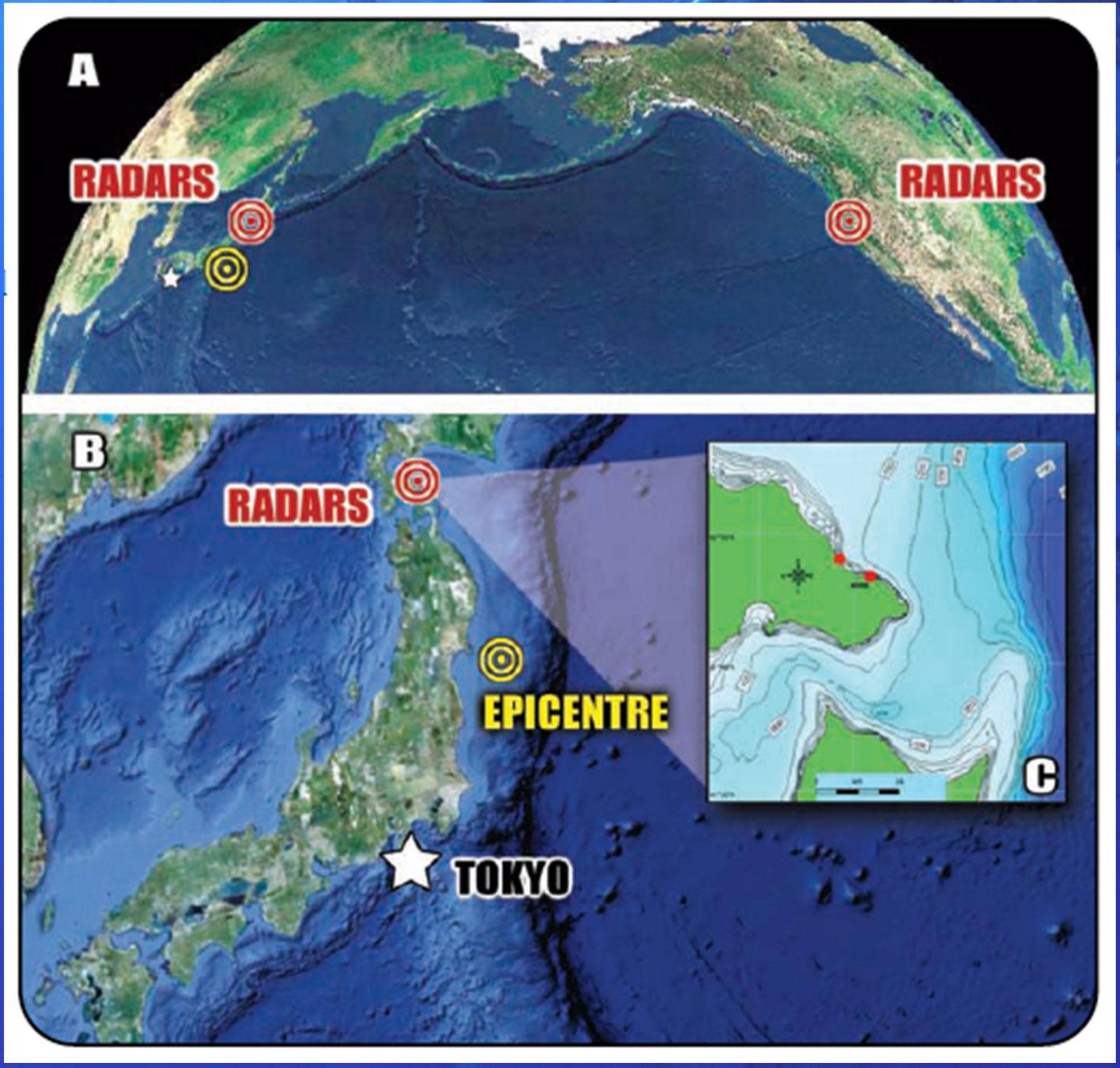


Animation: Orbital VELOCITY Across NJ Shelf

- Feature speed decreases
- Velocity increases as inverse 3/4 power of depth



The March 11 Tohoku-Oki Earthquake Event



Introduction to the Movies

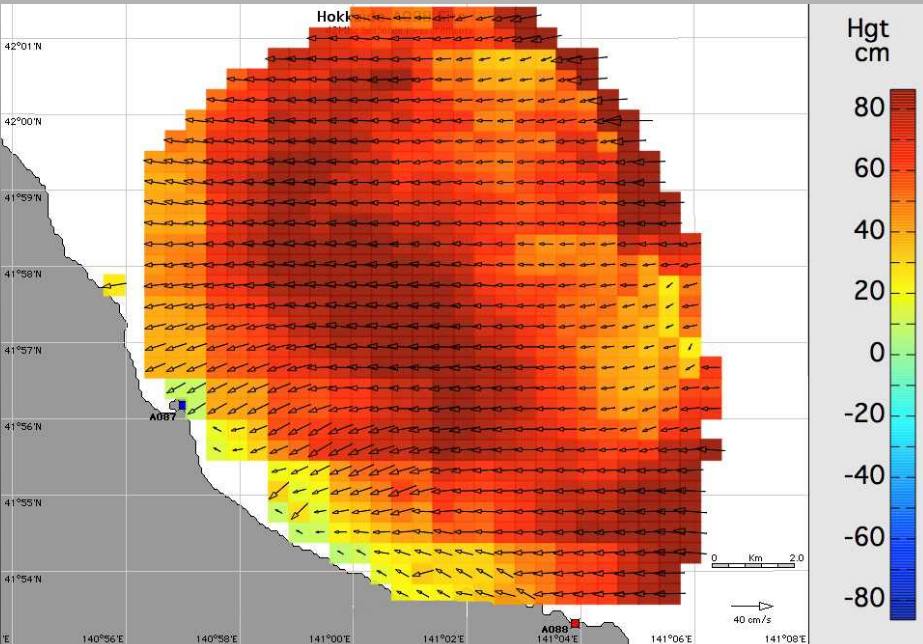
Vectors = Observed Surface Currents

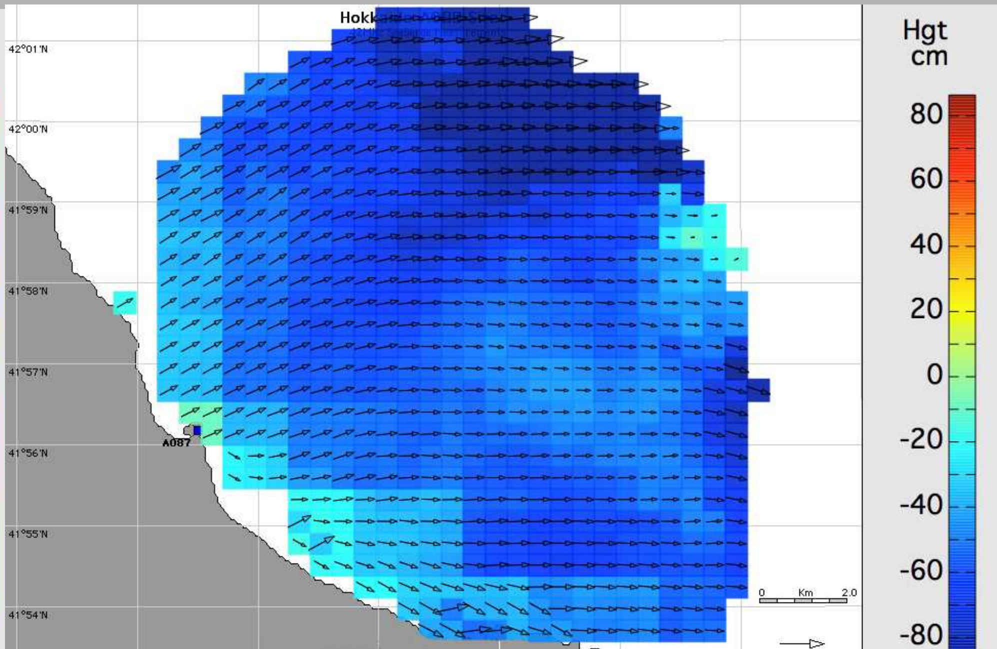
Color = Height calculated from currents

$$h(d) = \sqrt{\frac{d}{g}}\, v_o(d)$$

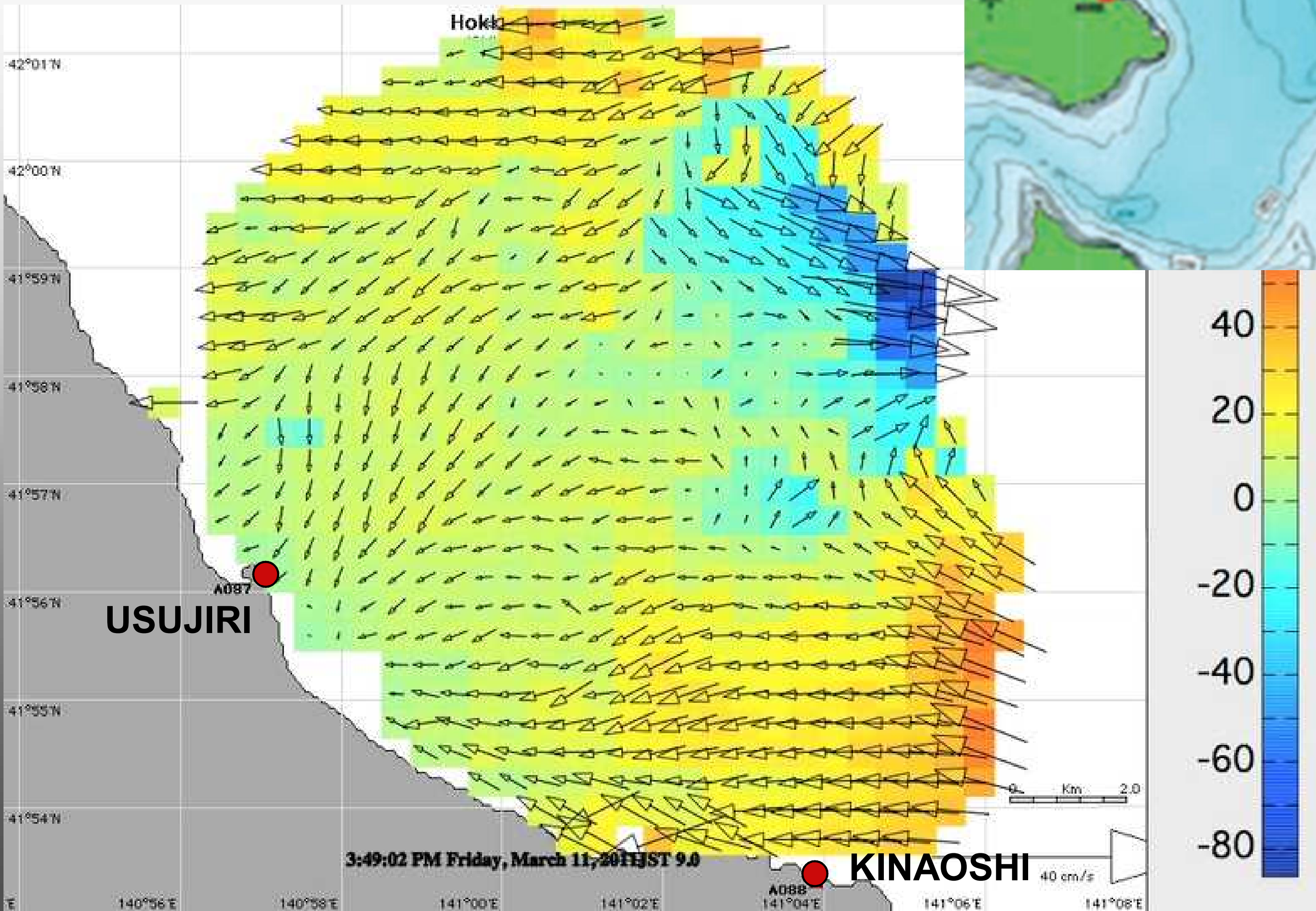
Time between images = 20 minutes
Red = high; Blue = Low

