Automatic Calibrations for Improved Quality Assurance of Coastal HF Radar Currents

Chad Whelan[1], Brian Emery[2], Calvin Teague[1], Donald Barrick[1], Libe Washburn[2] and Jack Harlan[3]

[1]Codar Ocean Sensors, Ltd, Mountain View, CA, USA
[2]University of California, Santa Barbara, CA, USA
[3]USIOOS Program Office, Silver Spring, MD, USA

Abstract*—CODAR Ocean Sensors, Ltd. and the University of California, Santa Barbara are developing a method by which HF radar antenna response patterns can be calibrated automatically over time. Currently, over 130 HF radar units are providing coastal surface current maps to the public via the U.S. Integrated Ocean Observing System (USIOOS): http://www.ioos.gov/hfradar/. These real-time data are used for Coast Guard Search and Rescue, Hazardous Materials Spills Response, Water Quality Monitoring, Monitoring Harmful Algal Blooms, Fisheries Management, Modeling, Marine Navigation, Ocean Energy Production. Techniques for improved, automated quality assurance of the data provided by coastal radar stations, such as the one discussed here, will improve the efficacy of efforts in these areas. Passing vessels provide a steady supply of targets for which the echoes in the HF Doppler spectra can be used as source signals. The Automatic Identification System (AIS) transmissions from these vessels provide the position and, therefore, bearing to the vessel. By associating the known AIS positions with HF Doppler echoes, a low-cost calibration procedure can be implemented which can reduce or eliminate more labor-intensive alternatives. This method is demonstrated using data from mid-range systems in the Santa Barbara channel that are operating in the 13 MHz band. A prototype package has been deployed on a system monitoring the Gulf of Farallones and the shipping lanes approaching the San Francisco Bay. Performance and data quality metrics for this prototype will be discussed.

***Index Terms*—HF Radar, Antenna Patterns, Surface Current Measurements, IOOS.**

I. INTRODUCTION

Currently, over 130 HF radar units are providing coastal surface current maps to the public via the US Integrated Ocean Observing System (IOOS): http://www.ioos.gov/hfradar/. These systems are providing ocean surface current maps that are used in Coast Guard Search and Rescue, Hazardous Materials Spills Response, Water Quality Monitoring, Monitoring Harmful Algal Blooms, Fisheries Management, Modeling, Marine Navigation, Ocean Energy Production. Quality assuring the data provided by coastal HF radars will improve the efficacy of efforts in these areas [1].

Commercial coastal HF radar systems are Doppler radars and can resolve range and radial velocity of targets extremely well. The two areas where errors tend to enter HF radar surface current data are in distinguishing signal from noise in the Doppler spectra and determining direction of arrival of the signals. The related problem is properly resolving any differences that may exist between the theoretical antenna response pattern and the antenna pattern at the site [2][3].

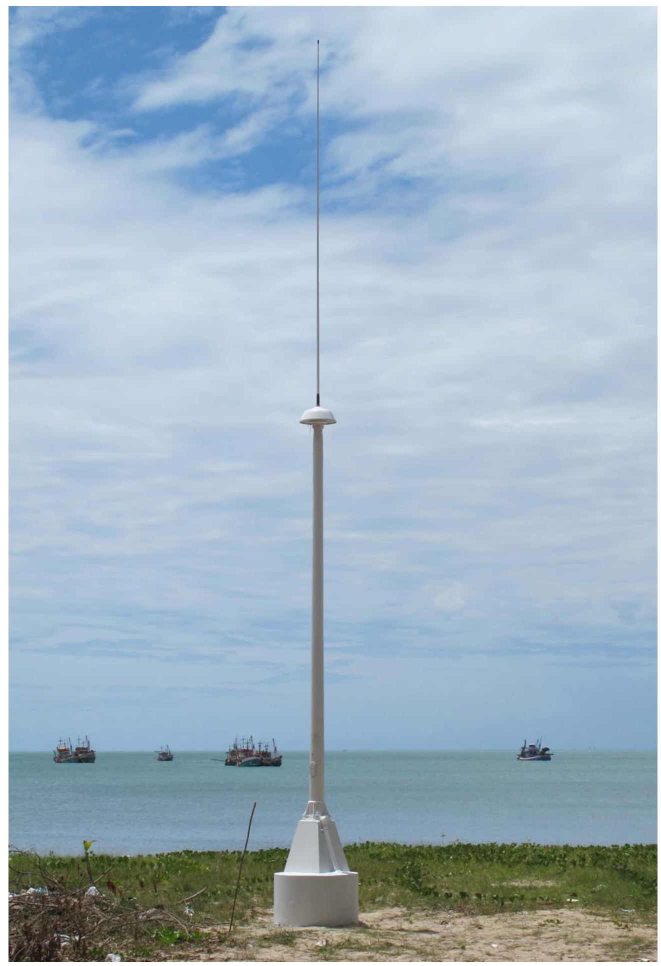

Fig. 1. SeaSonde compact cross-loop antenna installed at coast.

