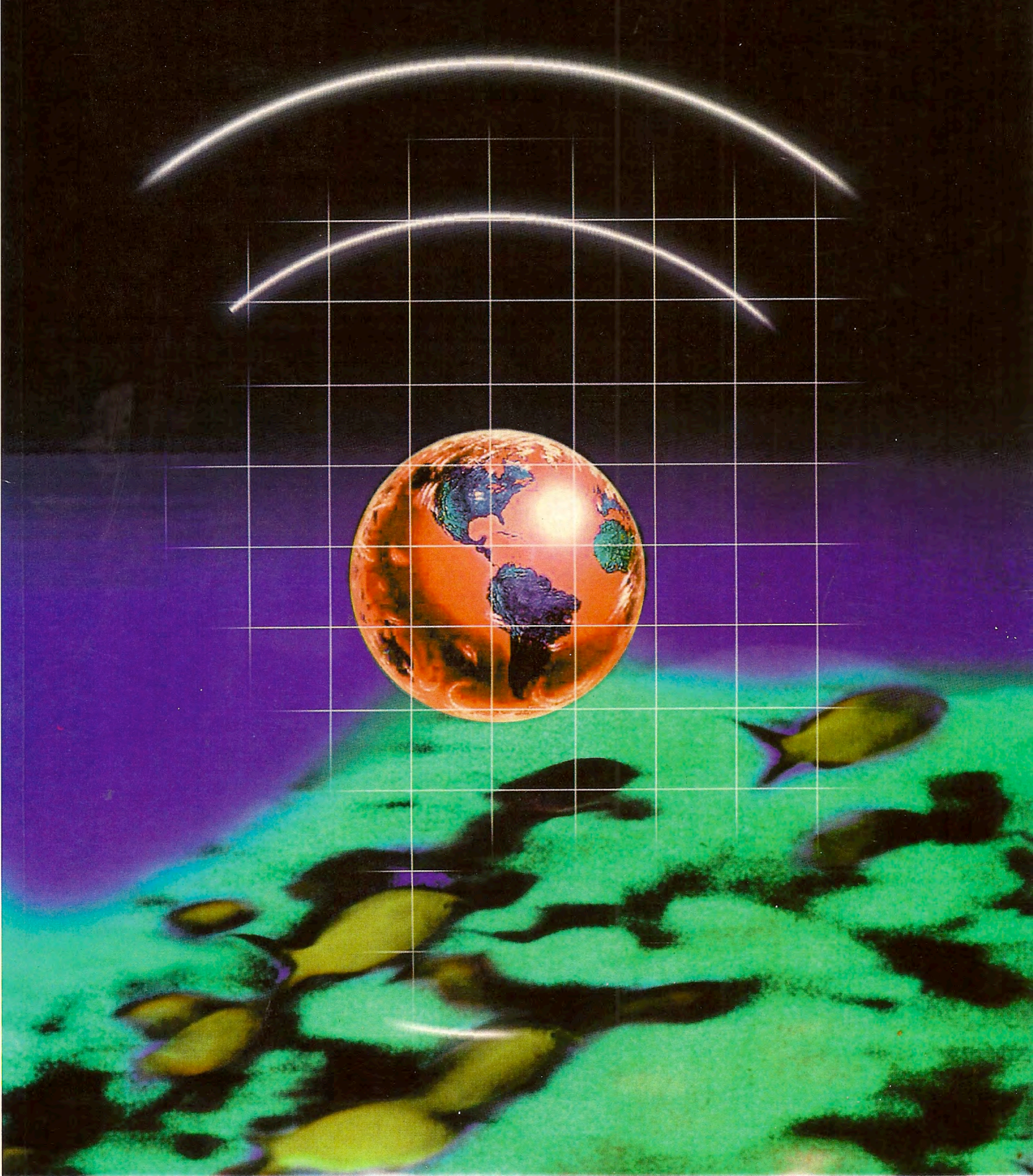
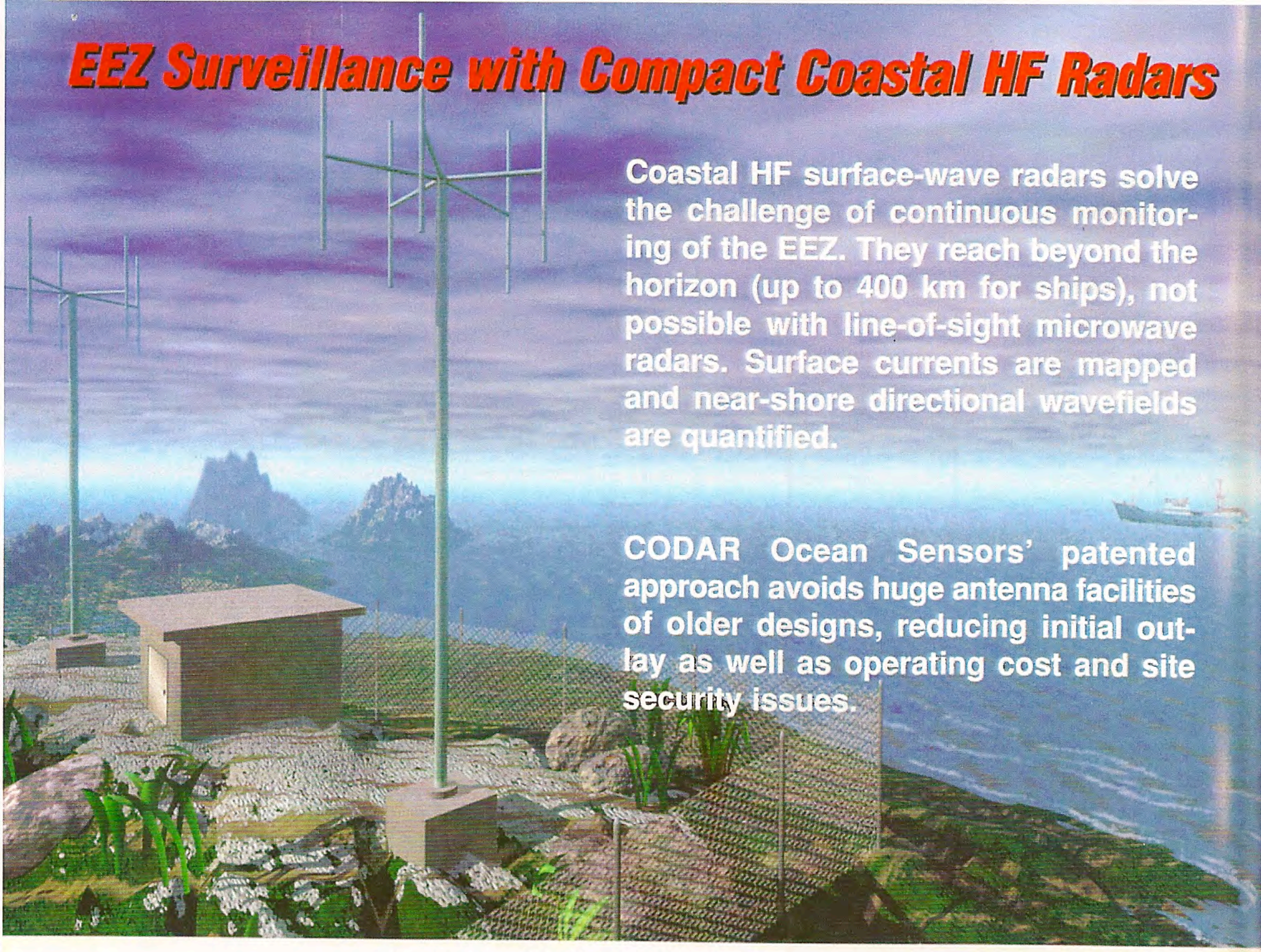
Edition 3