Tides removed

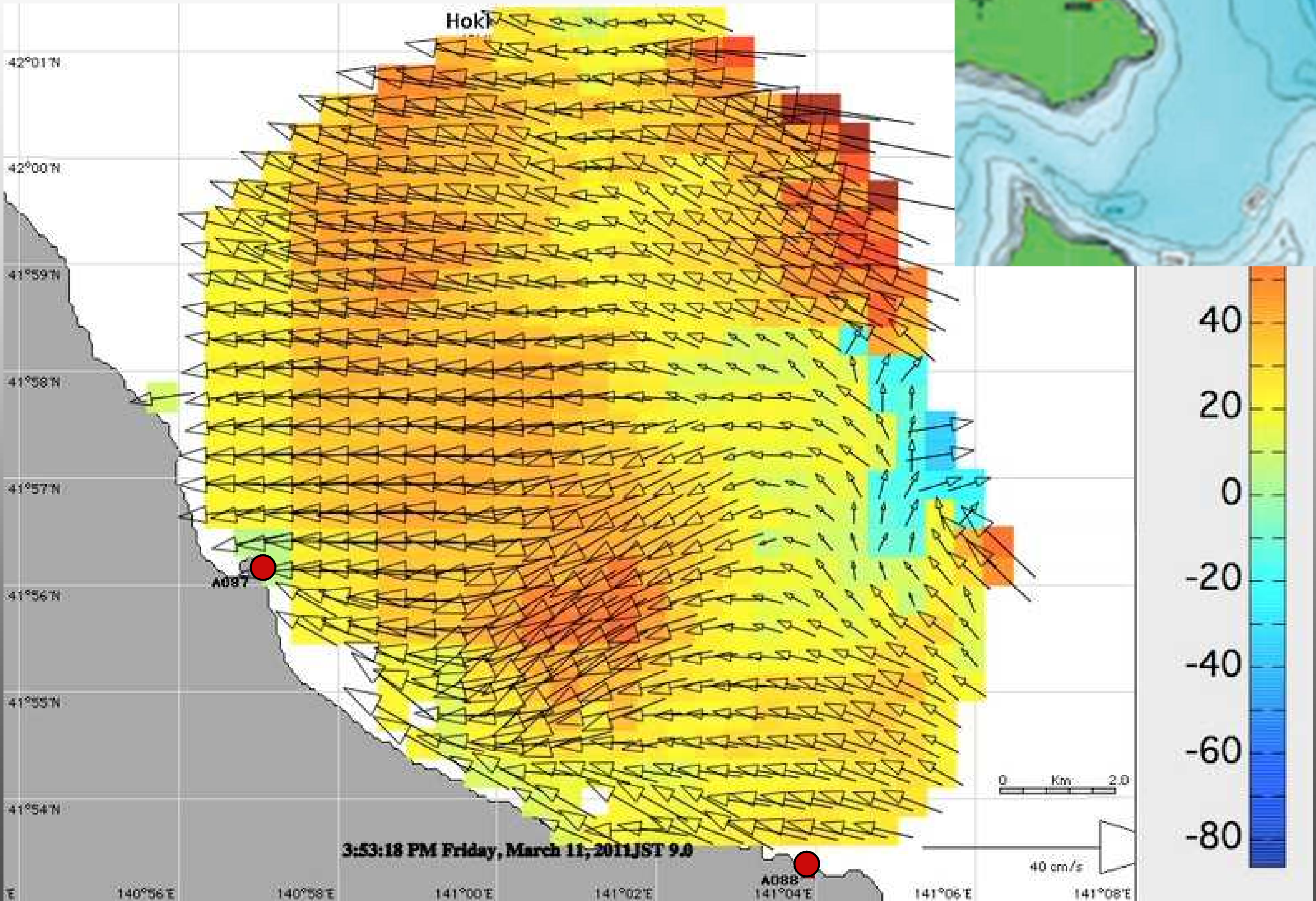




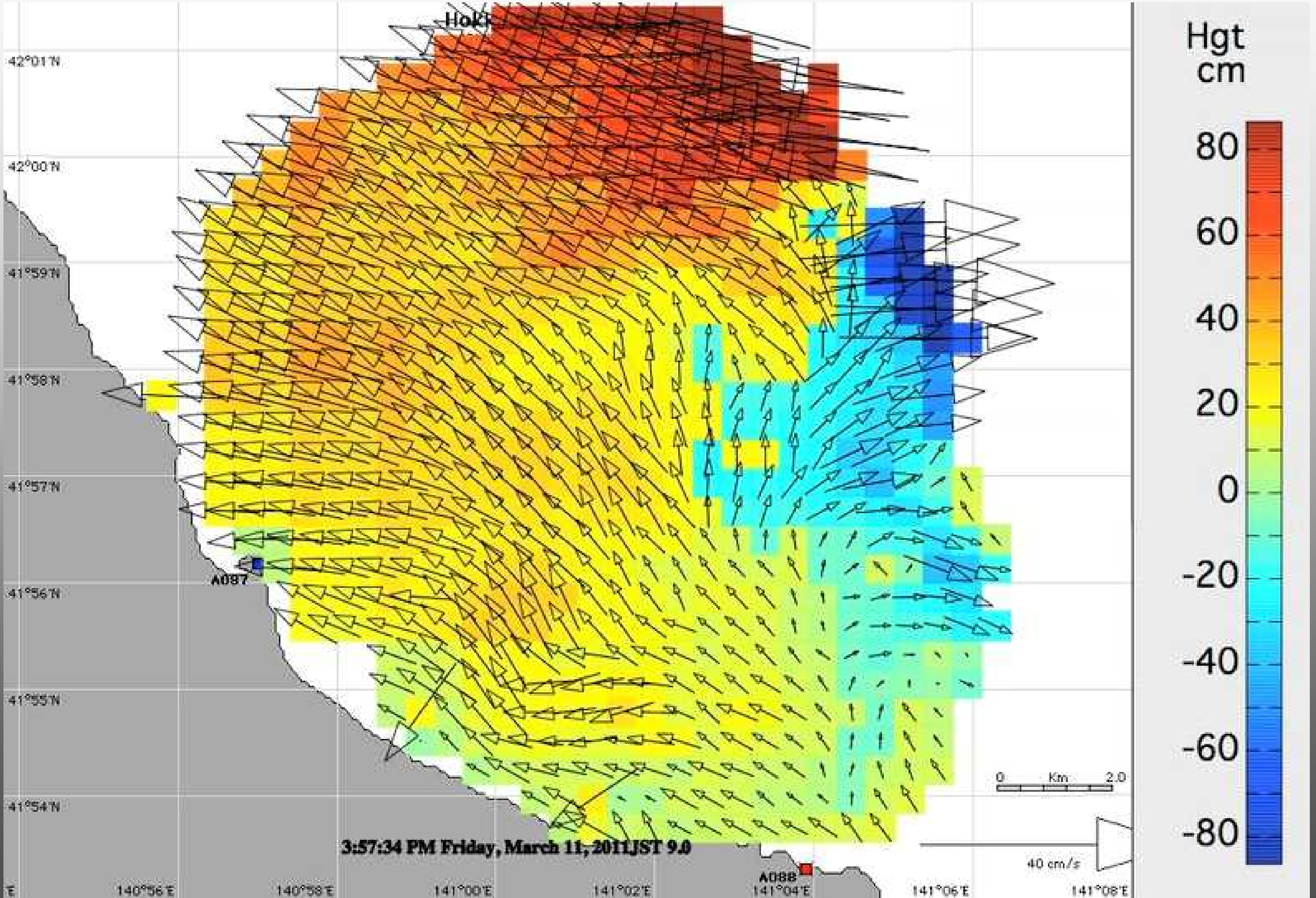
3:49 – WAVE CREST ARRIVES



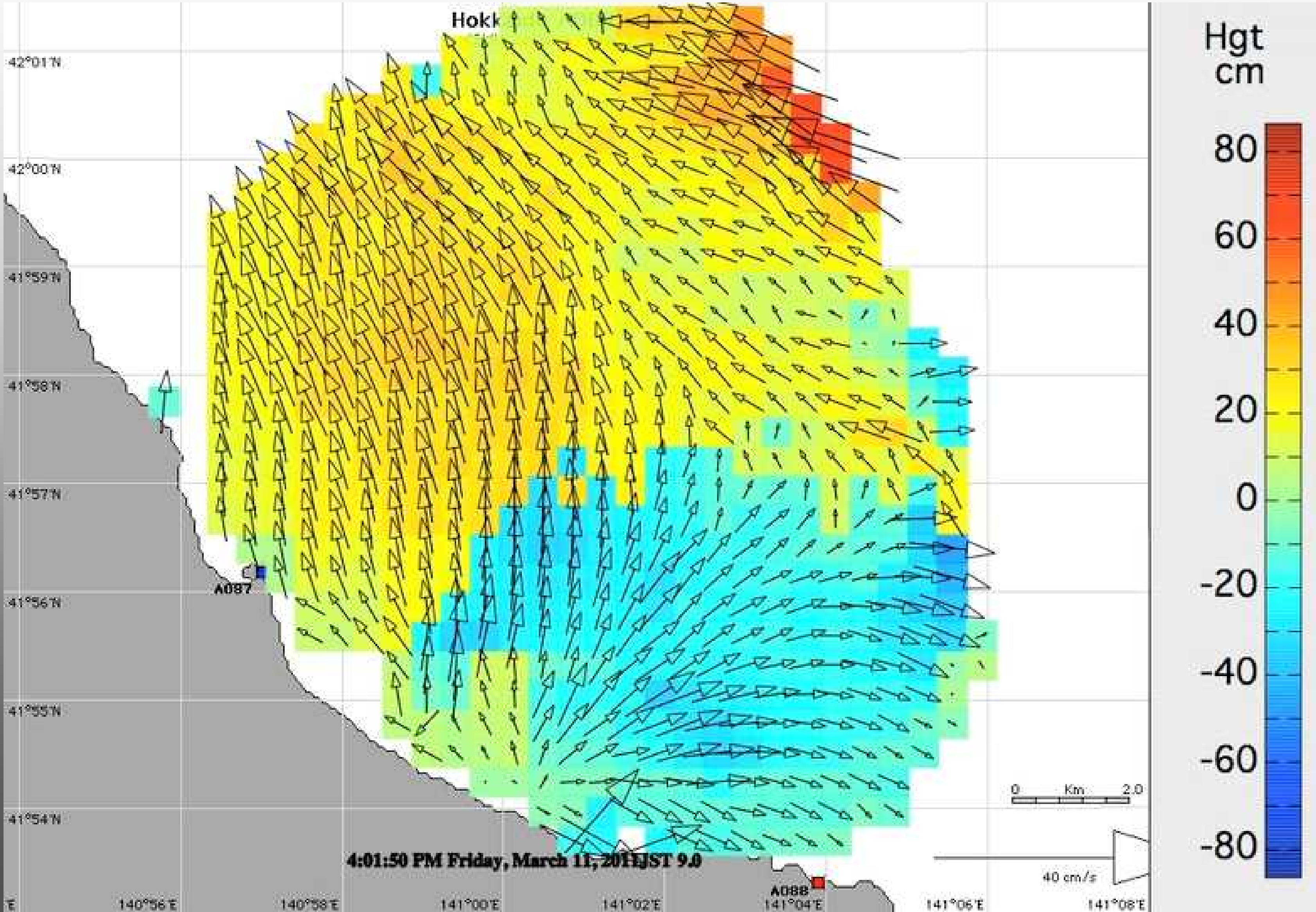
3:53 – WAVE COVERS AREA



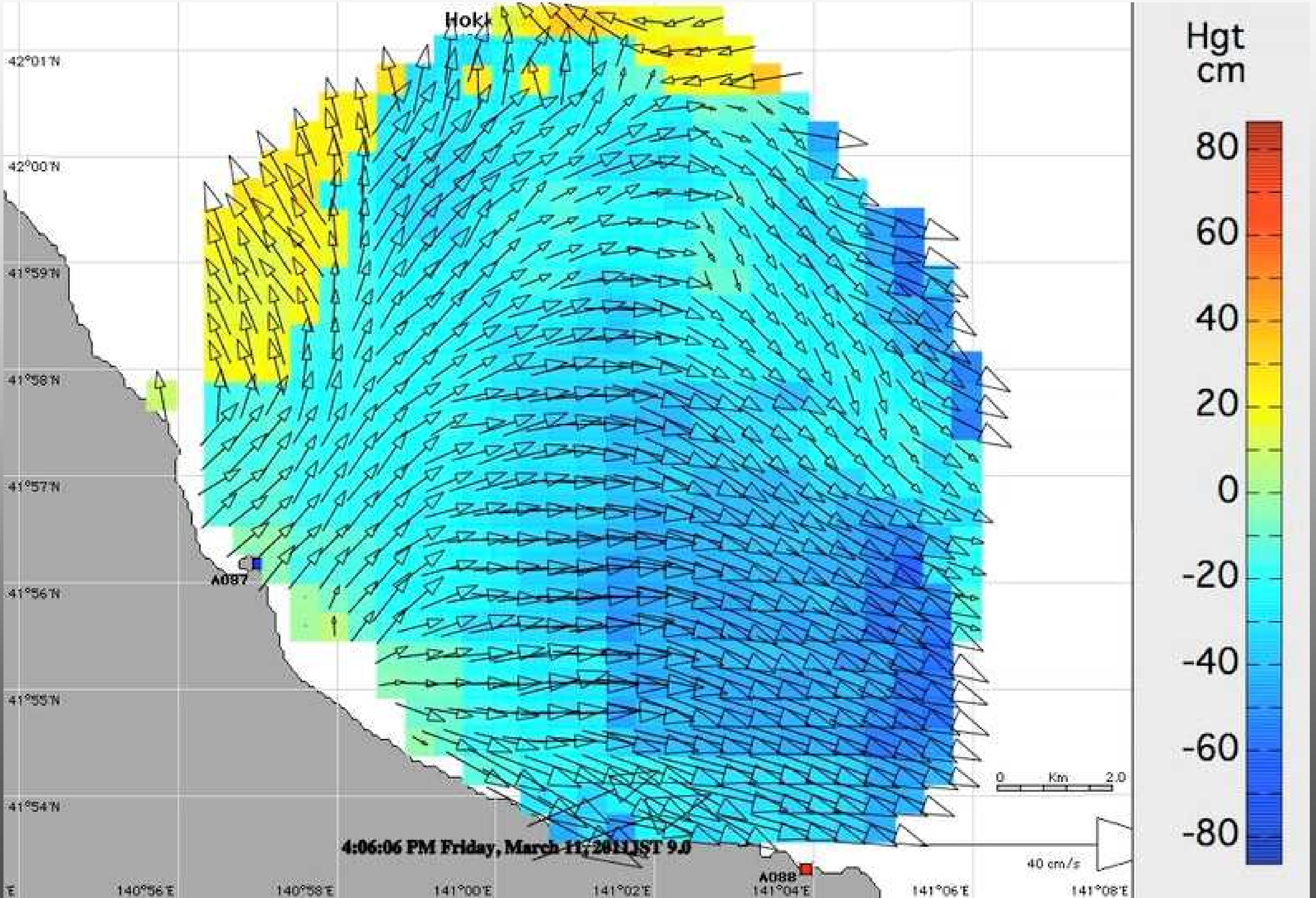
3:57 – MOVING THROUGH



4:01 – CREST & TROUGH



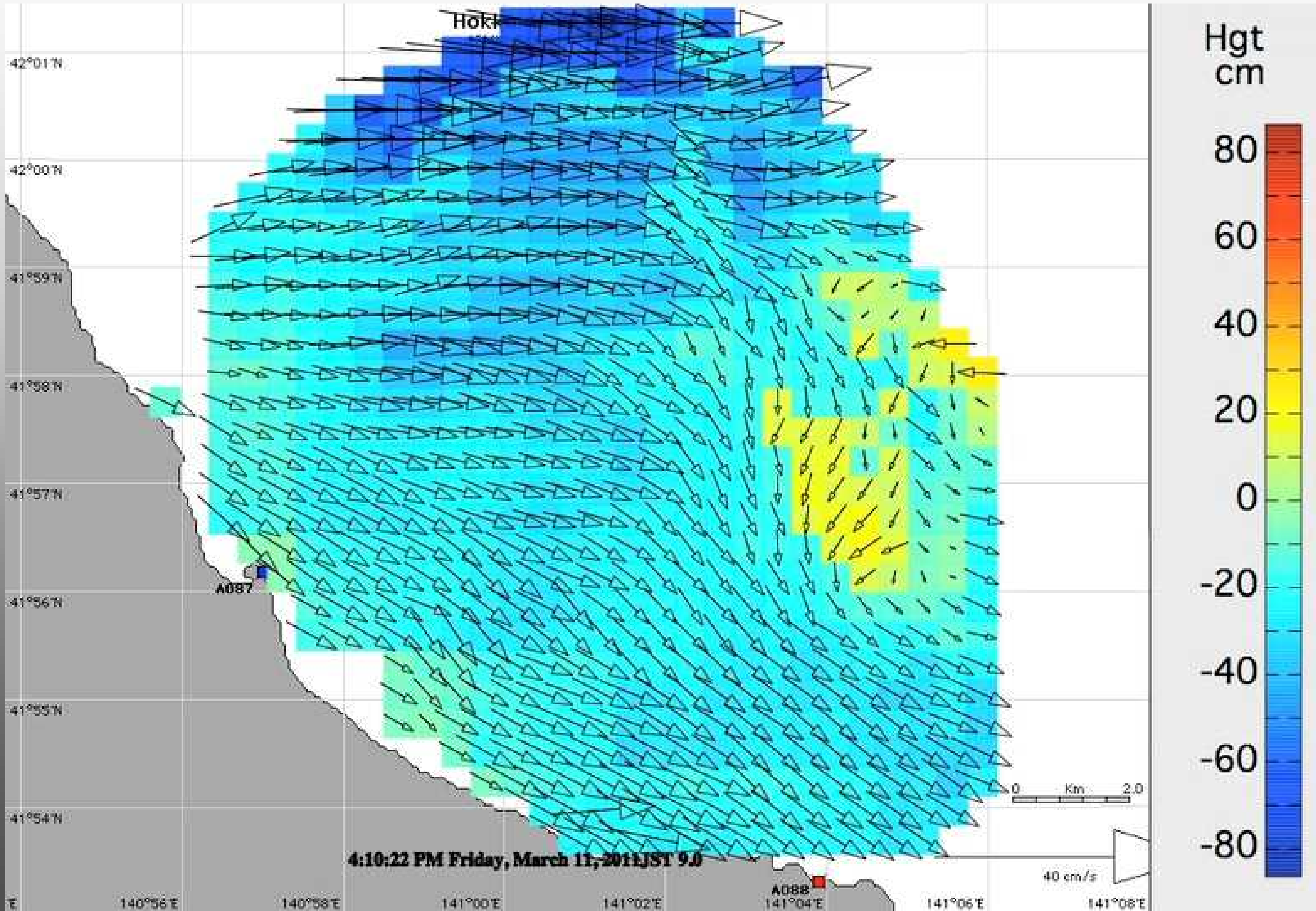
