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TITLE

ADAPTIVE NULLING OF SKYWAVE INTERFERENCE USING HORIZONTAL DIPOLE ANTENNAS IN A COASTAL SURVEILLANCE HF SURFACE WAVE RADAR SYSTEM

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ADAPTIVE NULLING OF SKYWAVE INTERFERENCE USING HORIZONTAL DIPOLE ANTENNAS IN A COASTAL SURVEILLANCE HF SURFACE WAVE RADAR SYSTEM

H Leong

Defence Research Establishment Ottawa, Canada

Abstract

This paper presents the results of a preliminary study of an adaptive system using horizontal antennas for the suppression of skywave interference in HF Surface Wave Radar (HFSWR). Four horizontal dipoles, configured as two separate crosses, were added to a HFSWR system that normally uses Vertically Polarized Antennas (VPAs). The data received from the dipoles were correlated with the data received from the VPAs to estimate and cancel the interference adaptively in the VPAs. The results of the study show that the technique worked well against the observed interference. The interference-plus-noise power was reduced by up to 13 dB, and the Bragg-to-Interference-plus-Noise-Ratio (BINR) was enhanced by up to 21 dB. The study also compared the effectiveness of the adaptive technique using one, two (different combinations) or four horizontal dipole antennas. This comparison indicates that the technique was more effective when all four horizontal dipoles were used.

Introduction

Night-time skywave interference is a major problem for a coastal surveillance HF Surface Wave Radar (HFSWR) that operates in the lower end of HF (e.g., 2-10 MHz). Ionospheric conditions at night favour the propagation of the interfering radio signals over long distances. This increases the number of interferers in the frequency band, making it difficult to find a clear channel to operate the radar.

The HFSWR signal is vertically polarized. The skywave interference, on the other hand, could be elliptically polarized [1] or partially polarized [2]. In theory, it is possible to exploit this difference in polarization characteristics to suppress the skywave interference. Horizontally polarized antennas (HPA) can be added as auxiliary antennas in a HFSWR system that uses vertically polarized antennas (VPA). The horizontally polarized components received by the HPAs can be used to estimate the interference component received by the VPAs (main antennas). A subtraction of this estimate from the outputs of the VPAs can then result in a suppression of the interference in the HFSWR.

Since the polarization orientation of the skywave interference changes with time and frequency, the system that employs the HPAs must be adaptive. Madden [3] has studied the feasibility of using this adaptive technique for the suppression of skywave interference in a practical HFSWR system. Promising results were reported from a HFSWR system that included one horizontal antenna element. We have carried out a similar HFSWR experiment, through a contract to Northern Radar Systems Limited of St. John's, Newfoundland, to study the effectiveness of this adaptive technique. Four horizontal dipole antennas, configured as two separate crosses, were used along with six VPAs from the HFSWR to receive the radar and interference signals. Figure 1 shows a top view of the antenna configuration.

The radar experiment took place on March 29, 1995 at Cape Race, Newfoundland. The experiment started at about 02:20 local time (LT) and finished at about 03:10 LT. A frequency-modulated interrupted continuous wave (FMICW) waveform was used in the experiment. The frequency-swept bandwidth was equal to 125 kHz and the waveform repetition interval (WRI) was equal to 110 milli-seconds. The HFSWR was operated at a nominal radio frequency of 5.811 MHz, with data fully sampled from all 10 antenna elements.

The data received from the horizontal dipole antennas were correlated with the data received from the VPAs to estimate and cancel the interference adaptively in the VPAs. The results from the interference cancellation are presented in this paper. Different combinations of the dipole antennas were used in the adaptive system to suppress the interference present in the VPAs. These included permutations of the dipole antennas in terms of the number of antenna elements, the orientation of the elements and the locations of the elements. A performance comparison of the adaptive system using the different dipole configurations is also given below.

System Configuration

Figure 2 shows the schematic of the adaptive system configuration. The main channels of the adaptive system consist of outputs from the VPAs, and the auxiliary channels consist of outputs from the HPAs. The outputs from the VPAs are summed after being equalized to the gain and phase of the second antenna element. This summed output implies that the radar receives echoes from the beam at the boresight of the VPA array.

