HF Radar detection of tsunamis

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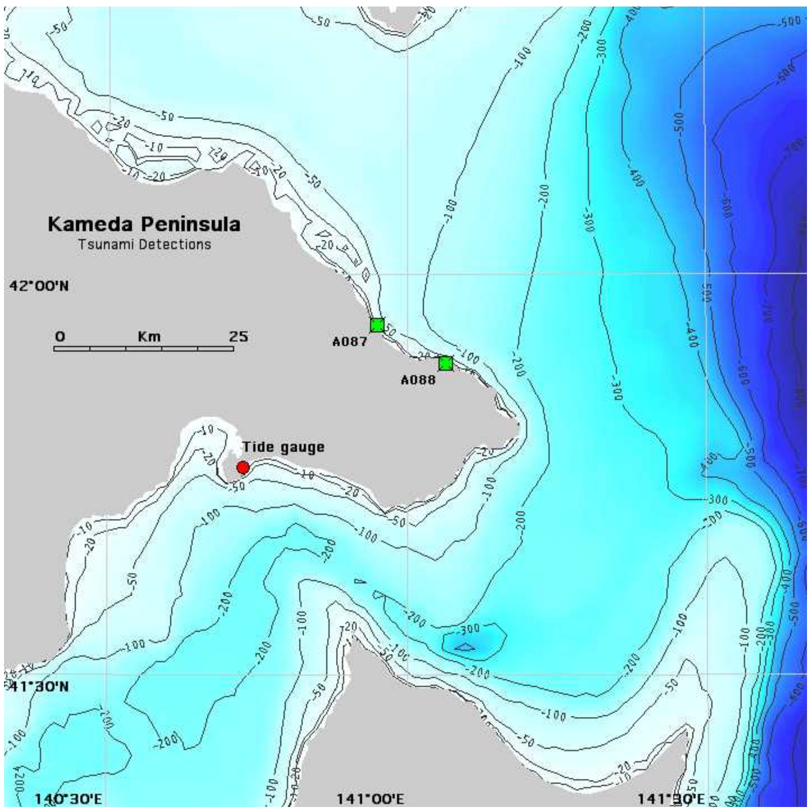
Codar Ocean Sensors

Analysis for tsunami current velocities, water levels

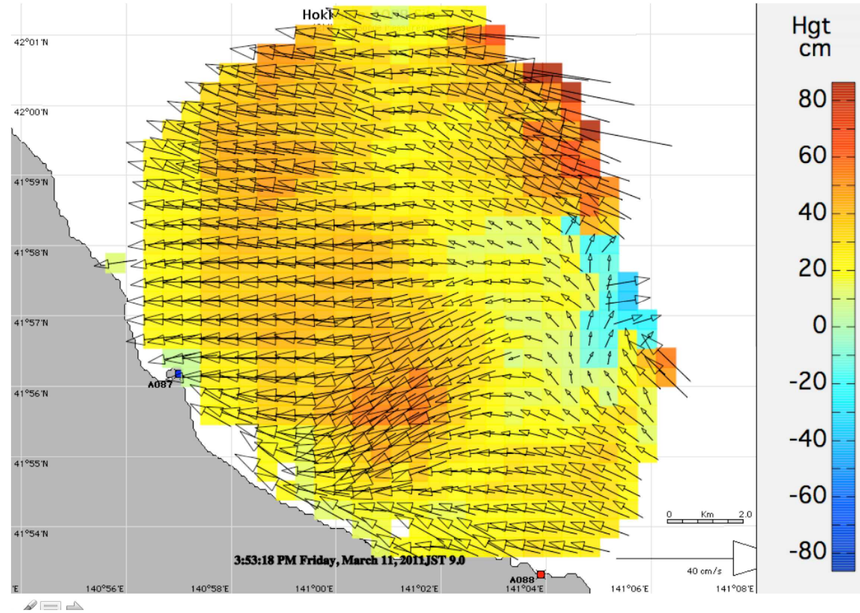
- **Two radars measure radial current velocity maps**
- **Radial velocities are combined to give total velocity**
- **Velocities are detrended to estimate the tsunami component**
- **Water level is calculated from detrended velocity & water depth**