4:06 – TROUGH



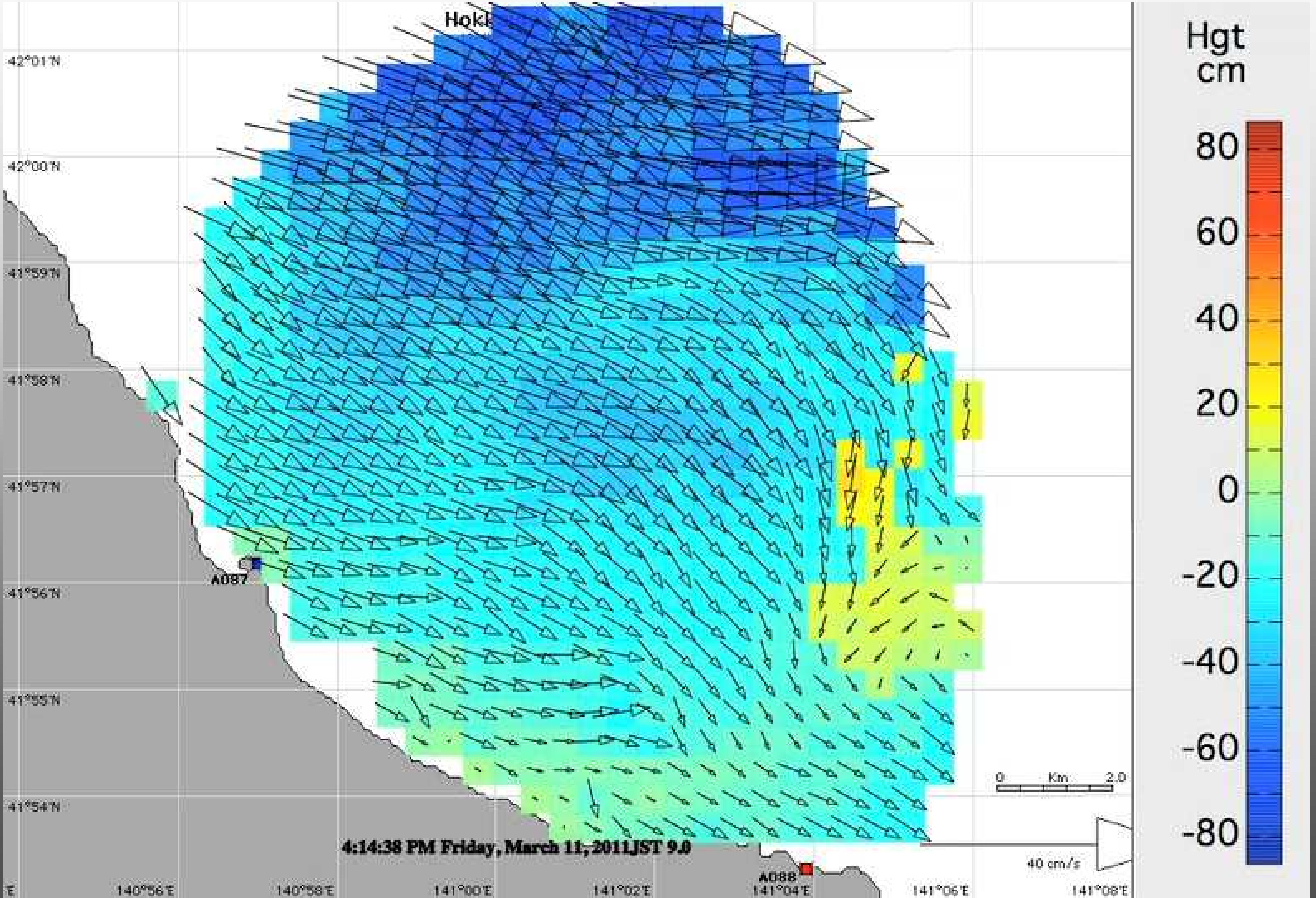
Hokk
42°01'N
42°00'N
41°59'N
41°58'N
41°57'N
41°56'N
41°55'N
41°54'N
A087
A088
4:06:06 PM Friday, March 11, 2011 JST 9.0
0 Km 2.0
40 cm/s
140°56'E
140°58'E
141°00'E
141°02'E
141°04'E
141°06'E
141°08'E
Hgt cm
80
60
40
20
0
-20
-40
-60
-80

