A Multi-system HF Radar Array for the New Jersey Shelf Observing System (NJSOS)

Josh T. Kohut, Graduate student; *Institute of Marine and Coastal Sciences, Rutgers University, USA*. (http://marine.rutgers.edu/cool)
Scott M. Glenn, Professor; *Institute of Marine and Coastal Sciences, Rutgers University, USA*. (http://marine.rutgers.edu/cool)
Don E. Barrick, President; *Codar Ocean Sensors, Ltd., USA*. (http://www.codaros.com/)

1. Introduction

High Frequency (HF) radar technology for the remote sensing of surface current fields has experienced rapid growth and acceptance within the scientific community in the last few years (Glenn et al., 2000b). Direct measurements of receive antenna beam patterns and comparisons with current meters have demonstrated that the compact CODAR antenna designs do provide accurate direction estimates for radial current vectors, even in cluttered environments (Kohut et al., 2001; Paduan et al., 2001, Kohut and Glenn, 2002). New long-range CODAR systems demonstrated at Oregon State and Rutgers typically achieve daytime ranges of over 200 km. However, at the lower frequencies (4.4-5.1 MHz) used by the long-range systems, spatial coverage is found to be highly sensitive to radio interference and noise, especially at night. A third system utilizing bistatic technology separates the transmitter and receiver providing a larger footprint for total vector calculation that extends right to the coast. These three systems deployed in the New York Bight will establish the world's first nested multi-static HF radar array for surface current measurement. The multi-static array, combined with new ocean color remote sensing systems, vicarious calibration

