History, Present Status, and Future Directions of HF Surface-Wave Radars in the U.S.

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ABSTRACT -- HF surface-wave radars (HFSWRs) offer two distinct advantages when used over the sea: with vertical polarization, they see beyond the horizon, and the interaction of their signals with ocean waves is simple and well understood. As a result, many HFSWR research test programs were conducted in the U.S., beginning 35 years ago. This author was fortunate to have been immersed in these programs from the beginning. Early projects by the Defense Department focused on military target surveillance: ships, aircraft, and missiles. In the mid-70s, their potential was explored for environmental measurements: surface currents and sea state.

Why after 35 years of testing and evaluation are none found in operational service today, except those made by CODAR for environmental monitoring? I discuss this question in the present paper. My answer is: they did not offer cost-effective solutions for military applications based on conventional technology. I summarize first the status of the technology, both conventional and CODAR's unconventional approaches. The big cost-driver has been the huge phased-array antenna systems that constitute "the conventional approach". These also raise an outcry of objection to installation at over-used, valuable, or pristine coastal locations because of their size and obtrusiveness. Perhaps some of the unconventional approaches taken by CODAR and summarized below will overcome these obstacles to military deployment.

I. THE PAST

A. Technology Description and Conventional Approaches Nearly all HFSWRs employ antenna systems that "floodlight" on transmit and parallel-process signals from multiple receive elements to determine target bearing. Conventional radar approaches then form narrow beams to determine bearing. At HF where the wavelength spans 10-100 meters, a "narrow beam" demands an aperture size for the array that has ranged between 100 meters and 1.5 km. Cables must be run to all of these -- typically monopole -- array elements, and constitute a source of bias as differential line parameters drift with temperature and humidity unless sophisticated calibration procedures are introduced. Furthermore, all coastal HFSWR antennas for ocean surveillance must be sited within ~200 meters of the waterline, otherwise large propagation losses are incurred over the land. This rules out compounds with metal fencing seaward of the antennas when monopole elements are used.

The remainder of the HF radar has never been much of a cost driver, except perhaps very high-powered transmitters. RF electronics of 35 years ago performed as well as those today, although today's are smaller with solid-state and PC-board technology. Computer technology of course has increased massively in processing capability while decreasing in size and cost. However, this was never an obstacle in even the earliest systems because data and processing rates at HF are three orders of magnitude lower than at microwave.

B. Military Applications The first HFSWR programs I was involved in were sponsored by DARPA and the Navy. Called Project Maybell, these programs -- begun in 1967 -- involved Raytheon; ITT; Sanders (afterward Lockheed/Sanders and now BAE); Sylvania (afterward GTE and now General Dynamics); General Electric; NRL; and Battelle. In fact, Raytheon has witnessed three different generations of HFSWR programs, beginning in 1968, with the last ending about 1989 when they transferred their HFSWR technology to their Canadian counterpart. None of these has led to operational use. Later, Lockheed/Sanders (now BAE) developed under Navy SPAWAR and DIA an HFSWR phased-array system focused on missile detection in the mid-1990s. That system never moved beyond the

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development stage, and is now mothballed by the Navy.

Missile detection is the most problematic HFSWR application. Sea-skimming cruise missiles have such low radar cross sections (RCS) that ranges perhaps only 40% greater than the 12-nmi Aegis range have ever been projected under optimal conditions. Viewed in the light of a large phased-array shipboard installation costing several tens of millions of U.S. dollars, this was not deemed a cost-effective answer. Ballistic missiles are seen, but microwave radars do a better job, providing greater information with better accuracy and more rapid updates. Likewise, aircraft detection has only been marginally better than microwave, not enough to justify the cost.

Ship detection and tracking seems more suited. The RCS is much larger and their movement smoother and easier to follow in Doppler space. Although large HFSWRs with high power have detected and tracked larger vessels to 400 km, the cost (both initial and operating) of such facilities has apparently been sufficiently high to keep them out of operational use.