4:10 – TROUGH REMAINS

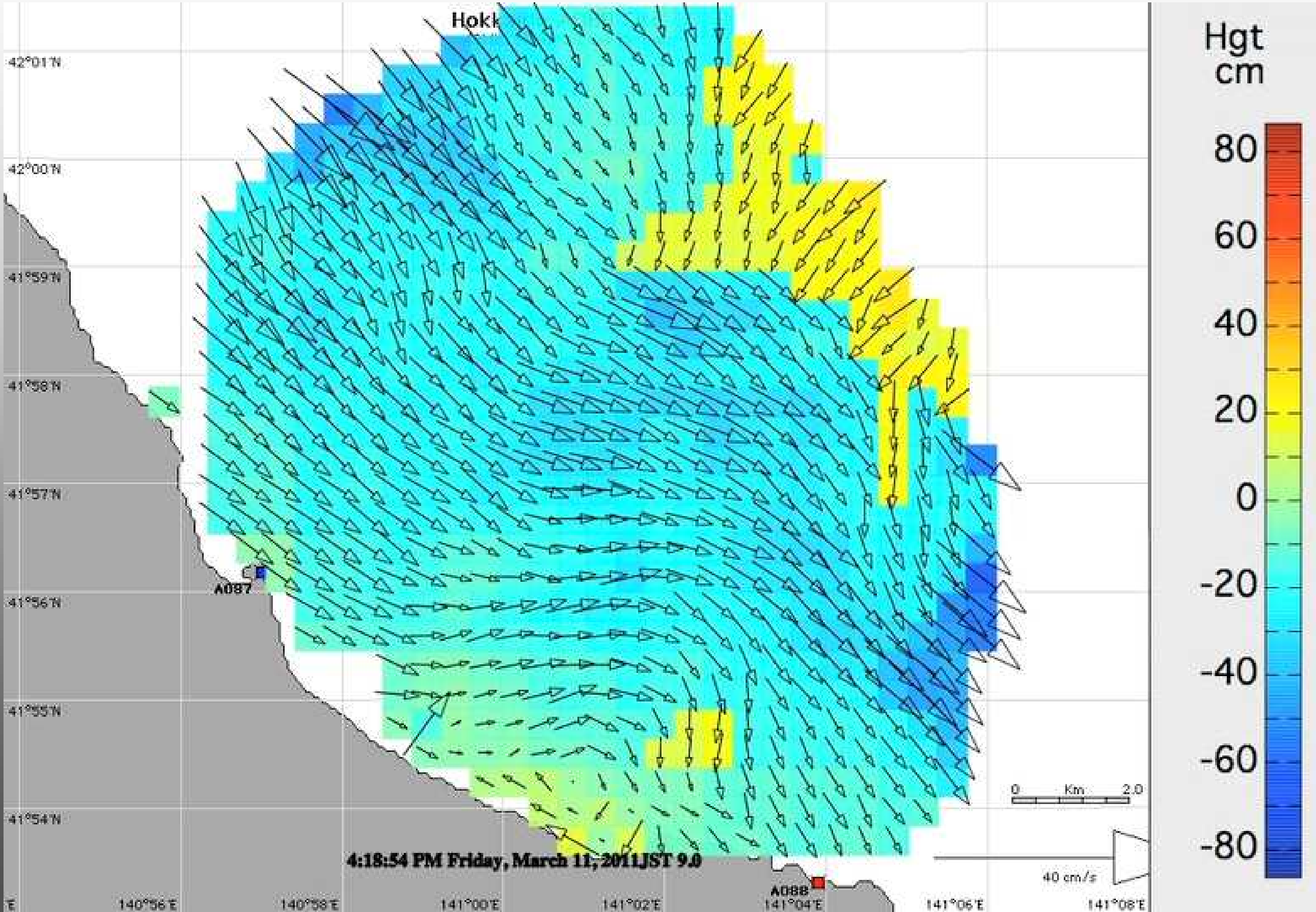
CODAR OCEAN SENSORS



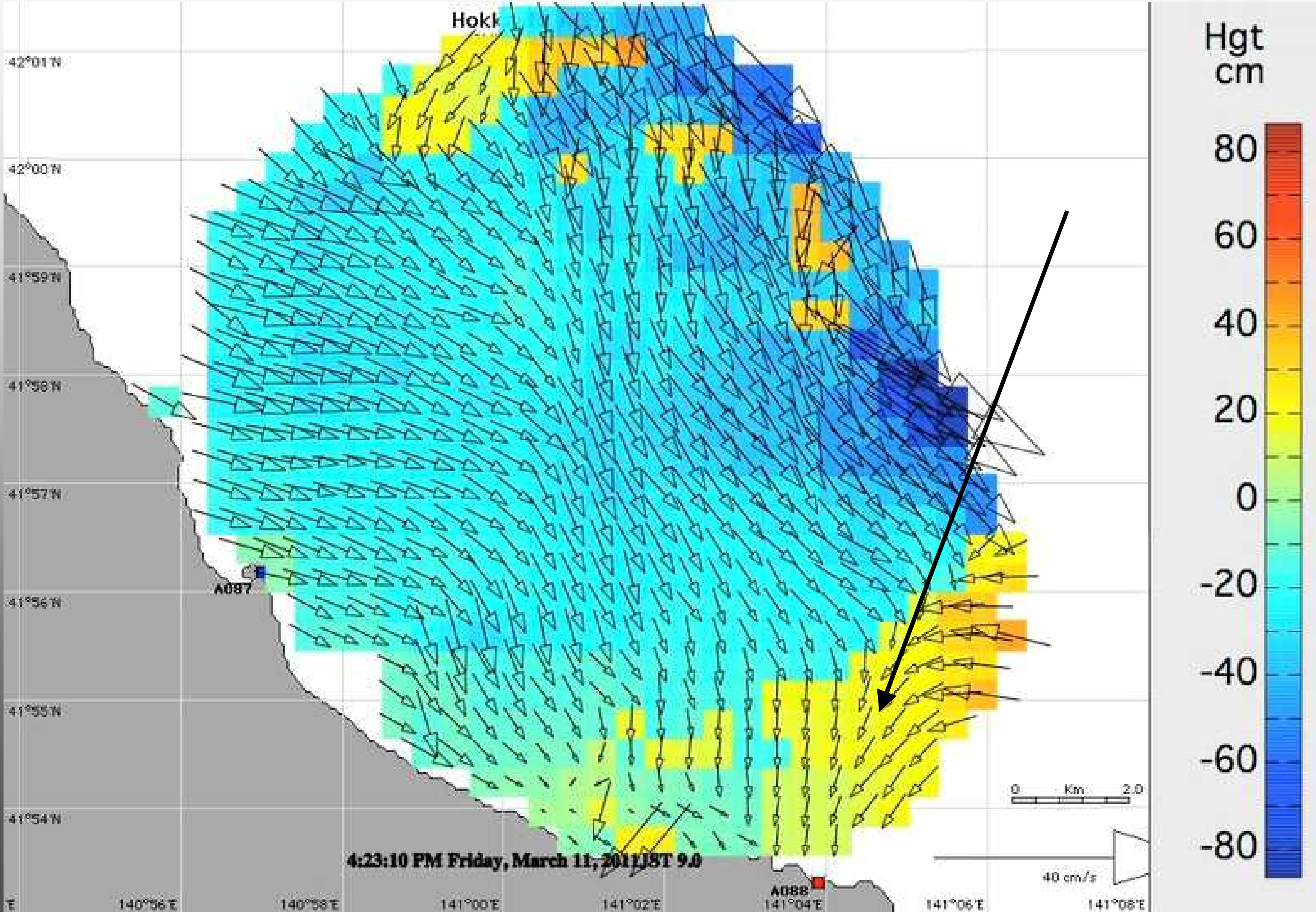
4:15 – TROUGH LASTS LONGER THAN CREST



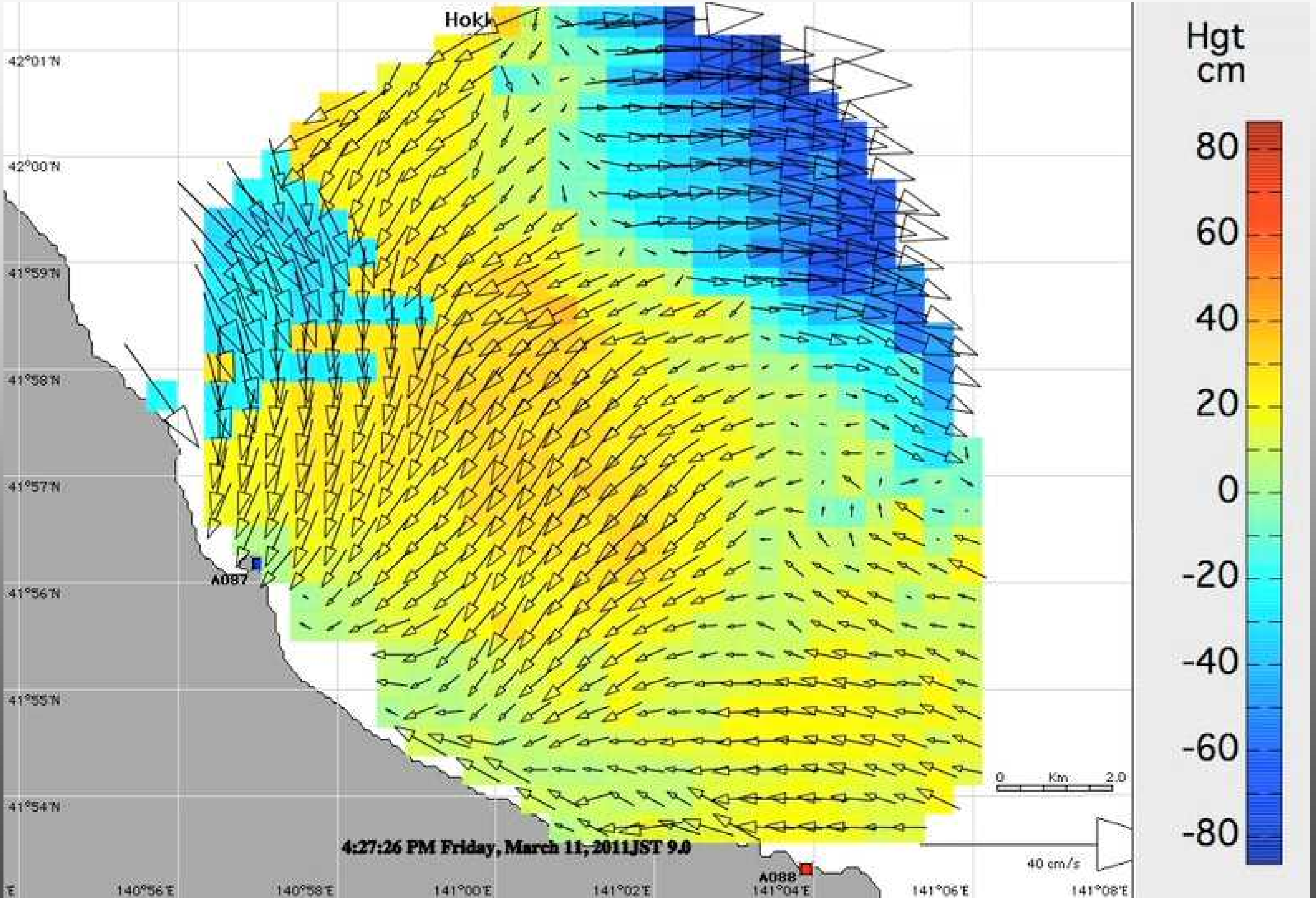
4:19 – TROUGH WEAKENS



4:23 – NEXT CREST APPEARS



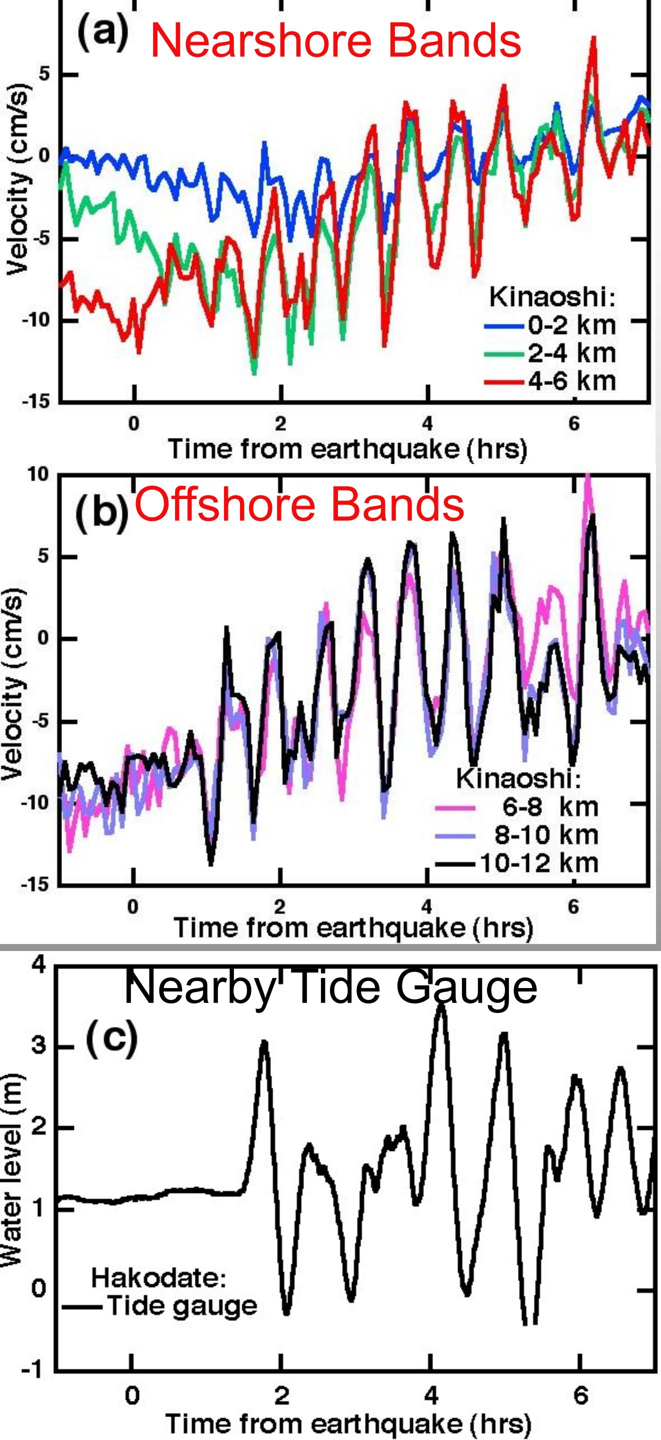
4:27 – NEXT CREST ARRIVES

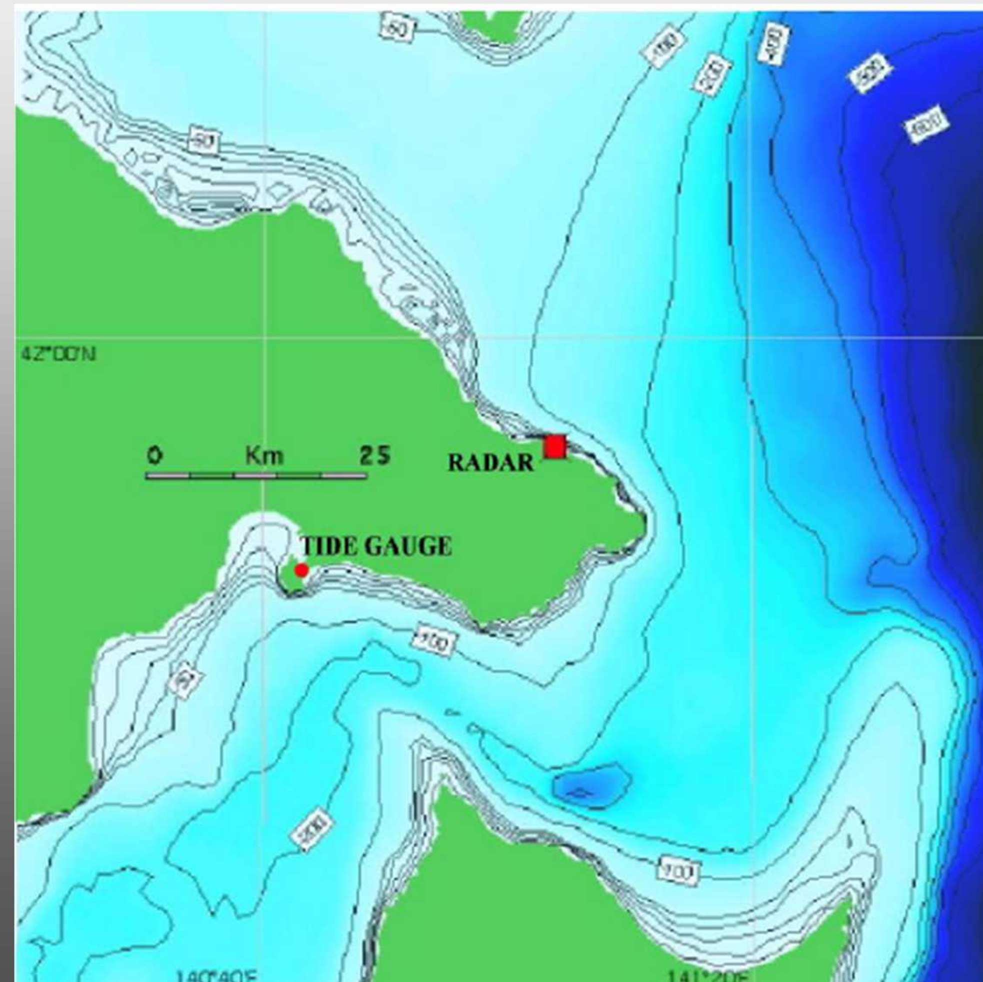