Hokkaido tsunami

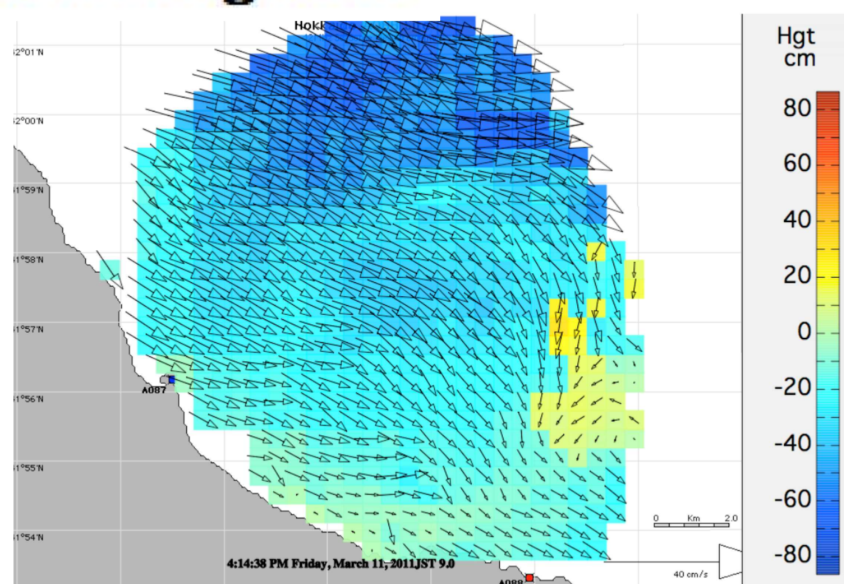
Current velocities and water levels

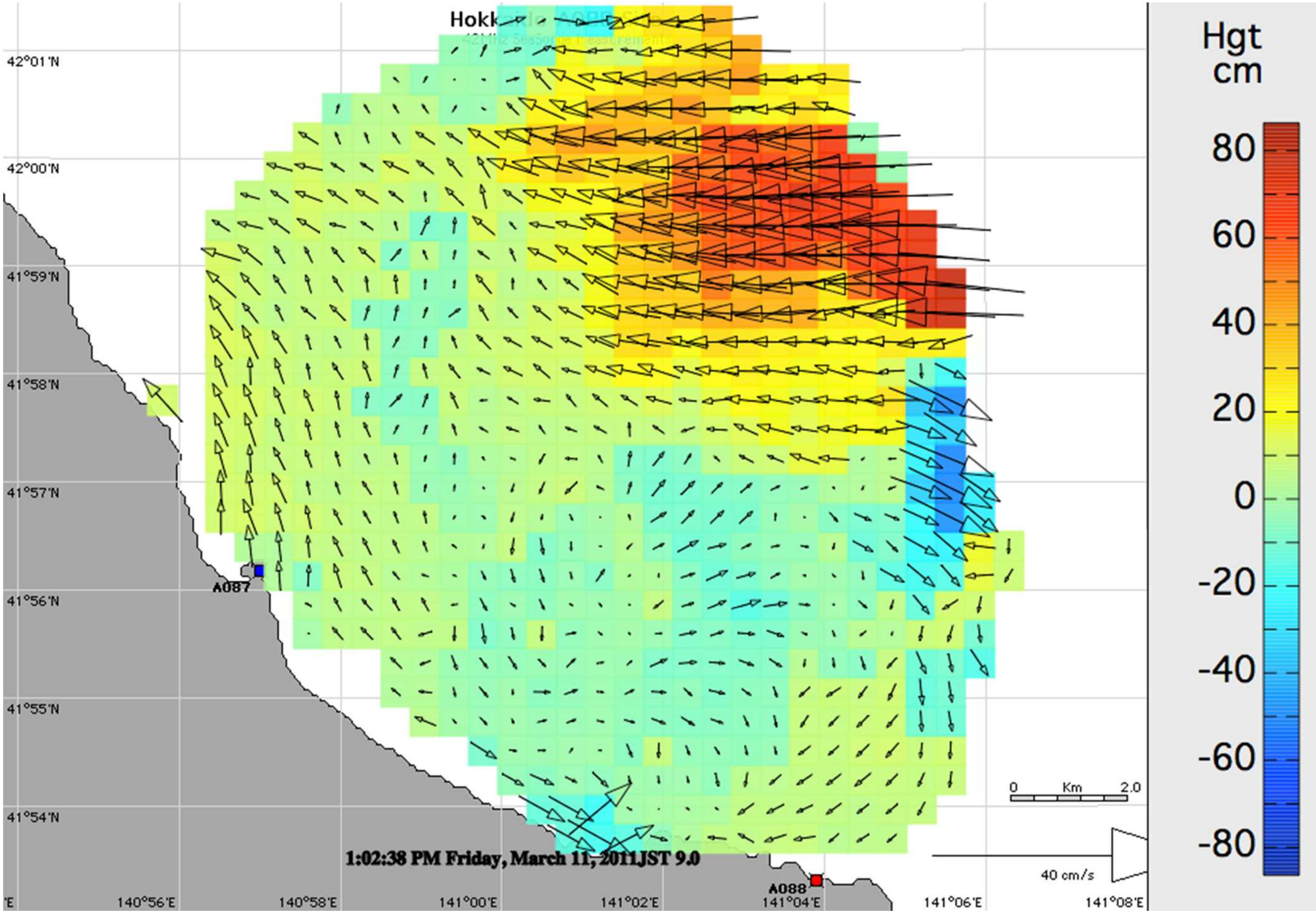


Tsunami arrival



Receding wave




42°01'N
42°00'N
41°59'N
41°58'N
41°57'N
41°56'N
41°55'N
41°54'N
140°56'E
140°58'E
141°00'E
141°02'E
141°04'E
141°06'E
141°08'E
A087
A088
0 Km 2.0
40 cm/s
1:02:38 PM Friday, March 11, 2011JST 9.0
Hgt cm
80
60
40
20
0
-20
-40
-60
-80

