A Bistatic HF Radar for Current Mapping and Robust Ship Tracking

Recent Bistatic Ship Tests Validate New Technology

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A bistatic High Frequency (HF, or 3-30 megahertz band) radar has been developed for dual-use application to ocean current mapping and ship vector tracking. The radar can be deployed in a multi-frequency version, allowing it to sample ocean currents at different depths between 20 centimeters and 3 meters, and thus map ocean current vertical shear. The multi-frequency feature allows for more robust tracking than single frequency HF radars by avoiding target fading due to echo nulls from frequency and azimuthal variations in ship radar cross section that occur using a single radar frequency. Modest ship classification can make use of these nulls and peaks. More details on the radar system can be found elsewhere, along with ocean current shear measurements. The bistatic capability is based on accurate system timing and radar frequency accurate to 2 millihertz, provided at each of two or more radar sites by rubidium clocks and GPS receivers. The primary site also transmits a monostatic signal and uses a 4 to 16-element receive array, and all sites use a transmit monopole or a short log periodic array for multiple frequencies. This bistatic approach reduces the infrastructure and coastal site requirements because of the need for just one receive-antenna array per radar system, with as many as two remote transmit sites, either side of the receive site, to maintain optimal spatial coverage along the coast. These units could be staggered to create a system of radars, providing continuous coverage along a coastline, alternating transmit and receive sites. This type of arrangement could be used to provide robust ship tracking along a country's coastline, and a modest estimate of type and tonnage of all vessel traffic based on target echo characteristics versus radar frequency. Due to its digital approach, the cost of these radars is substantially less than that of commercial HF radars currently available, none of which have a multi-frequency capability. The principle of how echo peaks and nulls can be used for classification is addressed here using the simple two mast ship model. However, the bulk cross section that dominate very large container ships requires a more complex scattering model that is not addressed here.

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BISTATIC SHIP TARGET SCATTERING MODEL

Bistatic scatter results when a signal from a transmit site far removed by tens of kilometers up or down the coast from the master site is received from target in an area some distance, R, offshore. The bistatic scattering angle, Φ_B, is used for both target scattering and Bragg sea scatter calculations, and represents the angle between the transmitted field from the bistatic site to the area offshore, and the scattered field from there to the master receive site. For the two-mast monopole model, masts separated by distance L, each element is assigned a height above the sea surface, which in turn determines the scattered field strength of each element. Their separation, L, determines how the scattered fields interfere in summing, producing peaks and nulls in the radar scattering cross section (RCS). When plotted as a three dimensional surface, using radar frequency and bistatic angles as X-Y coordinates, and RCS as the Z coordinate, the surface shows peaks and nulls that result from constructive and destructive interference of scatter from the two monopoles. These features can be used to provide a modest classification tool for a ship that can be represented by two or more masts. A single mast boat will not have interference nulls, but the frequency of the maximum echo will allow determination of the height of the mast, and thus provide an estimate of the size of the boat. A very large container ship will be dominated by the vertical hull structure and may show minor resonance effects, but will present a strong echo at lower HF frequencies the larger the ship, thus providing an estimate of tonnage.

The aspect of the target's course heading relative to the receiver array is Θ_A. Although the monopole RCS is omni-directional, the relative alignment of the monopole pair will determine RCS peak and null locations. The scattered fields from each element will add with a phase difference that is only function of the difference in phase path both to the transmit and receive sites. For the case of arbitrary bistatic and aspect angles, the ratio of scattered field, E_S, to incident field, E_T, is determined by rather simple equations, and these are used to provide the total bistatic RCS as a function of radar frequency and bistatic angle.

$$E_S/E_T \sim (\lambda^2\sigma_1)^{1/2}\exp\{ikx\} + (\lambda^2\sigma_2)^{1/2} \exp\{ik[x+L \cos \Phi_B, +L \cos(\Phi_B + \Theta_A)]\} \qquad (1)$$

$$\sigma_T = P_R/P_T \sim \sigma_1 + \sigma_2 + [(\sigma_1)^{1/2} \ (\sigma_2)^{1/2} \ ] \cos\{ik[x+L \cos \Phi_B, +L \cos(\Phi_B + \Theta_A)]\} \qquad (2)$$

An example test case demonstrates the classification method. The illumination geometry uses two bistatic sources, transmit sites 1 and 2, with the receive site located below them. The three arrows for each transmit site represent scatter paths for three positions of the target moving across the scattering area. These three boat locations generate three samples of bistatic RCS vs. frequency for each site, shown by the two sets of three vertical lines over the RCS. The blue lines represent the locus of RCS values for many radar frequencies measured for bistatic site 1, and the red lines represent site 2, as if one had continuous frequency coverage over the HF band. In practice, 15 or 30 frequencies are more likely, so that discrete samples would be occur along these lines to generate a matrix of frequency-bistatic angle samples for target classification. Both the maxima and deep minima would be used as the classifiers, with accuracy of classification increasing with greater number of aspect angle samples, and/or bistatic transmitter sources.