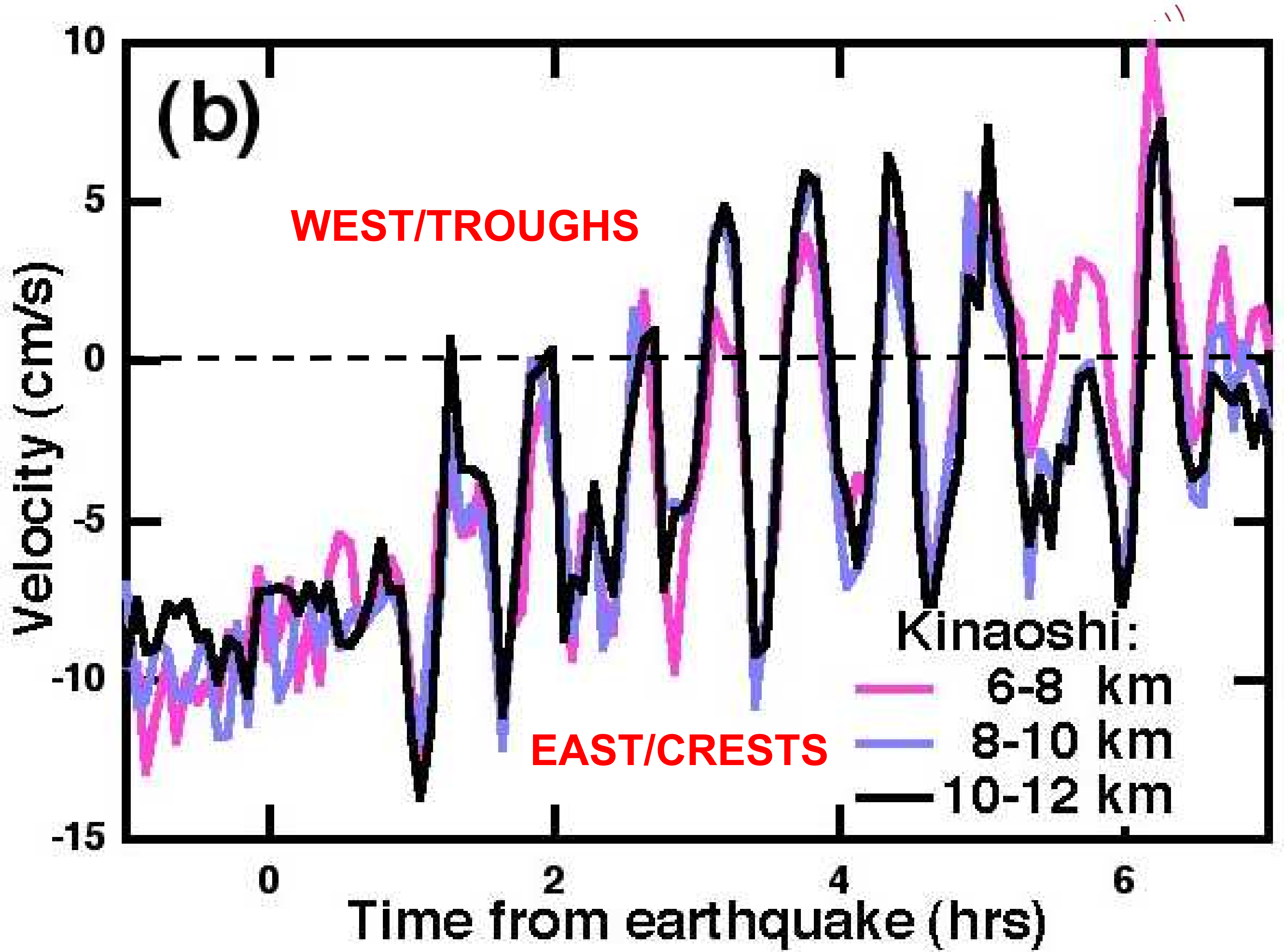
Play the Movie!!

Tsunami Observations on Hokkaido, Japan

Fluctuations from Kinaoshi radials

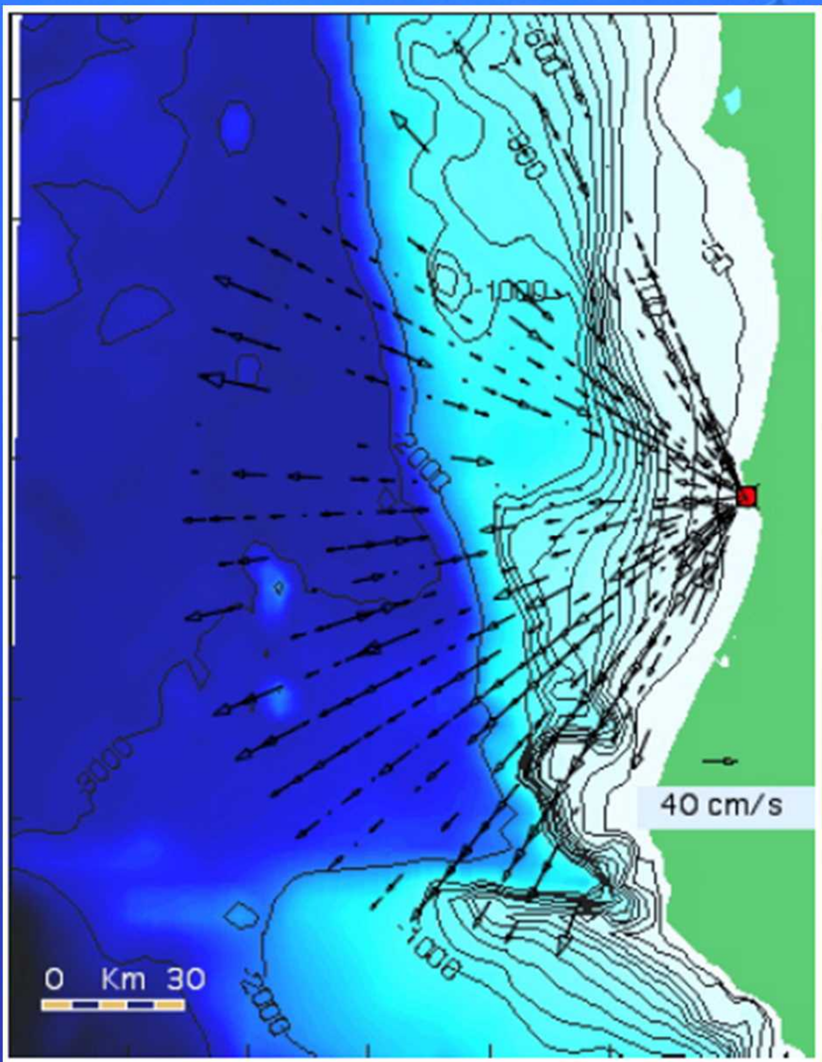


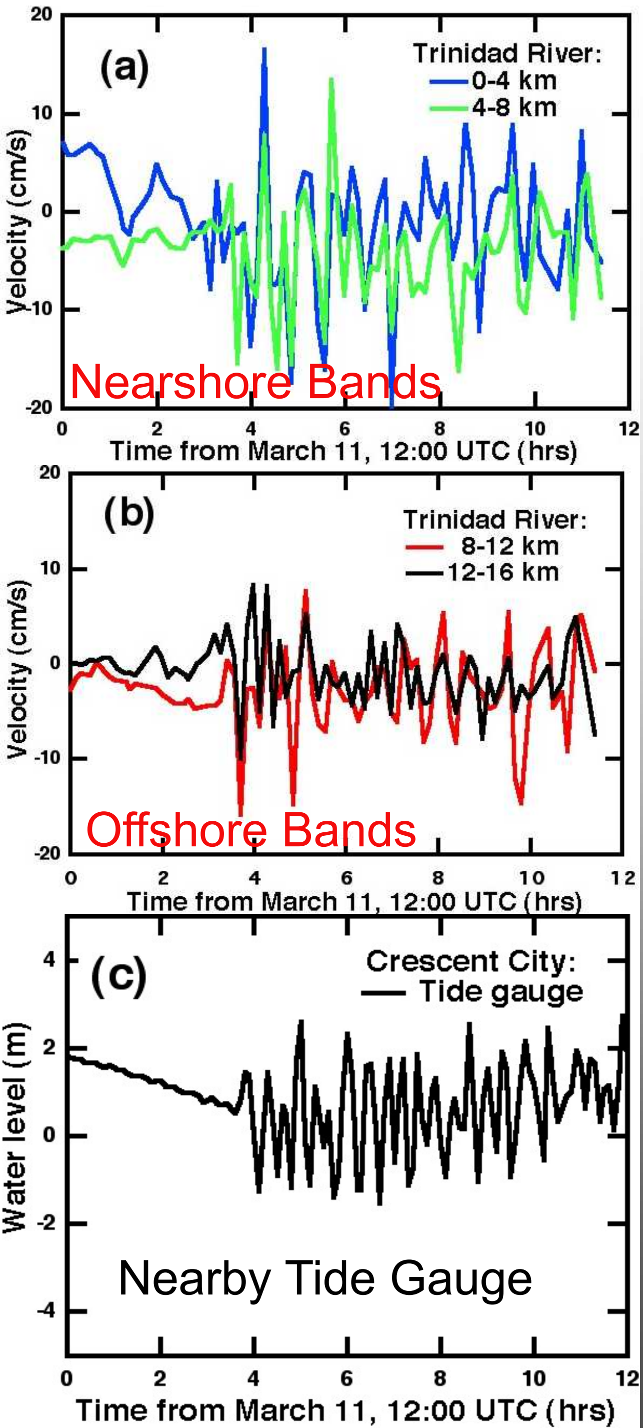




(b)
WEST/TROUGHS
EAST/CRESTS
Kinaoshi:
6-8 km
8-10 km
10-12 km
Velocity (cm/s)
Time from earthquake (hrs)
10
5
0
-5
-10
-15
0
2
4
6

Trinidad River Location (5 MHz)