These differences can be caused by nearby parasitic elements such as buildings, power lines, feed lines, and other electrically conductive structures as well as variations in the electromagnetic properties of the ground around the antenna.

Methods have been developed to measure the receive antenna response pattern. Typically, a transponder is transported in a path around the antenna that includes all bearings from which sea echo can be observed. The transponder provides a stable signal source and a co-located GPS receiver provides the position and, thus, direction of signal arrival. This measurement can be made by carrying the transponder and a GPS receiver on a walking path. Such a procedure requires enough open space around the antenna such that the transponder can be kept at least one radar wavelength away from the receive antenna and other near-field ferromagnetic objects to avoid mutual coupling and properly measure the antenna response to signals scattered in the far field over the water. A much better, more accurate practice and one that is suited to more sites is to transport the transponder and GPS receiver on a small boat 500 m - 2 km from the antenna. While this measurement provides high-quality results, there are increased logistics and costs involved with planning this sort of near-shore work on a small boat.

CODAR Ocean Sensors, Ltd. and the University of California, Santa Barbara are developing a method by which HF radar antenna response patterns can be measured automatically on the radar site. Using the echoes from passing vessels as source signals and obtaining their position and, thus, bearing from their Automatic Identification System (AIS) transponders, antenna responses can be measured automatically over time.

II. ANTENNA PATTERNS

The response of each HF antenna to an incident signal as a function of bearing is, by definition, the antenna pattern. The antenna response for a particular bearing can be understood in a physical sense as having an amplitude, $A_N(\boldsymbol{\theta})$, and phase, $\boldsymbol{\phi}_N(\boldsymbol{\theta})$, on antenna N for a signal arriving from bearing $\boldsymbol{\theta}$. Each antenna type has a theoretical directional response pattern based on the antenna design. That pattern is usually distorted, however, as an antenna interacts with other conductive and ferromagnetic material in the near-field environment. For beam-steering (BS) systems, unaccounted distortions in amplitude or phase of individual elements cause errors by widening beamwidth or increasing beam side lobes. For a direction-finding (DF) system, unaccounted distortions can cause errors in bearing solutions or gaps in coverage. In either case, to maximize the accuracy of output data products, antenna patterns should be calibrated at any HF RADAR installation.

For the most commonly used type of HF RADAR, CODAR Ocean Sensors' SeaSonde®, the compact receive antenna consists of three co-located antennas: a directional cross-loop antenna pair and a vertically-oriented omni-directional reference antenna. A SeaSonde compact receive antenna is shown in Fig. 1 with the directional cross-loop antennas contained in the dome and the reference antenna, a dipole with the top portion extending above the dome as a whip antenna and the lower portion inside the mast. Although this paper refers to the SeaSonde compact cross-loop system in describing antenna elements, the underlying algorithm can be extended to phased arrays used in BS or DF modes.

Normalizing by the omni-directional reference antenna allows the directional antenna pattern to be calibrated in a way that is independent of environmental signal losses, which can vary with wave state, ground characteristics, and other factors. Therefore, the six parameter antenna pattern is reduced to four normalized parameters: $A_{N3}(\boldsymbol{\theta})$, $\boldsymbol{\phi}_{N3}(\boldsymbol{\theta})$ where N = 1,2 representing each loop antenna [4]. An example of amplitude and phase patterns are shown in Fig. 2.

