Special Issue Peer-Reviewed Technical Communication

Phase Corrections of Small-Loop HF Radar System Receive Arrays With Ships of Opportunity

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***Abstract*—This paper is an extension of other work that addresses the use of radar echoes from ships of opportunity to determine the proper phase corrections for small-loop phased-array antennas used within high-frequency (HF) ground-wave radar systems. This technique also yields estimates for unknown ship bearings that (for cases where there is adequate signal-to-noise ratio of 20 dB or more) are consistent to within 2°–3° among measurements from independent radar frequencies. Within this paper, phase corrections gathered from actual ships of opportunity are compared to phase corrections gathered during a calibrated transponder run, in which the ship bearing is known. The phase corrections derived from the ship of opportunity presented in this paper were consistent with the known phase corrections to within 13.2° (for the worst case). Furthermore, the estimates of the ship bearings collected from the two usable radar frequencies were consistent to within 1° of each other.**

***Index Terms*—High-frequency (HF) radar, phase corrections, phased-array antenna, ship location, transponder.**

I. Summary of Previous Work

A previous paper [1] addresses the background for the method as well as a description of it. That paper outlines a technique based on observations of ships of opportunity that determines the phase corrections that must be applied to individual loop receiver antenna elements at each frequency of operation for high-frequency (HF) radar systems, which are generally used for the measurement of surface currents [2]. These phase corrections vary from antenna to antenna and from frequency to frequency and include the effects of electromagnetic propagation, antenna cable, and individual preamplifier electronics. Since these phase corrections for each antenna are based upon a sum of separate, random phase terms, the resultant phase correction for a given antenna and at a given frequency is normally distributed. Since this is the case for all antennas, their distributions are statistically identical and, neglecting mutual coupling effects, which are not accounted for and which we consider to be small for our loop antennas, the various antenna phase corrections are not a function of other antenna elements. Thus, independence is a reasonable assumption, which, along with the identical distributions, is critical to apply the methods outlined in [1].

This approach capitalizes upon the fact that for a single emitter at a given bearing angle, for a uniformly spaced array, the phase difference for uniformly spaced elements should be linear across the array. This is based upon linear array theory as described in any antenna text, such as that by Kraus [3]. As the number of uniformly spaced antenna elements increases, the accuracy of the phase corrections for a given element should improve, since the linear phase expression of the emitter signal as a function of the array element number will be more accurate with more elements.

Element phase corrections determined by this technique were compared in [1] with phase calibrations measured from "standard transponder runs." In a standard transponder run, a ship is equipped with a transponder that echoes the signals it receives at each of the frequencies of radar operation. The offset frequency of the echo is set to a unique frequency, such that it may be easily found and analyzed within the Doppler spectrum of each antenna. A ship with a transponder is then located at a known bearing. Given the bearing and the phase of the ship echo at the transponder signal's Doppler bin, phase corrections are incorporated for each antenna to compensate for the ship position relative to the broadside direction. Once this correction is incorporated, along with another correction to account for the time difference between adjacent antenna samples, the remaining phase associated with each antenna at this Doppler bin is the phase correction required for that antenna. By comparison of the results of transponder corrections collected at different ship bearing angles, self-consistency of the antenna phase corrections may be verified.

Since the position of the ship is known and the signal from the transponder echo has excellent signal-to-noise ratio (SNR) (often greater than 30 dB) the transponder-based antenna phase corrections provide the "standard" by which we compare phase corrections determined by the proposed technique (which involves ships of opportunity of unknown bearing). Should the comparison prove to be successful, alternatives may exist to determine the phase corrections in a manner besides the reliable, though costly, transponder runs.

Manuscript received November 24, 2004; accepted January 20, 2006. This work was supported by the U.S. Office of Naval Research (ONR) under Grant N00014-99-1-0174 (technical monitor: Dr. C. Luther and T. Paluszkiewicz) and by National Oceanic and Atmospheric Administration (NOAA) under Center for Integrated Marine Technology (CIMT), University of California at San Cruz (UCSC). **Associate Editor: L. R. Wyatt**.

