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The Effects of Sea Clutter on the Performance of HF Surface Wave Radar in Ship Detection and the Implication on the Radar Design

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Defence R&D Canada – Ottawa

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Abstract

The effects of sea clutter on the performance of HF Surface Wave Radar (HFSWR) operating in the frequency band between 3 and 5 MHz are studied in this technical memorandum. The HFSWR is designed to detect two classes of ships: large freighters with a Gross Registered Tonnage (GRT) in the order of several tens of thousands of tons and small vessels with a GRT of about 1000 tons. Representative levels of the radar returns from the large and small targets are estimated from the HFSWR at Cape Race, Newfoundland. The estimated returns are then compared with the sea echoes measured from the same radar to assess the capability of the radar under different sea conditions. The conclusions of the study are that, in the detection of the large ships, the radar performance is independent of sea state, but in the detection of the small ships, the radar performance is dependent on sea state. It is shown that if a radar employing conventional linear beamforming methods is to maintain the detection capability for the small ships, then the aperture of the receive array cannot be reduced from its current value.

Résumé

Le présent document technique traite de l'étude des effets de l'état de la mer sur l'efficacité du radar haute fréquence à ondes de surface (HFSWR) fonctionnant entre la bande de fréquence de 3 à 5 Mhz. Le radar est conçu pour détecter deux classes de navires : les gros navires de charge à jauge brute de l'ordre de plusieurs dizaines de milliers de tonneaux et les petits navires à jauge brute d'environ 1 000 tonneaux. Des niveaux représentatifs des échos radar produits par les grosses et les petites cibles sont estimés à l'aide du HFSWR de Cape Race (Terre-Neuve-et-Labrador). Les échos estimés sont ensuite comparés aux échos de mer mesurés avec le même radar afin d'évaluer la capacité de ce dernier à détecter les navires sous différentes conditions de mer. L'étude permet de conclure que pour la détection des gros navires, l'efficacité du radar est indépendante de l'état de la mer, mais que pour la détection des petits navires, elle dépend de l'état de la mer. Nous avons constaté que si le radar employant les méthodes de formateur de faisceau linéaire conventionnelles est pour conserver la capacité du radar à détecter les petits navires, il ne faut pas réduire l'ouverture du réseau de réception de sa valeur actuelle.

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Executive summary

The Effects of Sea Clutter on the Performance of HF Surface Wave Radar in Ship Detection and the Implication on the Radar Design

Hank Leong and Anthony Ponsford; DRDC Ottawa TM 2007-325; Defence R&D Canada – Ottawa; December 2007.

Introduction:

The performance of a HF surface wave radar (HFSWR) system operating in the 3-5 MHz band in the detection of ships in sea clutter is related statically to sea state. Data were measured from the HFSWR demonstration system at Cape Race, Newfoundland, Canada at the radar frequencies of 3.1 and 4.1 MHz for a few days per month over a period of eight months between January and August 2002. A subset of the data was selected to evaluate the capability of the radar in the detection of ship echoes in sea clutter. The objective of this evaluation is to determine the impact of sea clutter on the radar performance and the implication of this impact on the radar design.

The power of the sea clutter scattered back by the ocean patch in the radar's resolution cell is directly proportional to the Radar Cross Section (RCS) per unit area of ocean surface and the surface area of the ocean patch. While the RCS per unit area of ocean surface is dependent on the sea conditions (i.e., sea state), the surface area of the ocean patch is defined by the target range, and the range and azimuth resolutions of the radar. The HFSWR at Cape Race uses the conventional pulse-Doppler technique to extract target signals in the frequency domain and Fourier beamforming technique on receive to discern signals from different directions. Hence, the range and azimuth resolutions are inversely proportional to the bandwidth of the radar and the aperture of the receive array, respectively. The power of the sea clutter is therefore inversely proportional to the radar bandwidth and the receive-array aperture. Normally, the radar bandwidth cannot be increased due to the congestion of the HF band between 3 and 5 MHz. Only the receive-array aperture offers the radar designer an option to adjust the magnitude of the sea clutter scattered back to the radar. This technical memorandum (TM) will establish a minimum acceptable aperture for the receive array of the radar, based on the results of the performance evaluation.

Results and Significance:

Two classes of ships are expected to be detected and tracked by the radar: large freighters with a Gross Registered Tonnage (GRT) in the order of several tens of thousands of tons and small vessels with a GRT of about 1000 tons. The results of the evaluation indicate that, in the detection of the large ships, the radar performance is independent of sea state, but in the detection of the small ships, the radar performance is dependent on sea state. This latter conclusion imposes a constraint on the aperture of the receive array. If the radar using the conventional Fourier beamforming technique is to maintain the detection capability for the small ships, then the aperture of the receive array cannot be reduced from its current value. This implies that the linear receive array must have at least 16 elements, with a nearly optimum spacing between the adjacent elements (i.e., half-wavelength apart).

Sommaire

The Effects of Sea Clutter on the Performance of HF Surface Wave Radar in Ship Detection and the Implication on the Radar Design

Hank Leong and Anthony Ponsford; DRDC Ottawa TM 2007-325; R & D pour la défense Canada – Ottawa; décembre 2007.

Introduction:

L'efficacité du radar haute fréquence à ondes de surface (HFSWR) fonctionnant entre la bande de fréquence de 3 à 5 Mhz à détecter les navires établit une relation statistique avec l'état de la mer. Des données ont été recueillies avec le système démonstratif HFSWR de Cape Race (Terre-Neuve-et-Labrador), au Canada, aux fréquences radar 3,1 et 4,1 MHz, à raison de quelques jours par mois sur une période de huit mois s'étendant de janvier à août 2002. Un sous-ensemble des données a été sélectionné pour évaluer la capacité du radar à détecter les échos des navires en présence de clutter de mer. Cette évaluation vise à déterminer l'incidence du clutter de mer sur l'efficacité du radar et, par le fait même, sur la conception du radar.

La puissance du clutter de mer rediffusée par la zone d'océan comprise dans le volume de détection à résolution radar est directement proportionnelle à la surface équivalente radar (SER) par unité de surface de l'océan et à la superficie de la zone d'océan. La SER par unité de surface de l'océan dépend des conditions de la mer (c.-à-d. de l'état de la mer), mais la superficie de la zone d'océan comprise dans le volume de détection radar est définie par la distance de la cible et par les résolutions en distance et en azimut du radar. Le HFSWR de Cape Race emploi la technique conventionnelle **« pulse-Doppler »** pour extraire les signaux des cibles dans le domaine de fréquence et la technique d'un formateur de faisceau Fourier à la réception pour discerner les signaux venant de différentes directions. Par conséquent, la résolution en distance et en azimut est inversement proportionnelle à la largeur de bande du radar et à l'ouverture de ce réseau, respectivement. La puissance du clutter de mer est ainsi inversement proportionnelle à la largeur de bande du radar et à l'ouverture du réseau de réception. Normalement, la largeur de bande du radar ne peut pas être accrue en raison de l'encombrement de la bande HF entre 3 et 5 MHz. La seule option dont dispose le concepteur de radar pour régler l'amplitude du clutter de mer rediffusé au radar consiste à modifier l'ouverture du réseau de réception. Dans le présent document technique, nous allons établir une valeur minimum acceptable pour l'ouverture du réseau de réception, basé sur les résultats de l'évaluation sur l'efficacité du radar.