EEZ Technology

The Review of Advanced Technologies for the Management of EEZs Worldwide



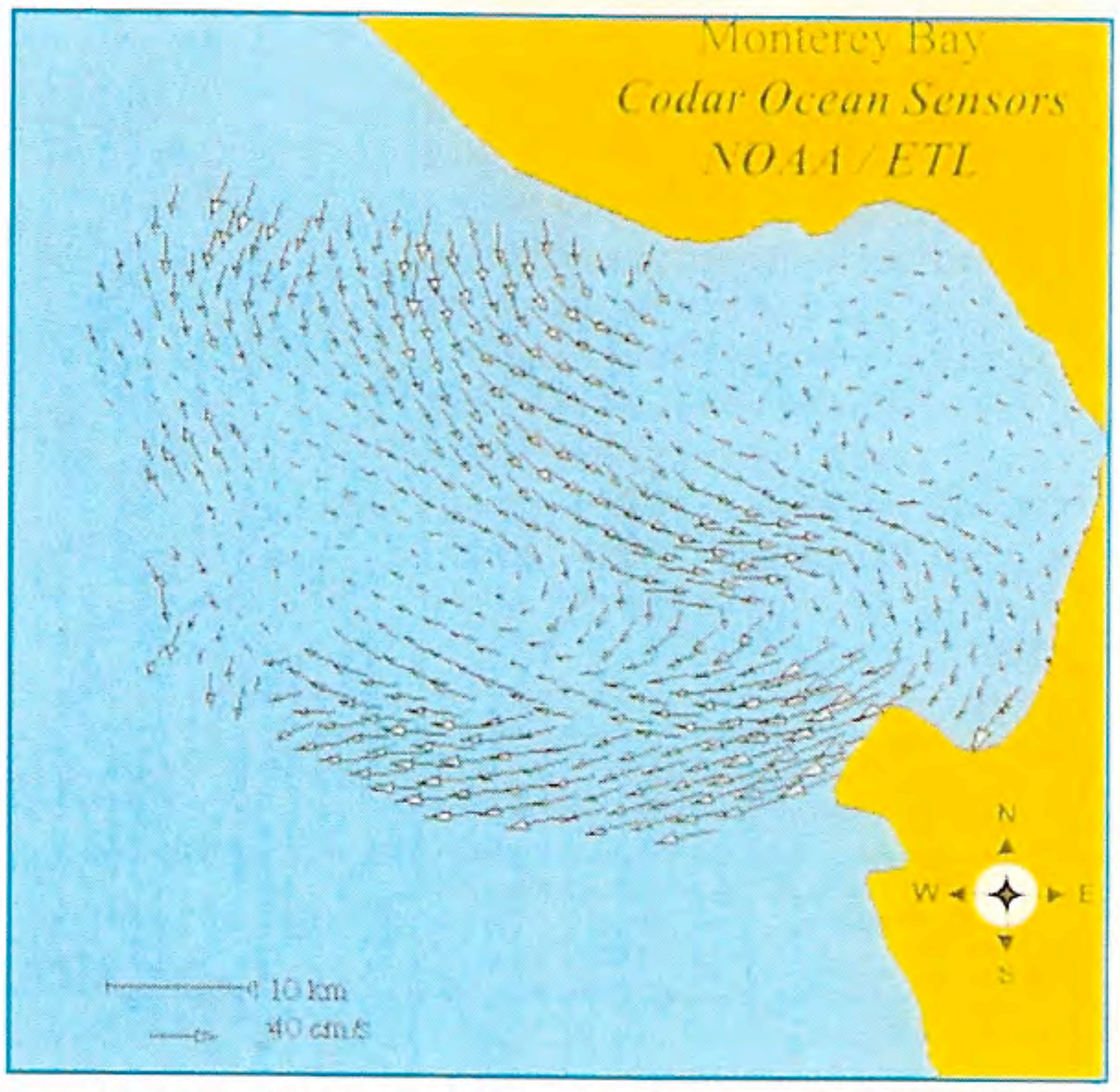
EEZ Surveillance with Compact Coastal HF Radars



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 initial outlay as well as operating cost and site security issues.

