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 not observed via height – rather by orbital velocity from shallow-water wave physics

\[
\begin{align*}
  v_p(d) & \propto h d^{-3/4} \\
  h_p(d) & \propto h d^{1/4}
\end{align*}
\]
Example for Hokkaido of Bands and Fitting of Radials from Single SeaSondes
Alert Software: Temporal Pattern Recognition Outputs a "Q-Factor" Trigger

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**

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

- **Lower Table: U.S. West Coast SeaSonde Observations**

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

- **Latest Alert Software Installed in Asia**

- **Warning Alert Time Critically Depends on Offshore Bathymetry**
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)

\[ \nabla \eta(x,y,t) = - \frac{1}{g} \frac{\partial \bar{v}(x,y,t)}{\partial t} \]

• Incompressibility of Water

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

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

Vector Equation for Velocity

\[ \nabla \nabla \cdot (d\bar{v}) - \frac{1}{g} \frac{\partial^2 \bar{v}}{\partial t^2} = \hat{0} \]

Scalar Equation for Height

\[ \nabla \cdot (d \nabla \eta) - \frac{1}{g} \frac{\partial^2 \eta}{\partial t^2} = 0 \]
Application to Real Bathymetry in Sunda Strait
Area of Interest: Near Labuhan

- Shallow bathymetry between Sumatra and Java gives longer observation times
Scalar height PDE solved on grid. From this the velocity is determined.

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

Bathymetry is defined from world database on this grid
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
Q-Factor Algorithm Detects Tsunami Arrival by Single Radar after Earthquake

SeaSonde Detections of Weak Tsunamis: Indian Ocean April 11, 2012

Hut Bay Detection Alert
Max Velocity = 9 cm/s
Max Height = 8 cm
Advance Alert: 14 minutes

Padang Detection Alert
Max Velocity = 10 cm/s
Max Height = 15 cm
Advance Alert: 14 minutes

Weak Aftershock Alert 2 Hours Later
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

June 12-13, 2013 Severe Bow Echo (low-end derecho)
Storm complex organized into forward propagating MCS over Indiana and traveled over 600 miles in 12 hours.
• 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 Tsunami Centers