Résultats and Importance:

On s'attend à ce que le radar permette la détection et la poursuite de deux classes de navires : les gros navires de charge à jauge brute de l'ordre de plusieurs dizaines de milliers de tonneaux et les petits navires à jauge brute d'environ 1 000 tonneaux. Les résultats de notre évaluation montrent que pour la détection des gros navires, l'efficacité du radar est indépendante de l'état de la mer, mais que pour la détection des petits navires, elle dépend de l'état de la mer. Cette dernière constatation impose une contrainte sur l'ouverture du réseau de réception. Pour conserver la capacité du radar utilisant la technique d'un formateur de faisceau Fourier à détecter les petits

navires, il ne faut pas réduire l’ouverture du réseau de réception de sa valeur actuelle, ce qui signifie que le réseau de réception linéaire doit comprendre au moins 16 éléments, espacés de façon quasi optimale (c.-à-d. espacement d’une demi-longueur d’onde entre les éléments adjacents).

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1 Introduction

HF surface wave radar (HFSWR) operating between 3 and 5 MHz can provide shore-based maritime surveillance of ships in the Exclusive Economic Zone (EEZ), at ranges up to 200 nautical miles (nm) [1]. However, the achieved radar performance can be limited by the presence of ionospheric clutter, external noise, external interference and sea clutter. For example, at night the presence of ionospheric clutter and external noise limits the performance at far ranges (e.g., > 200 km), while the presence of co-channel external interference can limit the performance at all ranges, and the presence of sea clutter associated with higher sea states can limit the performance at near ranges (e.g., < 200 km). Currently, there are intense efforts directed to mitigate the effects of ionospheric clutter [2-4], while effective techniques have been developed to cancel external interference [2, 5-7]. However, sea clutter is often ignored. Although there have been attempts to develop techniques to suppress sea clutter [8-9], it is believed that none of these techniques has been implemented in an operational HFSWR system.

In this technical memorandum (TM), the performance of HFSWR in the detection of two classes of ships in sea clutter is statistically related to sea state. These two classes of ships include freighters with a Gross Registered Tonnage (GRT) in the order of several tens of thousands of tons and small vessels with a GRT of about 1000 tons. Data were measured from the HFSWR demonstration system located at Cape Race, Newfoundland, Canada at the radar frequencies of 3.1 and 4.1 MHz. Data were recorded for a few days per month over a period of eight months between January and August 2002. A subset of the data was selected to evaluate the performance of the radar under different sea conditions.

The power of the sea clutter scattered back by the ocean patch in the radar's resolution cell is directly proportional to the Radar Cross Section (RCS) per unit area of ocean surface and the surface area of the ocean patch. While the RCS per unit area of ocean surface is dependent on the sea conditions (i.e., sea state), the surface area of the ocean patch is defined by the target range, and the range and azimuth resolutions of the radar. The HFSWR at Cape Race uses the conventional pulse-Doppler technique to extract target signals in the frequency domain and Fourier beamforming technique on receive to discern signals from different directions. Hence, the range and azimuth resolutions are inversely proportional to the bandwidth of the radar and the aperture of the receive array, respectively. The power of the sea clutter is therefore inversely proportional to the radar bandwidth and the receive-array aperture. Normally, the radar bandwidth cannot be increased due to the congestion of the HF band between 3 and 5 MHz. Only the receive-array aperture offers the radar designer an option to adjust the magnitude of the sea clutter scattered back to the radar. This technical memorandum (TM) will establish a minimum acceptable aperture for the receive array of the radar, based on the results of the performance evaluation.

The organization of the remainder of this TM is as follows. Section 2 reviews the characteristics of sea clutter in HFSWR. Section 3 describes the methodology used in the evaluation. Section 4 studies the effects of sea state on sea clutter, and Section 5 studies the effects of sea clutter on the performance of HFSWR in ship detection. The implication of the results from the study on the design of HFSWR is discussed in Section 6, and conclusions and recommendations are presented in Section 7.

2 Characteristics of Sea Clutter

Sea clutter in HFSWR comprises the first- and second-order components. The first-order sea clutter consists of two strong spectral lines known as Bragg lines, and the second-order sea clutter consists of a continuum and a few relatively strong discrete components. The Bragg lines are due to a resonant scattering of the transmitted radar signal by ocean waves that have a wavelength L equal to one half of the radar wavelength λ [10]. These ocean waves are deep-water gravity waves that follow the dispersion relationship [11, 12]

$$v_w = \pm \sqrt{\frac{gL}{2\pi}}, \tag{1}$$

where g is the gravitational acceleration (g=9.81 m/s^2) and v_w is the phase velocity of the ocean waves. The '+' and '-' signs in Equation (1) are respectively for ocean waves that travel towards and away from the radar. The phase velocities correspond to the Doppler shifts of

$$f_B = \frac{2v_w}{\lambda}, \tag{2}$$

If the ocean surface currents in the scattering ocean patch have no net radial velocity component, then the Bragg lines have the Doppler frequencies of

$$f_B = \pm \sqrt{\frac{g}{\pi\lambda}}. \tag{3}$$

However, if the ocean surface currents have a non-zero radial velocity component, v_c, then the Bragg lines have the Doppler frequencies of

$$f_B = -\frac{2v_c}{\lambda} \pm \sqrt{\frac{g}{\pi\lambda}}. \tag{4}$$

The second-order sea clutter results in a continuum between the Bragg lines and, at higher sea states, may contain other identifiable discrete components at Doppler frequencies beyond the Bragg frequencies, including spectral lines at the Doppler frequencies of $2^{1/2}$ and $2^{3/4}$ times the Bragg frequency [12]. The $2^{1/2}$ spectral line is due to a scattering of the transmitted radar signal by ocean waves with a wavelength equal to the radar wavelength or by non-sinusoidal ocean waves that have this wave harmonic. The $2^{3/4}$ spectral line is due to a double scattering of the radar signal in a manner similar to the "corner-reflector" electromagnetic effect. These discrete components are not as dominant as Bragg lines, but they sometimes can be visible in the Doppler spectrum.

Figure 1 shows an example of the power spectral data measured by the HFSWR at Cape Race. The radar frequency was 4.1 MHz, and the data were echoed from a range of 76 km. The Bragg lines and the second-order sea clutter spectrum are clearly visible in the spectrum. The Bragg lines have Doppler frequencies at ±0.207 Hz. The second-order sea clutter consists of a sea clutter continuum between the Bragg lines and a dominant discrete component at the Doppler frequency of -0.292 Hz, i.e., $-2^{1/2}f_B$.

