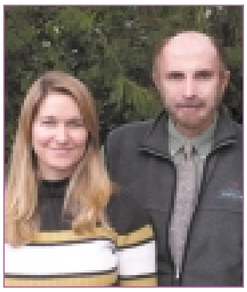
HF Surface – Wave Radar
Revisiting a solution for EEZ ship surveillance



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Why has High Frequency Surface Wave Radar (HFSWR), with four decades of development for ship and hard-target detection, never found its place in the operational surveillance world? We explore this question by reviewing its history and present status. We conclude it is not cost effective in its present configuration. We then suggest concepts being tested that will overcome these barriers and allow inexpensive, shore-based EEZ vessel surveillance.

Background

HFSWR exploits low-frequency signals' ability to propagate well beyond the visible horizon. This happens by diffraction over the curved conducting sea, independent of the atmosphere and ionosphere above it.

People frequently ask: is HFSWR new, I haven't heard of it before? No, it's not new! In fact, a version was built in the U.K. in 1938 to warn against German bomber attacks. Called "Chain Home", their three 120-m tall transmit and four 74-m receive towers graced the shores of the English Channel. This was a year before the breakthrough U.K. invention, the magnetron was delivered to the U.S. at the Massachusetts Institute of Technology (MIT); this was this device that triggered the explosion of microwave radars in the early 40s, in time to perform heroically during World War 2. In the meantime, Chain Home at 25 MHz languished, plagued by what was thought to be a German jammer but in fact turned out to be the intense Bragg sea echo we use today for HF current mapping radars.

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In the 60s, a major U.S. HFSWR program was launched by Defense Advanced Research Projects Agency (DARPA), dubbed 'MayBell'. In the usual DARPA fashion, competing companies were funded to the tune of several million dollars each, for a period of 5 years. They included Raytheon, ITT, Sanders(later to become Lockheed and then BAE), Sylvania, and NRL. At Battelle, the first author became DARPA's Technical Director for these efforts. They included bistatic; backscatter; mixed mode (skywave to target, surface wave back to the shipboard receiver); and even receivers that used 'signals of opportunity'. All were focused on detectability of hard targets: ships, aircraft and missiles, even Kelvin wakes from ships. These radars employed conventional phased-array technology to allow the receive antenna to form and scan narrow beams. At HF, the antennas were several hundred metres long, and had to be close to the shoreline. The radars were high powered, quite sensitive, and the tests were successful. Targets in all categories were seen, although ship wakes were barely detectable.

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At NOAA's Environmental Research Laboratories in 1972, Barrick persuaded management to develop an alternative to the large, costly phased-array technology for current and wave mapping that was holding back its acceptance. This led to the CODAR approach that replaces large phased arrays with compact direction-finding (DF) antenna units. One uses DF, for example, to rotate a loop antenna and find the bearing to a radio station. Our team left NOAA in the mid 80s to commercialise this concept as the SeaSonde®.

During this period, Don Barrick served as a consultant to Raytheon U.S. as two new generations re-examined phased-array technology for hard target detection in the late 70s and late 80s. As Raytheon U.S. abandoned HFSWR by 1990, Canada had