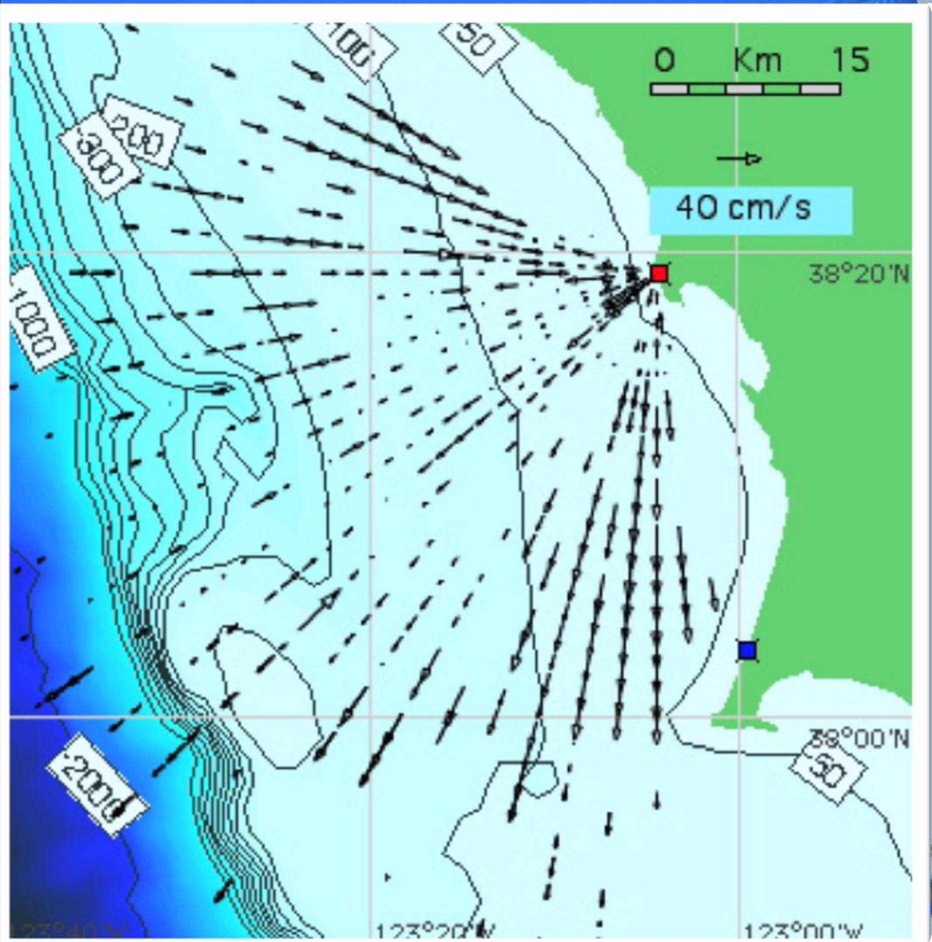


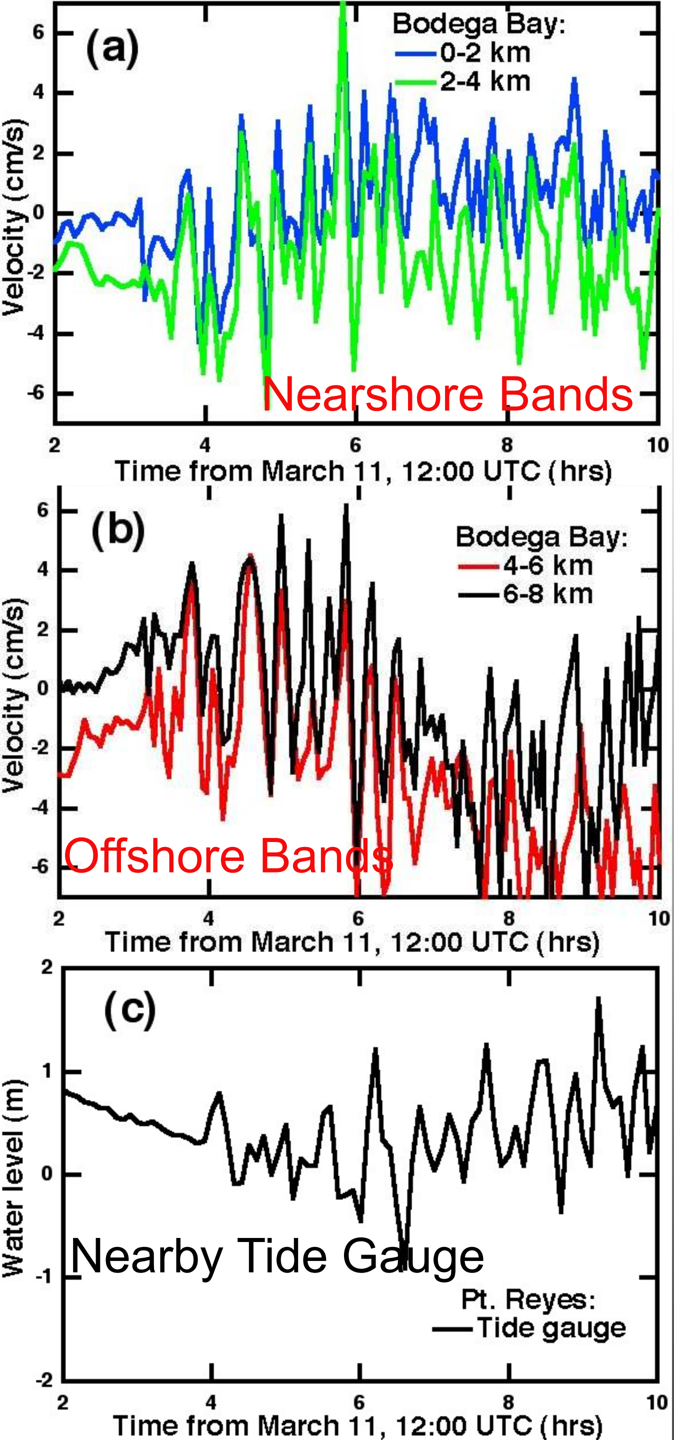
Tsunami Observations on U.S. West Coast

CODAR OCEAN SENSORS

- Tsunami seen by single radar at Trinidad River: 4.5 MHz
- Method #2: Onshore flow resolved in bands parallel to bathymetry
- Time series not detrended

Bodega Bay Location (13 MHz)



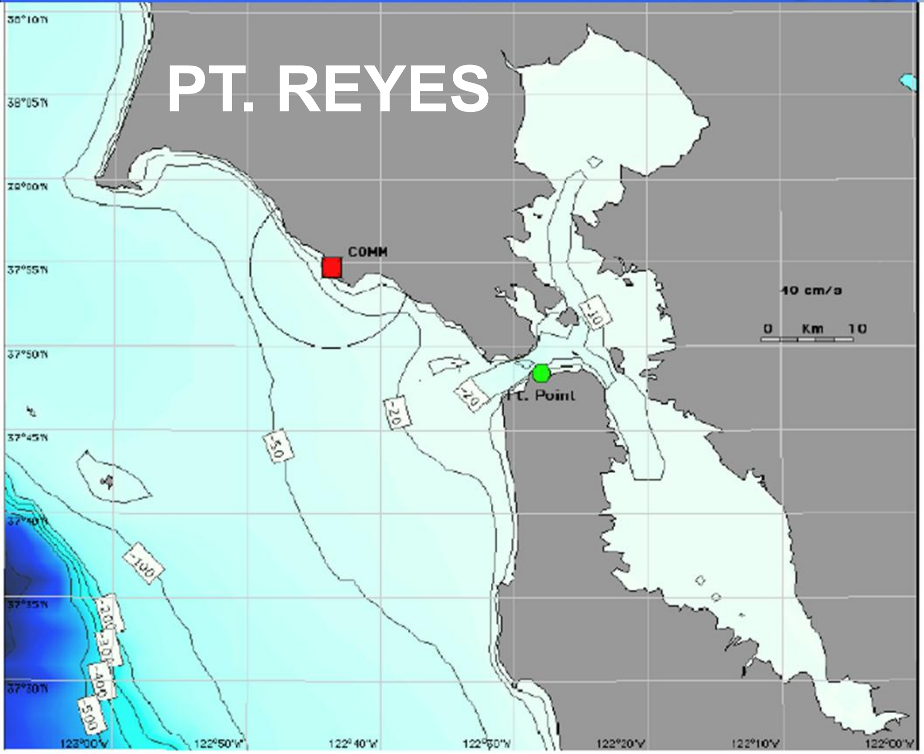


Tsunami Observations on U.S. West Coast

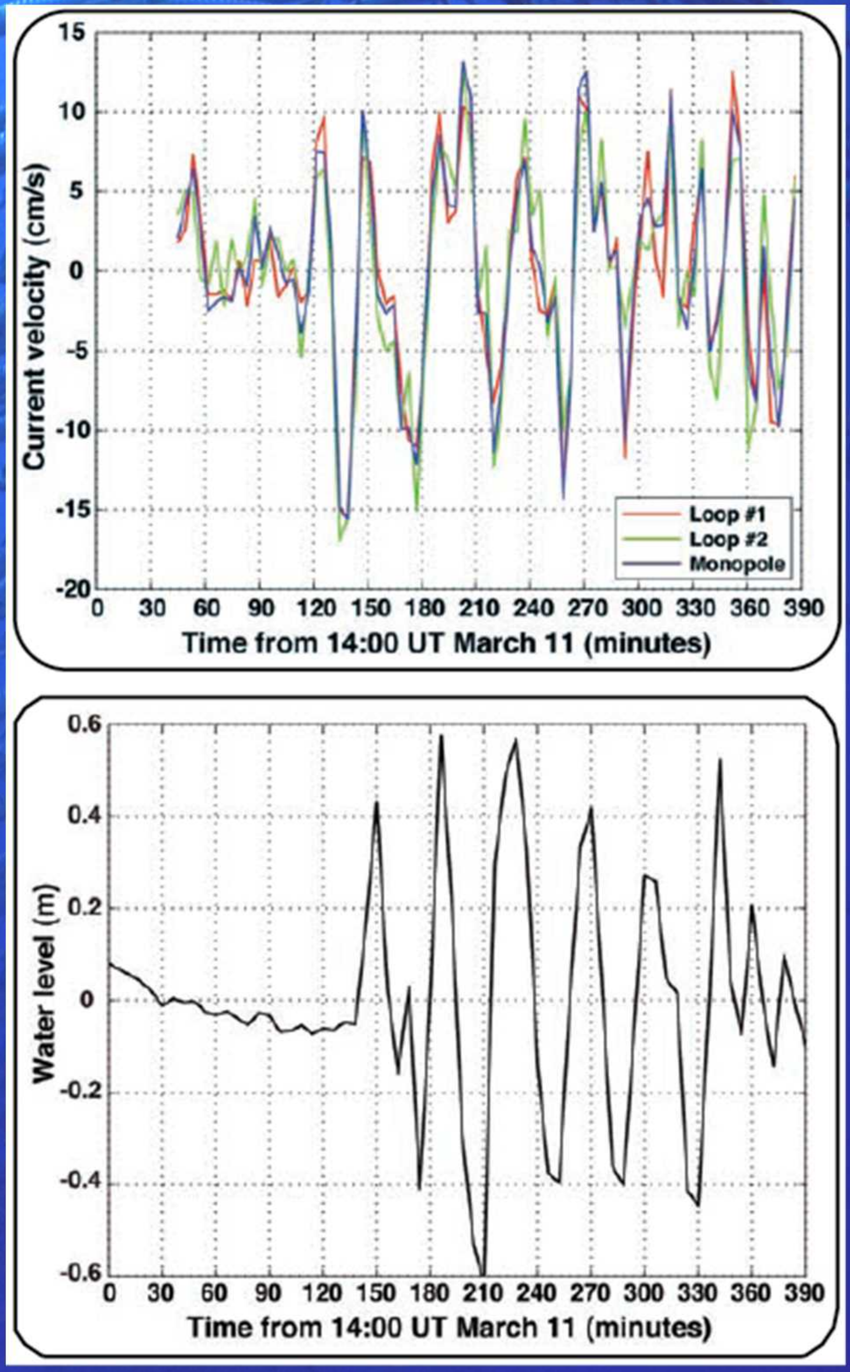
CODAR OCEAN SENSORS

- Tsunami seen by single radar at Bodega Marine Lab: 13 MHz
- Method #2: Onshore flow resolved in bands parallel to bathymetry
- Time series not detrended

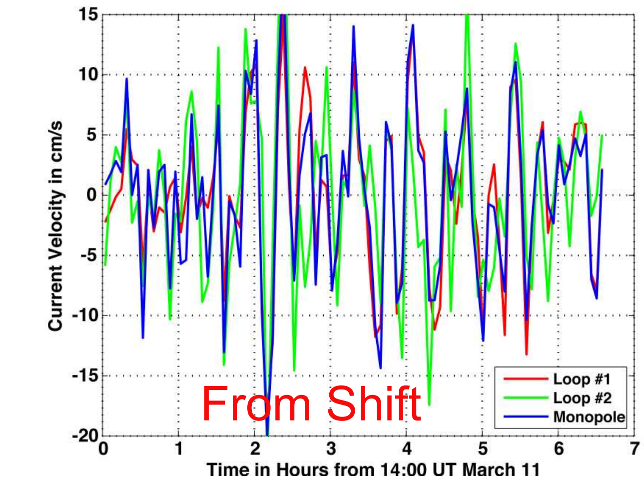
Commonweal Location (13 MHz)

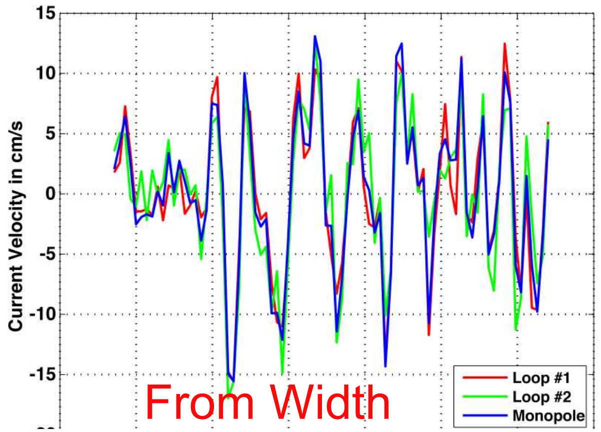


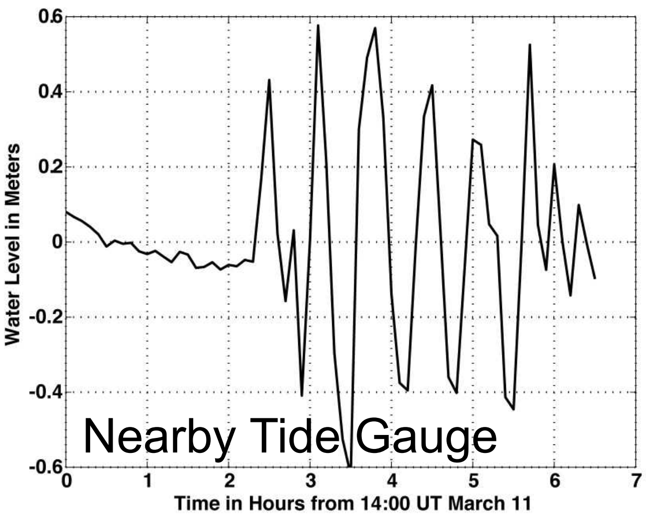
Tsunami Currents and Sea Level off Commonweal, California



Tsunami Observations on U.S. West Coast







- Tsunami seen by single radar at Commonweal: 13 MHz
- Method #3: Shift of Bragg peaks for three Rx antennas
- Method #3: Width of Bragg peaks for three Rx antennas
- Time series are detrended