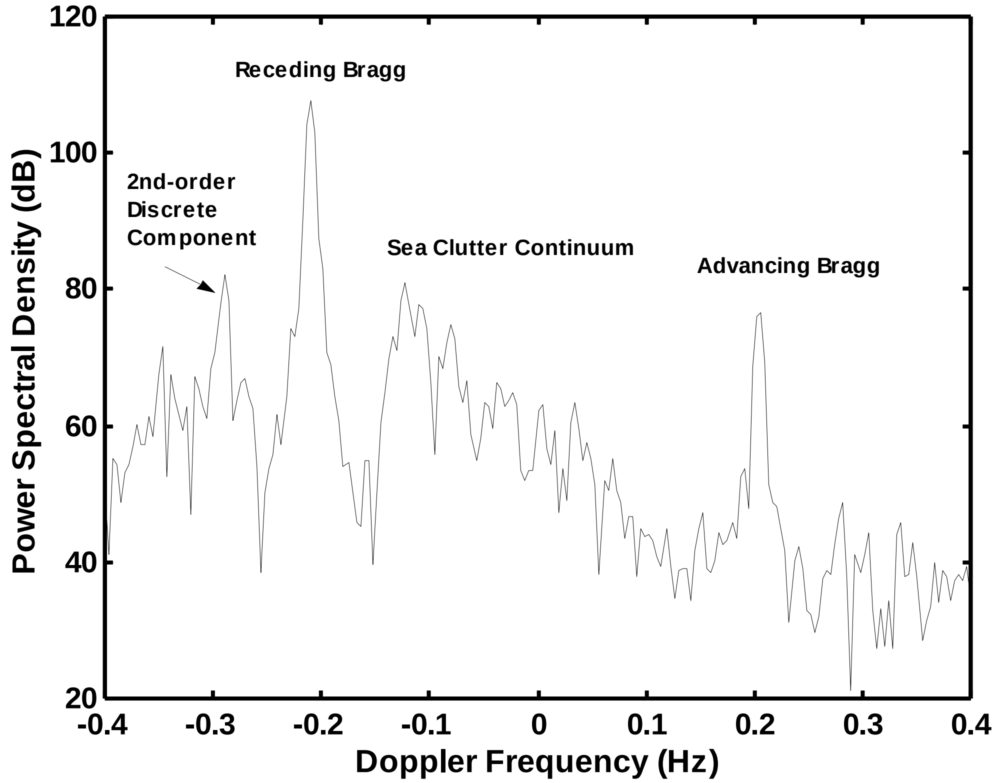

Figure 1 Sea clutter spectrum of HFSWR at the Radar Frequency of 4.1 MHz.

Vessels at ranges less than 200 km are typically detected in the sea clutter continuum. The clutter continuum, at any given Doppler frequency, is dependent on the radar frequency, wind speed, and wind direction. Detection of smaller, low speed targets is therefore heavily influenced by the continuum level, and hence, the wind speed and direction.

In general, the ocean waves grow with the surface wind, with energy being transferred from the wind to the waves. However, the growth of the waves cannot continue indefinitely. The transferred energy could be lost due to wave breaking and other dissipation. If the energy being added to the waves by the wind is equal to the energy being dissipated, the wave spectrum is saturated and the sea is fully developed. Under the fully developed sea condition, the wind will completely arouse the waves that have a phase velocity nearly equal to the wind speed, and it will also completely arouse all the waves of lower velocities [13]. For a given wind speed U, one can derive, from Equation (1), the minimum radar frequency required for which the resonant ocean waves can be saturated, and this critical frequency is given by

$$f_{crit} = \frac{cg}{4\pi U^2}, \tag{5}$$

where c is the speed of light. Alternatively, for a given radar frequency f, the minimum wind speed required for which the resonant ocean waves can be saturated is given by

$$U_{\min} = \sqrt{\frac{cg}{4\pi f}}. \tag{6}$$

At the radar frequencies of 3.1 and 4.1 MHz, the minimum wind speeds required are 8.7 and 7.5 m/s, respectively. It should be noted that the resonant ocean waves will not be saturated if the wind speed reaches the minimum just temporarily. The saturation can only be reached if the wind blows at a constant speed for a long time and over sufficient fetch [13].

Once saturation has been reached, the magnitude of the clutter continuum as seen by an HF radar does not increase with increasing wind speed. However, the Doppler extent of the continuum increases such that the troughs typically observed at the sides of the Bragg lines begin to disappear. Thus small vessels that are detected within these troughs, due to the absence of the second-order sea clutter, may be lost as the sea state increases.

When the radar operates at a frequency below the critical frequency, the sea is not fully developed and the energy contained within the Bragg resonant wave and associated continuum will be significantly less, thus allowing small vessels to be detected at longer ranges.

The shape of the sea clutter spectrum is dependent on the relative wind direction to the radar's look direction. The sea clutter spectrum is symmetrical about 0 Hz if there is a cross wind (i.e., perpendicular to the look direction of the radar). An up- or downwind would cause the spectrum to be tilted towards one side (upwind to the right and downwind to the left). A small ship when it is going against the wind in the radar's look direction is much more easily detected than when it is going along the wind direction.

Information contained in the sea clutter spectrum can be used for remote sea sensing. The Doppler shift of the Bragg lines from the resonant Bragg frequencies can be used to deduce the radial velocity of the surface currents in the scattering ocean patch, and the power ratio of the advancing and receding Bragg lines can be used to deduce the wind direction. The readers are referred to [14], for example, for an excellent review of remote sea sensing using HF radar.

3 Methodology of Evaluation

To evaluate the performance of the radar in the detection of ship echoes in sea clutter, one must have representative estimates of the sea clutter and the target signal levels at a variety of sea states that can be observed in the radar operation environment. This section describes the methods used to estimate the representative sea clutter and target signal levels.

3.1 Representative Sea Clutter Level

In this TM, only the effects of sea state on the overall level of the sea clutter continuum between the Bragg lines are considered. For each specified sea state, a group of data files from the collected radar data is chosen, and in each specified radar cell, the following procedure is used to estimate the mean power level of the sea clutter continuum between the Bragg lines:

1. For each dwell, the mean power level between the Doppler frequencies of $-0.85f_B$ and $0.85f_B$ is computed
2. Over all the dwells in the group of data files, the median of the mean power levels is obtained.

This median of the mean power levels is used to estimate the sea clutter level in the specified radar cell at the specified sea state.

It should be noted here that the magnitudes of the sea clutter spectrum due to different wind directions are averaged out in the procedure above. The shape of the sea clutter spectrum is also affected by the relative wind direction to the radar's look direction. Unfortunately, no adequate wind measurements are available to consider the effects of wind direction on target detection in the sea clutter spectrum.

3.2 Representative Target Signal Level

The radar is designed to detect and track two classes of ship targets: large freighters with a GRT in the order of several tens of thousands of tons and small vessels with a GRT of about 1000 tons. In this TM, the capability of the radar is evaluated in the detection of these two classes of vessel targets in the range interval in which the sea clutter is often the dominant background signal component.