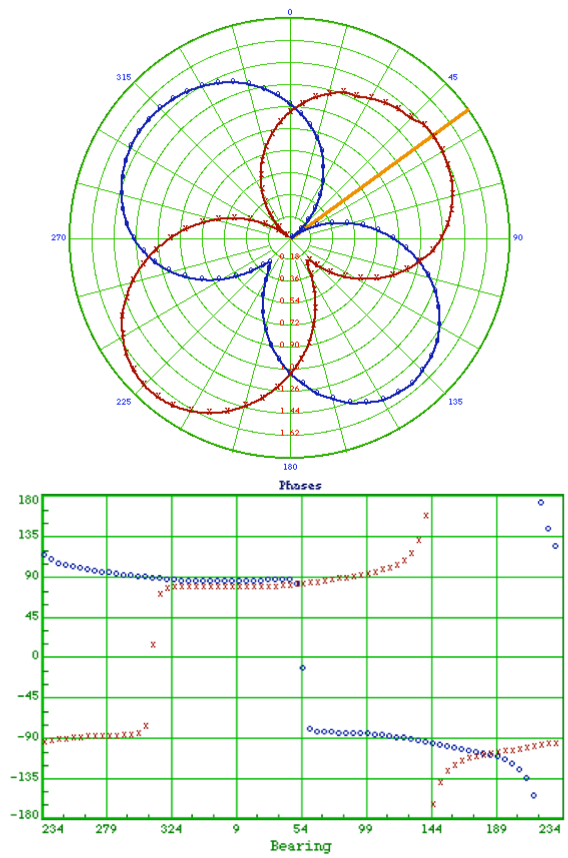

Fig. 2. Example normalized cross-loop amplitude directional pattern (top) and associated phase pattern (bottom) with red and blue plotted for loop 1 and loop 2 normalized values, respectively.

These patterns can also be expressed as real and imaginary amplitudes as in equations 1 and 2 and plotted for the same amplitude and phase plots above in Fig. 3. We note that the pattern examples shown here are minimally distorted: i.e., very close to ideal.

$$A_{N3re}(\theta) = A_{N3}(\theta)\cos(\phi_{N3}(\theta)) \quad (1)$$

$$A_{N3im}(\theta) = A_{N3}(\theta)\sin(\phi_{N3}(\theta)) \quad (2)$$

These normalized antenna pattern parameter values can be assumed to match the theoretical pattern associated with the antenna design, also referred to as an "ideal" pattern. For the normalized amplitude, $A_{N3}(\boldsymbol{\theta})$, of the cross-loop system, this would amount to two sinusoids in quadrature. When an ideal pattern is used for data processing, the phases will be assumed to be uniform values over each 180° loop antenna lobe measured empirically after manufacture or estimated from sea echo.

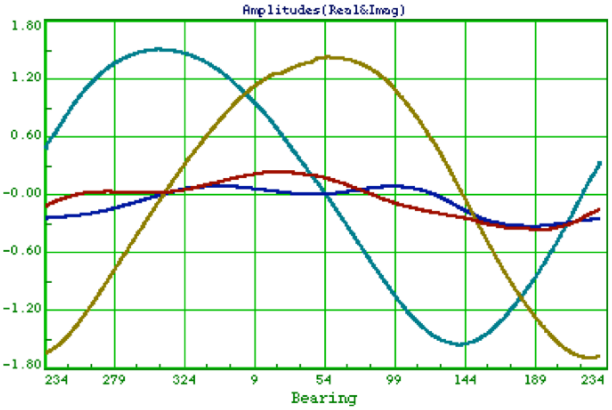

Fig. 3. Real, A13re (red) & A23re (blue), and imaginary, A13im (gold) & A23im (cyan) , antenna pattern components

Alternatively, a known signal source can be used to calibrate the normalized amplitude and phase measurements at each bearing. As described above, this can be done with a transponder that is transported in an arc around each receive antenna with the bearing provided by a small handheld GPS. Ideally, the transponder would be placed on a boat navigating an arc at 500 m – 2 km distance from the antenna to reduce near-field interactions. Calibrations have been made with the transponder hand carried, or placed on Jet Skis, all-terrain vehicles and even helicopters. Such methods are site-dependent, cost time and money, and, especially in the case of using a boat, are weather-dependent.

III. Vessel Echoes & AIS Positions

Vessel echoes are often present in unfiltered HF Doppler spectra. These echo peaks can be a nuisance without removing them when they are near to or overlapping the sea echo signals. This method utilizes these peaks before removal as they can be considered a signal source just like a transponder. In fact they have been used to calibrate antenna patterns of systems in the past without knowing the position of the vessel [5]. For DF systems, in particular, a more robust use should include the vessel's known position. This information can now be provided by AIS over broad stretches of coastlines around the world.

AIS data is transmitted on two VHF frequencies: Channel A on 161.975 MHz and Channel B on 162.025 MHz. International regulations require AIS to be fitted aboard all ships of 300 gross tonnage and greater engaged on international voyages, cargo ships of 500 gross tonnage and greater not engaged on international voyages and all passenger ships irrespective of size. The data packets are a 6 bit vector format in a NMEA encoded message [6]. These data packets are available to anyone who purchases and installs an inexpensive AIS receiver within VHF line of sight of the vessel. Data packets are broadcast every 60 seconds while the vessel is underway and more rapidly if actively maneuvering. Each data packet provides the ship's identity, type, position, course, speed, navigational status and other safety-related information.