Tsunami detection summary

- Get the radial current velocity map from the sea echo

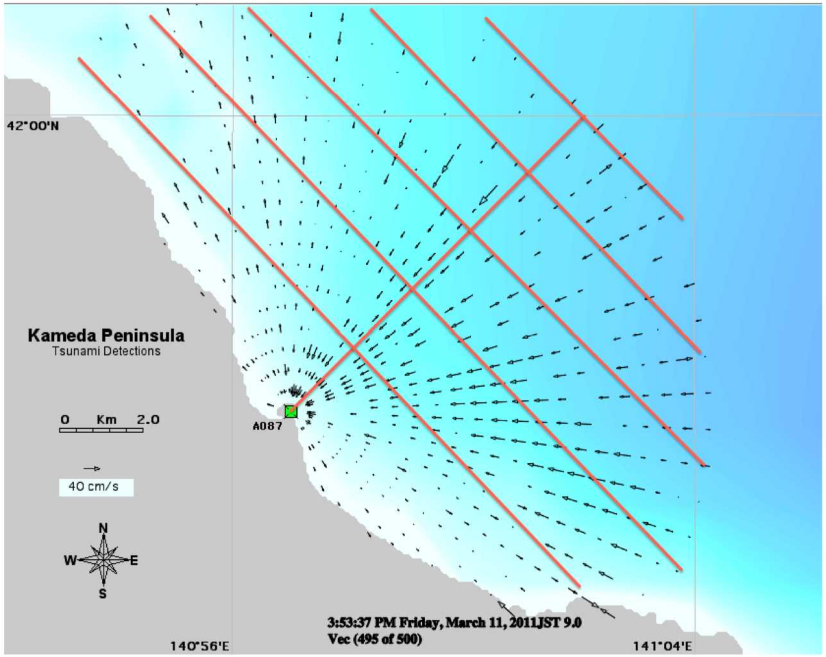
- Define 2-km area bands parallel to the depth contours

- Resolve the velocities perpendicular to the band

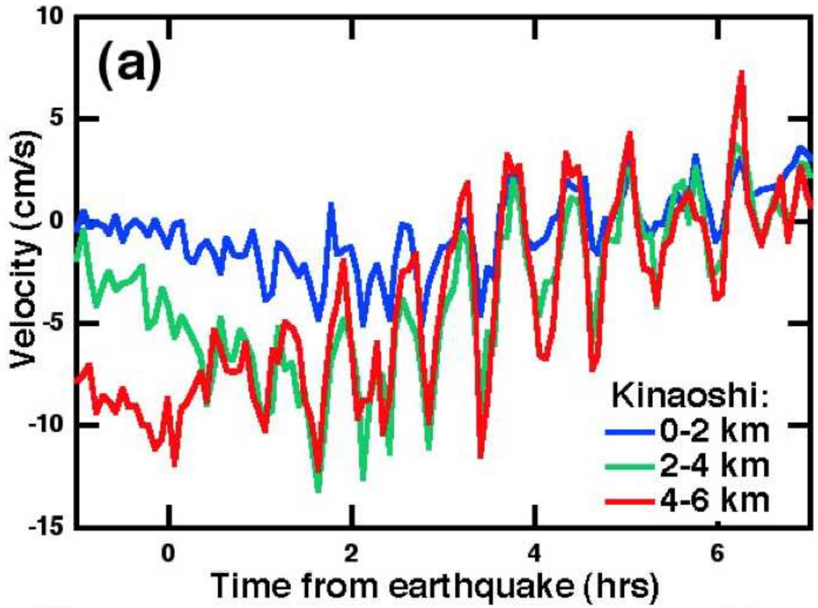
- In each band average the velocity components

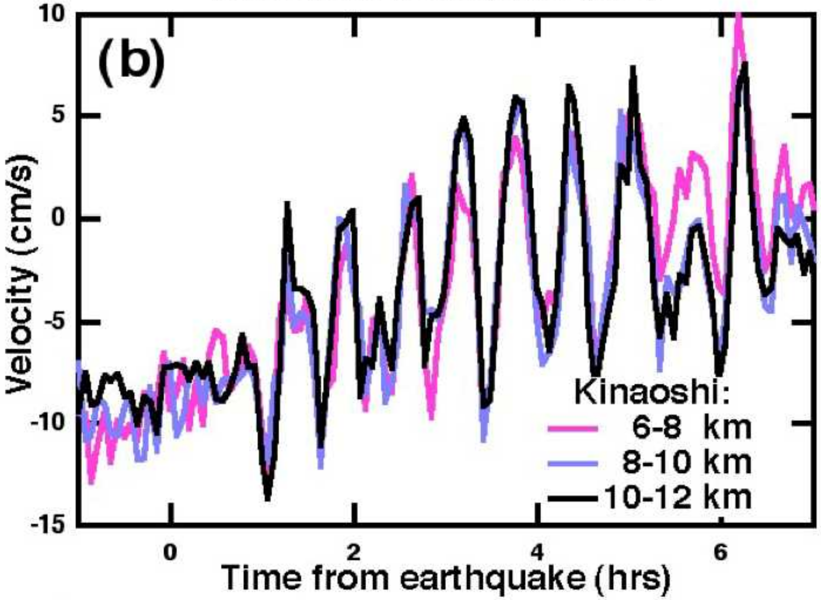
- Form a time series of the average velocity (4-minute resolution)