C. Environmental Applications The earliest phased array systems I was involved in for military purposes were built on San Clemente Island off California in the late 60s. As enthusiasm in their military potential waned by the early 70s, we began using them for sea scatter experimentation. Early results with those large systems showed that surface currents and sea state could be extracted [1, 2]. These early environmental measurements were made as I joined NOAA in 1972.

With enthusiastic support from NOAA, I set out to replace the huge obstacle to acceptance for coastal environmental measurements: the unacceptably large and costly phased-array antenna systems. Calling our concept CODAR, we tested a series of compact, direction-finding (DF) antennas for reception, including 3-element linear and 4-element square arrays, and culminating in the 3-element colocated set of crossed loops and monopole unit that are used today. Over 17 field tests were done at NOAA on CODAR, all supported by ground-truth comparisons. With NOAA's blessing and encouragement, my team left the government in the mid-80s to develop and market commercial versions. At that point, we invented an efficient, gated FMCW (linear swept frequency) waveform that allowed real-time processing with inexpensive PC desktop computers, further reducing the cost. These systems are now called SeaSondes.

II. PRESENT STATUS

Our SeaSonde® family of products is broken into three lines, based on operating frequency that define the maximum current-mapping coverage with 50 watts radiated power: (i) 24-27 MHz, which achieves spatial resolutions to 300 meters with maximum ranges 35-50 km; (ii) 12-14 MHz, that goes out to 60-80 km with resolutions selectable between 1-3 km; (iii) 4-5 MHz that reaches to 200 km, with typically 6-10 km resolution. Range cell size -- or resolution -- is limited by the spectral bandwidth allowed by the approving government agencies.

Sensing the Dopplers of low-velocity ocean waves, these SeaSondes had to deal with unwanted ship echoes: these became our "clutter" when making environmental measurements. Algorithms were developed to excise these nuisances. Recently there has been a renewed push to extend our systems for "dual use", by adding ship detection and tracking to the original current and wave monitoring tasks. This is especially relevant with our Long-Range SeaSondes that reach to 200 km, far beyond the line-of-sight limit of coastal microwave radars. Funded by the Navy and Coast Guard, these programs are now yielding evaluation test data that will be discussed at the conference.

Our company has sold over 140 of these compact units. This compares with about 40 non-CODAR HFSWRs of any kind ever built, only a handful of which are operating today. At present, there are no other HFSWR development programs underway by the U.S. government, nor are there any systems commercially available from U.S. companies for any purpose.

III. FUTURE TRENDS AND DIRECTIONS

A. GPS Multi-Frequency Sharing In our lower two HF bands of operation, there are many other spectral users. These are primarily broadcast stations or maritime and aeronautical radio users who exploit the skywave mode to communicate over long distances. In fact, there is not a single 3-kHz channel anywhere in the HF band that is not used by one or more licensees part of the time, somewhere in the world. These signals can interfere with HF radars and vice versa thousands of kilometers away, when skywave conditions are favorable. Likewise, HF radar users can interfere with each other on the same band even though a significant distance separates them. As SeaSonde radars proliferate, the ability of each to obtain approvals for separate bands is impossible.