The Compact EEZ-Sonde™ Receive Antenna System



Currents Mapped by Seasondes on Monterey Bay

Observations:

- Ship Activities Monitored
- Surface Currents Mapped
- Aircraft Detected and Tracked
- Wavefields Measured

Features:

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

★ *The originators of HF radar ocean surface monitoring*
★ *30 years experience in this field: commercial and defense*
★ *Over 40 HF radars sold: exceeds total by all others*

CODAR Ocean Sensors

1000 Fremont Avenue, Suite K,
Los Altos, CA 94024, USA
Telephone: (408) 773-8240 Fax: (408) 773-0514

EEZ Surveillance - The Compact HF Radar Alternative

Donald E. Barrick, *Codar Ocean Sensors Ltd., Los Altos, CA, USA*

ABSTRACT

The nature and tradeoffs behind coastal HF surface-wave radar systems for EEZ surveillance are reviewed. An unattractive feature of conventional designs is the large size of their receive antennas, with the attendant high initial and operating costs. We examine an alternative that offers nearly the same sensitivity with a highly efficient signal waveform and much smaller antennas that can be located inside an unmanned fenced compound.

NATURE OF EEZ SURVEILLANCE

The United Nations Convention on the Law of the Sea (UNCLOS) of 1992 confers extensive rights of exploitation within an Exclusive Economic Zone (EEZ), covering a span out to 200 nautical miles (M). Exploitation of the EEZ by a participating country carries responsibilities along with the economic benefits. These include:

- Prevention of smuggling, terrorism, and piracy
- Fisheries management and protection
- Vessel traffic services (VTS) and policing
- Search and rescue
- Ocean surface environmental data collection and dissemination
- Pollutant detection, control, and cleanup

All of these responsibilities require real-time surveillance within this 200 M coastal zone. Targets on or near the surface are most problematic because they cannot be detected to great distance by coastal line-of-sight systems. Desired observables - and those we will be addressing - are:

- Ships and boats
- Low-flying aircraft
- Surface currents
- Surface wavefields

The first two observables are hard-body 'targets', visible to radars or to passive optical, infrared, or radiometric sensors (including the eyeball). They may be friendly in nature, i.e., licensed to operate in the EEZ, and in some cases have filed movement plans with the local government. Licensing often requires that the vessel carry a transponder to facilitate its tracking as well as identify the carrier. Monitoring ship movements aids in fisheries management, vessel traffic services, search and rescue, and floating pollutant cleanup. Besides observing friendly surface vessel activities, surveillance involves the detection, tracking, identification, and control of unknown or hostile ships and aircraft.

The last two observables - surface currents and wavefields - play an obvious role in all six items listed above. The complex coastal surface flows are particularly hard to map continuously by conventional means. They are not detectable by infrared scanners; nor can they be mapped effectively by subsurface point sensors like moored current meters or bottom-mounted acoustic Doppler profilers. They impact heavily on search and rescue, floating pollutant control and cleanup, fishing, vessel traffic management, and offshore petroleum or mineral recovery.

What are the alternatives for observing the four items listed above? Patrol aircraft can observe ship and low-flyers by radar and visually. To search a 90°