Teleost, a 2405-ton Canadian Coast Guard Ship (CCGS), was used as a control target during the trial on Jan 4-7, 2002. The ship sailed outbound along a radial direction of the radar, turned around and then sailed inbound. Echoes were measured from the ship on the outbound (stern-on) at the radar frequency of 4.1 MHz, and on the inbound (bow-on) at the radar frequency of 3.1 MHz. In [15], the radar cross section (RCS) values of Teleost, large freighters and small vessels with GRT of about 1000 tons were studied and compared. It was found that Teleost and large freighters have comparable angle-averaged RCS (over aspect angle) at the radar frequencies of 3.1 and 4.1 MHz, and that small vessels with GRT of about 1000 tons have an angle-averaged RCS of about 10 dB less than that of large freighters. It was also found that the RCS values of Teleost at its stern-on and bow-on aspects are about the same, and these values are approximately the same as its aspect-angle-averaged RCS. In this TM, the measured power return from the control target Teleost at one of the end-on aspects, *S*, is used as the representative power return from the large freighters, and the measured power minus 10 dB, *S*-10 dB, is used as the representative power return from the small vessels.

These representative target signal powers are then compared with the median of the mean power levels between the Bragg lines. From this comparison, the effect of sea state on the performance of HFSWR in the detection of the ship targets in sea clutter is evaluated.

4 Effects of Sea State on Sea Clutter

The effects of sea state on the mean power level of the sea clutter spectrum between the Bragg lines are studied in this section. The sea clutter tends to dominate over other background signals at ranges less than 200 km. The attenuation of the mean clutter power level at different sea states is then illustrated with respect to range at ranges less than 200 km.

The HFSWR demonstration system at Cape Race employed a log-periodic transmit antenna, and a linear and uniform receive antenna array of 16 doublet elements. The transmitter antenna floodlighted the ocean surface off the coast of Newfoundland, and the receiving doublets, each consisting of two kite-shaped monopoles, were phased end-fire to receive the radar backscatter from the ocean surface. The separation between the adjacent doublets was 33.33 m ($\lambda/2$ at the design frequency of 4.5 MHz). The transmitting and receiving arrays were essentially co-located. Hence, the radar was in a monostatic configuration.

Two weather buoys operated by the Department of Fisheries and Oceans Canada at Nickerson Bank (46.4^{o} N, 53.4^{o} W) and Tail of the Bank (43.7^{o} N, 51.7^{o} W), respectively, provided hourly measurements of the ocean wave spectra and wind velocities in or near the coverage of the radar at Cape Race. Nickerson Bank was slightly outside the radar coverage, but the Tail of the Bank was at the far side of the radar coverage (range=346 km; azimuth=40^{o} clockwise from the boresight of the receive array). In this TM, the significant waveheight ($H_{1/3}$) measured by the weather buoy at the Tail of the Bank is used to indicate roughly the sea state in the radar coverage during the radar measurements. By definition, the significant waveheight is defined as four times the square root of the area under the variance spectrum of the water surface elevation [16].

Tables 1 and 2 show the dates and times of the selected measurements and the corresponding ranges of significant waveheights, respectively, at the radar frequencies of 3.1 and 4.1 MHz. At each radar frequency, four groups of data files were chosen, representing the data measured under different sea states. At 3.1 MHz, the data were measured in sea states with significant waveheights between 1.3 and 1.5, 2.0 and 2.5, 2.7 and 3.0, and 5.5 and 6.5 m, respectively. These sea states are described in the Douglas scale as calm, moderate I, moderate II, and very rough, respectively. Note that, at 3.1 MHz, there is no data for the rough sea state with a significant waveheight of about 4 m. At 4.1 MHz, the data were measured in sea states with significant waveheights between 1.8 and 2.1, 2.6 and 3.1, 3.6 and 4.2, and 4.5 and 6.3 m, respectively. In this latter case, the sea states are described as nearly calm, moderate, rough, and very rough, respectively. Tables 1 and 2 also show the wind speeds obtained from [17] corresponding to the various Douglas scales.

The Coordinated Universal Time (UTC) is used for the measurements, which is 3.5 and 2.5 hours ahead of the local time in the non-daylight and daylight saving times in Newfoundland, respectively. Ideally, the subset of data chosen should have been as large as possible, in order to get the best possible representation of the sea clutter statistics. However, during night-time, the spectrum near 3.1 MHz was quite congested and strong external interference was often observed in the measured data. To avoid contamination of the sea clutter by the interference, only the 3.1-MHz data measured during daytime were used. The 4.1-MHz channel appeared to be clear at all time. Little or no external interference was observed in the data measured at 4.1 MHz. Hence, no time restrictions were imposed on the 4.1-MHz data.

The Cape Race HFSWR demonstration system was a monostatic pulsed-Doppler radar system, capable of operating simultaneously at two radar frequencies. However, the radar was undergoing a period of testing between January and August 2002, and sometimes, the radar operated at a single frequency only. Here, a subset of the data measured over the eight-month period was chosen to show the variation of the sea clutter level with sea state. The selected data were measured at the radar frequency of either 3.1 or 4.1 MHz, but they were not always measured simultaneously.

Table 1 Selected HFSWR Data at 3.1 MHz

Date of Measurement	**Dwell No.**	**Time of Measurement (UTC)**	**$H_{1/3}$ (m)**	**Corresponding Wind Speed**	**Sea State**
April 2, 2002	1-51	13:31:23 – 17:09:51	1.3 – 1.5	< 5 m/s	Calm
May 2, 2002	1-91	13:05:56 – 19:39:10	2.0 – 2.5	5 – 8 m/s	Rough
Jan 29, 2002	180-229	10:10:52 – 13:44:58	2.7 – 3.0	8-10 m/s	Rough
Jan 27, 2002 Feb 9, 2002	1-51 50-111	15:10:54 – 18:49:23 13:20:57 – 17:03:47	5.5 – 6.5 5.5 – 6.3	10-14 m/s	Gale

Table 2 Selected HFSWR Data at 4.1 MHz

Date of Measurement	**Dwell No.**	**Time of Measurement (UTC)**	**$H_{1/3}$ (m)**	**Corresponding Wind Speed**	**Sea State**
Jan 7, 2002	1-145	03:13:44 – 13:44:56	1.8 – 2.1	5 – 8 m/s	Calm
Jan 5, 2002	1-224	21:13:35 – 13:28:12	2.6 – 3.1	8-10 m/s	Rough
Jan 4, 2002	1-142	02:24:27 – 12:40:33	3.6 – 4.2	8-10 m/s	Moderate Gale
Feb 8, 2002 Feb 9, 2002	1-158 1-159	22:07:48 – 09:33:48 09:49:21 – 21:19:44	5.5 – 6.3 4.5 – 5.5	10-14 m/s	Gale

The procedure described in Section 3.1 is used to estimate the mean power level between the Bragg lines, and this procedure is repeated for each and every cell in the radar beam along the direction of the control target. Figure 2 shows the medians of the mean clutter levels as functions of range at the radar frequency of 3.1 MHz. As expected, the higher the sea state, the stronger the mean clutter level. In general, the medians of the mean clutter levels decrease monotonically with range. However, there is also a local peak (local maximum) caused by the clutter reflected from the E or F regions of the ionosphere:

1. In all the attenuation curves except the one for the sea state with $H_{1/3}$ between 2.7 and 3.0 m (green), there is a strong peak at the range of about 110 km due to the reflection of the transmitted radar signal from the E region of the ionosphere.

