HF RADAR Tutorial
Principles of Operation, Data Products & State-of-the-Art
Chad Whelan
SeaSonde Site Layout

Climate-Controlled Shelter with Power, Communications

> 11 MHz:
Single T/R antenna
SeaSonde Site Layout

Climate-Controlled Shelter with Power, Communications

> 11 MHz:
Single T/R antenna

< 11 MHz:
Separate T & R antennas
Compact Omnidirectional Antenna
Compact Electronics
Low Power (<200 Watts)
How Does It Work?
SeaSonde is a Doppler Radar

Measures velocity of target towards or away from the Radar
Bragg Scattering

<table>
<thead>
<tr>
<th>Freq (mhz)</th>
<th>$\lambda_R$ (meters)</th>
<th>$\lambda_o$ (meters)</th>
<th>$T_o$ (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>60</td>
<td>30.0</td>
<td>4.4</td>
</tr>
<tr>
<td>13</td>
<td>23</td>
<td>11.5</td>
<td>2.7</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
<td>6.0</td>
<td>2.0</td>
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<tr>
<td>42</td>
<td>7</td>
<td>3.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Groundwave Propagation

Line-of-sight

Skywave Propagation

Ionosphere
SEA SURFACE CURRENTS AND WAVES

HF Radar Derived Wave Height and Direction - Bodega Bay, CA

Note: the date/time axis in these charts is in UTC (PST -8/PDT -7).

Current Velocity Doppler Spreading
Bragg Waves Approaching
2nd Order

Doppler Frequency (Hz)

Wave height is in meters, measurements are ~ 2-18 km (~1-11 miles) offshore.

BML1 2010-04-26 02:00 at 5.994 km

<table>
<thead>
<tr>
<th>Height</th>
<th>Period</th>
<th>Wave</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2m</td>
<td>8.8s</td>
<td>308°</td>
<td>271°</td>
</tr>
</tbody>
</table>
Radial Currents

Sea

Land

Echo Strength (dBm)

Doppler Frequency (Hz)

Sea

Land

CODAR Ocean Sensors
www.codar.com

HF RADAR Tutorial
Bergen, Norway
June 10, 2013
Compact Crossed Loop Omnidirectional Antenna

• 3 co-located antennas

• Unique combination of amplitude & phase for each antenna = 6 parameters for each bearing

• MUSIC Direction Finding on each Doppler bin
Long Range SeaSonde
6 km Range Resolution
Radials Produced to ~190 km

Standard SeaSonde
1.5 km range resolution
Radials Produced to ~50 km
## Considerations for Choosing Frequency

<table>
<thead>
<tr>
<th>Freq. (MHz)</th>
<th>Ants</th>
<th>Radar $\lambda$ (m)</th>
<th>Ocean $\lambda$ (m)</th>
<th>Current Depth (m)</th>
<th>Max Speed (m/s)</th>
<th>Range (km)</th>
<th>Range Res. (km)</th>
<th>Sat. $H_{1/3}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>2</td>
<td>67.3</td>
<td>33.6</td>
<td>2.0</td>
<td>6.5</td>
<td>160-220</td>
<td>3-6</td>
<td>25</td>
</tr>
<tr>
<td>5.3</td>
<td>2</td>
<td>57.0</td>
<td>28.5</td>
<td>2.0</td>
<td>6.0</td>
<td>150-200</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>9.3</td>
<td>2</td>
<td>32.2</td>
<td>16.1</td>
<td>1.6</td>
<td>4.5</td>
<td>90-130</td>
<td>3-6</td>
<td>19</td>
</tr>
<tr>
<td>13.5</td>
<td>1</td>
<td>22.2</td>
<td>11.1</td>
<td>1.3</td>
<td>3.7</td>
<td>60-90</td>
<td>3</td>
<td>13</td>
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<tr>
<td>16.2</td>
<td>1</td>
<td>18.6</td>
<td>9.3</td>
<td>1.0</td>
<td>3.4</td>
<td>45-65</td>
<td>1.5</td>
<td>11</td>
</tr>
<tr>
<td>24.5</td>
<td>1</td>
<td>12.2</td>
<td>6.1</td>
<td>0.7</td>
<td>2.8</td>
<td>30-50</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>26.2</td>
<td>1</td>
<td>11.4</td>
<td>5.7</td>
<td>0.6</td>
<td>2.7</td>
<td>25-45</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>39.3</td>
<td>1</td>
<td>7.6</td>
<td>3.8</td>
<td>0.3</td>
<td>2.2</td>
<td>15-25</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>42.3</td>
<td>1</td>
<td>7.1</td>
<td>3.6</td>
<td>0.3</td>
<td>2.1</td>
<td>15-25</td>
<td>0.3</td>
<td>3</td>
</tr>
</tbody>
</table>
Factors Affecting Performance