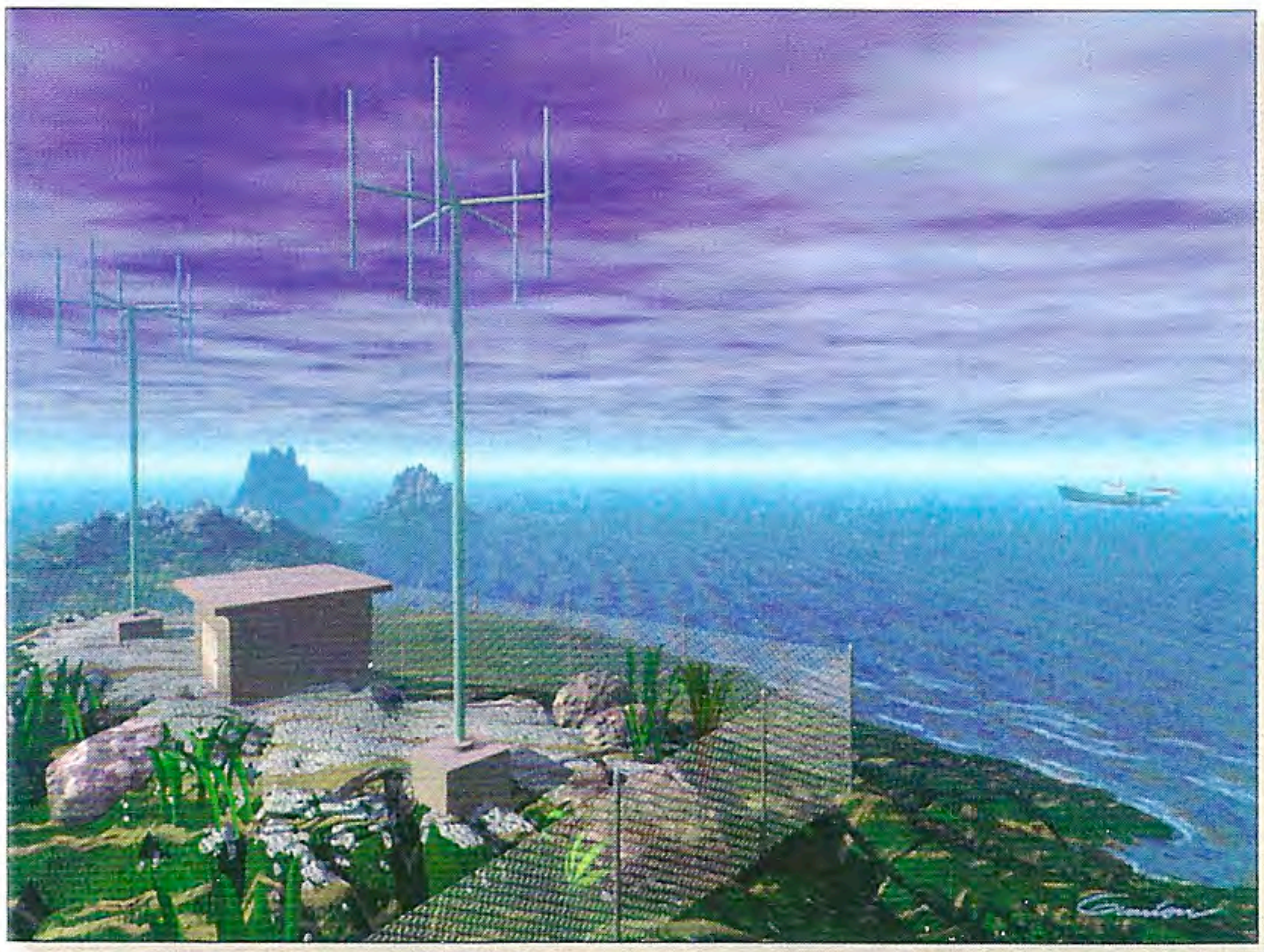
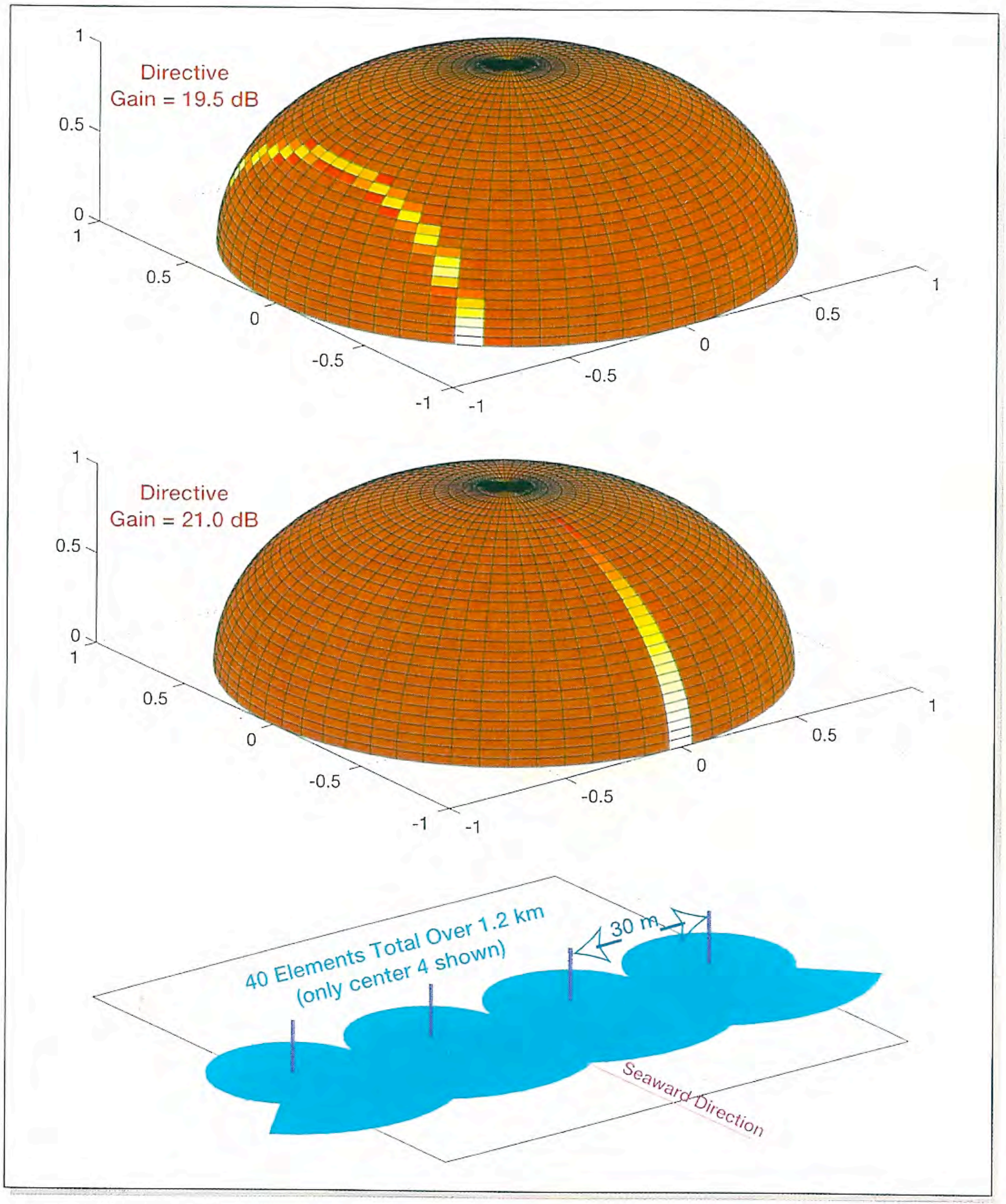