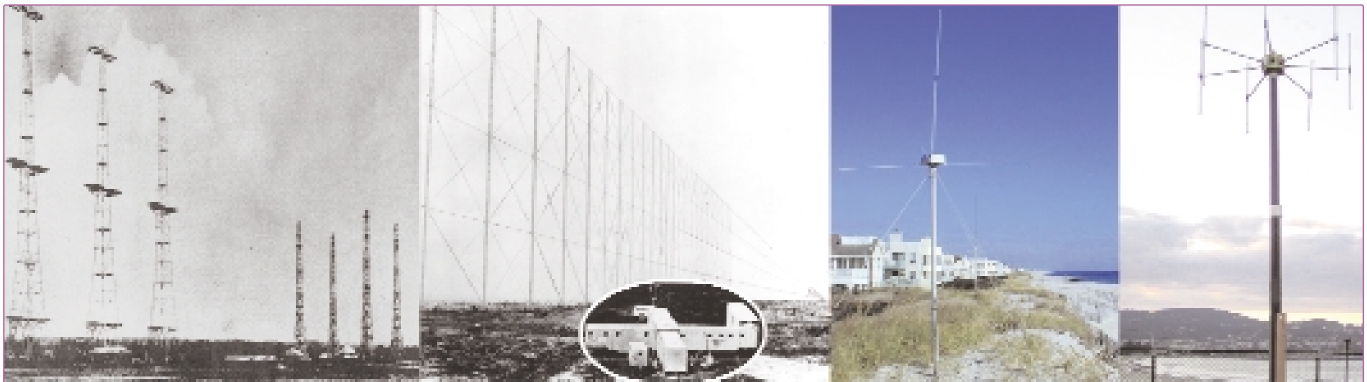

Figure 1. Evoluation of HF receive antenna technology (from left to right) ' Chain Home' at English Channel, 1938; phased array on San Clemente Island 1972; commercial seaSonde®, 1999; compact superdirective receive array, 2003.

already established a foothold, the only other major player in the West. This began with work at Memorial University of Newfoundland, continuing at C-CORE, NRSL (Northern Radar Systems Limited), and Raytheon Canada in the late 80s. The latter company has developed and demonstrated prototype phased array systems on the Newfoundland coast that see ships and icebergs at useful distances.

Present Status: Low-cost, compact SeaSonde® HFSWRs (presently intended for current mapping) have taken off: 150 units sold in the last decade (most within the last five years). The majority costing of the order of $100K complete operate unattended in real time. The marketplace seems to have voted them a success, as they constitute 85% of the HFSWRs in the world today.

On the other hand, despite the long history, HFSWR for hard target detection is not used by neither Navies or Coast Guards anywhere in the world operationally. Why not? Much is known about its performance from the tests 30 years ago and subsequent analyses. One can only conclude it has not offered a cost-effective surveillance solution. Its large phased-array antenna system is the cost driver: both initial outlay and operating expenses. During Summer 2003, initial request for information and proposals from the Canadian Government suggested budgets of C$55M for purchase and installation of five HFSWR backscatter radars operating between 3-5 MHz with antennas that each require close to 1 km linear span of beach real estate. In the U.S. with the tragic Sept 11, 2001 terrorist attack, the vulnerability of our coasts is demanding that HFSWR surveillance again be evaluated.

A higher radar frequency will help echo strength a lot, but added beyond-the-horizon propagation loss more than makes up for the echo increase, killing visibility at longer ranges. There is no point in painting a rosier picture; if such optimism were supportable, we'd be seeing a profusion of HFSWRs for ship surveillance.

Technical issues and ways around these cost barriers

Any HFSWR's performance is highly dependent on the environment: external noise fluctuations, sea clutter, radio interference levels, sea state effect on propagation loss, and current field are all beyond control of the operator. The HFSWR designer is left with only two parameters at his disposal to increase sensitivity (thence detection range against any target): transmit power and receive antenna directivity. This assumes optimum use of waveform and signal processing. Two critical parameters illustrate the stark nature of sensitivity on performance.

Detection range

Take 4.5 MHz as an example frequency for long-range vessel surveillance. Assume a target is detected at 200 km. A 3-dB (factor of two) increase in system sensitivity (transmit power or receiver antenna directivity) will increase range by 20 km. Hence, an increase of 10 dB (a factor of 10) increases range by 70-80 km. That's a lot!

Target size

It's the vertical height above water that matters for HFSWRs. A target is resonant when this height is a quarter wavelength (15m for 4.5 MHz). The echo increases modestly for larger sizes. But vertical heights smaller than this reduce the echo drastically, as the target drops into the 'Rayleigh region'. A rule of thumb: below resonance, target echo goes as the sixth power of the height. Cut the height in two and the echo drops by 64 (18 dB). This could result in a decrease in detectable range to 80km if it was originally seen at 200km. Taken to an extreme, the difference between a 15-m vertical mast (e.g., fishing trawler) and a 2-m height (a 'go-fast' drug runner) could be as great as $(92/15)^6 = 10^{-5}$, a -50 dB drop.

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For vessels and ships, however, cost of alternative surveillance such as aircraft patrols is even higher. Many past issues of EEZ Technology have made this point well.