Warning Issues

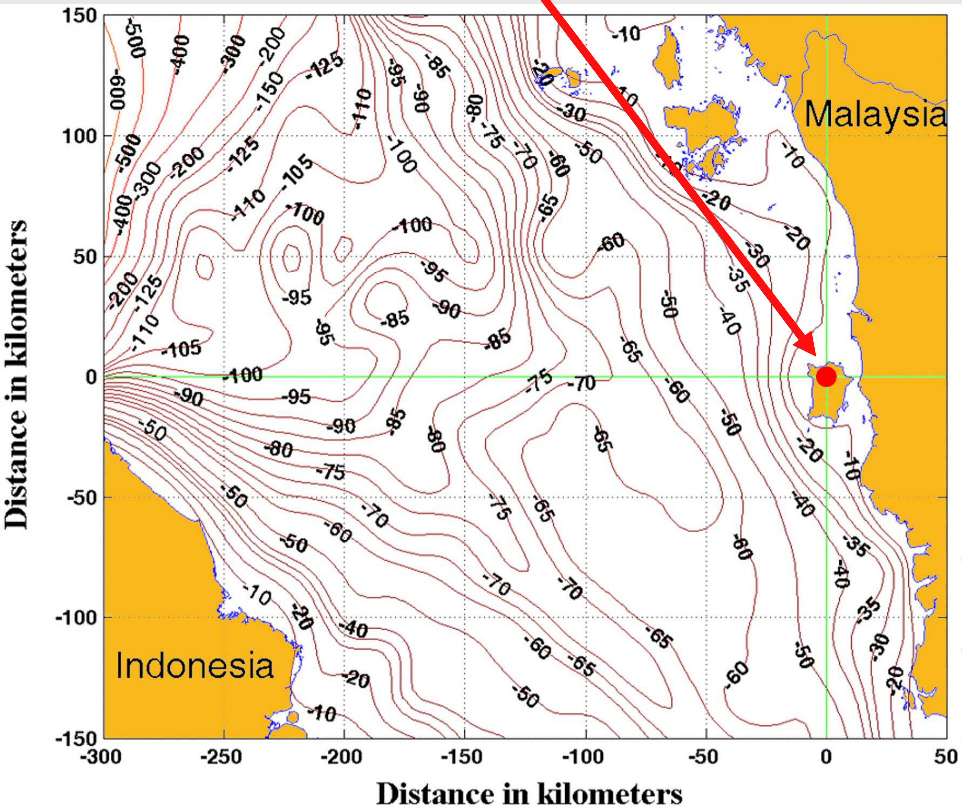
- Bathymetry most important by far!
  - Narrow shelf = little warning time
  - Broad shelf = longer warning time
- Ambient conditions /background currents
  - Ability to distinguish tsunami from the rest of the currents via magnitude and coherence
  - Automatic pattern recognition
- Temporal resolution
  - Tradeoff between accuracy and averaging time
- Radar frequency & spatial resolution
  - Not very important

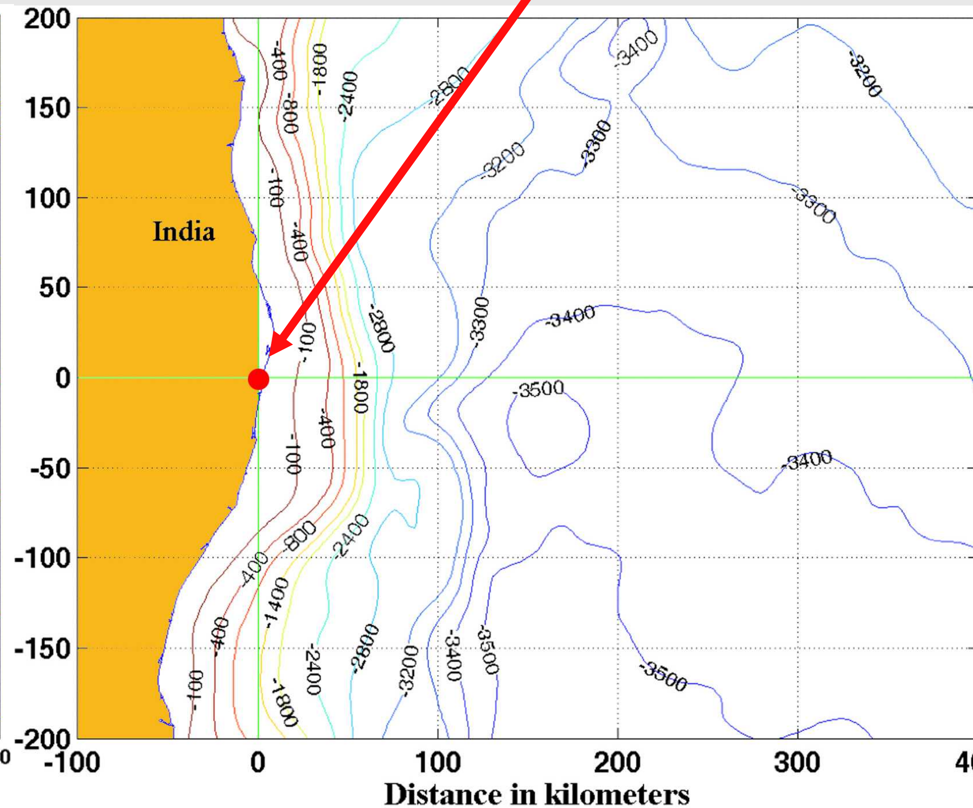
Available Observation Time?

It All Depends on Shelf Depth

Penang, Malaysia

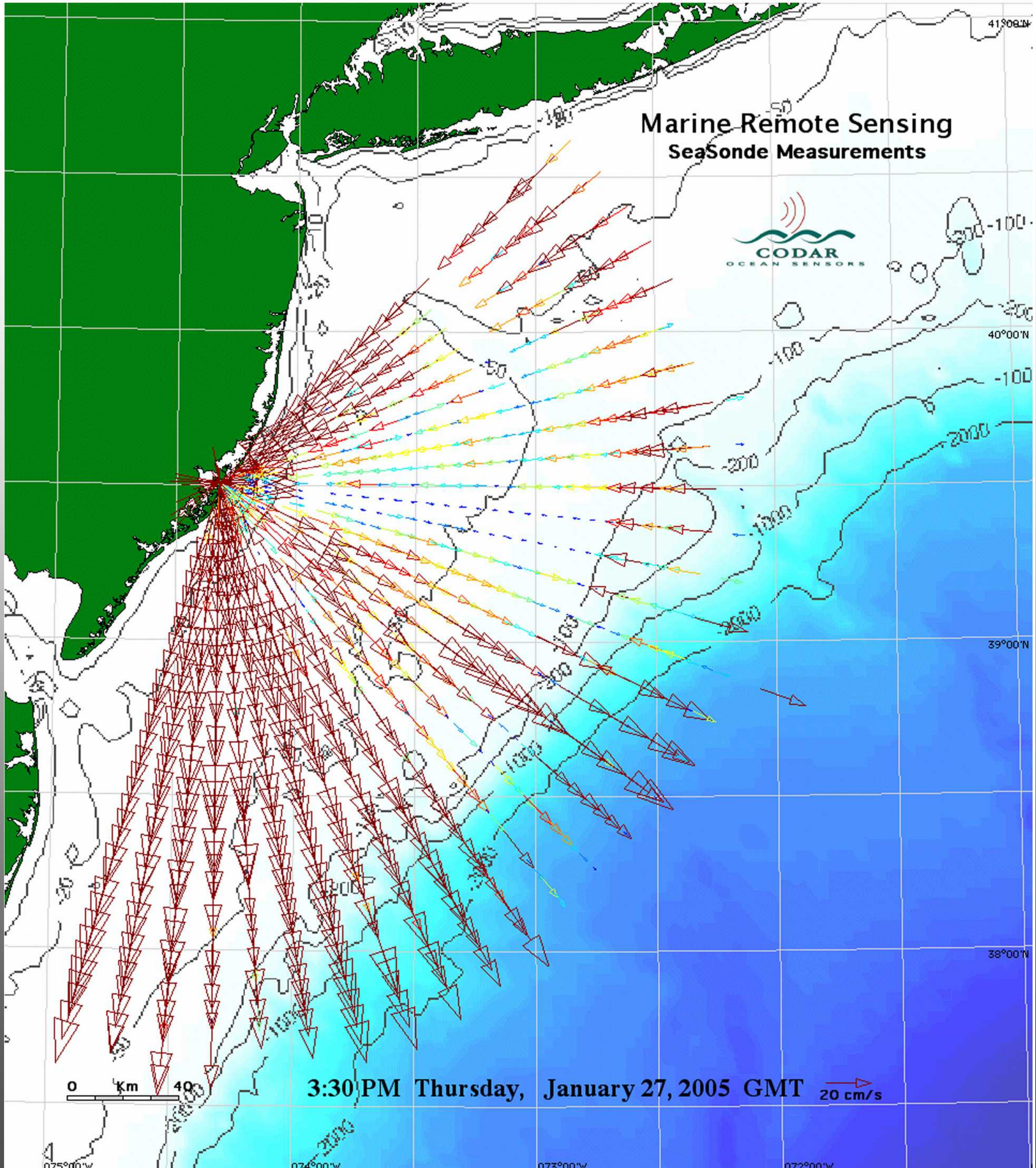
Chennai, India





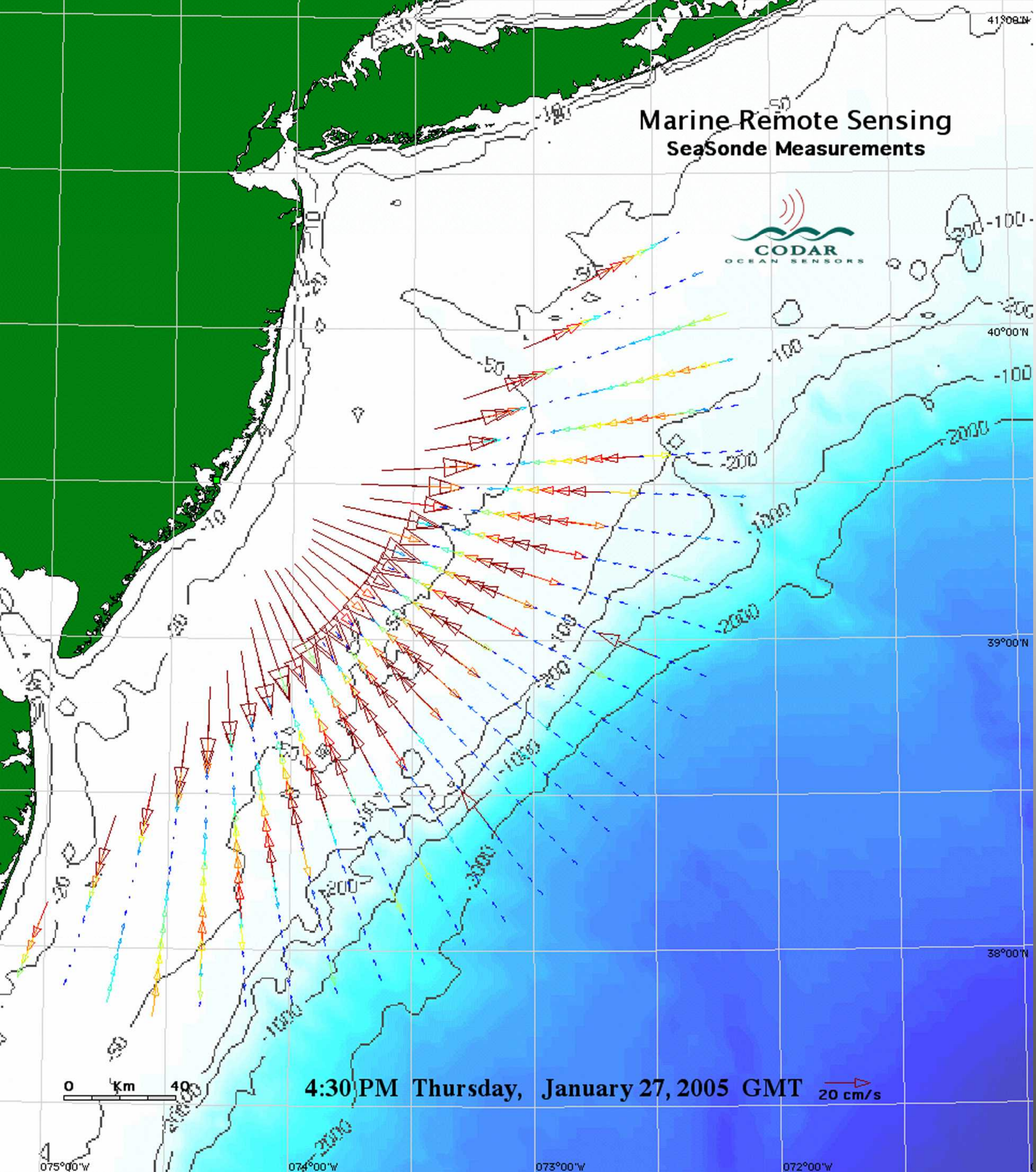
Shallow Extended Shelf: <u>2 Hours</u>

Narrow Shelf: <u>< 20 Minutes</u>



SeaSonde Radial Vector Map – Typical Background

New Jersey, USA



Tsunami Radial Vector Signature

60 min after reaching shelf

Tsunami Heights & Orbital Velocities At Various Depths

4000 m		1000 m		500 m		200 m	
Height (cm)	Orbital Velocity (cm/s)	Height (cm)	Orbital Velocity (cm/s)	Height (cm)	Orbital Velocity (cm/s)	Height (cm)	Orbital Velocity (cm/s)
10	0.5	14	1.4	17	2.4	36	7.9
20	1.0	28	2.8	34	4.7	71	15.7
50	2.5	71	7.0	84	11.8	178	39.4
100	4.9	141	14.0	168	23.5	356	78.7