- Apply pattern recognition to detect tsunami arrival

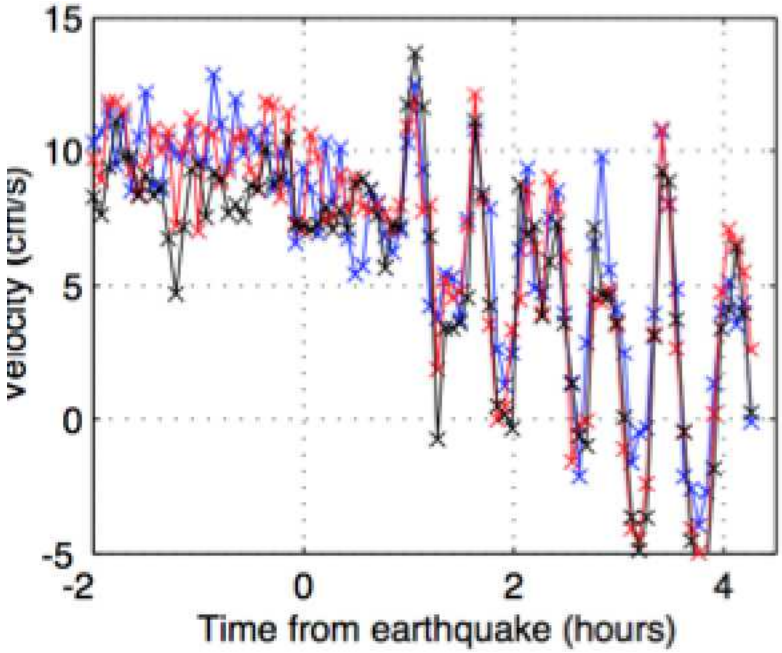


Velocity oscillations during the 2011 Japan tsunami

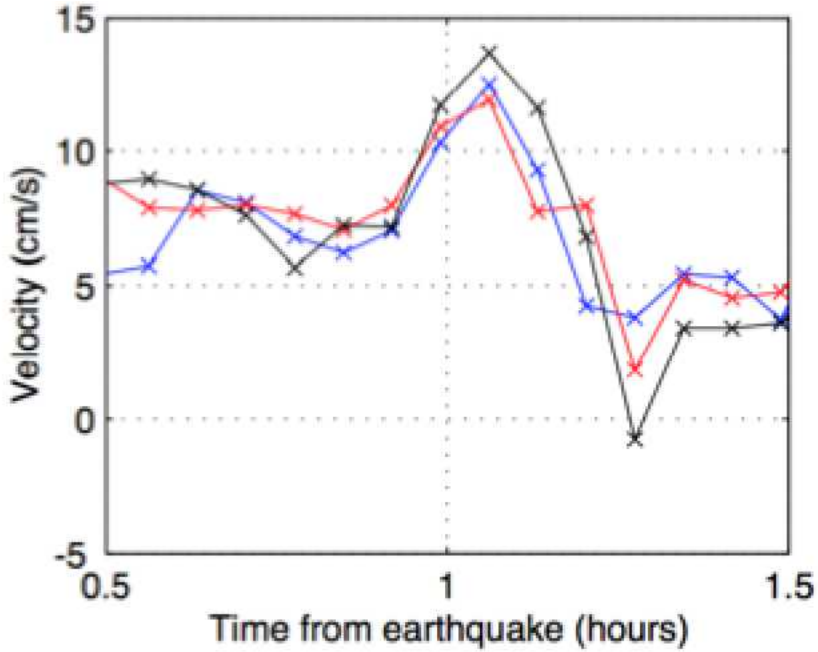




Velocity vs. time for 3 neighboring area bands



From 2 hrs before the quake until 5 hrs after

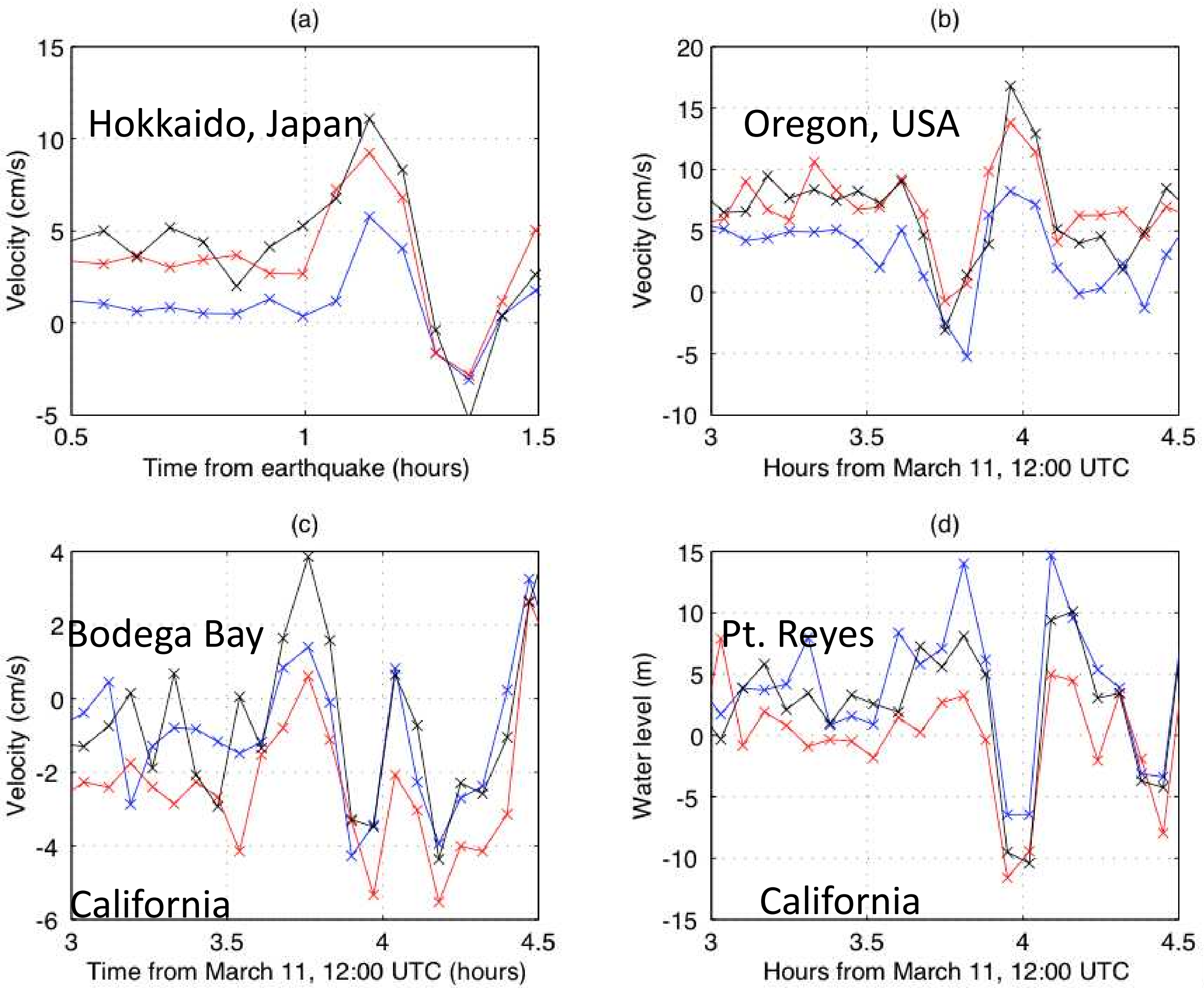


Around the tsunami arrival

Indication of tsunami arrival:

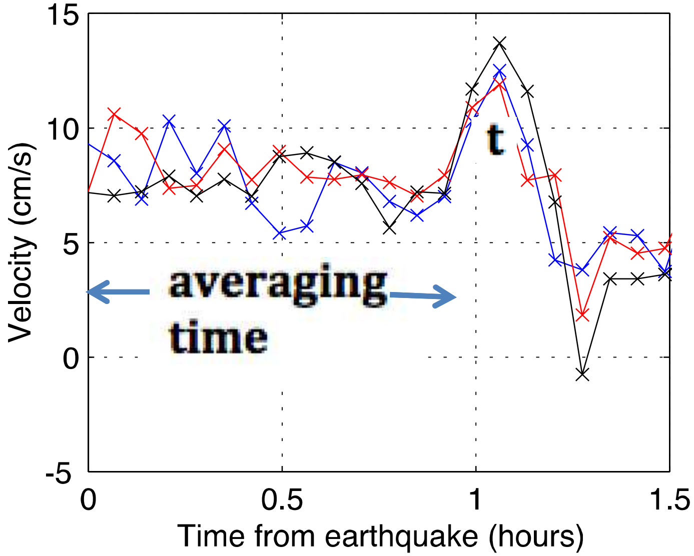