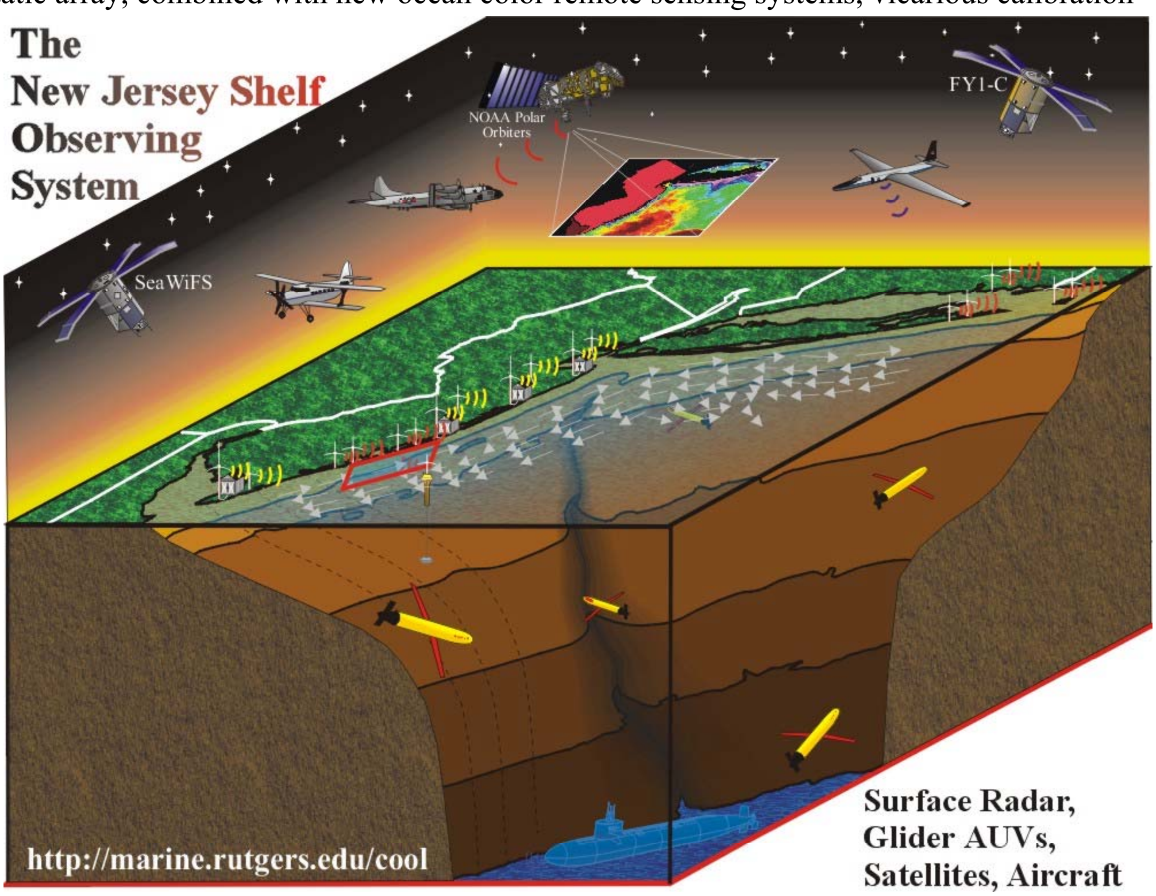

Figure 1. New Jersey Shelf Observing System (NJSOS)

capabilities, and a fleet of four long-duration autonomous underwater gliders, will establish the New Jersey Shelf Observing System (NJSOS) as a premier site for the development of new autonomous observation technologies (Figure 1). NJSOS serves as an efficient model for the developing NorthEast Observing System (NEOS) efforts to establish a complete CODAR network running from the Gulf of Maine to Cape Hatteras. This unprecedented high-quality dataset will be available for scientific studies, real time operational users, and will challenge modelers with spatially extensive assimilation/validation datasets for years to come. This paper will describe the HF radar component of this observatory focusing on the standard, long-range and bistatic CODAR SeaSonde systems.

2. Standard SeaSonde

Since 1998, Rutgers has operated a pair of standard SeaSonde (40 km) CODAR sites off the southern coast of New Jersey as part of the Longterm Ecosystem Observatory (LEO) (Figure 2). LEO is a coastal observatory centered around two underwater nodes connected to shore through a fiber optic cable (Grassle et al., 1998; Glenn et al., 2000a; Schofield et al., 2001). The CODAR system compliments many other remote and *in situ* measurements within a 30 x 30 km grid. Maps of the raw, tidal, detided, and filtered current fields, and their divergence and vorticity, are routinely generated and displayed on the Web (http://marine.rutgers.edu/cool/codar.html) in real-time. Recent validation results using the LEO ADCPs indicate that distortions in the receive antenna's beam pattern are not due to hardware configurations, but are primarily due to the local environment, which, depending on the circumstances, may not be adjustable (Kohut and Glenn, 2002). The ADCP comparisons indicate that using the measured receive antenna beam patterns optimizes system performance by improving the placement of the CODAR-derived radial current velocities in the proper directional bins. Figure 3 illustrates this point by comparing the RMS difference between the ADCP measured velocities and those derived

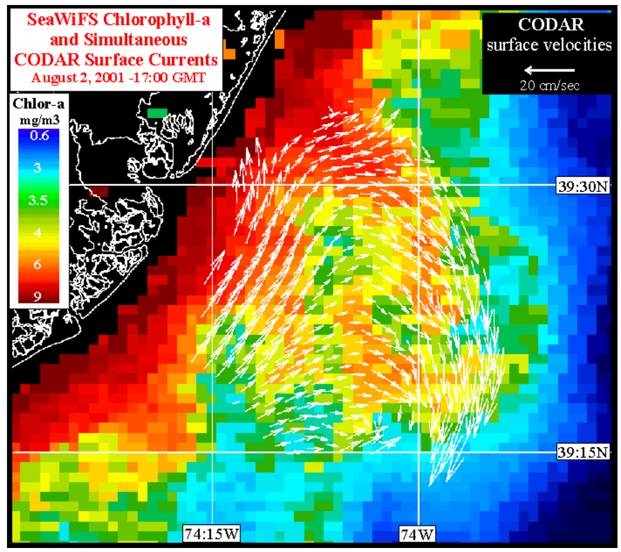

Figure 2. ***Standard CODAR surface currents overlaid on a SeaWiFS satellite image of Chlorophyll-a concentrations.***