HF Radio Noise Sources
  Man Made Broadcasts
  Natural Sources (Auroral, Lightning, etc.)

Shallow Water

Local Wave Climate
  Fetch Limitations
  Saturation at Higher Frequencies

Very Strong or Very Weak Range of Currents

Site Conditions (Antenna Interactions, Propagation Loss)

Salinity
Example Radial Vector File
SeaSonde QA/QC

Antenna Pattern Measurement/Calibration
1st Order Bragg Identification Algorithms
Vessel Echo Detection & Removal
Ionospheric Echo Detection & Rejection
Burst Noise (Lightning) Removal
Outlier Removal
Radio Signal Interference Rejection Per-Doppler Solution SNR thresholds
MUSIC parameter thresholding
Example Total Vector File
Regional/National Networks

Case Study: U.S. West Coast

- 60+ SeaSondes
- Mixed frequencies: 5, 13, 25, 42
- Nested Resolutions
- >2000 km of coastline covered
Nested Resolutions

7 & 12

Doran County Park
Dorsey Bay
San Francisco Bay
Sausalito

Long Peak

Tomas Bay
Dundre Bay
Drakes Bay

5 & 12

12

1 km

2 km

6 km

½ km

CODAR Ocean Sensors
www.codar.com

HF RADAR Tutorial
Bergen, Norway
June 10, 2013
Validations


Validations


Alfonso, Marta, Enrique Alvarez and Jose Damian Lopez (March 2006), Comparison of CODAR SeaSonde HF radar operational waves and currents measurements with Puertos del Estado buoys, Final report of Puertos del Estado, Spain.

Ullman, D., et. al. (June 2003), “Use of Coastal Ocean Dynamics Application Radar (CODAR) Technology in U.S. Coast Guard Search and Rescue Planning”, U.S. Coast Guard Research and Development Center Report No. CG-D-09-03.
Network Monitoring & Data Management
Site RATH

RATH Strathmere, NJ Rutgers-BPU 13MHz CODAR Site
Seasonde Standard Range
Located 39°11.921’N, 074°39.151’W, Bearing 198.0° NCW
CF 13.450000 MHz, BW -49.630 kHz, GPS Alignment 26300.0 us
Blanking 668.8us with Pulse Shaping with Blank Delay 8.6 us
Site Time 2013-06-09 10:33:05 UTC

Radials

2013-06-09 09:00 UTC
Meas ±37.5 min.
Ideal ±37.5 min.
2013-06-09 09:37 UTC
Meas -25.2 hr.

Spectra

2013-06-09 10:20 UTC
CSS covers ±7.5 min.
2013-06-09 10:24:29 UTC
CSQ covers +4.0 min.
**Site**

- **RATH** Strathmere, NJ Rutgers-BPU 13MHz CODAR Site
- **SeaSonde** Standard Range
- **Located** 39°11.921'N, 074°39.151'W, **Bearing** 198.0° NCW
- **CF** 13.450000 MHz, **BW** -49.630 kHz, **GPS Alignment** 26300.0 us
- **Blanking** 668.8us with **Pulse Shaping** with **Blank Delay** 8.6 us
- **Site Time** 2013-06-09 10:35:05 UTC

**Alerts**

- **Nothing To Report** (for 1 hour 48 mins).