- Velocities deviate sharply from background
- Velocities in different area bands are strongly correlated

Typical velocity patterns signaling tsunami arrival



PATTERN RECOGNITION: FOUR STEPS

Step 1: Define the "Velocity deviation function" $V_D(t)$



Define three area bands b=1, 2, 3

For each band:

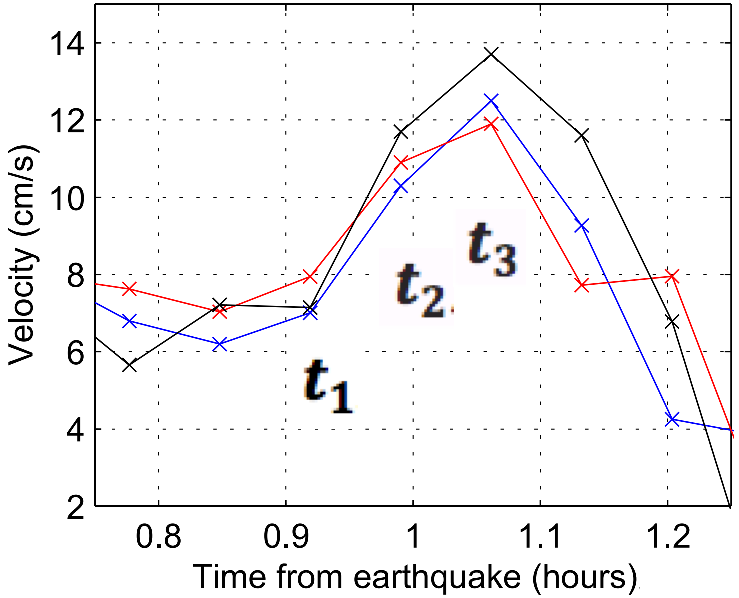
(a) Get velocity time series $v_b(t)$

(b) Calculate average velocity, v_{av}, and standard deviation, σ, over the preceding hour.