2. For the calm sea with $H_{1/3}$ between 1.3 and 1.5 m (blue), there is also a second, but weaker, peak near the range of 220 km. This is due to the second-round reflection of the transmitted radar signal by the E region, i.e., the transmitted signal is bounced off the E region, reflected by the sea surface, bounced off the E region again and returned to the radar receivers. This

second-round reflection is visible in the radar data because of the very low level of sea clutter.

3. For the sea state with $H_{1/3}$ between 2.7 and 3.0 m (green), there is no local maximum near the range of 110 km, but there is a strong peak at the range of about 245 km. This latter peak is due to the reflection of the transmitted radar signal by the F region of the ionosphere. The set of data used for the green curve was measured early in the morning (on Jan 29, 2002), mostly during the dawn hours when the E region was not established. In the absence of the E region, the transmitted radar signal was reflected from the F region, leading to the local peak at the range of about 245 km.

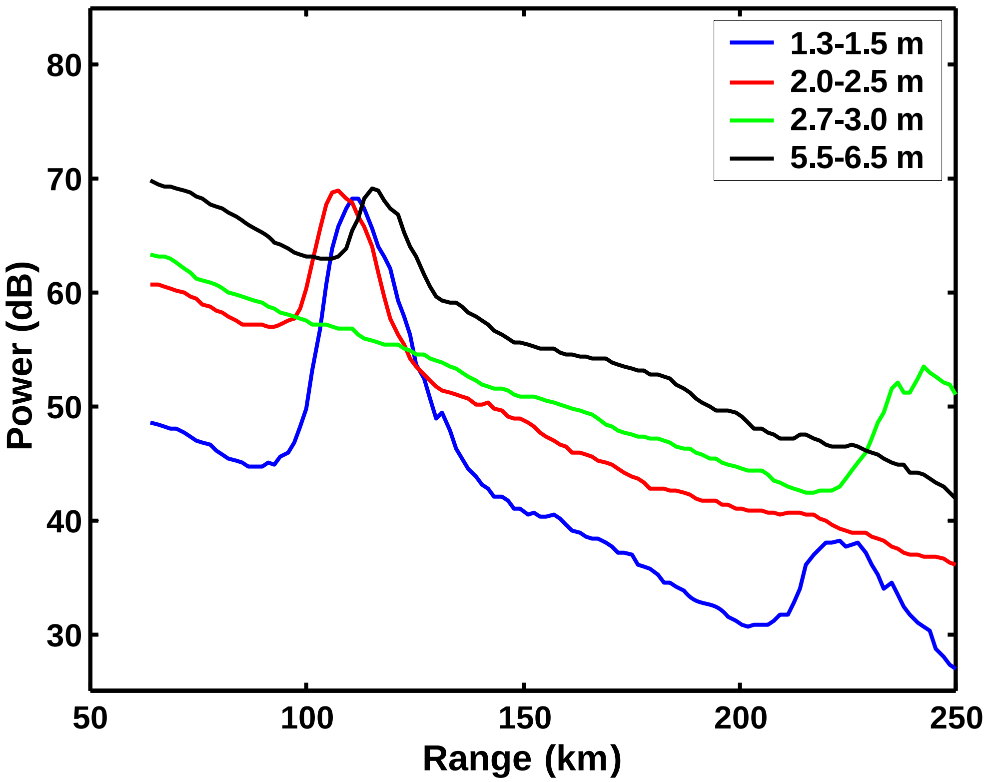

Figure 2 *The median of the mean clutter levels between Bragg lines at the radar frequency of 3.1 MHz as a function of range.*

It should be noted that the strong peak near the range of 110 km is typical of the radar data measured during daylight hours when the radar operates at a frequency below the critical frequency of the E region. During the daylight hours, the gas particles in the E region are ionized. Below the critical frequency, the transmitted radar signal is reflected back by the E region.

Figure 3 shows the medians of the mean clutter levels as functions of range at the radar frequency of 4.1 MHz at the various sea states. Again, the higher the sea state, the stronger the mean clutter level. The medians of the mean clutter levels also decrease monotonically with range. No strong peak is observed in Figure 3 at ranges up to 250 km, except in the attenuation curve for the calm sea state with $H_{1/3}$ between 1.8 and 2.1 m (blue) where a small hump is observed at the range of about 110 km. The radar frequency of 4.1 MHz was mostly greater than the critical frequency of the E region. Hence, there was very little reflection of the transmitted radar signal at 4.1 MHz from the E region. The low level of clutter reflected from the E region is only mildly visible in the curve for the calm sea, when the sea clutter level was very low.

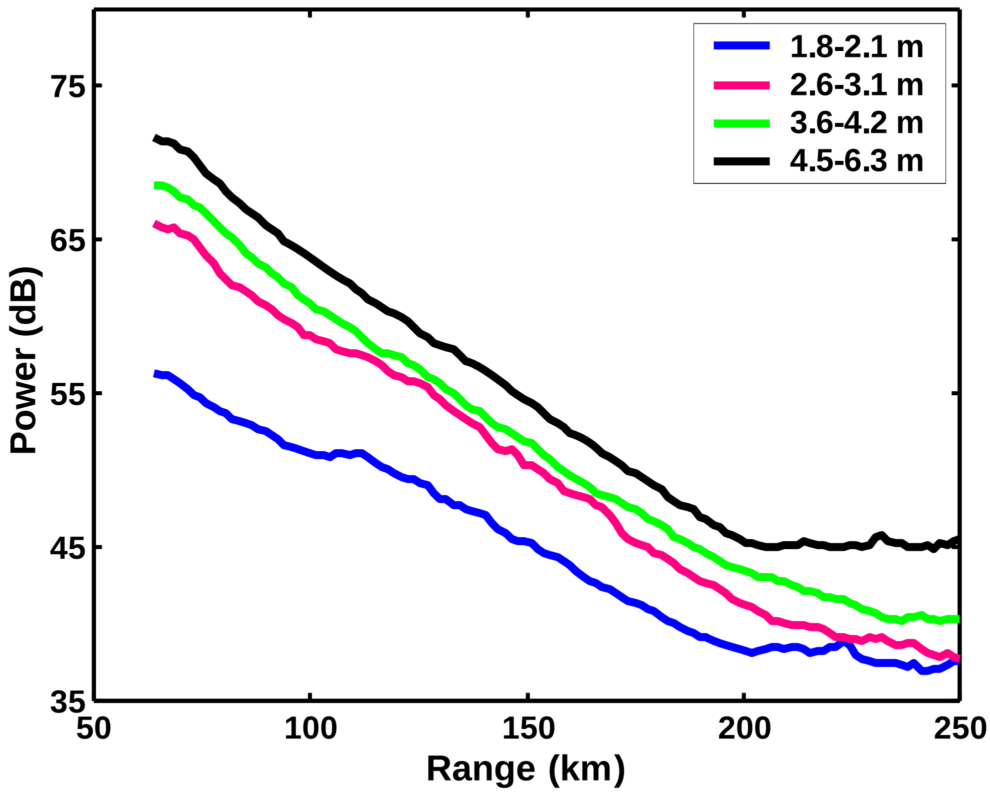

Figure 3 *The median of the mean clutter levels between Bragg lines at the radar frequency of 4.1 MHz as a function of range.*