Referring to Figure 2, z is the summed output at a selected range bin, and x_1, x_2, x_3 and x_4 are the outputs from the HPAs at the same range bin. Let column vectors $\mathbf{a} = [x_1\ x_2\ x_3\ x_4]^T$ and $\mathbf{w} = [w_1\ w_2\ w_3\ w_4]^T$, then the output of the adaptive system is given by

$$s = z - \mathbf{w}^H\mathbf{a} \qquad (1)$$

where $\mathbf{w}^H = [w_1^*\ w_2^*\ w_3^*\ w_4^*]$ is a row vector comprising the complex weight coefficients applied to the outputs of the HPAs.

The summed output consists of the vertically polarized components of the radar return and the interference, and the HPA outputs consist of the horizontally polarized components of the radar return and the interference. The interference arises because of the presence of other users in the same frequency band. A HFSWR detects targets at distances beyond the line of sight via surface-wave propagation. It is well known that the attenuation of a horizontally polarized HF surface wave signal is much larger than that of a vertically polarized HF surface wave signal [4]. In the presence of strong interference, it is assumed that, while both the vertical and horizontal antennas sense the interference signal, only the vertical antennas receive the radar signal. This implies that any radar signals received by the HPAs are considered to be negligible.

Let R_v and I_v respectively represent the radar signal and interference component summed from the VPAs, and $\mathbf{I}_h$ represent the interference components from the HPAs. Then the output of the adaptive system can be written as

$$s = (R_v + I_v) - \mathbf{w}^H\mathbf{I}_h \qquad (2)$$

The power of the output, p, is given by the ensemble average of the quantity ss^*, denoted by $E[ss^*]$. If the radar and interference signals are statistically stationary and are uncorrelated with each other, then the output power p is given by

$$p = E[R_v R_v^*] + E[(I_v - \mathbf{w}^H\mathbf{I}_h)(I_v - \mathbf{w}^H\mathbf{I}_h)^*] \qquad (3)$$

A necessary condition for interference suppression is that the output power p is minimized with respect to the real and imaginary parts of the weight coefficients, w_1, w_2, w_3 and w_4. This implies that the second term of Equation (3) is minimized while the first term is left unchanged. Note that the first term represents the power of the radar signal in the summed output of the VPAs.

Equations (2) and (3) illustrates the importance of the assumption in the signal model. If the outputs of the HPAs contain some radar signals, then the optimal weight coefficients obtained from the minimization could result in a distortion of R_v in the output of the adaptive system [5].

Referring to the system output given by Equation (1), the weight vector that would minimize the output power p is given by the unconstrained Wiener solution [5]

$$\mathbf{w} = \mathbf{R}_{aa}^{-1}\,\mathbf{r}_{az} \qquad (4)$$

where $\mathbf{R}_{aa}^{-1}$ is the inverse of the covariance matrix constructed from the outputs of the HPAs, defined as $\mathbf{R}_{aa} = E[\mathbf{a}\mathbf{a}^H]$, and $\mathbf{r}_{az} = E[\mathbf{a}z^*]$ is the cross-correlation vector between the outputs from the HPAs and the sum of the VPAs. Substituting this optimal weight vector in (1) would then result in the suppression of the interference.

Adaptive Algorithm

Following the approach taken by Madden, we use the sample matrix inverse (SMI) method [6] to estimate the weight coefficients. For each waveform repetition interval, the covariance matrix $\mathbf{R}_{aa}$ and the cross-correlation vector $\mathbf{r}_{az}$ can be approximated by using the samples in the last N range bins as follows

$$\begin{aligned} R_{aa} &\approx \frac{1}{N}\sum_{k=M-N+1}^{M} a_k a_k^H \\ r_{az} &\approx \frac{1}{N}\sum_{k=M-N+1}^{M} a_k z_k^* \end{aligned} \qquad (5)$$

where M is the range bin corresponding to the maximum range of the radar. For the current set of radar data, M = 240 and N = 60 were selected.

Experimental Results

Different combinations of the horizontal antennas were chosen to form the adaptive system. The performance of these different configurations could be compared to determine the optimal configuration of the dipole antennas. Specifically, the following configurations were considered in our study:

(1) Adaptive system using one horizontal dipole of different orientations (broadside or boresight);

(2) Adaptive system using two horizontal dipoles, including (a) orthogonal and collocated, (b) orthogonal and separated, and (c) parallel and separated;

(3) Adaptive system using all four horizontal dipoles.