Getting to lower cost part 1: Multistatics

Our company has been developing and testing bistatic and multi-static HFSWR variations for five years. The difficulty with bistatics is synchronising the signals at separated transmitter and receiver. The breakthrough that mitigated this is our use of GPS signals as a timing base that staggers the modulation cycling of multiple signal sources, all still transmitting at the same time. One separated transmitter operating with two backscatter radars turns these two into four. In addition, one of the backscatter transmitters can be a bistatic source for the other receiver, now producing five potential radar looks at the same target. Add another transmitter, and the radar looks increase

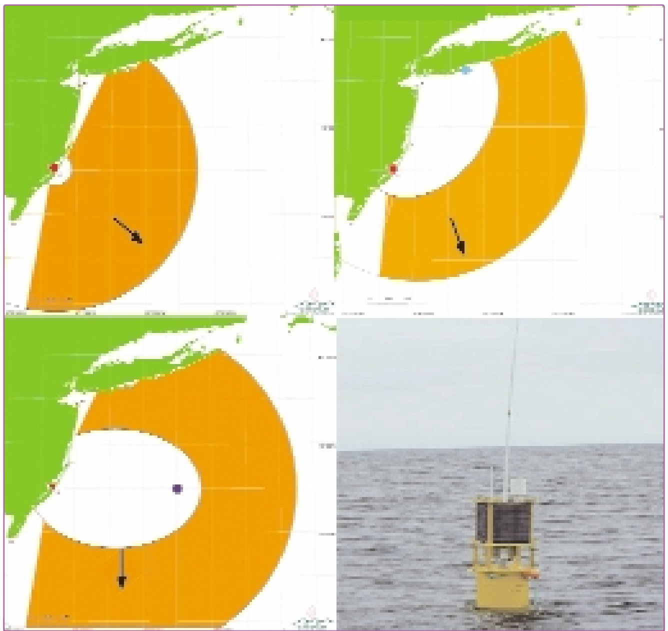

Figure 2. Three 'looks' at the same target. Upper left: backscatter system, Upper right: bistatic 'look' using Long Island transmitter: Lower left: bistatic 'look' using spar buoy transmitter; Photo at Lower right; bistatic transmitter on spar buoy operating off New Jersey coast.

with the number of permutations among them, growing to a very big number!

We have been testing solar-powered buoy transmitters (Figure 2) off the East coast of the U.S., both at 25 MHz and at 4.5 MHz. In addition to increasing the number of looks at the same target, proper positioning extended the range of the low-powered (50-w radiated) SeaSondes® from 200km in the backscatter mode to 330km bistatically.

Finally, multi-statics increase system robustness. The intense Bragg HF sea clutter masks a large part of the velocity region

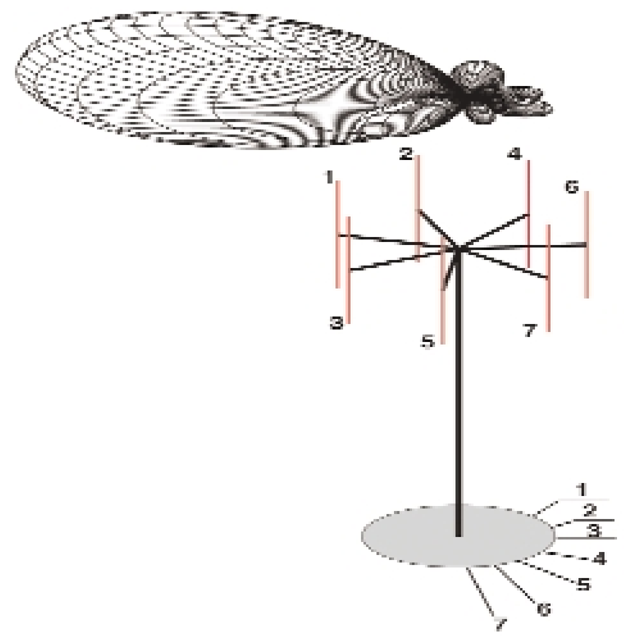

Figure 3. Pattern of a circular 7 element superdirective array with beam steered to left.

where ships are found. Here is an inexpensive countermeasure against a single radar: the boat wanting to elude detection measures the radar frequency with a simple commercial digital tuner, and adjusts vessel speed to hide in the strong sea-echo Bragg peak. But with multiple looks from different directions or bistatic geometries, it is impossible to be hidden to more than one.

Getting to lower cost part 2: Compact super directive receive arrays

Conventional HFSWR receive phased arrays employ a line of vertical monopoles over a good ground screen, spaced ~1/2 wavelength apart. At 4.5 MHz, for example, the wavelength is ~67 m; thus a 32-element array would be 1 km long and would – at best – provide a directive gain of 20 dB (relative to an isotropic antenna in free space). More directive gain is the same as more transmitted power; 3 dB remember, lets you go 20 km further.