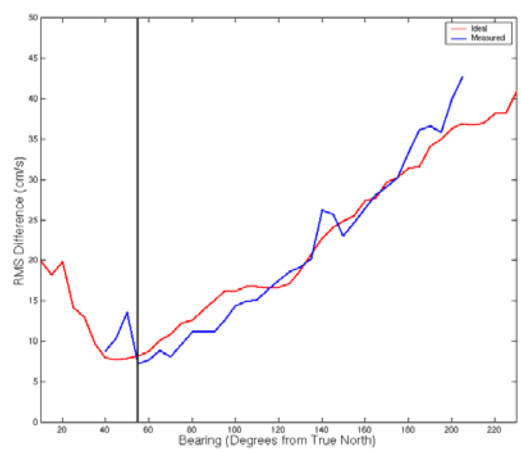

Figure 3. ***RMS difference between the radial component of the velocity measured by an ADCP and derived from CODAR using idealized (red) and measured (blue) receive antenna beam patterns for the Brigantine Beach CODAR system.*** ***The actual direction to the ADCP is indicated by the vertical black line***

from CODAR using both idealized (cosine/sine dependent) and measured beam patterns. The idealized beam pattern produces a broad minimum with the smallest RMS offset 10 degrees from the actual direction to the ADCP (solid black line). The measured beam pattern produces a narrow minimum in the RMS located exactly in the direction of the ADCP, even in the cluttered environment of a developed New Jersey beach. The optimized CODAR current and divergence fields overlaid on satellite imagery (Figure 2) were used each summer during the annual Coastal Predictive Skill Experiments at LEO to improve biological adaptive sampling of phytoplankton distributions (Kohut et al., 1999; Schofield et al., 2001).

3. Long-range SeaSonde

In 2000, the first of five long-range SeaSonde (200 km) CODAR sites for the New Jersey Shelf Observing System (NJSOS) was deployed. Typical daytime radial coverage for the first east coast long-range CODAR site located in Loveladies, New Jersey extends as far as 200 km offshore (Figure 4). The initial deployment of the Loveladies long-range CODAR revealed an expected but surprisingly severe reduction in the nighttime coverage due to radio interference. Unlike the higher frequency (approximately 12, 24, or 48 MHz) HF radar systems that can operate at virtually any frequency without noticeable increases in the night-time radio noise, long-range CODARs should ideally operate at the quietest frequency available in the region.

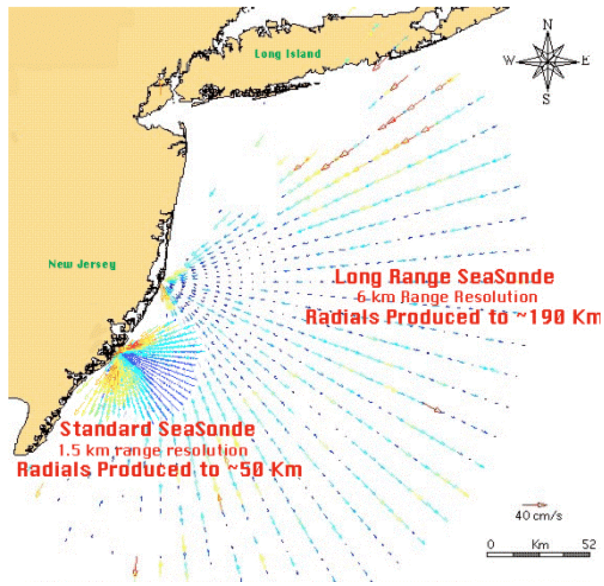

Figure 4. Comparison of radial current vectors from a long-range CODAR site located in Loveladies, NJ and a standard site in Brigantine, NJ. Radial bins are 6 km wide for the long-range system and 1.5 km wide for the standard system.

In 2001, two additional long-range sites in Wildwood and Sandy Hook New Jersey were deployed to form a long-range CODAR network. The initial approach was to establish these two sites at the extreme northern and southern extent of the New Jersey coast first, then fill in the remaining sites where additional coverage was needed. Coverage out to the shelf break is common, and extends well south of Delaware Bay (Figure 5). Vector coverage nearshore is lacking due to the standard Geometric Dilution Of Precision (GDOP) constraints on any shore-based monostatic HF Radar system deployed along a straight coast.