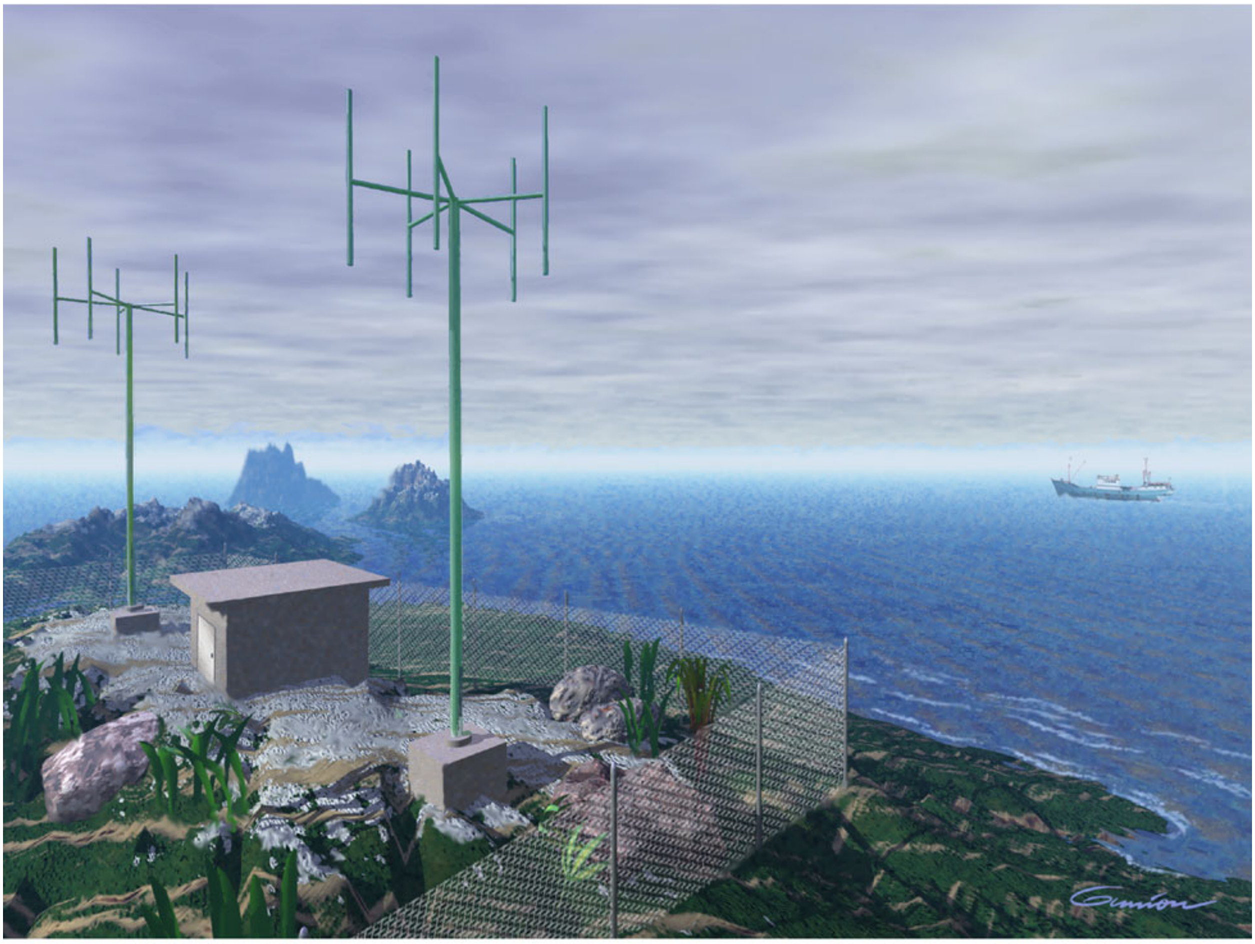

Figure 1. EEZ-Sonde™ receiving antennas within remote, secure facility. Designed for 5 MHz-band operation, two 5-element pentagon arrays of dipoles are mounted on 20-m masts.

CODAR has solved this problem by using GPS signals as a time reference. This invention allows precise synchronizations of their modulations, so that as many as 30 stations can share the same frequency at the same time without mutually interfering. Our digitally synthesized FMCW waveform makes this possible. After demodulation, the other stations' signals are separated, falling outside of the region containing that radar's information. GPS timing also enables bistatic operation, where several transmitters' signals can be processed simultaneously in a single receiver. GPS timing is now standard on all SeaSondes delivered that operate in the lower bands. By thusly grouping many HF radar stations into two or three bands over the past year, complaints by radio listeners to "the ticking clock" radar-signals they had been hearing throughout the lower HF bands has virtually ceased.

B. Multi-Static and Multi-Site Augmentation for Currents and Ship Surveillance CODAR has developed and is testing low-powered transmitter units with GPS synchronization. These have been deployed on solar-powered buoys and offshore platforms, to operate in conjunction with shore-based backscatter units. One bistatic transmitter operating with two backscatter radars effectively transforms the original two into four radars. In addition, one backscatter radar's signal serves as a bistatic source for the other backscatter unit, so we can now have five or six simultaneous radar observations with only two receivers and processors.