Can one achieve the same directive gain with a receive antenna system that does not demand 1 km of unobstructed beachfront access, encumbered with all of the necessary cabling?

The answer is: yes!

CODAR has resurrected an old concept that was viewed with suspicion for decades: superdirective arrays. Mathematically, one can find a true solution for phasings that allows formation of a narrow, highly directive beam even when all of the elements are squeezed into a space a fraction of a wavelength. Seems too good to be true? What is wrong with this picture? The array is inefficient, as the sum of the signals from the phased, array elements is very low, compared to the signal from a single element. For transmit or for receive at microwave, this would be no good at all. For receive at HF, this is not relevant, because external noise exceeds internal by 40-70 dB. So, as one reduces size and thereby lowers target signals, one also knocks down the external noise, in direct proportion. The trick is to stop before internal noise dominates. Up to that point, one pays no penalty in system sensitivity, but realises a huge advantage in terms of size and cost. Designing around this tradeoff is the heart of CODAR's invention.

The photo (Figure 1) and directivity plot (Figure 3) shows a 7-element circular dipole array mounted on a post, tested to prove our concept at 25 MHz.. At 4.5 MHz, two such posts near the reflecting sea have a directive gain also of 20 dB (like the 1km linear array example above). The posts are separated by 80 m, and the array radius is 6m (the wavelength being 67m). This antenna can be fenced in for security and needs no ground screen (unlike the linear monopole array).

Could the cost advantages of multistatics and superdirective receive arrays penetrate the invisible barrier to HFSWR acceptance for vessel surveillance that has blocked operational acceptance for four decades? We're betting on it!

ABOUT THE AUTHORS

Donald Barrick received a B.E.E., M.Sc., and Ph.D. from the Ohio State U. in electrical engineering. From 1972-1983 he served as Chief of the Sea State Studies Division of the U.S. National Oceanic and Atmospheric Administration's Wave Propagation Laboratory in Boulder, CO; there he developed compact HF radar systems for real-time mapping of ocean currents and waves. In the mid 80s, he founded CODAR Ocean Sensors, Ltd., a company that has created and developed the SeaSonde® line of HF radars. His scientific interests include radar remote sensing, electromagnetics, antennas, signal processing, and applications to oceanography and marine operations.

Laura Pederson is the Director of Marketing for CODAR Ocean Sensors, Ltd. With a background in science television and education, Laura joined the company in 1996 to develop a broader market for the advanced SeaSonde® product line.