VHF BISTATIC EXPERIMENT

The bistatic system was tested in the Very High Frequency (VHF, or 30-300 megahertz) band, which allows for shorter range and higher range resolution than can be achieved at HF frequencies. The technology transfers directly to the HF band, with slower analogue-to-digital (A/D) conversion rates required due to lower radar frequencies and corresponding Nyquist frequencies. The heart of the digital radar is the Imaging Science Research (ISR) Octopus transceiver card, which has both a programmable pulsing capability and eight receive channels per card. For a sixteen-element array, a second similar receiver card in the same computer provides eight additional receive channels. At the bistatic transmit-only site, an ISR Exciter card is used to generate the pulsed waveforms. For long-range operation to 150 kilometers using a 10% duty cycle and a kilohertz pulse-repetition-frequency, for example, a 100-microsecond pulse is transmitted, forcing a 15-kilometer blind area from the radar. The echo data is compressed to 10-microseconds or 30-meter range resolution, achieving a 20-dB pulse compression gain. This allows a 250-watt peak power pulse to be compressed to the equivalent of a 25-kilowatt peak-power pulse using frequency-modulated pulse waveforms, yet only represents 25 watts of average power. A shorter pulse could be used to cover ranges inside of the 15-kilometer area on alternating triggers, for example.

Two identical VHF radars were stationed at two corners of a 500-meter sided test area square at opposite diagonal corners. Log-periodic antennas were used for transmitting, and 8-element arrays of 2-meter monopoles were used for reception. The experiment was conducted at the U.S. Army Corps of Engineers Field Research Facility (FRF) pier, with the first radar mounted at the end of the pier and the second on the dune at the north property line. The FRF Lighter Amphibious Re-supply Cargo (LARC) boat was used as the target and was run in straight-line course across the seaward third corner of the test area to provide a sequence of target bistatic aspect angles. Both radars were run at modest power using vertical polarization above 50 megahertz, with non-overlapping frequencies, and each transmitted simultaneously. Data were recorded digitally with both radars without real-time pulse compression, so that each radar could be used to process its own monostatic echo, as well as the bistatic echo at the second radar frequency using appropriate pulse compression reference functions used with each radar. The pulse was swept over 5 megahertz, which resulted in 30-meter range resolution after pulse compression. Tests were run using just a single frequency in each case to provide maximum data rates and high signal-to-noise ratio for targets and sea clutter.

A Doppler spectrum for the case of the boat running at 45 degrees angle to the radar layout described above produced the strongest radar echo for all five aspects that were used between 0 and 90 degrees. The amphibious landing craft had no real mast, but a wide plate hull surface as the dominant scattering element, so little to no resonance effects were seen. For such a target, the flat plate hull is expected to produce its strongest echo for the 45-degree course, as specular scatter from the hull occurs for this case.

The Bragg lines for bistatic scatter are due to ocean wave components with wavenumber, K, given by $K = 2k \cos(\Phi_B)$, where k is the radar wavenumber, and Φ_B is the bistatic angle from above. For long ranges, the bistatic echo approaches the monostatic value, $K=2k$. For short ranges, the bistatic angle opens up and longer ocean waves are responsible for the Bragg echo, causing the Doppler shift to decrease. The results obtained confirm this expected behavior with Doppler shift. However, for the HF spectrum and very short ranges, the Bragg echo strength is expected to drop significantly, as the ocean waves the above wavenumber relationship become longer than typical ocean wave spectra support (20 –100 second wave periods).

Plans are in place to begin testing bistatic scatter using a single HF frequency at the U.S. Army Field Research facility. A part of the plan is to confirm the bistatic behavior of the HF Bragg echoes, and an attempt will be made to measure ocean currents with the system. Mapping of local shipping traffic with the system is also planned, with ultimately the use of multiple radar frequencies to begin investigations of bistatic ship echoes and the classification potential of such a system. The same digital radars will be used as were used for the VHF experiments, as the radars can transmit and digitize up to 100 MHz in frequency. Only antennas need be changed to support HF operation.