To improve nearshore coverage in the vicinity of LEO during the July 2001 Coastal Predictive Skill Experiment, a temporary long-range site was deployed at the Tuckerton field station. Despite the presence of barrier islands to seaward, the salt marsh on which the transmit antenna was deployed proved to be a very efficient ground plane, increasing the signal strength well beyond what was lost propagating over the barrier islands. Figure 6 illustrates the resulting 6 km resolution long-range vectors plotted on the same map as the 1.5

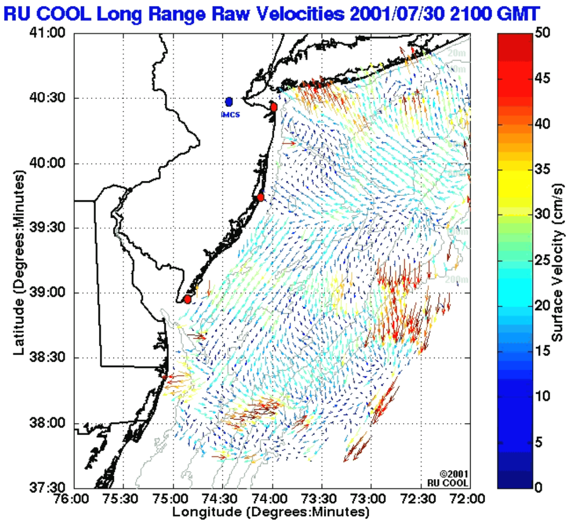

Figure 5. Total vector coverage for four long-range CODAR systems operated along the New Jersey coast.

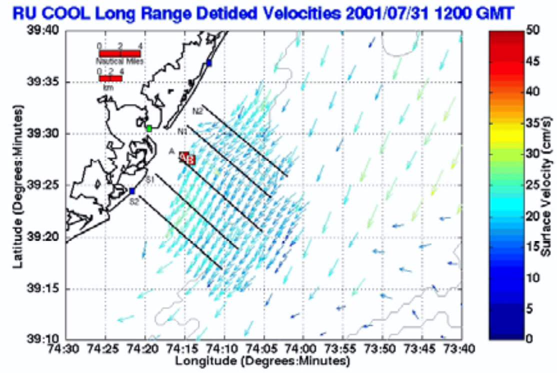

Figure 6. Enlargement showing total vector currents derived from the long range (6 km, 3 hour average) and the standard range (1.5 km, 1 hour average) CODARs in the vicinity of LEO.

km resolution vectors from the standard SeaSonde systems. The agreement is quite good in regions of overlap, and the far field vectors reveal interesting features flowing into the high-resolution field. Adding radial velocities from the single Tuckerton long-range site was critical to the accurate reproduction of total vectors nearshore. Similar maps to Figure 6 generated without the Tuckerton long-range site do not agree as well in the overlap region, an expected consequence of GDOP.

4. Bistatic SeaSonde

Existing monostatic systems use the phase of the transmitted signal to interpret the signal from the receiver, requiring the transmitter and receiver to be physically connected. Using the GPS satellite-timing signal, CODAR Ocean Sensors was able to synthesize the transmitted signal at the receiver, allowing the transmitter and receiver to be physically separated for the first time. Separating the transmitter from the receiver converts the monostatic backscatter system into a bistatic forward-scatter system (Figure 7). As the separation between transmitter and receiver grows, the constant time delay circles of the monostatic system are stretched into constant time delay ellipses with the receiver and transmitter at the foci. Just

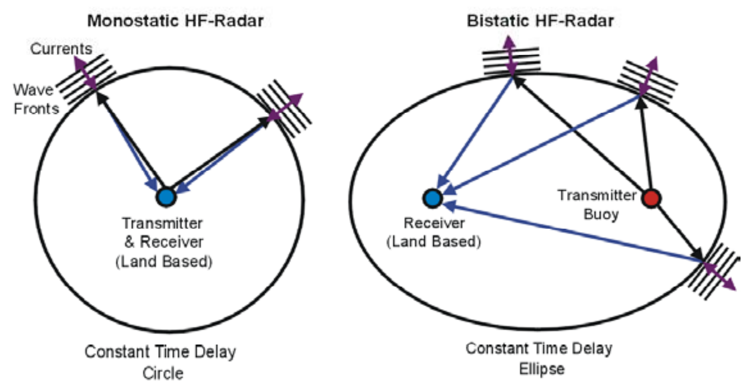

Figure 7. Illustration of the extension of monostatic backscatter to bistatic forward-scatter HF radars.

as the monostatic systems return estimates of the current component perpendicular to the constant time delay circles, bistatic systems return estimates perpendicular to the constant time delay ellipses. These current components lie along radials for the monostatic system and along hyperbolas in the bistatic system. To date there have been four bistatic SeaSonde tests including shore-to-shore, ship-to-shore, and buoy-to-shore with the standard SeaSonde and a final ship-to-shore test with the long-range SeaSonde.