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Digital Object Identifier 10.1109/JOE.2006.886238

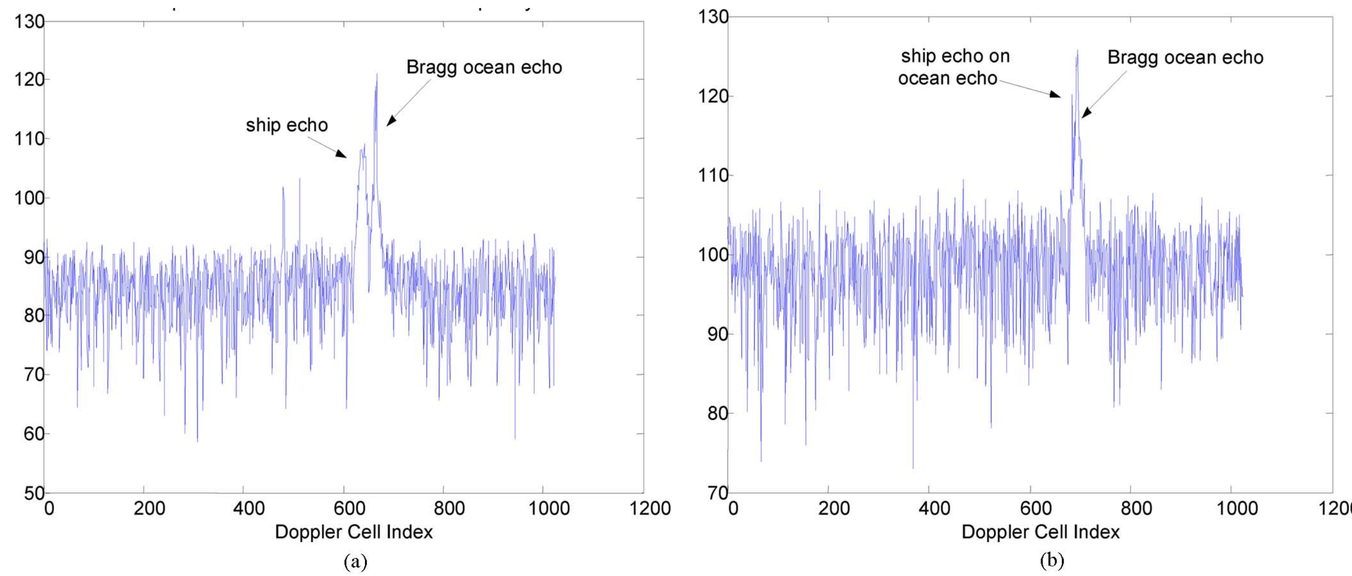

Fig. 1. Doppler spectra at (a) 4.8 MHz and (b) 6.8 MHz. Note that at 4.8 MHz, the ship echo is distinct from the Bragg echo, yet at 6.8 MHz the ship echo occurs at the same frequency as the Bragg echo.