SUMMARY

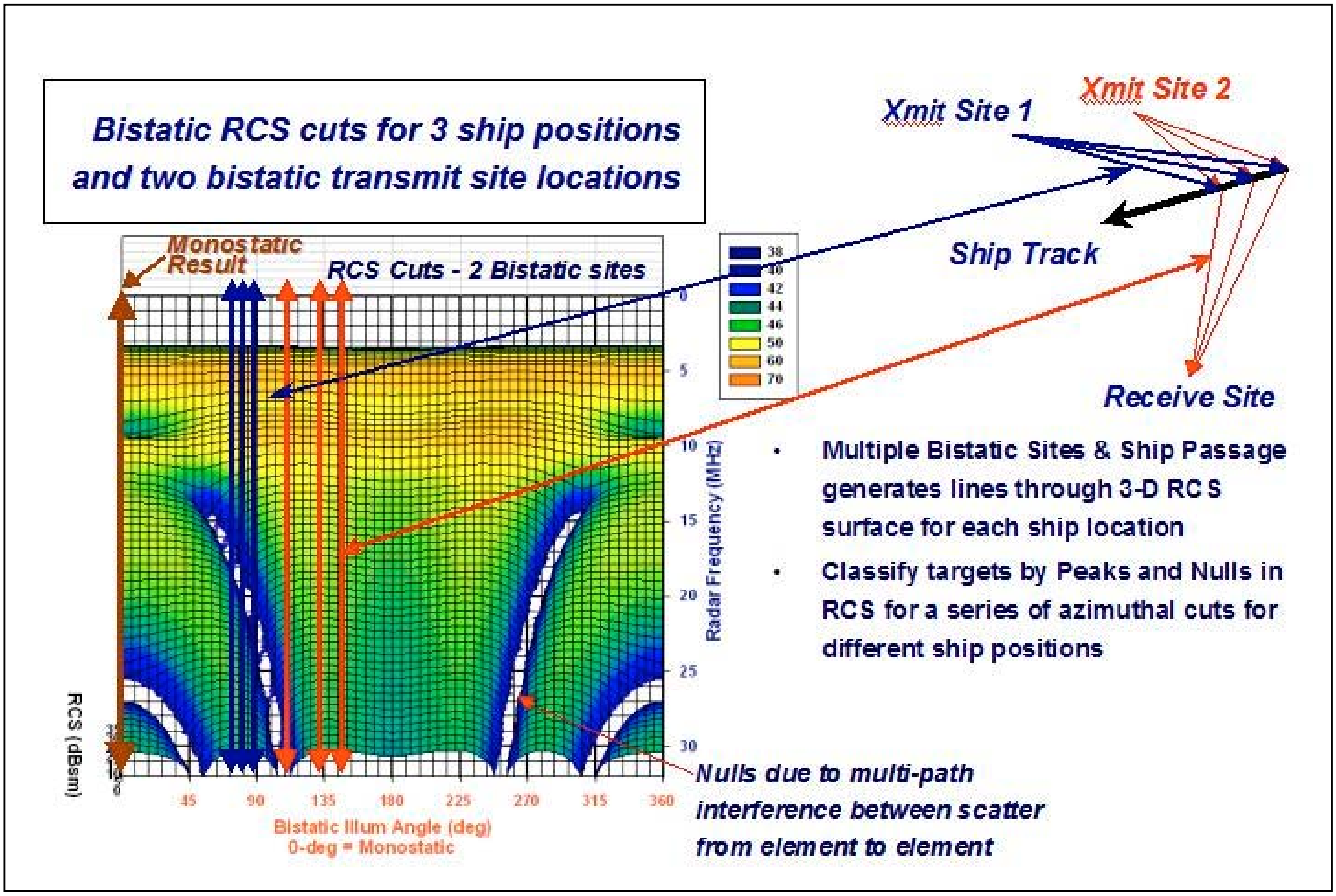
A successful demonstration of a pair of radars has been made operating at VHF in a bistatic mode. Doppler spectra sea echoes show the expected change in Doppler shift of the Bragg lines with radar range, as longer ocean waves are Bragg resonant for short ranges and bistatic angles approaching 90 degrees. Experiments conducted with a small boat target show strongest echoes at a course of 45 degress relative to both sites, at which angle specular scatter from the flat plat structures of the craft provide the dominant scattering mechanism. A simplified bistatic scattering model is presented for resonance effects from a pair of monopoles, typical of what one might expect from small fishing boats. The model does not apply for the landing craft target that was used in these experiments, so no resonance effects were observed as flat plate elements provided the strongest scattering source. Future tests are planned at HF that will attempt to track local commercial shipping traffic off the North Carolina coast from the FRF field site. Results will be presented at both the ISR web site as well as that of the U.S. Army Field Research Facility. For a full list of references on material discussed, please contact Dennis Trizna at dennis@isr-sensing.com

BIO

After a 31-year career with the Naval Research Laboratory and the Office of Naval Research, Dr. Trizna established Imaging Science Research in 2001, for research and development of new remote sensing systems. Coherent microwave and standard marine radars represent a second thrust of the company in this endeavor.