5 Effects of Sea State on Ship Detection

In [15], the radar cross sections of Teleost, the large freighters, and the small vessels with a GRT of about 1000 tons were studied, and the relative differences between the RCS values of the three kinds of vessels were established. Based on the results of the study, it is decided to use in this TM the measured power return from Teleost at either the stern-on or bow-on aspect, *S*, as the representative power return from the large freighters, and the measured power return minus 10 dB, *S*-10 dB, as the representative power return from the small vessels. These representative power returns are then compared with the levels of sea clutter shown in Figures 2 and 3 to evaluate the HFSWR performance in the different sea states.

5.1 Extrapolated and Calibrated Target Signals

The echoes from Teleost at the radar frequency of 4.1 MHz were measured at the ranges between 150 and 250 km, and the echoes from Teleost at the radar frequency of 3.1 MHz were measured at the ranges of about 395 km. These measurements were then extrapolated and calibrated to other ranges using the propagation attenuations computed for various wind speeds. Strictly speaking, the target signal attenuation should have been compared with the attenuation of the sea echoes obtained under the same sea condition. However, as shown later, sea clutter impacts on the radar performance in high sea states only. Hence, it was decided that the measured target signals would be extrapolated and calibrated using the propagation attenuation computed at the wind speed of 30 knots to form a single worst-case reference curve.

The wind speed on board Teleost was estimated to be 30 knots at the time of the 4.1-MHz measurement and 20 knots at the time of the 3.1-MHz measurements. To obtain the signal attenuation of Teleost at the wind speed of 30 knots at the radar frequency of 4.1 MHz, it is only required to extrapolate the measured target signal to the other ranges using the attenuation curve computed at that wind speed. However, to obtain the signal attenuation of Teleost at the wind speed of 30 knots at the radar frequency of 3.1 MHz, it is necessary to further calibrate the extrapolated curve with the difference of the two-way propagation attenuations computed for the wind speeds of 20 and 30 knots. Figures 4 and 5 show the signal attenuations of Teleost, respectively, at the radar frequencies of 3.1 and 4.1 MHz at the wind speed of 30 knots.

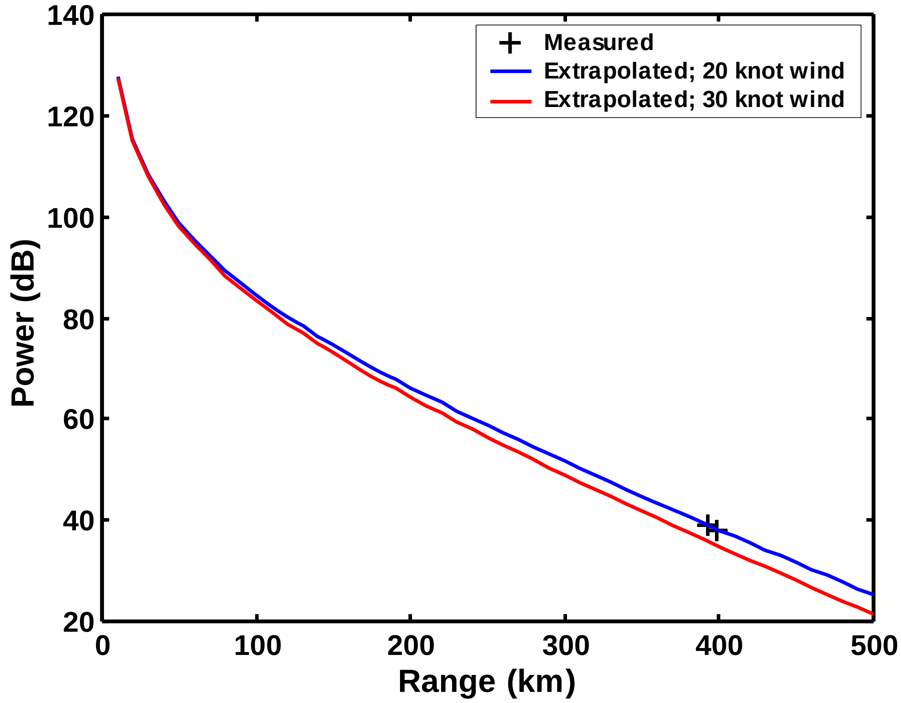

Figure 4 Signal attenuations of Teleost at the radar frequency of 3.1 MHz.

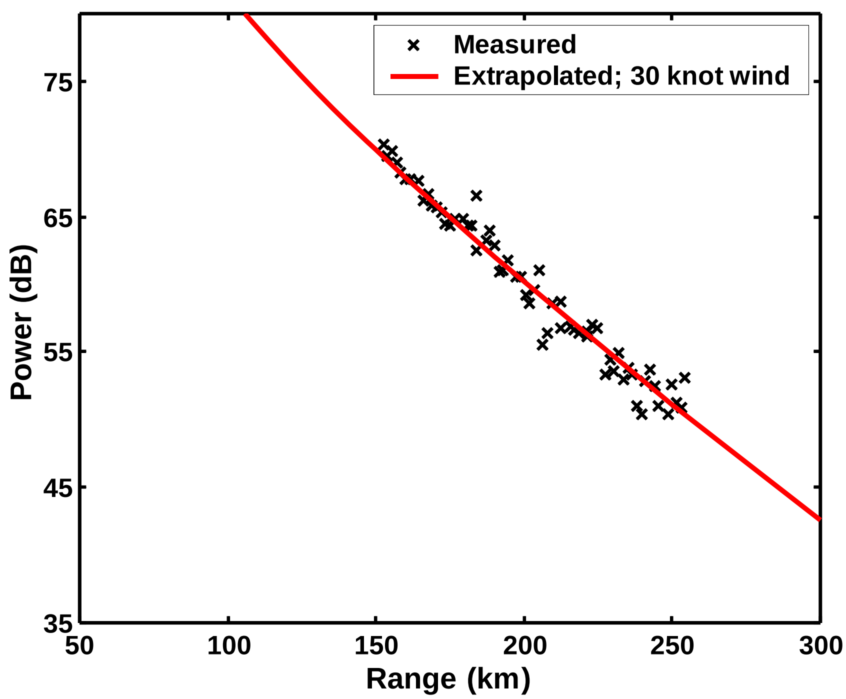

Figure 5 Signal attenuations of Teleost at the radar frequency of 4.1 MHz.