**Receiver**

- **SeaSonde Receiver-SSRX-USB-AWGIII-02011336**
- **CODAR Advanced Waveform Generator III**
- **Firmware Version** 3.10 May 5, 2012 Timing 633A Acquisition 9301
- **Running** for 10 hours 18 minutes and 33.0 seconds
- **Chassis Temperature** is 29.1 °C
- **Humidity** 50% with a Dewpoint of 1.2°C
- **Power Supplies** are good at +5.1V, -5.0V and +12.2V

**Transmitter**

- **Power 33 Watts Forward, 0 Watt Reflected**, VSWR 1.1:1
- **Chassis Temperature** 27.0 °C
- **Amplifier Temperature** 31.0 °C
- **Power Supplies** are good at +5.0V and +24.2V

**Data**

- **Logging Range Series** at 180 ranges by 512 sweeps.
- **Logging CrossSpectra** at 359 ranges by 512 dopplers
- **Logging CrossSpectra** at 359 ranges by 512 dopplers at 8.0x rate
- **Logging CrossSpectra** at 359 ranges by 256 dopplers at 4.0x rate
- **Logging CrossSpectra** at 359 ranges by 128 dopplers at 2.0x rate
PORTUS
A SeaSonde-centered marine information system

The main aim of PORTUS is to enhance the utility and usability of SeaSonde HF radar data.

PORTUS provides a multi-user, easy-to-use geographical interface to foster HF radar data use and data sharing.

PORTUS is also able to manage and integrate data from other measurement instruments and models and fuse them with SeaSonde.
General PORTUS features (I)

Reliable and efficient data storage and data management

Powerful and user friendly Google maps based web interface

Dubai SeaSonde HF radar data in PORTUS
General PORTUS features (II)

3. Seamless importation and integration of all surface currents and waves data into third party IT systems

4. Extra monitoring and reporting tools to track system status and the physical medium status
5. Value added data products based on SeaSonde: STPS
• Surface Currents Short Term Prediction System
• Data fusion with third party observations and models

STPS based on NOAA modeled winds and SeaSonde measured currents
General PORTUS features (IV)

6. Value added data products based on SeaSonde: OPEN
   - 25h average, divergence, convergence maps
   - Comparison with models (currents, waves, SST, etc.)

Spanish National Ports and Harbours Authority (PdE) buoy network (left) and Gibraltar Strait HF Radar System in its Portus Marine Information System
SHARE® & Multi-Static
### ITU Ocean Radar Frequency Allocations (kHz)

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 438 - 4 488</td>
<td>4 438 - 4 488</td>
<td>4 438 - 4 488</td>
<td></td>
</tr>
<tr>
<td>5 250 - 5 275</td>
<td>5 250 - 5 275</td>
<td>5 250 - 5 275</td>
<td></td>
</tr>
<tr>
<td>9 305 - 9 355</td>
<td>No allocation</td>
<td>9 305 - 9 355</td>
<td></td>
</tr>
<tr>
<td>13 450 - 13 550</td>
<td>13 450 - 13 550</td>
<td>13 450 - 13 550</td>
<td></td>
</tr>
<tr>
<td>16 100 - 16 200</td>
<td>16 100 - 16 200</td>
<td>16 100 - 16 200</td>
<td></td>
</tr>
<tr>
<td>24 450 - 24 600</td>
<td>24 450 - 24 650</td>
<td>24 450 - 24 600</td>
<td></td>
</tr>
<tr>
<td>26 200 - 26 350</td>
<td>26 200 - 26 420</td>
<td>26 200 - 26 350</td>
<td></td>
</tr>
<tr>
<td>39 000 - 39 500</td>
<td>No allocation</td>
<td>39 500-40 000</td>
<td></td>
</tr>
<tr>
<td>42 000 - 42 500</td>
<td>No allocation</td>
<td>No allocation</td>
<td></td>
</tr>
</tbody>
</table>
Modulation
Multiplexing

Share Bandwidth
Multiple Systems can sweep through same band without interfering

Multistatic Operation
Use Sea echo from another’s site’s transmission (requires $10^{-11}$ precision oscillator*)