Figures 3a and 3b show, respectively, the Doppler power spectral densities of the summed output from the vertical antennas and the output from one of the horizontal antennas, obtained from range-bin No. 27 (32.4 km) before the interference suppression. The data from the main channel and the auxiliary channel were processed as follows: a 1024-point FFT was first used to integrate the data in the time domain along with a Blackman window [7], and the power spectra of the data were then averaged over 24 contiguous integrations. A reference signal with a frequency of 4.4 Hz was injected into the data before the Doppler processing, and the power spectral densities in Figure 3 were then normalized to this reference signal. As shown in Figure 3, a high level of interference[1] was present in the main and auxiliary channels. The first-order sea echoes (Bragg lines), which normally dominate in the Doppler spectrum, could not be observed in the output of the main channel in Figure 3a. The interference was also strong in the output of the auxiliary channel. As shown in Figure 3b, no radar signal was observable in the Doppler spectrum.

[1] The source of the interference was believed to be external, although there could be contribution from other sources such as ionospheric spread clutter. In theory, however, the adaptive technique should work against either ionospheric clutter or skywave interference.

Figure 3c shows the power spectral density of the output from the adaptive system using all four horizontal dipole antennas. This represents the best performance of the adaptive system configurations indicated above. The same Doppler processing procedure was used for the output data from the adaptive system, and the power spectral density of the data was also normalized to the reference signal at 4.4 Hz. As shown in Figure 3c, the interference was suppressed considerably and the Bragg lines could easily be observed. The Bragg lines are characteristic features of the sea echoes at HF, resulting from the scattering of the transmitted radar signal by ocean waves that have a wavelength exactly equal to one half of the wavelength of the radar along the look direction of the radar. In the absence of any ocean currents in that direction, the Doppler frequencies of the Bragg lines are given by $f_B=\pm\sqrt{g/(\pi\lambda)}$ [8], where g is the gravitational acceleration (g=9.81 m/s^2), and λ is the radar wavelength. The HFSWR at Cape Race was operated at the radio frequency of 5.811 MHz. Hence, the Bragg lines in Figure 3c would have the Doppler frequencies of ± 0.246 Hz.

Let P_B be the peak amplitude of the power spectral densities in a small window centred around one of the two Bragg frequencies. Let n_B be the Doppler bin that contains the peak amplitude (the Bragg line could appear at a slightly different frequency because of ocean currents). For the current set of data, the size of the small window was chosen to be 7 Doppler bins. The power spectral densities on the left and right sides of the Bragg line are estimated by

$$P_{BL} = \frac{1}{7}\sum_{n=n_B-10}^{n_B-4} P_n \qquad P_{BR} = \frac{1}{7}\sum_{n=n_B+4}^{n_B+10} P_n \tag{6}$$

where n is the Doppler-bin number and P_n is the power spectral density at Doppler bin n. The Bragg-to-interference-plus-noise ratio is defined as:

$$\text{BINR} = 10\log_{10}P_B - (10\log_{10}P_{BL} + 10\log_{10}P_{BR})/2 \tag{7}$$

where BINR is in decibels. As shown in Figure 3a, the BINRs were 0 dB or less for the Bragg lines before the interference suppression. However, after the interference suppression, the BINRs were found to be about 16 and 21 dB, respectively, for the advancing and receding

Bragg lines. Note that there could be second-order sea clutter in the Doppler spectrum after the interference suppression. To reduce the effect of the second-order sea clutter on the estimate of BINR, a logarithmic scale was used in the averaging of P_{BL} and P_{BR}.

The performance of the adaptive system can also be measured by the ratio of interference-plus-noise powers (RINP) before and after the interference suppression. The interference-plus-noise power is calculated as a sum of the samples in the Doppler power spectrum, excluding those at the Bragg frequencies and the reference signal at 4.4 Hz. If P_b and P_a represent the interference-plus-noise power before and after interference suppression, respectively, then the performance indicator RINP is given by P_b/P_a. The RINPs of the different adaptive system configurations are shown in Figure 4 as functions of range. The horizontal antennas used in each configuration are described in the legend and caption of Figure 4. This includes the number of horizontal antenna elements, the choice of the elements, and the orientation and relative location of the elements. As shown in Figure 4, the RINPs were more or less constant across range except that there was a rapid increase at the very close ranges. An interference signal normally does not attenuate with range. Hence, the constant RINP across range is what one would expect. The rapid increase, however, was associated with the eclipsing range of the radar. Figure 4 also shows some periodic dips in the RINPs, particularly evidenced in the RINP obtained from the system using horizontal dipole elements 1 and 2. These dips resulted from the suboptimal pulse-compression scheme used by Northern Radar Systems Limited for the processing of the FMICW data.