4a. *Standard Bistatic SeaSonde*

The bistatic CODAR configuration was first demonstrated in Monterey Bay, California by transmitting across the bay to a receiver on the other side (Figure 8). The constant time delay ellipses are clearly visible in the spacing of the hyperbolic velocity components. The second bistatic test demonstrated ship-to-shore transmissions offshore Tuckerton, New Jersey (Figure 9). Figure 9a shows the radial current components from the shore-based transmitter and receiver operating in monostatic mode. Figure 9b illustrates the simultaneous hyperbolic current components obtained from a ship-based transmitter and a shore-based receiver operating in bistatic mode. Note that the nearshore bistatic vector components are at an angle to the coast, thereby reducing the GDOP when near-shore total vector currents are calculated. Figure 9 also illustrates that the GPS timing allows the system to operate at the same

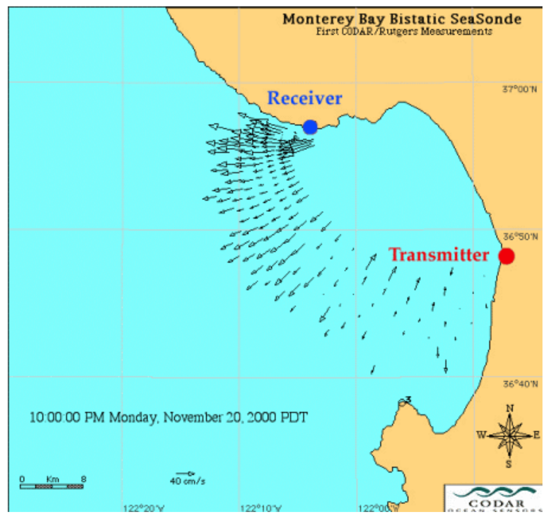

Figure 8. Demonstration of the bistatic CODAR for shore-to-shore transmissions across Monterey Bay, California.

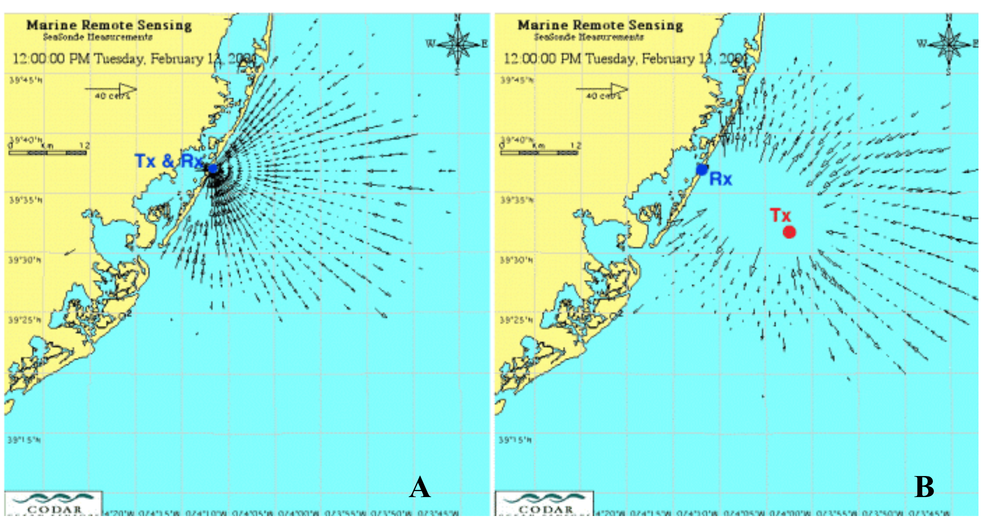

Figure 9. Demonstration of simultaneous (a) monostatic and (b) bistatic operation of a CODAR system offshore New Jersey. The transmitter (Tx) was located on shore in (a) and offshore on a boat in (b). The same shore-based receiver (Rx) was used in each case.

frequency in monostatic and bistatic mode simultaneously. Using GPS time as a reference, the timing of the frequency sweeps for each CODAR system can be adjusted so that the returns from the ship and shore transmitters can be uniquely identified. The final test with the standard bistatic system involved the deployment of a bistatic transmit buoy offshore of a standard SeaSonde shore site (Figure 10). The buoy, manufactured by the Ocean Science Group, was deployed on December 2, 2001 and is continuing to transmit a coupled signal with the shore site in Brant Beach, New Jersey. Again this system is using GPS timing to discriminate between the signal originating from the buoy and that originating from the shore site allowing bistatic and backscatter fields to be measured simultaneously.