Form $D_b(t) = [v_b(t) - v_{av}] / \sigma$

Then: $V_D(t)$ = Absolute value $[D_1(t).\, D_2(t).\, D_3(t)]$

Step 2: Define the "Velocity correlation function" $V_C(t)$



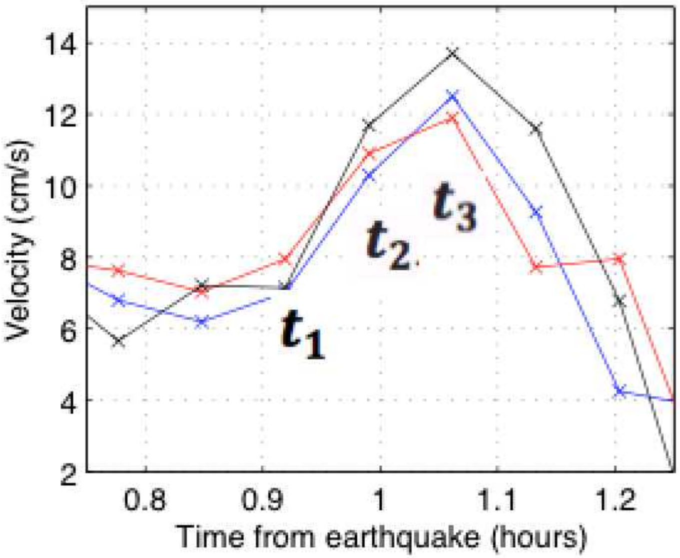
Take three consecutive times t_1, t_2, t_3

If for all bands b=1,2,3:

EITHER $v_b(t_2) > v_b(t_1)$ and $v_b(t_3) > v_b(t_2)$ (Approaching wave)
OR $v_b(t_2) < v_b(t_1)$ and $v_b(t_3) < v_b(t_2)$ (Receding wave)

THEN: $V_C(t_3) = 100$, otherwise $V_C(t_3) = 1$

- **Step 3: Define the velocity increment function $\Delta V_I(t)$**



Calculate change in velocity from t_1 to t_3

$$\Delta v_b(t_3) = v_b(t_3) - v_b(t_1)$$

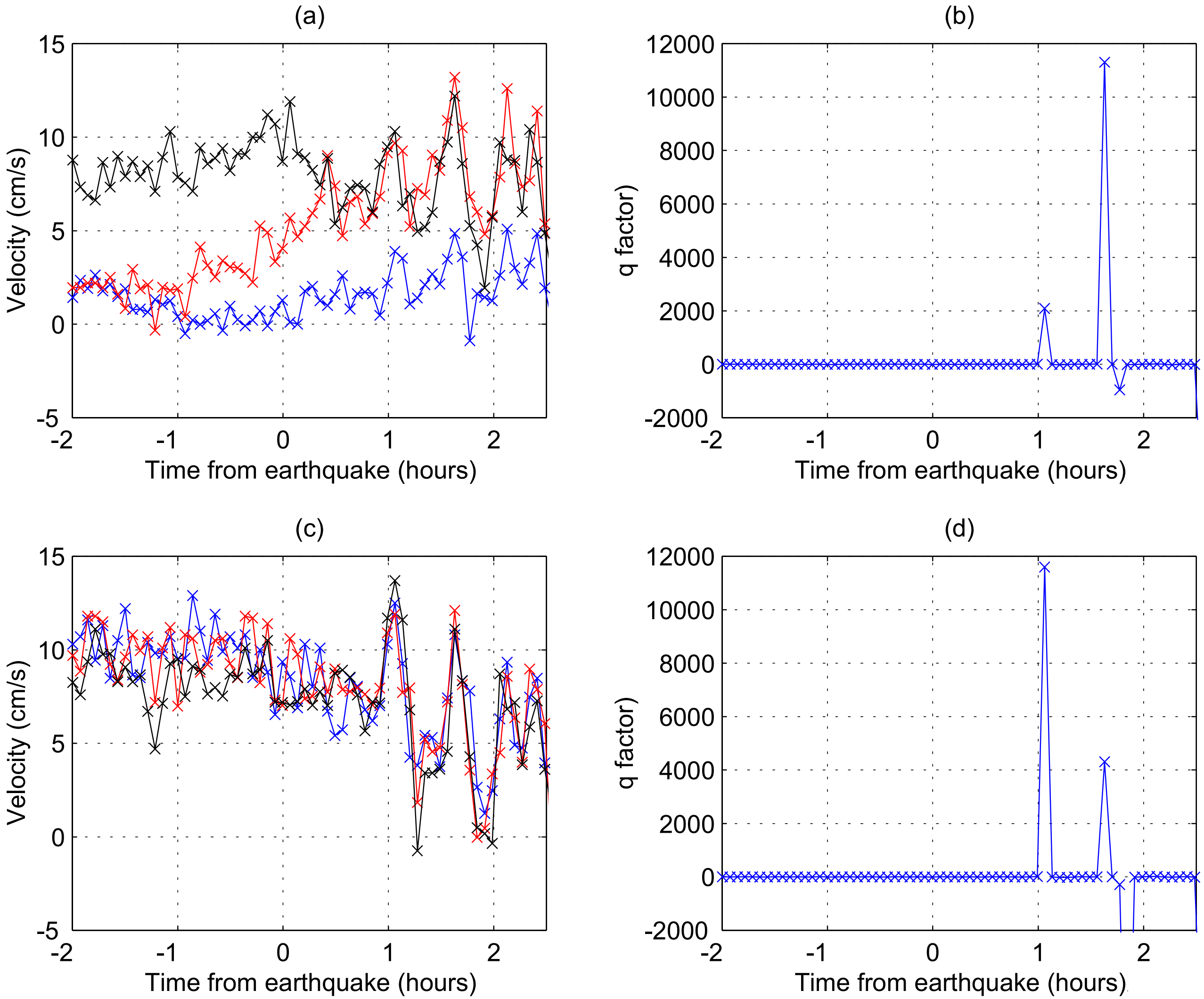
THEN: $\Delta V_I(t_3) = \Delta V_1(t_3) + \Delta V_2(t_3) + \Delta V_3(t_3)$