ENQUIRIES

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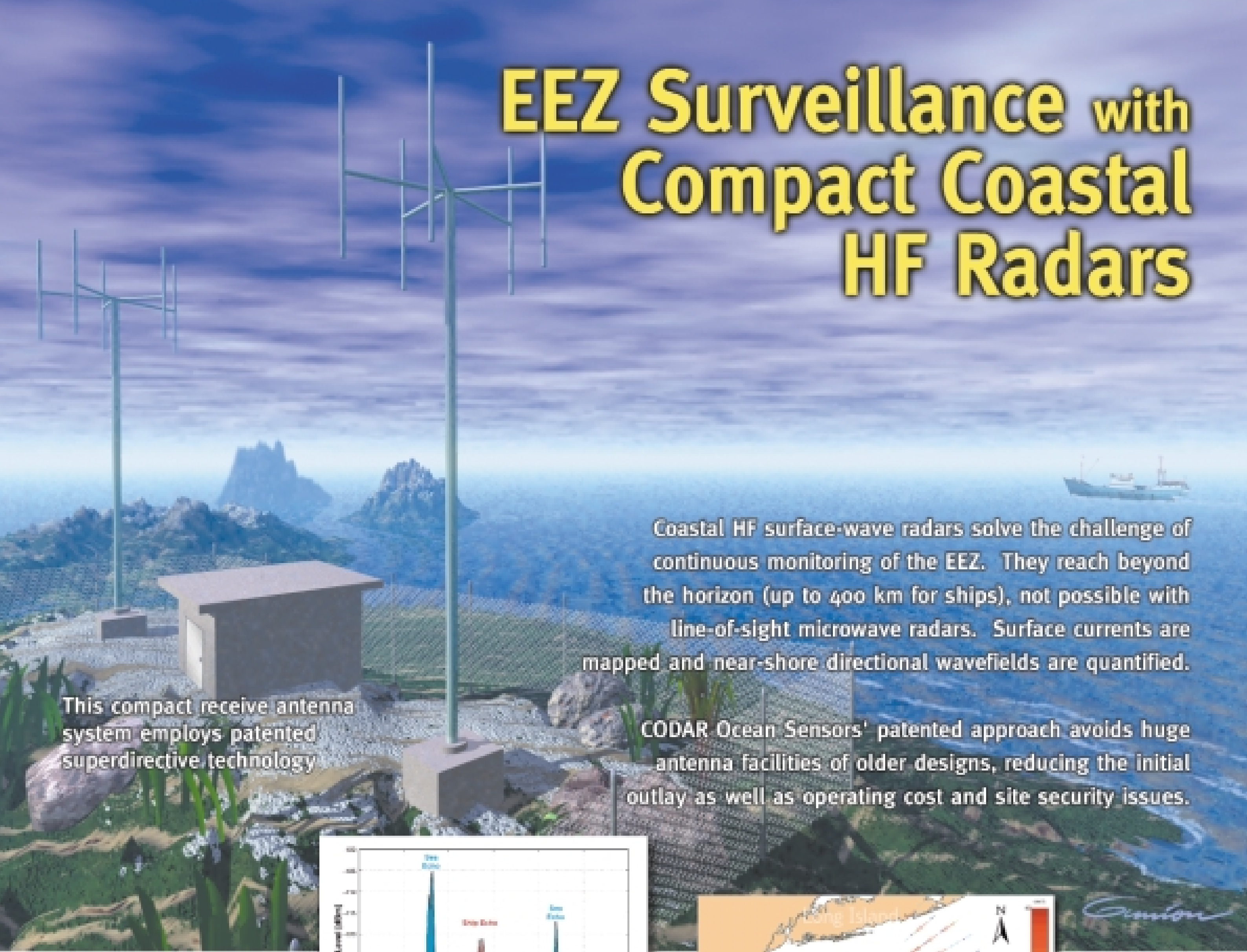
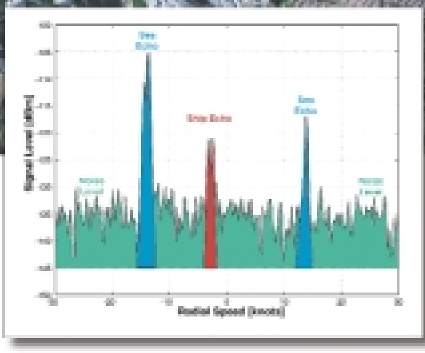
EEZ Surveillance with Compact Coastal HF Radars



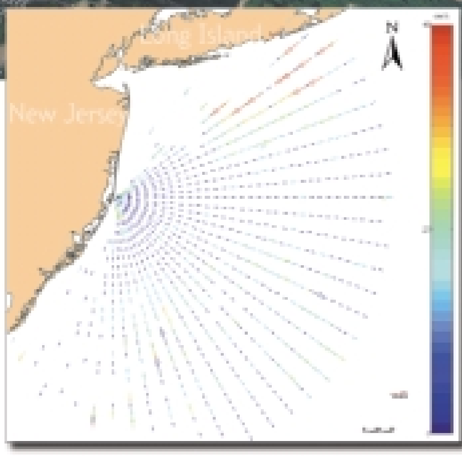
Coastal HF surface-wave radars solve the challenge of continuous monitoring of the EEZ. They reach beyond the horizon (up to 400 km for ships), not possible with line-of-sight microwave radars. Surface currents are mapped and near-shore directional wavefields are quantified.

CODAR Ocean Sensors' patented approach avoids huge antenna facilities of older designs, reducing the initial outlay as well as operating cost and site security issues.

This compact receive antenna system employs patented superdirective technology



Ship Doppler echo from 180 km lying between sea-scatter peaks



Data set showing surface current radial velocity vectors averaged from 6pm to 8pm, 26July2000 GMT. Courtesy of S. Glenn, J. Kohut, Rutgers U.

Observations

- Ship Activities Monitored
- Surface Currents Mapped
- Wavefields Measured

Features

- Small Coastal Site Footprint
- Minimal Station Security
- All Weather Operations

About CODAR

- The originators of HF radar ocean surface monitoring
- 35 years experience in this field: commercial and defense
- Have produced over 85% of all HF radars ever built for ocean monitoring

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