With an AIS receiver installed at or near an HF RADAR site, each passing vessel's position, course and speed can be turned into range and range rate (Doppler frequency). With these values, a search can be implemented to identify the vessel's echo peak in the Doppler spectrum. See Fig. 4 for an example of two vessels that are transiting past the Coal Oil Point (COP) SeaSonde in the Santa Barbara Channel. Gray highlighting is added to identify the range of radial velocities that each vessel reported via AIS during the FFT window. Gray shaded areas show ranges of radial velocities of two ships The ships are the 280 meter Cosco Hongkong, and 213 meter Wan Hai 313. The increase and decrease of signal backscattered from the ships can be seen as the ships move through the Santa Barbara Channel. Signal scattered from ocean surface waves (containing ocean current information) can be seen just inside of +/- 500 cm/s.

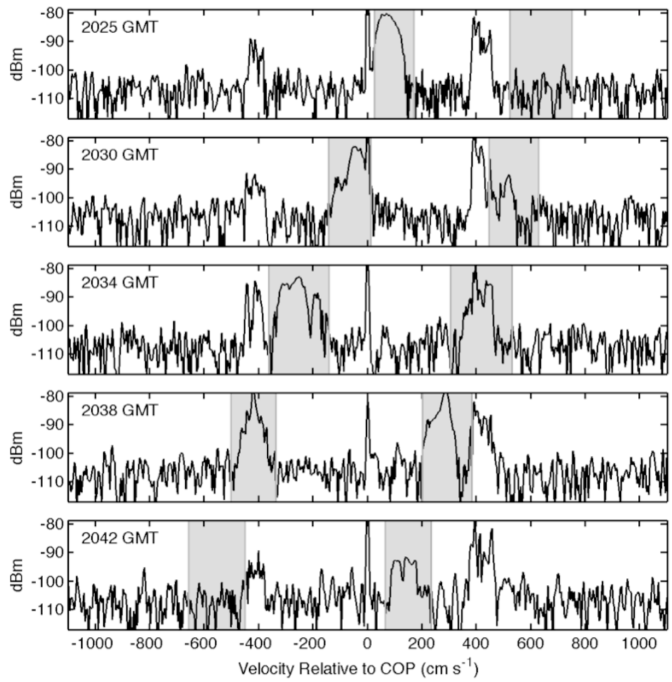

Fig. 4. Five sequential HF radar cross spectra from Coal Oil Point on 6 December 2008. For each plot, the vertical axis shows signal power (dB), and the horizontal axis shows radial velocity (derived from Doppler shifted frequency).

Once a peak matching the AIS data packet is found, a form of Infinite Impulse Response (IIR) filter is employed, along with other methods of computing the signal to noise ratio (SNR) in order to filter out more noisy data. SeaSonde software employs an IIR filter to remove ship backscatter in real time. For a real time process, this method is computationally efficient. When using archive data along with AIS ship reports, the IIR filter can be simplified to a moving average filter and effectively produce the same result. In this case, when an AIS report suggests the presence of a ship in a given range cell, the moving average of the cross spectra in the range cell is computed over +/- 0.5 hrs, and then subtracted from the 256 second Doppler FFT. This method removes the slowly varying background signal (such as from waves, currents, and some kinds of interference) from transient signals, such as ship backscatter. The SNR above background is archived for use in data screening.

Due to the unusual noise characteristics in some of the cross spectra collected around the Santa Barbara Channel, SNR of the ship backscatter is also computed using two additional methods. A standard method of computing SNR in Doppler spectra assumes noise levels are the average energy in the Doppler cells near the edges of the cross spectra, away from the sea-echo regions. Thus, a ship's signal level would be compared to the noise level found at Doppler frequencies that typically exhibit very low levels of signal. To screen out certain types of interference, we additionally compute SNR relative to Doppler frequency bins adjacent to the ship peak (within the same range cell), and then again relative to the same Doppler bins in adjacent range cells. Thus we effectively have four methods for computing SNR, with the rationale being that an ideal ship peak will have a strong, well defined signal peak, with low noise levels in adjacent Doppler and range cells.

The filtered peak data is binned to the bearing precision desired for the antenna pattern (typically 1°-5°) and averaged to provide some statistical stability. Thus, an ensemble of antenna pattern measurements is stored for each bearing with a varying number of measurements per bearing. The length of time to produce a stable antenna pattern for all bearings will, of course, depend on the level of vessel traffic and orientation of the tracks to the antenna.

