A Bistatic HF Radar for Current Mapping and Robust Ship Tracking

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Objective:

- Develop methods for Classification / Identification of ships and small boats using Multi-Frequency HF radar in Bistatic mode
- Emphasize clear channel operation by allowing optimal choice of radar frequency vs. time-of-day
  - Diurnal ionospheric variation impacts frequency availability/selection
    - Lightning propagating via ionosphere sets noise levels-diurnal behavior
    - Diurnal propagation enhancement impacts channel occupancy
- Dual-Use Coast Guard application for mapping current shear and vector winds for SAR operations
Approach:

- Develop RCS Library of Ship Classes vs. Radar Frequency
  - Interleaved Pulse Frequency switching important - simultaneity
  - Large ships will have significant RCS at low frequencies
  - Complicated superstructure will have RCS interference nulls
  - Use as many frequencies as available to optimize both detection / ID
  - Bistatic operation, 3rd-Dimension added:
    - azimuthal-RCS variation enhances ID

- Identify HF Bistatic RCS Spectral peaks + nulls as ship classifiers
  - Based on work conducted in ‘70’s at NRL
Radar Background:

- **HF Radar is a** *Coherent* (Doppler) Radar
  - Can measure velocities (as a police speed radar, different wavelengths)
  - Developed at NRL, SRI late 60’s, classified, NOAA began Codar late 1970’s

- **HF Radar operates @ 3-30 MHz (between A.M. and low TV bands)**
  - Advantage - over-the-horizon coverage - 200 km coverage capable
  - Large antenna elements (ham radio types), ~100-m coastal site required

- **Long-range coverage by Surface-wave propagation**
  - Unique to HF and lower - salty sea surface ~perfectly conducting
Doppler spectrum analysis of Coherent Radar samples provides individual target echoes at different radial velocities:

- Ship’s Radar Cross Section ~ Received Power in Doppler filter
- Ship’s speed ~ to radial velocity linearly
- Detection Strategy - Auto-sort targets from Bragg lines either side of zero Doppler
Long-Range Target Detection Limitation with most available HF radars:
Lack of assured 24-hr 200-km coverage using single frequency HF Radars

Single Issue that Impacts Detection / Long-range Current Maps:
* High Quality **Signal-to-Noise Ratio (SNR)**

- **both** Signal Strength & Noise variability must be examined

- **HF Spectrum Noise** (varies diurnally due to ionosphere, solar traverse)
  - Other HF users respond to ionospheric OTH coverage, =>crowded spectrum
  - Creates noisy HF Radar channel diurnally
  - Limits maximum km-range of coverage vs. time-of-day

- **Signal Strength** - Bragg Line echo proportional to Directional Wave Spectrum
  - If low frequency is chosen for long range propagation, drop in winds and local sea state will limit echo strength
  - Better choice at night might be frequency above the MUF
  - Surface wave propagation loss increases with radar frequency
A. Noise Spectrum / Channel Occupancy Issue:
(Spectra courtesy of: S. Rodriguez, Radar Division, Naval Research Lab)

Night-time spectrum
* Other-user spectral peaks crowd into Low frequency region, < 10 MHz
* Background Lightning noise, OTH Ionospheric propagation there

Day-time Spectrum
* Low-frequency background drops (D-region absorption during day)
* High-frequency user increase due to daytime ionosphere propagation
Example Spectrum: Doppler vs. Range at each Azimuth

From ISR MFR Navy Experiment, single frequency of 32 set shown
Bragg echoes expected @ 0.204 Hz
Ambient currents shift < 0.01Hz
Short-range coverage for ship tests (3 ship echoes seen)
Set of 4 MFR Simultaneous Doppler-Range Spectra

2.370 MHz shows effect of weaker Signal Strength vs. Range
4.895 MHz shows effects of Higher Noise floor
RCS Variability vs. Frequency used as Classification Tool
Model Ship RCS: Bulk Echo + $\lambda/4$ monopoles (vertical structures)

(Trizna/Xiao IEEE OE Special Oct-05 issue on HF Radar Applications)

Monopole RCS frequency dependence:

- 10-MHz $\lambda/4$ monopole is 7.5 m high
- Ocean Ground Plane produces image of induced currents, thus a dipole RCS
- 10 Mhz resonant peaks at ~9.4 MHz as shown below
- Odd $\lambda/4$ peaks also appear
- Low Frequency decline as $\lambda^7$
- Use as a RCS Calibration tool

7.5-m monopole over water has peak 200 m$^2$ RCS
Large ship RCS is dominated by bulk RCS source beam-on then by monopoles, with interference nulls when observed bow/stern-on.