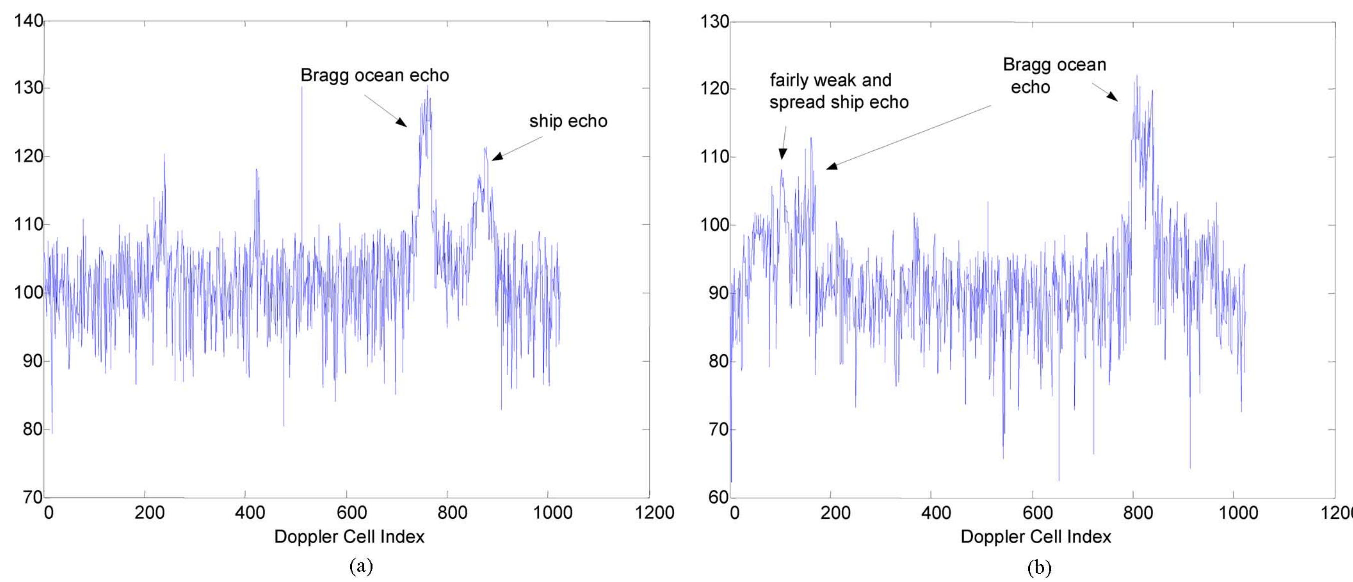

Fig. 2. Doppler spectra at (a) 13.38 MHz and (b) 21.77 MHz. Note that at 13.38 MHz, the ship echo is clearly identifiable to the right of the Bragg echo. At 21.77 MHz, the ship echo has aliased to the negative Doppler frequencies and is weaker and spread out, rendering it unusable.

Within [1], the technique was successfully applied to a mock trial case that consisted of a ship carrying a transponder, where the results obtained with the new technique reliably and consistently determined both the position of the ship and the phase corrections associated with each of the receive antenna array's elements at each frequency of operation. However, [1] presented no trial with an actual ship of opportunity.

II. Phase Calibration From and Location of a Ship of Opportunity

To apply the technique described in [1] to random ships, ship echoes of sufficient strength at as many frequencies as possible must be found within existent data sets. One such run was found from a data set collected during the Coastal Ocean Plume Experiment (COPE–3) on October 31, 1997, near Norfolk, VA. As can be seen in the Doppler spectra that follow, usable echoes were identified in two out of the four frequencies of operation of the radar. The four Doppler spectra in Figs. 1 and 2 that follow represent radar echo return collected from one of the eight antennas at each of the four frequencies of the multifrequency radar system. Ship echo from a single ship is evident at both 4.8 and 13.38 MHz; however, at the other two frequencies the echo from this ship is either contaminated by ocean echo (at 6.8 MHz) or else spread out and not of sufficient SNR (at 21.77 MHz).

Phase information is retrieved from each antenna at the Doppler frequencies associated with the maximum peaks of the ship echoes. Note that the spectra in Figs. 1 and 2 are associated with only one of the eight receiver antennas. While the spectra from the other seven antennas will have similar magnitudes at a given frequency, the phase terms at the locations of the peak

TABLE I
DIFFERENCE BETWEEN PHASE CORRECTIONS IN DEGREES OBTAINED FROM SHIPS OPPORTUNITY AND STANDARD TRANSPONDER RUNS FROM THE TWO USABLE FREQUENCIES SHOWN IN FIGS. 1 AND 2