From Figure 4, one can make the following observations:

(i) The system performance improved with an increasing number of horizontal antennas. Among the systems studied, the best performance was obtained from the one using all four horizontal antennas. The RINP of this system was greater than 13 dB;

(ii) Among the systems with two horizontal elements, the system using orthogonal dipoles performed the best. Furthermore, the antenna locations appeared to have little effect on the system performance. As shown in Figure 4, the system performance was essentially the same, whether the orthogonal antennas were separated or collocated. The RINPs of these systems could be more than 10 dB;

(iii) The system using one horizontal dipole antenna did not appear to be adequate; the system performance varied with the orientation of the horizontal antenna. The RINP of this system varied between about 4 and 6 dB.

Future Work

The results above are encouraging, particularly for a HFSWR operating in a severe interference environment. In practice, however, the horizontal antennas can pick up the radar signal. For the adaptive system to work properly, the horizontal antennas must be carefully designed to have a minimal pick-up of the radar signal. More experiments are required to determine the effectiveness of this technique in a practical HFSWR system.

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References

1. Davies, K., 1990, "Ionospheric Radio", p.235, Peter Peregrinus Ltd., London, UK.
2. Leinwoll, S., 1959, "Shortwave Propagation", p.65, John Ryder Publisher, Inc., New York.
3. Madden J M, 1987, "The Adaptive Suppression of Interference in HF Ground Wave Radar", Radar 87, IEE Int. Conf., London, U.K., pp.98-102.
4. Colin, R., 1985, "Antennas and Radiowave Propagation", p. 388, McGraw-Hill Company, USA.
5. Widrow B, Glover J, McCool J, Kaunitz J, Williams C, Hearn R, Zeidler J, Dong E and Goodlin R, 1975, "Adaptive Noise Cancelling: Principles and Applications", Proc. of IEEE, 63, 12, Dec., p.1692.
6. Reed I, Mallett J and Brennan L, "Rapid Convergence Rate in Adaptive Arrays", 1974, IEEE Trans. AES-10, pp. 853-863.
7. Harris F J, 1978, "On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform", Proc. of IEEE, 66, 1, Jan., p.51.
8. Crombie D D, 1955, "Doppler Spectrum of Sea Echo at 13.56 Mc/s", Nature, 175, pp. 681-682.

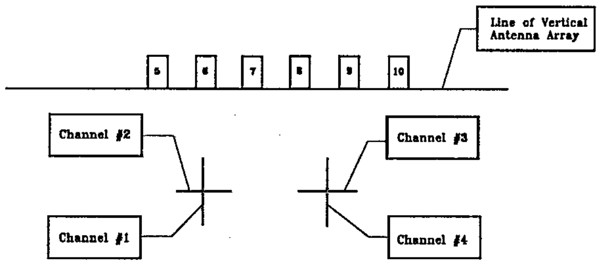

Figure 1 Receiving Antenna Configuration (Top View)