Multi-static augmentation serves two functions. It extends coverage to distances not reached by coastal backscatter units. In addition, it provides multiple observations of the same point. For current mapping, this improves the accuracy of the total vectors, as they are based on an overdetermined solution with many scalar estimates. The same is true for ship detection, confirmation, identification, and tracking, but here yet another limitation is overcome: a ship's echo can be easily masked in the Doppler of a single radar by the first and second-order sea echo, since their velocities are similar. In fact, an easy countermeasure for a hostile vessel is to listen to the frequency and calculate/use the speed that will provide this masking. Two or more looks from different directions will always eliminate this single-radar limitation.

C. Compact Superdirective Arrays for Narrow-Beam Scanning CODAR has invented and is now testing a compact alternative to linear phased arrays for beam forming and scanning. Our alternative provides the same directive gain on receive as the multi-wavelength span of the conventional linear array, but is confined to a much smaller, fenced-in compound. Fig. 1 depicts this system at 5 MHz for HFSWR operation.

When an array comprised of an odd number of identical elements like dipoles is configured around a circle, one can synthesize and scan a narrow-beam pattern over 360°. The pattern is invariant with scan angle and frequency, as long as the array radius is less than a quarter wavelength. As array radius decreases, output signal strength as well as external noise drops. Signal-to-noise ratio (SNR) does not suffer until external noise approaches internal, at which point further size reduction is detrimental to performance.

Two or more masts elevate their circular dipole arrays to an optimum height about 3/8 wavelength, and are spaced slightly more than a wavelength apart. The multiple masts serve two purposes. The arrays from each are phased together to further increase directive gain and narrow the beamwidth, thereby increasing SNR and reducing clutter. In addition, the array signals from the separate masts are used in our MUSIC DF algorithm to increase the target's angular accuracy to a value much smaller than the beamwidth. If the masts are near the water, another advantage is elimination of the large, expensive ground screen required under the conventional monopole arrays, while still realizing the image enhancement of the highly conducting sea surface forward of the antennas.

The twin-mast 5-element configuration of Fig. 1 provides slightly greater directive gain than a conventional 20-element half-wavelength-spaced linear array that would span 600 meters at 5 MHz.

D. Shipboard Applications There continues to be interest in operating HFSWRs from vessels underway, although past programs involving phased arrays have not found operational favor because of the antenna size/cost issue. Our company is involved in a Navy program to demonstrate the capability of current mapping from vessels underway for rapid environmental assessment. Two problems must be overcome in this case.

(1) HF antenna patterns are significantly distorted by the metallic superstructure. On receive, this introduces bearing biases unless accounted for. Transponder pattern measurements serve as calibration to reduce biases. However, a ship's topside is a dynamic environment, with mobile cranes and booms whose varying configurations change the pattern from what existed when it was measured. This issue must be considered when siting the antenna unit.

(2) Vessel motions -- both its cruising and its response to waves -- introduce their own Doppler shifts on the radar signals. Ship translational velocity in general will be much greater than the velocity of currents to be measured. In principle, ship course/speed obtained from GPS can be "backed out" of wave/current velocities. In practice, the success of this is limited by a number of factors. These limitations and methods to overcome them are being examined within our Navy program. Results will be summarized in this presentation.

IV. CONCLUSIONS

If the past and present serve as guides in the U.S., the CODAR approach has found wide acceptance and a significant market as an oceanographic monitoring tool. Whether it comes into operational use against military or other hard-target applications depends on its cost vs. effectiveness ratio. Cost in the past has been driven by large receive antenna size. Our approach to reduce its size by novel superdirective schemes could overcome this obstacle.

E. References

1. Barrick, D. E., J. M. Headrick, R. W. Bogle, and D. D. Crombie (1974), Sea backscatter at HF: Interpretation and utilization of the echo, *Proc. IEEE* , vol. 62, pp. 673-680.

2. Stewart, R. H. and J. W. Joy (1974), HF radio measurements of surface currents, *Deep Sea Research,* vol. 21, pp. 1039-1049.