Figure 1
View of compact receive antenna system layout for HF surface-wave coastal surveillance radar near 5 MHz. Two superdirective pentagon arrays on 15-m masts are employed for high directive gain (19.2 dB) when phased together, and high target angle accuracy when employed with MUSIC direction-finding algorithm. Fenced compound is secure and unmanned

Figure 2
Directivity patterns of classic 40-element half-wavelength-spaced monopole antenna array at 5 MHz. Lower sketch shows layout of middle 4 elements, along with underlying ground screen (blue). Upper plots show power intensity vs elevation and bearing, white being strongest and dark red weakest. Middle plot is for seaward horizon beam steer; upper is 45° horizon steer



quadrant out to 200 M requires 3 aircraft 4 hours on station in sequential patterns, as pointed out in the Surveillance and Electronic Detection Section of EEZ Technology (Launch Edition). A single ship needs 66 hours to complete this fixed search. Both ship and aircraft patrols are therefore expensive, and hence appropriate only in times of heightened tension or suspected incursion. A shore-based microwave radar is limited by the visible horizon; for a radar elevated 100 m above the sea, this detection distance for surface targets is 28 km. Doubling the height to 200 m extends this limit to 50 km, only ~13% of the required 200 M (or 370 km) EEZ swath. Satellites have neither the spatial nor the temporal resolution to provide this surveillance in real time. Finally, HF over-the-horizon (OTH) radars that reflect their signals from the ionosphere have been employed for surface target surveillance, out to distances of 4000 km. The antennas for these systems are huge (2-3 km in extent). Their initial and operating costs are hence too great to be considered for EEZ usage, except perhaps for a country like Australia where an inland OTH radar is ideally positioned to observe much of its coastal region.

HF radars also operate in a mode where the signal fields - being vertically polarised - are diffracted along the highly conducting sea well beyond the visible horizon. Such systems are known as surface-wave radars (SWR), and distances to several hundred kilometres can be achieved. Hence, these radars offer the prospect of cost-effective surveillance of the EEZ from the coast. The nature and tradeoffs of a SWR for this purpose are the subject of the present paper.

COASTAL HF RADAR HARDWARE CONFIGURATION

HF surface-wave radar (SWR) antennas must be located close to the water in order to couple signals to and from the sea efficiently. Allowed distances are 1-2 wavelengths, e.g., 60-120 m at 5 MHz. Being up high on a cliff or bluff is neither a benefit nor a detriment, as it is with line-of-sight radars. However, an HF antenna cannot be up high