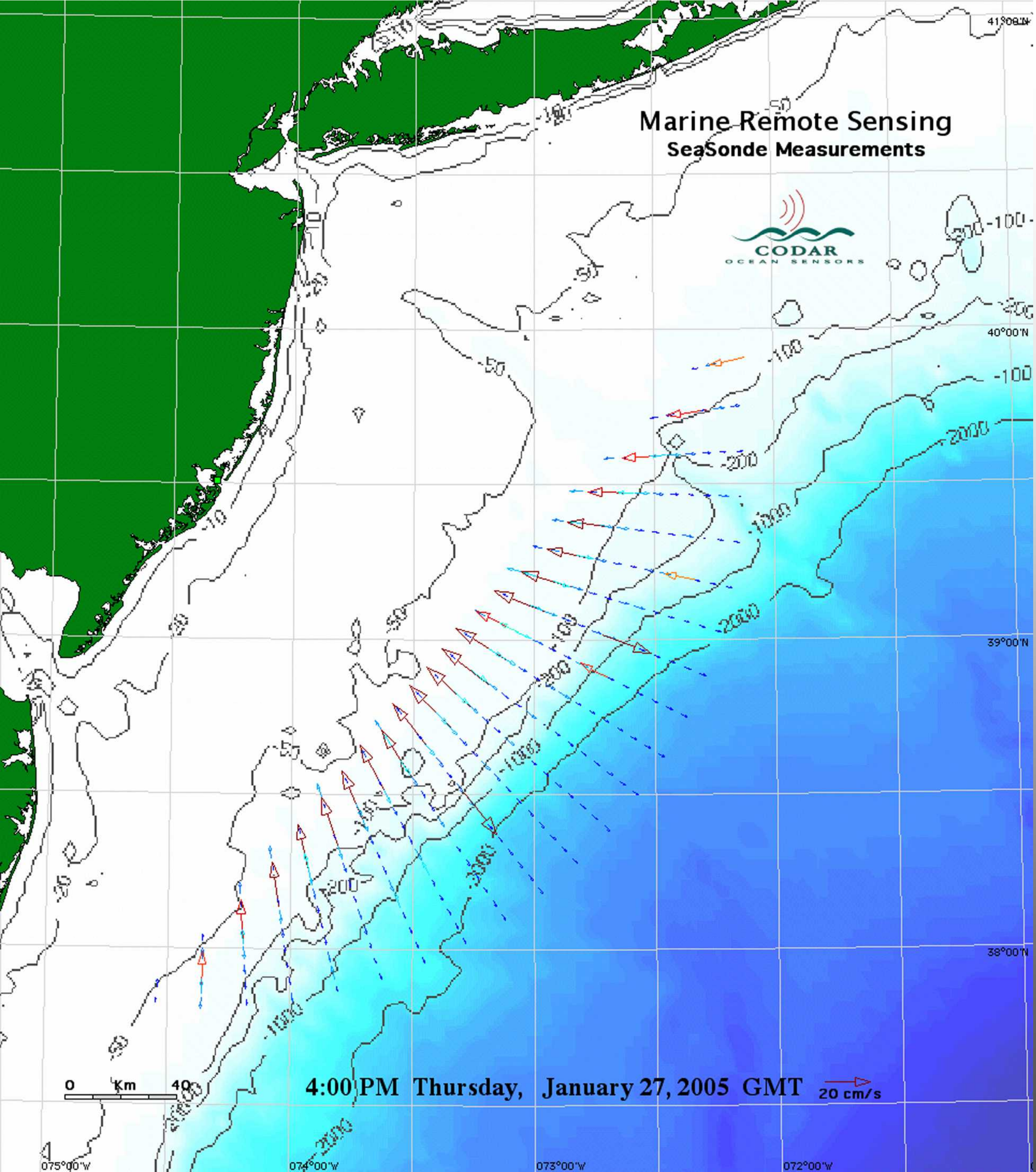
Detection Possible

Detection Most Likely

SUMMARY

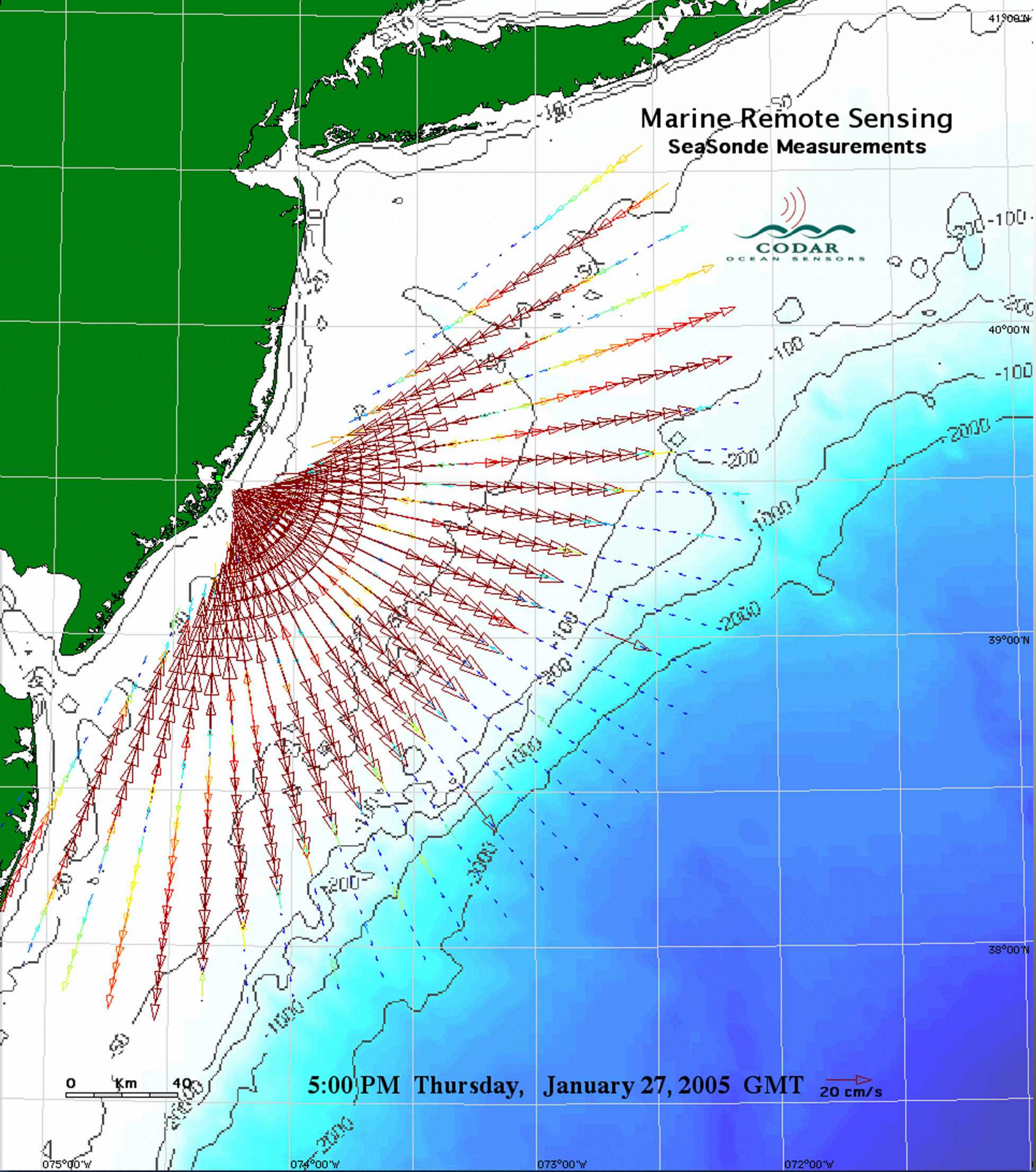
- Coastal HF radars can easily detect surface velocities due to a tsunami wave
- Even a single radar is valuable sensing radial velocities
- Allows post-analysis of how the wave propagated into the impacted region
- Allows 3-D verification of numerical models
- Warning time depends primarily on the bottom topography, i.e. shelf width

Extra Slides for Questions



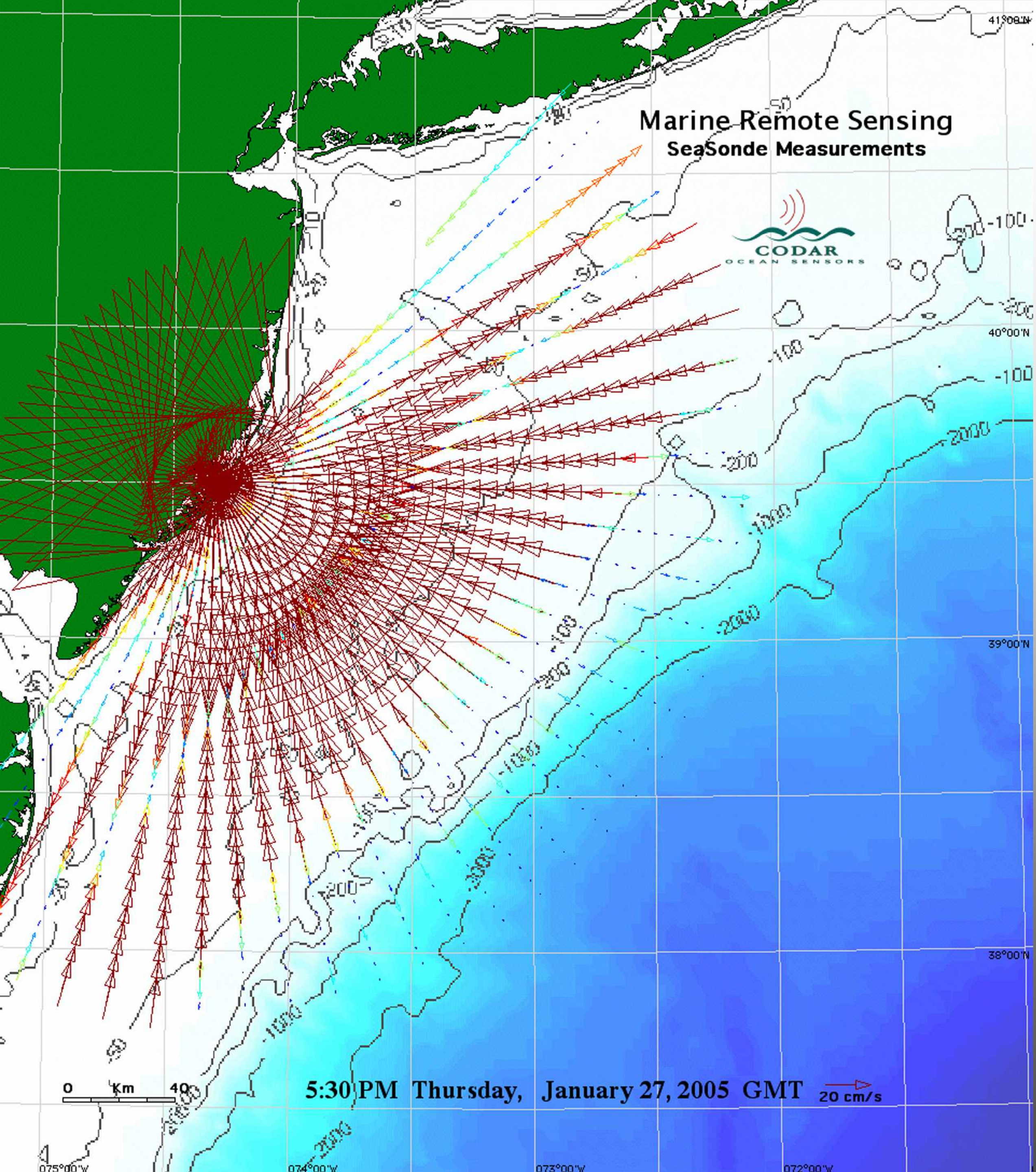
Tsunami Radial Vector Signature

30 min after reaching shelf



Tsunami Radial Vector Signature

90 min after reaching shelf



Tsunami Radial Vector Signature

120 min after reaching shelf

Developing a Space-Time Pattern Recognition System Based on Bathymetry/Hydrodynamics

- **Navier-Stokes Hydrodynamic Model for Horizontal Surface Velocity** [Lipa, B.J., D.E. Barrick, J. Bourg, B.B. Nyden. (2006), "HF Radar Detection of Tsunamis", *J. Oceanog.,* vol. 62, pp. 705-716]

[Many NOAA publications by Titov, Gonzalez, Mofjeld]

- **Full 2-D Time-Dependent Shallow-Water Hyperbolic PDE Wave Equation**

$$\nabla\nabla\cdot\left[d(x,y)\,\overline{V}(x,y,t)\right] - \frac{\partial^2\overline{V}(x,y,t)}{g\partial t^2} = \overline{0}$$

Green's function approach – delta-function time source at outer radar boundary

- **Frequency Domain: Sinusoidal Frequency Analysis, Elliptic PDE**

$$\nabla\nabla\cdot\left[d(x,y)\,\overline{V}(x,y,\omega)\right] + \frac{\omega^2}{g}\overline{V}(x,y,\omega) = \overline{0}$$

Eigenfunction approach – lowest bathymetry-based modes define velocity pattern

These 2nd-order PDEs are solved for single-site radar radial velocity patterns using MATLAB PDE Toolbox