Freq. (MHz)	Ant. 1	Ant. 2	Ant. 3	Ant. 4	Ant. 5	Ant. 6	Ant. 7	Ant. 8
4.8	0.0°	9.7°	-5.2°	0.6°	10.9°	13.2°	-3.4°	6.9°
13.4	0.0°	5.7°	1.1°	1.1°	6.3°	0.6°	1.7°	2.3°

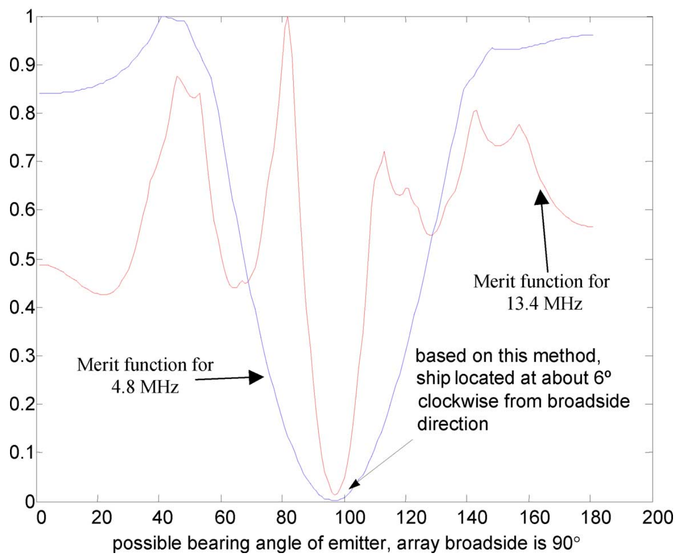

Fig. 3. Scaled merit function as a function of angle. Minima correspond to likely emitter locations.

magnitudes will differ. Table I illustrates the difference between phase corrections obtained from the ship of opportunity and those obtained from a standard transponder run as is described previously. Note the worst case difference of 13.2°. This is less than the angular resolution of this array at the highest frequency, so it is within an acceptable range for this system. We expect that this worst case difference will decrease as the SNR improves, which would be the case for a system that operates in a pulse-compression mode, with higher transmit power, and for a greater percentage of the time. With these improvements in the SNR, ship targets would have a higher SNR and be more prevalent within the spectra at the closer ranges.

Fig. 3 illustrates the scaled merit functions as described in [1] associated with the phases from the receive array at the frequencies 6.8 and 13.38 MHz. The location at which the function is a minimum identifies the probable bearing angle of the ship with respect to the array broadside. For this case, that value is 6°. The fact that in this instance both usable frequencies' data independently locate the ship at 6° is very encouraging.

III. CONCLUSION

A technique, based on ship targets of opportunity, for correction of uniformly spaced, small-loop array element phase in HF radar phased-array antennas and for ship target location has been demonstrated with some very encouraging initial results for an eight-element, small-loop system. In addition to the determination of the phase corrections for each of the eight receiver elements, this technique also yields a bearing angle for the ship of opportunity. We note that this technique does not estimate amplitude errors or amplitude response patterns. Such amplitude patterns are especially important for colocated antenna systems, such as for coastal ocean dynamics application radar (CODAR) SeaSondes. Some of the key requirements to apply this method to a given data set are that the ship is the only emitter in a given Doppler frequency bin and that the ship echo is of adequate SNR (a minimum of about 20 dB for each antenna), preferably at multiple frequencies. A limitation of this system is that it does not account for mutual coupling between antenna elements, which is not significant in the cases explored in this paper, since the receive elements were small loops, but which would be more prevalent in the case of whips. This technique can potentially reduce, or even eliminate, the need for costly transponder runs for some HF systems. Potentially, the technique will allow far more frequent phase correction and, thus, more accurate measurements of surface currents, winds, and waves. In addition, it can provide valuable information on ship positions.

ACKNOWLEDGMENT

The authors would like to thank the Naval authorities at the Fleet Combat Training Center, Atlantic, Dam Neck, VA and the Army authorities at Ft. Story, Cape Henry, VA, for permission to place field sites at these two facilities and for support during the COPE–3 experiment.

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