FIGURES

FIGURE 1: A photo is shown of a multi-frequency monostatic radar site at the US Army Corps of Engineers Field Research Facility, with a 4 loop-element receive array and a short log periodic transmit array



Bistatic RCS cuts for 3 ship positions and two bistatic transmit site locations

- Multiple Bistatic Sites & Ship Passage generates lines through 3-D RCS surface for each ship location
- Classify targets by Peaks and Nulls in RCS for a series of azimuthal cuts for different ship positions

Nulls due to multi-path interference between scatter from element to element

FIGURE 2: Bistatic scattering plan view and resulting RCS measures, with geometry shown for 3 locations of a ship along course. Each bistatic location gives three different azimuthal angle RCS measure. The monostatic result is fixed at 0 degrees bistatic angle, and assumes negligible change in aspect along course.

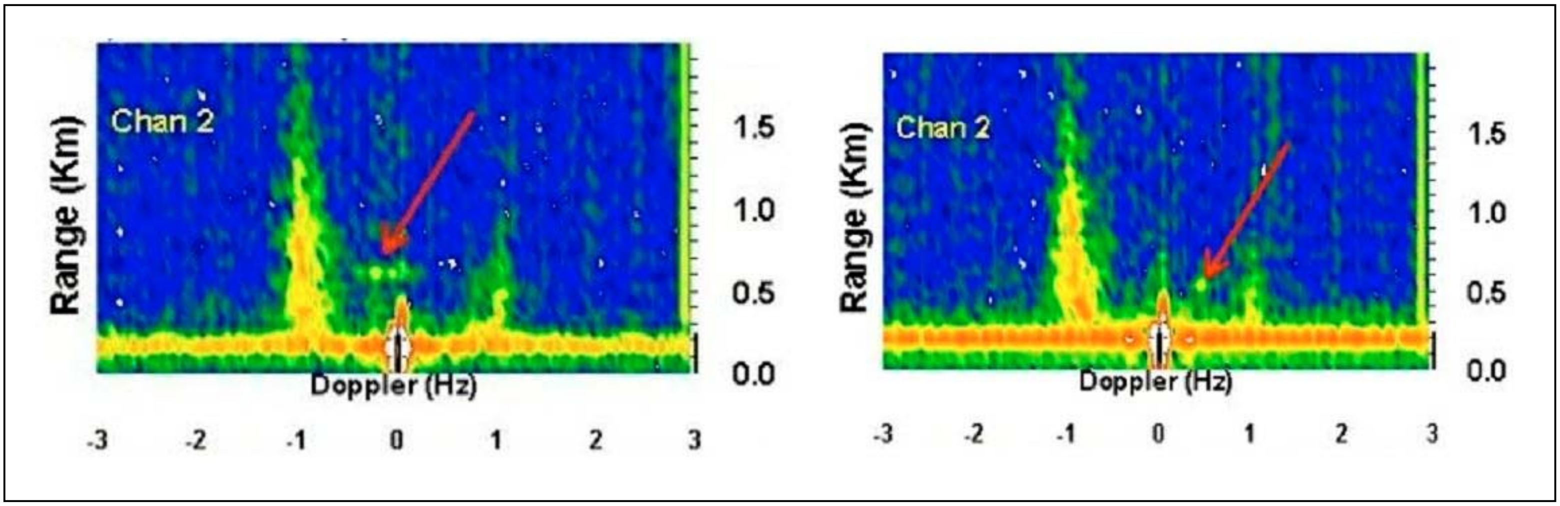


FIGURE 3: Doppler spectra for one radar frequency, target receding in the left pane, and approaching on right. Note the bistatic Bragg lines at ± 1 Hertz, which skew inward with shorter range and extreme bistatic angles, due to longer ocean waves Bragg resonance and corresponding lower Doppler shift. The stronger recede Bragg echo (negative Doppler) was a result of winds from the south.