Stern/Bow Vs Beam-aspect RCS ratio is 20 dB or more

Smoothed curve of beam & stern RCS for CGN9 (Headrick & Rachuba, NRL/MR/5309-98-8173)
**Small RCS Example - fishing boat (RW Bogle, DB Trizna, NRL Report 3322, July 1976)**

- **Metal Mast = 54.5 ft = 16.6 m**
  - $= \lambda/4 @ 4.5$ MHz

**Ship Classification**

**Bistatic Multi-frequency HF Radar**
2nd Small RCS Example
Southern Comfort II Pleasure Boat
with possible monopole resonances, but smaller RCS than monopole
3rd Small RCS Example
Navy Torpedo Retrieval Boat (TRB)
Several monopole resonances
Bistatic Operation

Extra Dimension added by bistatic scatter using separated sites
Bistatic Transmitter - minimal space, Xmit only
Receive Site - both Xmit/Rcv, Receive array of antennas
Bistatic RCS Model for 2-mast ship

2 masts are 3.75, 2.5 m High (8, 12 MHz resonance), spaced 7.5 m
Monostatic RCS is cut through surface at 0-deg
    Far more complexity and useful information available over 180-deg
Bistatic RCS Model for 2-mast ship

Plan view of previous plot, emphasizing RCS Peaks, Nulls
Monostatic / Bistatic radar placement shown below right
Ship track is dark line, generates multiple azimuth samples of RCS
Bistatic Experiment

Bistatic experiment conducted at Army FRF site, VHF band

- Both sites use GPS receivers imbedded in ISR Transceivers
- Both sites coupled to own Rubidium Clocks for master RF Clock signal
- Accurate in Doppler frequency to few mHz, equivalent few cm/s radial speed in Doppler
Bistatic Experiment

Transmitted spectra from two sites at different frequencies
Along with receive spectrum in black
Bistatic Experiment

Two Bistatic Doppler spectrum examples for target approach / recede runs

- Strong, wide-band signal at 150-m is direct path pulse from bistatic transmitter
- Pulse compression allows 30-m resolution using 5 MHz bandwidth at 60 MHz
- Bragg lines show curved Doppler shape at short range - different ocean waves
- Experiment validated Bistatic Collection / Processing capability
In Summary:

- Multi-frequency HF radar *mitigates noisy channels* - diurnal variation
- Multi-frequency HF radar *allows ship RCS Spectroscopy* as ID tool
- Bistatic operation expands to an *added dimension of RCS variability*
  - RCS peaks and nulls are classifiers
  - Low frequency RCS suggests very large ships (tankers, container ships, large naval vessels)
- Testing of system at HF underway in 4th Q 2008
ISR HF Radar for Navy Applications

- Right and lower-left show transmit and 4-element DOA receive array for Navy test data shown earlier.
- Lower right shows older 25-element beam-pointing HF radar.
- ISR 16-element radar would be half the length of latter, and use very small antenna elements.
B. Signal Strength Issue - Variable Ambient Wave Energy:

* Bragg-line echo $\sim L = \lambda/2$ spectral component of ocean wave spectrum

* Long-range HF radar operation at $\sim 4.5$ MHz varies with sea state

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**Model Wave Spectra, 5 & 10 m/s winds**

Pierson Moskowitz $f^{-5}$ dependence

Provides prediction of Maximum Range for frequency choice vs. wind speed

e.g., 21 dB Loss at 6 MHz going from 10 $\rightarrow$ 5 m/s winds: 150 km $\rightarrow$ 30 km maximum warning

30 dB Loss at 4 MHz $\rightarrow$ 150 km $\rightarrow$ 15 km maximum warning

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Radar Frequency, MHz

Bragg wave energy, @ 10 & 20 kt, $\sim$ 5-10 m/s:

$\Rightarrow$ 30 dB drop at 4 MHz,

$\Rightarrow$ Factor of 10 in range coverage capability, so desired 150-km coverage drops to 15 km at 4 MHz.
Radar Technology Foundation:

Octopus: 8-channel Digital Radar Transceiver

- 8-channel 100 MHz with 1-256 on-board sum =>8 to 16 bit + 9-bit digital filter prior to Doppler FFT
  - FPGA's, Digital Down Converters + Cell phone technologies ported to radar world
- Exciter - transmitter - coherent pulsed waveform digitally generated
  - On-board GPS receiver for bistatic synchronization, location