5.2 Comparison between Target Signal and Sea Clutter

The power returns from the ship targets can now be compared with the levels of sea clutter at the different sea states. In classical Constant-False-Alarm-Rate (CFAR) detection algorithms, the target signal threshold is set at a certain level above the mean power level of the background signal (interference plus clutter and noise). Let *V* denote the detection threshold and *C* denote the mean clutter level. If the target signal power, *S*, is greater than *C*+*V* (in decibel scale), then the presence of a target is declared. Equivalently, one can compare *S*-*V* with *C*. If $S\text{-}V > C$, then the presence of a target is declared. In the HFSWR demonstration system at Cape Race, the detection threshold *V* was set at 8 dB. Hence, comparing *S*-8 dB with *C* determines the performance of the radar in the detection of the large vessels, and comparing *S*-10-8 dB, or *S*-18 dB, with *C* determines the performance of the radar in the detection of the small vessels.

Figure 6 shows this comparison at the radar frequency of 3.1 MHz. Three observations can be made from Figure 6:

1. The large vessels can be detected, irrespective of the sea states.
2. The small ships cannot be detected in the very rough sea with $H_{1/3}$ between 5.5 and 6.5 m at ranges beyond 105 km.
3. The small ships also tend to less likely be detected during daytime at ranges around 110 km when there is the presence of strong E-region reflection.

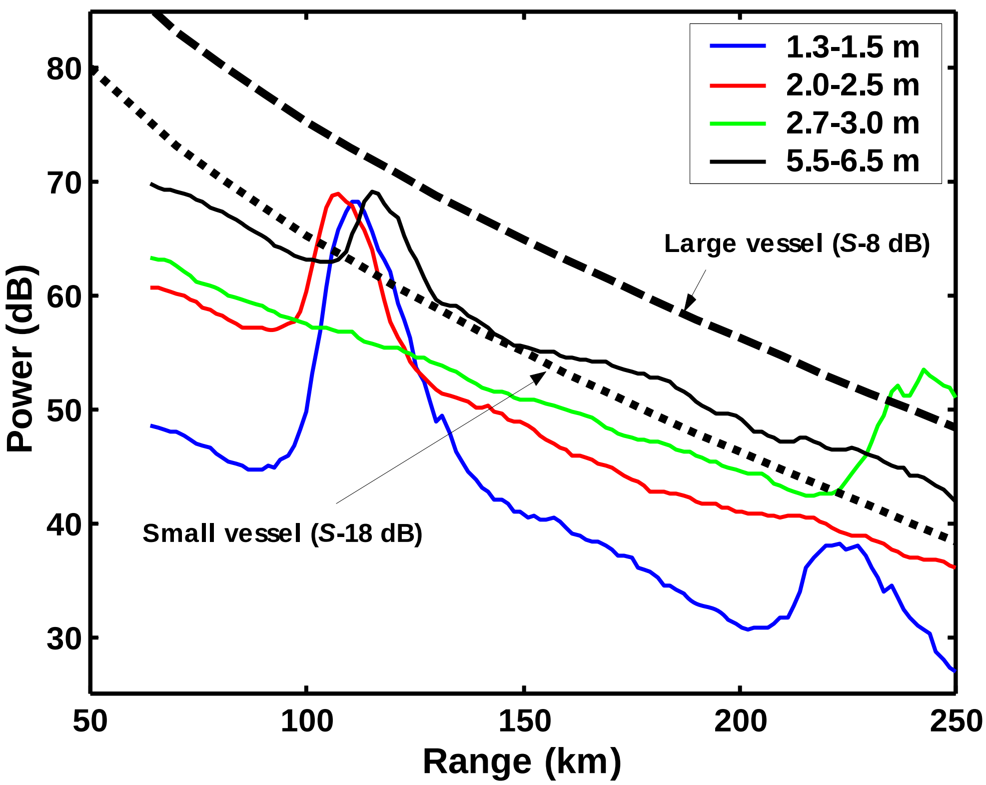

Figure 6 Detection capabilities of the HFSWR in the sea clutter continuum between the Bragg lines at the radar frequency of 3.1 MHz.

Similarly, Figure 7 shows the comparison at the radar frequency of 4.1 MHz. Three observations can also be made from Figure 7:

1. The large vessels can also be detected, irrespective of the sea states.
2. The small ships cannot be detected in the very rough sea with $H_{1/3}$ between 4.5 and 6.3 m at ranges beyond 95 km.
3. The small ships also cannot be detected in the rough sea with $H_{1/3}$ between 3.6 and 4.2 m at ranges beyond about 150 km.

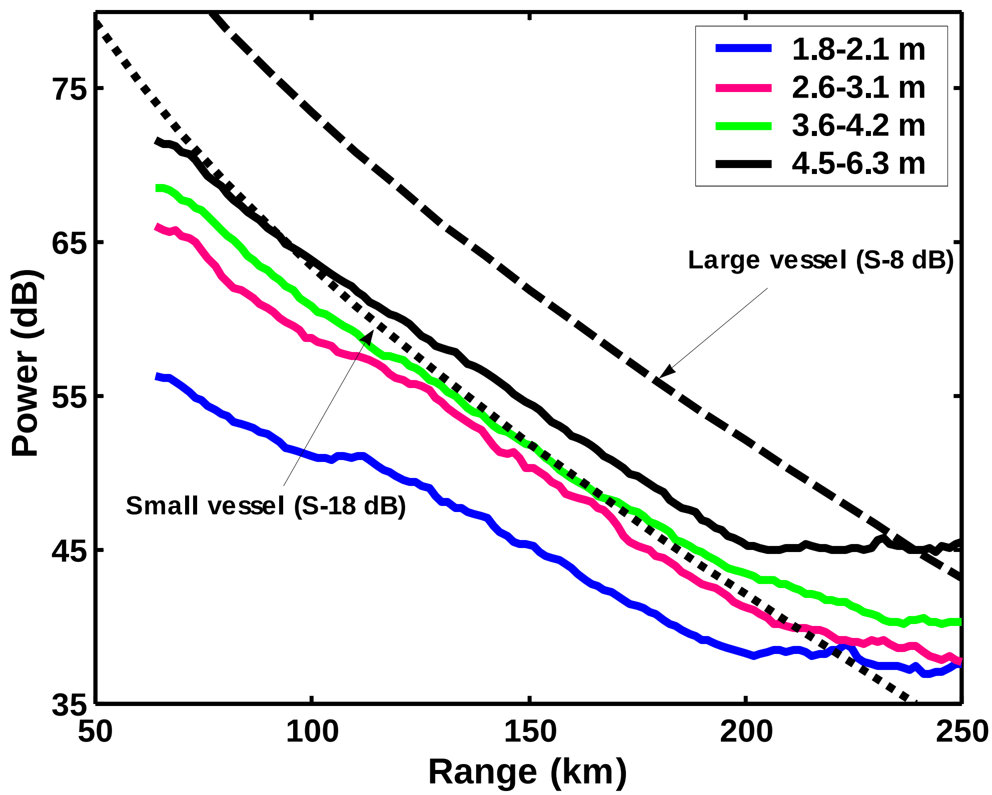

Figure 7 *Detection capabilities of the HFSWR in the sea clutter continuum between the Bragg lines at the radar frequency of 4.1 MHz.*

Hence, sea clutter from the very rough/rough seas has an impact on the performance of the radar in the detection of the small ships, depending on the radar frequency. The radar seems to perform better in sea clutter at the frequency of 3.1 MHz than at the frequency of 4.1 MHz. However, the radar at 3.1 MHz often cannot detect the small ships near the range of 110 km due to the presence of the E-region reflection. Hence, it is necessary to have the second channel at the radar frequency of 4.1 MHz to help the radar to track the small ships through the E-region clutter at 3.1 MHz. The readers are referred to [18] for the benefits of having dual-frequency operation in HFSWR.