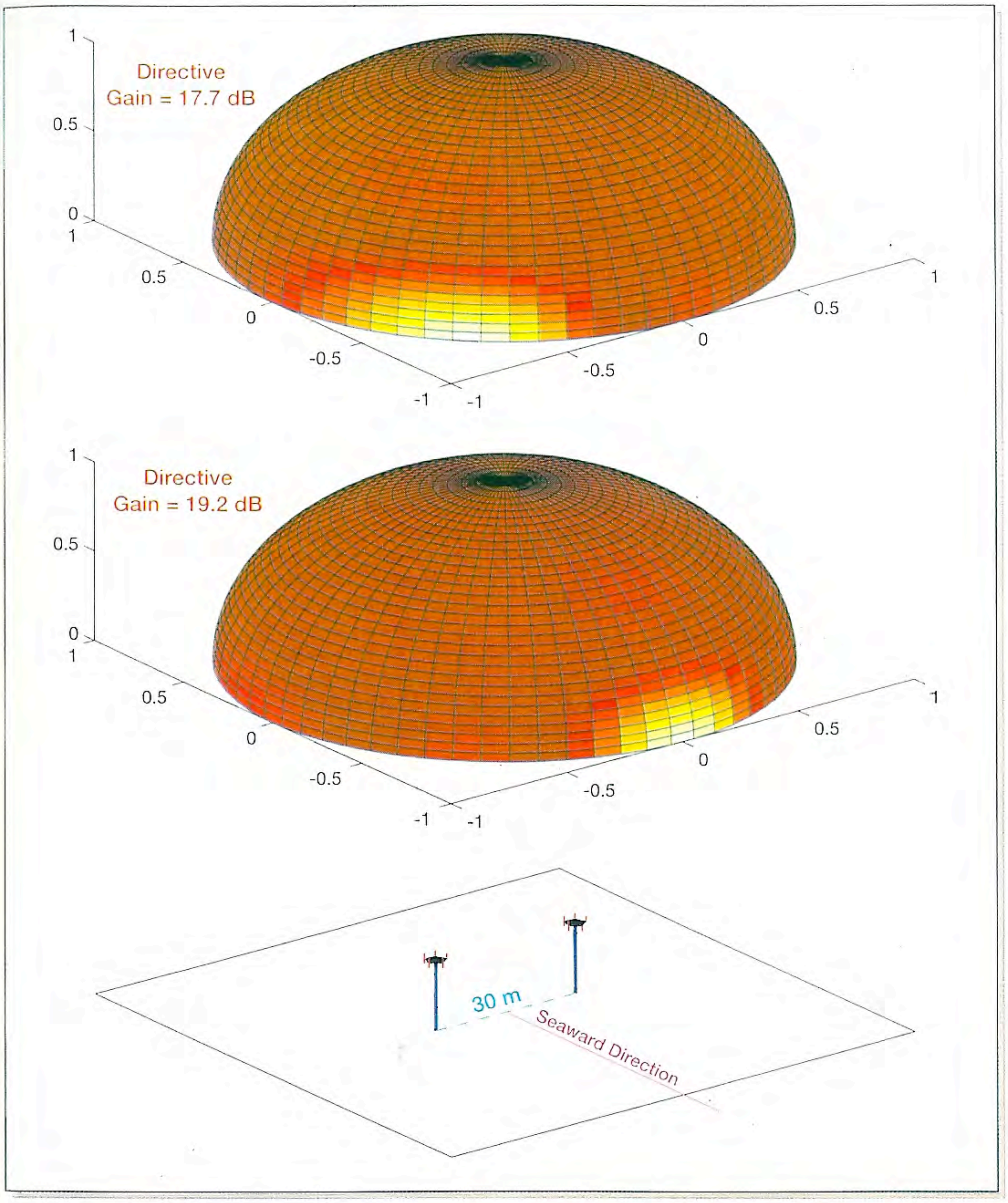


Figure 3
Directivity patterns of compact CODAR 2-mast pentagon receive array at 5MHz. Lower sketch shows orientation of 20-m high masts protected within a fenced compound. Upper plots show power intensity vs elevation and bearing, with white being strongest and dark red weakest. Middle plot is for seaward horizon beam steer; upper is 45° horizon steer

and far back, as could a microwave radar perched on a coastal mountain 1 km high and 5 km back from the sea.

Metal fences or other obstructions may not block the HF antennas from the surf edge - unless the antenna is elevated well above the fence top. This can be a problem, because most countries defend public coastal access except on military bases. Hence, a 1 km long antenna array within 100 m of the water is easily accessed by small boats or pedestrians walking the beach. Security then becomes an issue, and round-the-clock guards to protect an antenna drives up operating costs. In addition, there are high initial costs for a long array facility with accompanying ground screens and cabling.

If the antennas are compact, housing for the electronics and their environmental protection (heat and air conditioning) can be weatherproof containers in small sheds. A fenced enclosure around the antenna and shed then provides adequate security so that the site can be unmanned. Data are transferred by modem both ways to/from the site, allowing remote checking of the electronics' operating status.

NATURE OF HF SURFACE-WAVE RADAR AND TRADEOFFS

Although coastal HF SWRs have been tested in the U.S. and U.K. as early as the '60s, they have yet to reach operational status against ship or aircraft targets. The reasons have to do with the following tradeoffs. To achieve the greatest distances, the operating frequency must be low (e.g., 3-6 MHz) where their wavelength is 50 – 100 m. At 3 MHz, surface-wave loss over the sea to 300 km is not much greater than it is in free space, where radiated signal power diverges inversely with distance squared. However, lowering the frequency to 3-6 MHz has three negative impacts:

1) Antenna sizes tend to scale with the wavelength, increasing the initial and operating costs for the systems.

2) Target reflectivity (called the radar cross section, or RCS) tends to drop rapidly as target size becomes less than half a wavelength.

3) Noise increases and interference problems arise in this crowded part of the radio spectrum.