IV. Results

The method as described here was implemented on data collected at the Coal Oil Point (COP) SeaSonde station inside the Santa Barbara Channel. In Fig. 5 are plotted the normalized real (R) and imaginary (I) antenna pattern parameters for loop antenna 1 relative to reference antenna 3 (A13) and loop antenna 2 relative to reference antenna 3 (A23), all versus bearing. Gray scattered dots represent all solutions remaining after filtering using a 13 dB SNR based on local noise estimates; the dotted line represents the pattern as most recently measured using a transponder as a source signal and the solid line with black dots represents the mean value of all solutions falling within the 5° bin centered on each dot. Although there is quite a bit of scatter in the raw solutions, the final antenna pattern derived from vessel echoes matches quite closely the recent antenna pattern measured using a transponder source signal, which demonstrates the validity and robustness of the method presented here.

V. Summary

A viable method for generating antenna pattern data using HF echoes from vessels of opportunity and their positions as reported by their AIS transponders is presented here. This method has been implemented for real-time automatic antenna pattern generation on a number of California SeaSonde HF radar stations. Evaluation of this method is now focused on sites with different ship traffic characteristics and at different HF transmit frequencies. Further work is needed to establish quality indicators for ship derived antenna patterns. It is envisioned that this method will provide a cost-effective method for performing antenna pattern measurements as an alternative to using transponders.

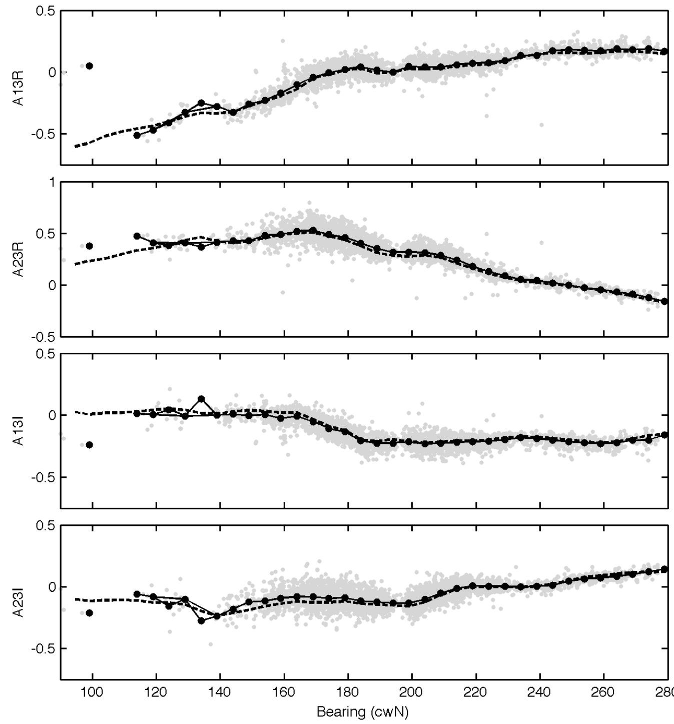

Fig. 5. Normalized antenna pattern measurements from raw vessel echoes with 13 dB IIR filter threshold (gray dots), mean values at 5° bins (black dots) and most recent transponder antenna pattern (dotted line).

Acknowledgment

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References

[1] Harlan, J., E. Terrill, L. Hazard, C. Keen, D. Barrick, C. Whelan, S. Howden, and J. Kohut. "The Integrated Ocean Observing System High-Frequency Radar Network: Status and Local, Regional, and National Applications." *Marine Technology Society Journal*, Vol. 44, 122-132 (2010).

[2] Kohut, J.T., and S.M. Glenn. "Improving HF Radar Surface Current Measurements with Measured Antenna Beam Patterns." *Journal of Atmospheric and Oceanic Technology*, Vol. 20, 1303-1316 (2003).

[3] Paduan, J. D., K. C. Kim, M. S. Cook, and F. P Chavez, 2006. Calibration and Validation of Direction-Finding High-Frequency Radar Ocean Surface Current Observations, IEEE J. of Oceanic Engineering, vol. 31, no. 4, DOI 10.1109/JOE.2006.886195

[4] Barrick, D. E. and B. J. Lipa (1997), Evolution of bearing determination in HF current mapping radars, Oceanography, vol. 10, no. 2, pp. 72-75.

[5] Fernandez, D. M., J. F. Vesecky, and C. C. Teague, 2003, Calibration of HF radar systems with ships of opportunity, Proc. Intl. Geosci. Remote Sens. Symp. (IGARSS), vol. 7, pp 4271-3.

[6] International Maritime Organization website, http://www.imo.org, 2012.