Figure 10. Standard System bistatic Buoy.

4b. Long-range Bistatic SeaSonde

The first test of the long-range bistatic system was run off the R/V Endeavor between December 1, 2001 and December 8, 2001. The ship was setup with a long-range transmitter and antenna that was coupled with the shore site in Loveladies, New Jersey. During the cruise, the transmitted signal was continuously measured in Loveladies. Once again GPS timing allowed the shore site to operate in bistatic and monostatic modes simultaneously. The cruise track included two stations located approximately 140 km offshore where the ship

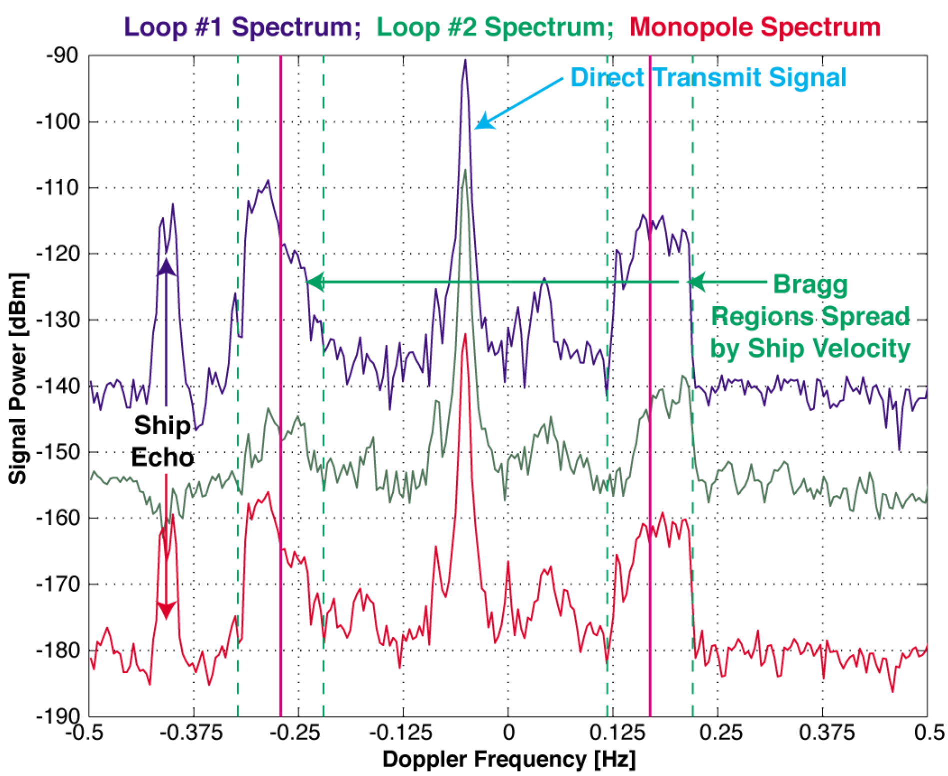

Figure 11. Bistatic cross-spectra measured at the Loveladies long-range site for loop #1 (blue), loop #2 (green), and the monopole (red). Bistatic transmit signal, ship echo, and resonant Bragg scatter peaks are shown.