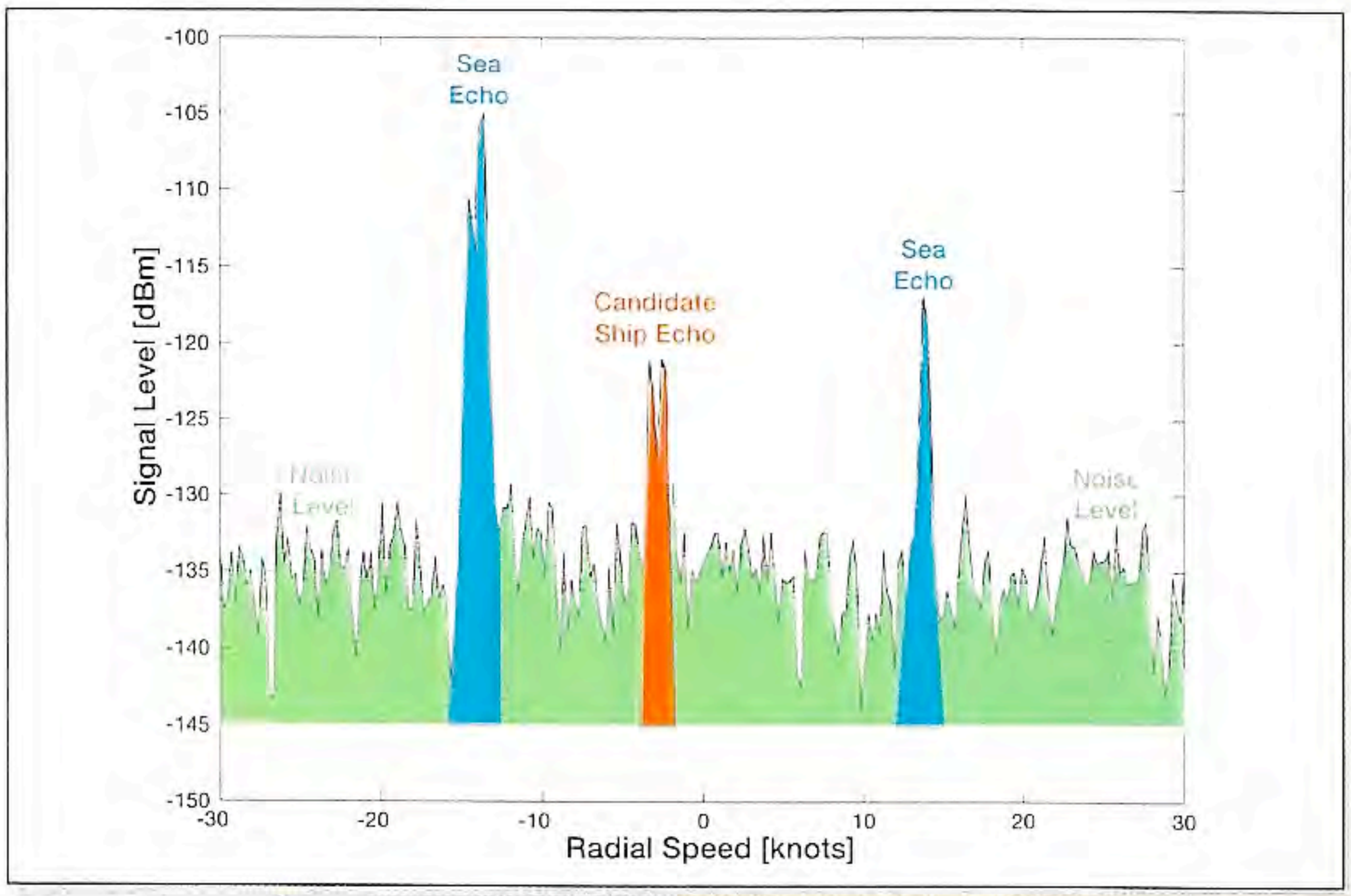


Figure 4
Target spectrum observed with CODAR SeaSonde system at Santa Cruz, CA on April 17, 1998 at 4.9 MHz from 180 km range. 13-minute time-series data sample was processed to produce this spectrum. Sea clutter Bragg echo peaks are shown in blue. Likely ship target is red peak, having echo strength typical of vessel with 15-m mast. This compact current-mapping system radiates 45 watts and employs two low-gain (omni-directional) post-mounted antennas

At upper HF (e.g., 25 MHz), propagation losses beyond the horizon mount rapidly, and ships are not detectable beyond ~80 km. Although aircraft reflectivity is larger here, it is offset by the even greater propagation losses when they fly low. Hence, use of HF SWRs for hard-target detection has up to now been confined to research demonstrations. They have found much wider commercial application for real-time mapping of ocean surface currents when combined with compact, low-cost antenna systems. The CODAR SeaSonde® operates in bands near 12 and 25 MHz, achieving distances out to 70 km with only 45 watts of power and two post-mounted antennas. The company has built and sold over 40 radars of this type, exceeding the total HF radars produced elsewhere world-wide for any application.

Besides its compact antennas, a second hallmark of the CODAR is the use of a unique highly efficient, digitally generated continuous-wave (CW) signal waveform and its subsequent processing by a simple personal computer. This waveform allows low peak radiated power - less than 4 kW - compared to 100 kW needed by other facilities for the same coverage (see Fig. 4).

The compact antennas and methodology we have applied to surface current and wavefield mapping must be revisited for ship and aircraft targets. For currents and waves, the radar target is a continuous complex, comprising the ocean waves within a large circular radar cell. In that case, high signal gain in one particular direction is less important because a simultaneous view with a low-gain broad beam is equivalent to the sequential scan of a high-gain narrow beam. For the hard-target case, maximising received signal gain at its bearing is important, as reduced gain translates to significantly reduced surveillance range. We review next the conventional, large phased-array antenna approach, followed by a description of a compact alternative that provides nearly equivalent hard-target sensitivity.

THE PHASED ARRAY VIS A VIS THE COMPACT SUPERDIRECTIVE ARRAY APPROACH

Normal radar antennas have dimensions transverse to the desired view that are many wavelengths. This allows a narrow beam to be formed and scanned, and defines the conventional angular resolution (in radians) as the ratio of the wavelength to the antenna length. For hard targets, it also increases their signal-to-noise ratio inversely with this ratio. This is known as the antenna's directive gain. A linear array of whip antennas along the coast, properly combined, provides greater gain than a single whip. At 5 MHz where the radio wavelength is 60 m (ideal for long-range ship surveillance), a 1.2 km long array has a bearing beamwidth of 1/20 radian, or about 3° minimum at broadside, increasing to 4.3° at ±45°. Its gain increases the hard-target signal-to-noise ratio by a maximum factor of 40 (or 16 dB). A "classic" linear array of this length would have 40 such whips 15 m high (a quarter wavelength), fed against a metallic ground screen for better performance. The 3-D patterns of such an array are shown in Fig. 2. This conventional HF SWR receiving antenna is called a phased array, because one scans the beam over a ±45° bearing sector by applying precalculated linearly progressive phase settings to the signals received by the array elements. This scanning is done in "software" without mechanically rotating the antenna, as is common at microwave frequencies where wavelength and antenna sizes are much smaller. Its disadvantage is the use of 1.2 km coastal land close to the water and the attendant security requirements in areas that are normally open to public access.

CODAR Ocean Sensors employs an alternative, compact design to achieve equivalent hard-target gains without the requirement for extensive coastal land use and the accompanying high operating costs. Five short 2-m whips are grouped as a pentagon. The pentagon is elevated 20 m on a pole, and two such poles are spaced 30 m (half wavelength) apart, illustrated in Fig. 1. Hence, the entire receive antenna is placed inside an unmanned fenced compound near the water no more than 36 m long by 10 m wide, eliminating the need for round-the-clock security and associated costs. Its directive gain is 19.2 dB, compared to the 21 dB gain of the large 1.2 km, 40-element phased array. Patterns are shown in Fig. 3, having a narrower elevation but wider bearing beam, but essentially the same solid-angle beamwidth and directive gain as the much larger phased array.

The principle behind this compact receive array is 'superdirectivity'. Phasings for closely spaced elements are derived by mathematically maximising the directive gain in the direction desired. Superdirectivity has been known to antenna engineers for over five decades, but has not found practical application till now. The reason is inefficiency: the combined signal from the closely spaced, nearly anti-phased elements is low. A smaller captured target signal would hurt if one were competing with internal receiver noise, which is independent of antenna spacings. At HF, however, this inefficiency on receive is not a problem, because the limiting noise is external, of atmospheric origins coming from thunderstorms. At 5 MHz, this external noise is typically 50 dB greater than internal. The superdirective antenna reduces external noise on average by the same factor that it reduces the target signals. Our patented design principle trades compactness for reduced efficiency until the latter is within 10 dB of the external/internal noise ratio. The combined receiver noise factor and antenna inefficiency can be as poor as -40 dB at 5 MHz without suffering any signal-to-noise penalty over the much larger phased-array receive antennas. A superdirective array is never used for transmit where one wants maximum radiated power. Transmit antenna size has not been an issue, as both types of systems use smaller, wide-view floodlighting antennas to simultaneously illuminate the entire surveillance area.