*CODAR-patented GPS-disciplined oscillator waveform works worldwide
Scattering Geometry

Multi-Static

Receive signals and sea echo coherently from multiple other SeaSondes

Bistatic

Monostatic

T/R

T
Collect Multi-static data simultaneously with monostatic data
Open Mode Analysis
OMA domain
Data filled in the domain

Red: open boundary
Black: closed boundary
Non-divergent Modes $\psi_i$ (Dirichlet)

$\alpha_1^\Psi \star + \alpha_2^\Psi \star + \alpha_3^\Psi \star + \ldots$

Non-rotational Modes $\varphi_i$ (Neumann)

$\alpha_1^\varphi \star + \alpha_2^\varphi \star + \alpha_3^\varphi \star + \ldots$
Boundary Modes $\varphi_i^b$ (Flow in and out the domain)

Any current field can be expanded in the interior and boundary modes:

$$\vec{u} = \sum_{i=1}^{\infty} \alpha_i^\psi \hat{k} \times \nabla \Psi_i + \sum_{i=1}^{\infty} \alpha_i^\varphi \nabla \varphi_i + \sum_{i=0}^{\infty} \alpha_i^b \nabla \varphi_i^b$$

**OMA Current field construction:**

Minimizing a cost function to determine the ideal combination of modes which gives the **best fit to available measurement data** (i.e radial vectors)

OMA reconstructed fields from radials
OMA reconstructed fields from radials

20 Sept 1000 GMT

Standard LS LOCAL combining method

10:00 AM, Monday, September 20, 2010
Vel (388 of 388)

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HF RADAR Tutorial
Bergen, Norway
June 10, 2013
Short Term Predictions from Mode Coefficients

Trailing Time Series

\[
\begin{align*}
\alpha_1^\Psi (t_{-12}) & \ldots \alpha_1^\Psi (t_0) \\
\vdots & \vdots \\
\alpha_N^\Psi (t_{-12}) & \ldots \alpha_N^\Psi (t_0) \\
\alpha_1^\phi (t_{-12}) & \ldots \alpha_1^\phi (t_0) \\
\vdots & \vdots \\
\alpha_N^\phi (t_{-12}) & \ldots \alpha_N^\phi (t_0) \\
\alpha_1^b (t_{-12}) & \ldots \alpha_1^b (t_0) \\
\vdots & \vdots \\
\alpha_N^b (t_{-12}) & \ldots \alpha_N^b (t_0)
\end{align*}
\]

Fit trends to each trailing coefficient time series: diurnal, semi-diurnal, inertial, linear & constant.
Short Term Predictions from Mode Coefficients

Trailing Time Series

\[
\alpha_1^\Psi (t_{-12}) \ldots \alpha_1^\Psi (t_0) \\
\vdots \\
\alpha_N^\Psi (t_{-12}) \ldots \alpha_N^\Psi (t_0) \\
\alpha_1^{\phi} (t_{-12}) \ldots \alpha_1^{\phi} (t_0) \\
\vdots \\
\alpha_N^{\phi} (t_{-12}) \ldots \alpha_N^{\phi} (t_0) \\
\alpha_1^b (t_{-12}) \ldots \alpha_1^b (t_0) \\
\vdots \\
\alpha_N^b (t_{-12}) \ldots \alpha_N^b (t_0)
\]

Predicted Time Series

\[
\alpha_1^\Psi (t_{+1}) \ldots \alpha_1^\Psi (t_{+12}) \\
\vdots \\
\alpha_N^\Psi (t_{+1}) \ldots \alpha_N^\Psi (t_{+12}) \\
\alpha_1^{\phi} (t_{+1}) \ldots \alpha_1^{\phi} (t_{+12}) \\
\vdots \\
\alpha_N^{\phi} (t_{+1}) \ldots \alpha_N^{\phi} (t_{+12}) \\
\alpha_1^b (t_{+1}) \ldots \alpha_1^b (t_{+12}) \\
\vdots \\
\alpha_N^b (t_{+12})
\]
Tusen Takk!