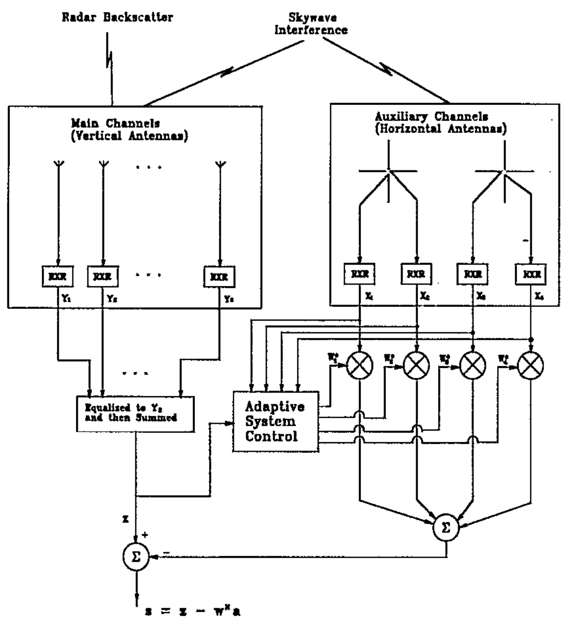

Figure 2 Adaptive System Configuration

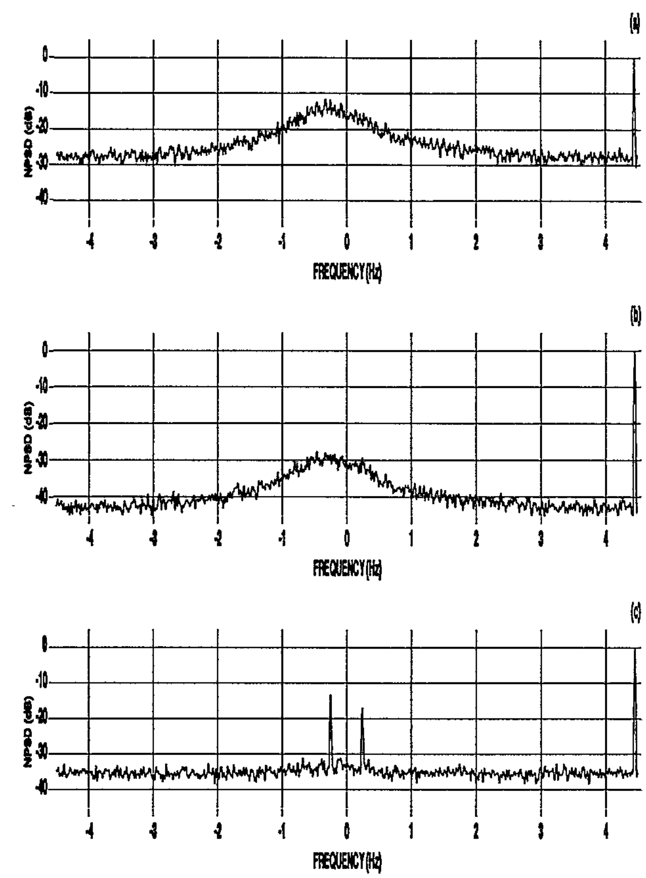

Figure 3 Normalized Power Spectral Densities of (a) summed outputs from six VPAs, (b) outputs from HPA #1, and (c) outputs from the adaptive system using all four HPAs (Range = 32.4 km; 1024-point FFT with Blackman Window, Coherent Integration Time = 114 seconds; Incoherent Integration Time = 45.5 minutes)

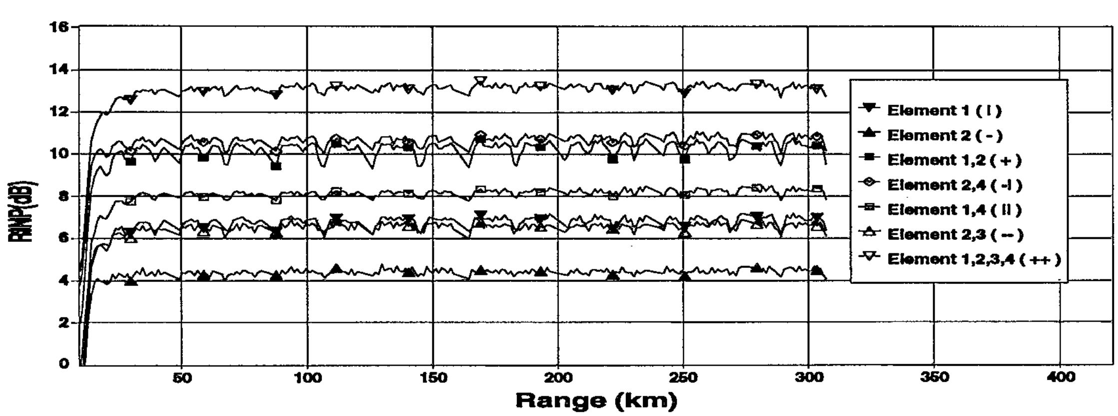

Figure 4 Ratio of Interference-plus-Noise-Powers (RINP) Before and After Interference Suppression Using Different Adaptive System Configurations (The signs in the brackets of legend labels indicate the orientation of the horizontal dipole antennas: I, pointing to the sea; -, parallel to the sea; +, orthogonal & collocated; -I, orthogonal & seperated; II or --, parallel & seperated)

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