The superdirective beams from each of the pentagon arrays on the two masts are then constructively phased to produce an even higher-gain, smaller-beam signal. This maximises gain so a target is detected at greatest possible range. To actually determine its bearing, another principle is employed: direction finding. Each signal from the two masts is used with the well-known MUSIC algorithm to estimate target angles, whose accuracy becomes proportional to signal-to-noise ratio. This is similar to the "phase-monopulse" technique used with microwave tracking radars.

Another feature of each small superdirective pentagon receive array is the fact that its beam pattern does not change as the applied phasings rotate it over 360°, in stark contrast with the pattern of a linear array, as seen in Fig. 2. Our elevated array eliminates of the need for an efficient ground screen under the antenna when located near the water, a significant benefit. A conventional array requires a ground screen of horizontal wiring under all the elements, extending 30-60 m forward and along its entire length, e.g., 72,000 m^2, to avoid near-field losses. Such a system is expensive, and its life is normally limited by the corrosive nature of the beach environment. Table 1 summarises these and additional advantages our approach.

TABLE 1. CODAR SUPERDIRECTIVE RECEIVE ARRAY FEATURES.

- Lower initial costs
- Adequate site security by unmanned fenced compound -less operating cost
- 10 antenna elements and receive channels compared to 40:19 dB vs 21 dB directive gains, respectively.
- No ground plane required under receive antenna
- Better coverage vs bearing (up to 360° - suitable for islands, peninsulas)

EFFICIENT FMCW WAVEFORM GIVES LONG RANGE WITH LOW RADIATED POWER

High peak radiated powers are problematic. They generate a considerable amount of heat because the transmit amplifiers are bulky and inefficient. They become sources of interference to other spectrum occupants. Finally, they stress the receiver system, because undamped high powers can damage its front end and limit its dynamic range, i.e., the ability to see weak signals in the presence of the very strong transmit signal.

CODAR HF radar systems employ a continuous-wave (CW) signal whose format has its frequency swept linearly, repeating at a rate slightly above the maximum expected Doppler shifts from targets. After analogue demodulation in the receiver, the low data rate digital data stream is spectrally analysed, first to give target range, followed by target Doppler. Doppler is directly proportional to the velocity of the moving target. Our CW signal is not pulsed, so that its peak power is the same as its average power, thereby achieving the maximum possible efficiency. The signal with its swept frequency format is generated digitally, separately, in both the transmitter and the receiver. The sweep width determines the range cell size, and this is controlled remotely by modem.

Normally, one is not able to operate a radar with a continuous signal when the transmitter and receiver are colocated, because the strong transmit signal overwhelms the receiver and prevents its proper linear operation. Our EEZ design employs a transmit antenna facility that is separated from the receive site by 10-15 km. The path between them greatly attenuates this strong signal. In addition, the transmit antenna is designed so that it points a null toward the receiver, thereby decreasing further the transmit signal. But the signal is still sufficiently strong that the receiver can self-synchronise and software-lock to the direct transmit signal, eliminating the need for ultra-stable frequency sources at each site.

An example of surface-target signals seen on April 17, 1998 by our CODAR SeaSonde® system at 4.9 MHz with this FMCW signal format is shown in Fig. 4. These echoes were recorded at Santa Cruz, California at a radar range of 180 km. Only omnidirectional transmit and receive antennas were used, and the average radiated power was 45 watts. Without the higher antenna directive gains and radiated powers of our EEZ design, we observe:

- Sea-echo peaks with nearly 30 dB signal to noise ratio;
- A candidate ship echo with 14 dB signal to noise ratio, at a radial speed of ~3 knots.

The echo magnitude of the ship corresponds to a boat or ship with a 15-m mast as its principal vertical reflector, a typical medium-sized vessel.

CONCLUSIONS

A highly efficient FMCW signal format and superdirective receive antenna array form the basis of a coastal EEZ surface-wave surveillance radar design with only 4 kW power whose antennas can be located inside a secure fenced compound. This compares in performance with classic systems having a conventional antenna over 1 km long and a radar transmitter that emits over 40 kW peak power.

ABOUT THE AUTHOR

Dr. Donald E. Barrick specialised in electromagnetics, radar, sea-surface clutter, and hydrodynamics of the upper ocean at the Ohio State University and Battelle Memorial Institute. In the 1970s he headed up the Sea State Studies Division of the National Oceanic and Atmospheric Administration's Wave Propagation Laboratory where he developed compact, low-cost HF radar systems for real-time mapping of ocean currents and waves. Since 1984 he has worked in industry, founding CODAR Ocean Sensors, Ltd. and serving as President. He and the staff have published over 100 journal papers and hold several patents in this field. They have sold over 35 compact coastal SeaSonde HF radars, more than the total HF radars produced by all other groups world-wide.

IF YOU HAVE ANY ENQUIRIES REGARDING THE CONTENT OF THIS ARTICLE, PLEASE CONTACT:

Donald E. Barrick
CODAR Ocean Sensors, Ltd.
1000 Fremont Avenue, Suite K
Los Altos, CA 94024
USA

Tel: +1 408 773-8240
Fax: +1 408 773 0514
Email: Don@CodarOS.com