remained on station for approximately 2.5 days. In addition to these stationary positions, scatter was measured while the ship was in transit. Figure 11 shows the measured cross-spectra of the ship's signal measured at the shore site. This particular cross-spectra was measured as the vessel steamed away from the Loveladies site toward the east at a speed of about seven knots. Its distance was about 40 km from the receiver at this point. The echo falls four time-delay cells later than the direct signal. A remnant of the direct signal is seen as the strongest peak in the three antenna signal spectra because it is so intense. Note that the position of the direct signal is shifted negatively, corresponding to the departing ship velocity of ~7 knots. The expected Bragg positions for resonant backscatter are shown as the vertical pink lines, symmetrically arrayed about the receding ship Doppler peak. In the fourth range cell the Bragg peaks would have been very narrow if the vessel were not moving, however the motion of the ship spreads these peaks. The theoretical limit of the spread is shown as vertical green dashed lines surrounding the Bragg positions (vertical pink lines). Observe that the measured first order region falls within these expected limits. In addition to ocean surface scatter used to measure currents, the signal may also scatter off large objects such as ships. An object must have a vertical length scale on the order of a quarter wavelength or greater to scatter the transmitted signal. For a long-range bistatic system operating at 4.8 MHz, this length scale is about 15 m. Figure 11 shows an example of a ship echo in the measured cross-spectra. Since the echo is absent in the measured Loop #2 signal, the ship is in the null of the cross-loop. The location of this ship can therefore be estimated as 40 km away at a bearing of about 161 degrees true. The measurements taken during this weeklong cruise provide the necessary data to develop algorithms to calculate surface current fields and perhaps ship tracks from measured bistatic cross-spectra.

5. Conclusions

The GPS timing that allows the transmitters and receivers to be operated at the same frequency in monostatic and bistatic mode simultaneously is a critical step for the construction of an array of CODAR systems. Using GPS time as a reference, the timing of the frequency sweeps for each CODAR system can be adjusted so that the returns from individual sites can be uniquely identified. With this information, combinations of several monostatic and/or bistatic systems all operating at the same frequency are possible. It is this discovery we choose to exploit as we redesign a nested CODAR grid for the New York Bight. By adding GPS timing to synchronize our existing long-range network, all five systems could be operated at the same optimal frequency if desired. Long-range monostatic site deployments could take advantage of the coastal geometry of the New York Bight to enable bistatic shore-to-shore transmissions as demonstrated across Monterey Bay. Bistatic operation will further decrease GDOP errors nearshore without the need to install complete monostatic systems. Offshore points within view of multiple sites will experience a significant decrease in the GDOP error of the total current vectors, since total vectors will now be estimated from N^2 rather than N components. The greater number of available components means smaller radii averaging circles in the total vector calculation can be used, enabling the network to better resolve fronts. This long-range bistatic array will provide additional current maps for total vector calculation. Successful tests of this configuration could lead to offshore long-range bistatic deployments on buoys, ships or on convenient NOAA platforms like Ambrose Light, introducing new geometries for total vector calculation. The combination of the long-range and standard bistatic CODAR systems will provide a nested grid of surface current measurements for the New York Bight with higher resolution near the shore.

6. Acknowledgements.

This work was funded by the Office of Naval Research, the National Ocean Partnership Program , and the great state of New Jersey. ADCP data provided by the Mid-Atlantic Bight National Undersea Research Center with additional support from the National Science Foundation.

7. References

Glenn, S.M., W. Boicourt, B. Parker and T.D. Dickey, 2000: Operational observation networks or ports, a large estuary and an open shelf. *Oceanography*, 13, 12-23.

Glenn, S.M., T.D. Dickey, B. Parker and W. Boicourt, 2000: Long-term real-time coastal ocean observation networks**.** *Oceanography***,** 13, 24-34**.**

Grassle, J.F., S.M. Glenn and C. von Alt, 1998: Ocean observing systems for marine habitats. *OCC '98 Proceedings*, Marine Technology Society, November, 567-570.

Kohut, J.T. and S.M. Glenn. 2002: Calibration of HF radar surface current measurements using measured antenna beam patterns. *J. Atmos. Ocean. Tech*., Submitted.

Kohut, J. T., S. M. Glenn and D. E. Barrick, 1999: SeaSonde is Integral to Coastal Flow Model Development. *Hydro International,* 3, 32-35.

Kohut, J.T., S.M. Glenn and D.E. Barrick, 2001: Multiple hf-radar system development for a regional longterm ecosystem observatory in the New York bight. *American Meteorological Society: Fifth Symposium on Integrated Observing Systems*, 4-7.

Paduan, J.D., D.E. Barrick, D.M. Fernandez, Z. Hallok and C.C. Teague, 2001: Improving the accuracy of coastal hf radar current mapping. *Hydro International*, 5, 26-29.

Schofield, O., T. Bergmann, W.P. Bissett, F. Grassle, D Haidvogel, J. Kohut, M. Moline and S. Glenn, 2001: The long term ecosystem observatory: an integrated coastal observatory. *IEEE J. Ocean. Engin*., In press.