- **Step 4: Form the tsunami detection factor "q-Factor"**

$$q(t_3) = V_D(t_3) \,.\, V_C(t_3) \,.\, V_I(t_3)$$

Example 1:
Japan earthquake, March 2011 Kinaoshi, Hokkaido

Velocity q-factor



Bands 1-3

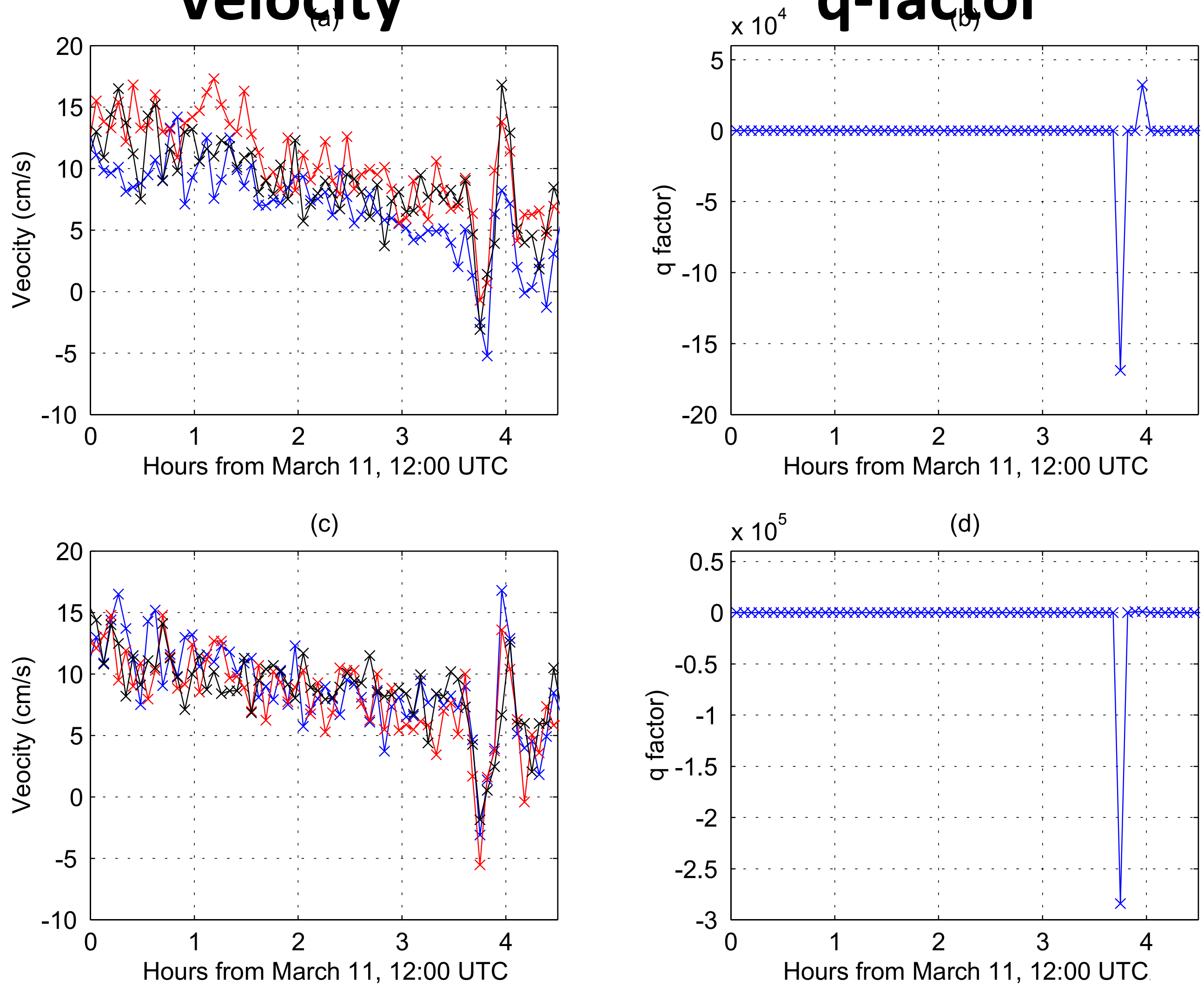
Bands 4-6

Example 2

Japan earthquake, March 2011 Yaquina Head, Oregon

Velocity

q-factor

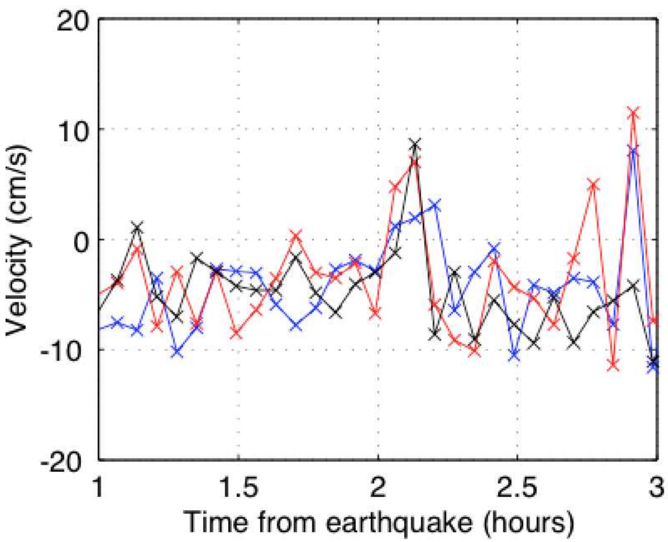


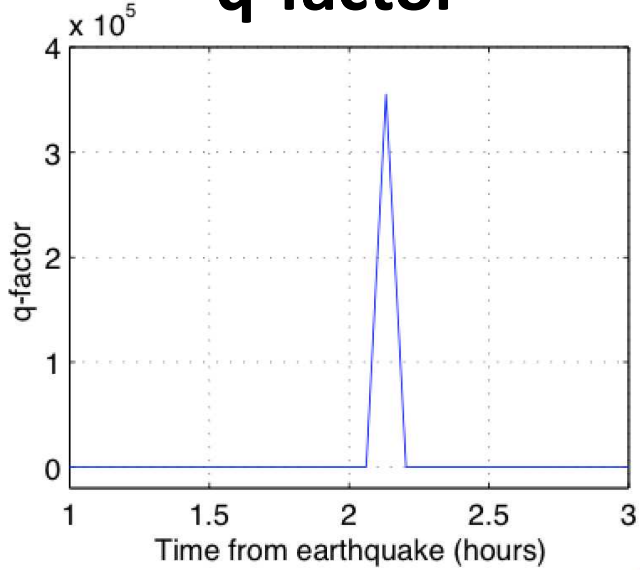
Bands 2-4

Bands 4-6

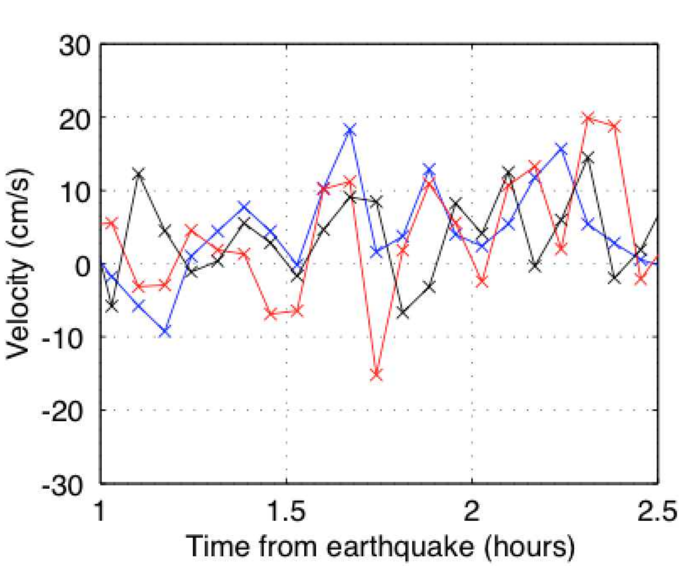
Example 3: Indonesia earthquake April 2012

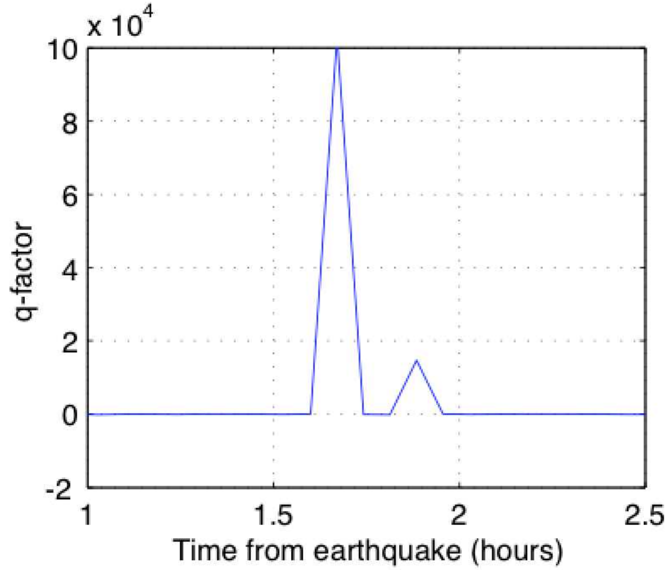
Velocity q-factor





Padang, Sumatra





Hut Bay, India

Japan March 11, 2011 JST

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

US West Coast March 11, 2011 UTC

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

Indonesia, India April 11, 2012 UTC

Radar (XMTR Freq)	*Arrival time (UTC)*	*Tide gauge*	*Arrival time (UTC)*	*Water-level change*
PDNG (14Mhz)	10:46, 12:33	Teluk Bayur	10.53	0.15m
HUTB (4Mhz)	10:18	Port Blair	10:28	0.05m

Conclusion:

- Tsunamis detected by 16 SeaSondes
- Extensive database collected for software development
- Tsunami arrival was detected about 8 minutes after the first appearance in the radar coverage area with water depth< 200m.
- Radar arrival times preceded tide gauge times by 19 minutes (Japan), 15 minutes (USA), 8.5 minutes (Indonesia/India) (averaged)
- Tsunami height small to moderate 5cm – 2m, narrow continental shelf.
- Increased warning time for large tsunamis and shallow water extending offshore

Future work:

- Improve detection algorithm by including more tsunami characteristics e.g. spatial patterns

- Develop methods to quantify the suitability of radar system and location for tsunami detection

- Field software deployment

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