6 HFSWR Design Considerations

For each transmitted radar pulse, the powers returned from the target, P_t, and from the sea, P_s, are amplified by the same system gain, and the target-signal-to-sea-clutter power ratio (SCR), $\eta = P_t / P_s$, can be written as

$$\eta = \frac{\sigma_t}{\sigma_s}, \tag{7}$$

where σ_t and σ_s are the radar cross sections of the target and the sea, respectively. The radar at Cape Race is a monostatic radar that floodlights on transmit and beamforms on receive. Hence, the radar cross section of the sea illuminated by the radar can be written as

$$\sigma_s = \sigma_0 R \, \Delta\theta \, \Delta R, \tag{8}$$

where R is the target range, ΔR is the range resolution of the radar, $\Delta\theta$ is the azimuth resolution of the receive antenna array, and σ_0 is the RCS per unit area of the sea surface. Hence, the SCR is inversely proportional to the target range, and the range and azimuth resolutions.

Over n radar pulses, the received power from the target could be improved by the factor of n, but the received power from the sea is essentially unchanged as the second-order sea clutter continuum is considered as a wide-band signal. Hence, the SCR can potentially be improved by the factor of n. However, the factor of n, which is directly proportional to the coherent integration time, is normally chosen to maximize the SCR or the target-signal-to-noise ratio (SNR) while ensure that there is no range walk in the targets[1]. Furthermore, this choice of n is made possible if, and only if, the radar operating frequencies are available for the entire coherent integration period. Unfortunately, as noted in [19], the spectrum in the lower portion of the HF band is very congested at night. It is expected to be very difficult to find any radar bands available at night for even a short period of time (e.g., 10 s). Hence, the option of using n to increase the SCR is quite limited.

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[1] This can be illustrated with the setup of the radar at Cape Race. An 8-bit phase coded pulse (Frank code) is used as a transmit waveform in the radar at Cape Race. The bit length in the coded pulse is about 20 µs, giving a range resolution of about 7.5 km. In an attempt to increase the range accuracy, the received echo to the transmitted pulse is over-sampled. The sampling rate is set at 125 kHz, corresponding to a sampling period of 8 µs, yielding a range accuracy of 1.2 km. Strictly speaking, if the radar is to maintain this range accuracy, the coherent integration time, T, must be chosen such that, within the time T, all the ship targets to be detected do not travel for more than 1.2 km in range. Ship targets are capable of travelling at a speed of 15 knots (7.7 m/s). Hence, if the radar is designed to detect the ship targets with radial speeds of up to 15 knots, then the coherent integration time of the radar cannot exceed 155 s. In reality, it is rare that the ships would travel radially at their maximum speeds. Hence, a longer coherent integration time may be used. For example, the radar at Cape Race uses a coherent integration time of about 262 s. This implies that there is a radial speed tolerance of 8.9 knots (4.6 m/s) only, if the radar is to maintain the range accuracy of 1.2 km. In conclusion, the signal processing aspects of the radar dictate that the option of using n to increase the SCR is to be limited.

From Equations (7) and (8), it can be observed that, among all the other system parameters available, the SCR is dependent on the bandwidth of the radar and the aperture of the receive array only. The radar at Cape Race uses the conventional pulse-Doppler technique to extract target signals in the frequency domain and Fourier beamforming technique to discern signals from different directions. The range resolution of the radar is inversely proportional to the radar bandwidth, and the azimuth resolution is inversely proportional to the aperture of the receive array. Hence, the SCR is directly proportional to the radar bandwidth and the receive-array aperture. To increase the SCR, it is necessary to increase either the radar bandwidth or the receive-array aperture. However, the radar bandwidth normally cannot be increased due to the spectrum congestion in the lower portion of the HF band. Meanwhile, there are economic incentives to reduce the receive-array aperture. Unfortunately, the results of the current study indicate that, if the radar using the conventional Fourier beamforming technique is to maintain the detection capability for ships with a GRT of 1000 tons, then the aperture of the receive array cannot be reduced from its current value.

The above discussion is based on the fact that the target and sea echoes are amplified by the same system gain and that this amplification is effectively cancelled in the calculation of SCR. To better illustrate how a reduction in the receive array aperture affects the received powers from the target and the sea, one should consider the amplifications of the target echo and the sea echo separately. In this case, the antenna gain, or more precisely, the directive gain of the receive array has to be considered. The directive gain of the receive array, after beamforming, is directly proportional to the array aperture. A reduction in the array aperture results in a loss of directive gain that affects both the target return and the sea clutter. Meanwhile, as discussed above, a reduction in the array aperture leads to an increase in the array beamwidth. This increases the surface area of the ocean patch in the radar's resolution cell, and therefore, increases the magnitude of the clutter response.

In the radar receiver, the increase in the clutter magnitude due to the larger patch area is effectively cancelled by the reduction in the directive gain of the receive array. The net effect of a reduced array aperture on SCR really comes from a reduction in the signal strength of the received response from the target.

It should also be pointed out that the design of the current linear receive array is a compromise for the radar operating in a dual-frequency mode in the frequency range between 3 and 5 MHz. The spacing of the elements in the current receive array is optimum at one half of the wavelength at the design frequency of 4.5 MHz. The SCR can be slightly improved if the element spacing is optimum at the radar operating frequency. In theory, the half-power beamwidth of a linear array is given by [20]

$$\Delta\theta \approx \frac{0.866\lambda}{Nd\cos\theta_0}, \tag{7}$$

where N is the number of elements in the array, d is the separation between adjacent elements, and θ_0 is the beam-steering angle measured clockwise from the normal of the receive array. At the boresight direction of the receive array, the half-power beamwidth at the design frequency is about 6.2^o, whereas the half-power beamwidth of the current receive array at the radar frequency of 3.1 MHz is about 9.0^o and the half-power beamwidth of the current receive array at the radar frequency of 4.1 MHz is about 6.8^o. These latter two half-power beamwidths are slightly larger than the half-power beamwidth at the optimum design frequency. Hence, for the same number of receive elements, the SCR at the radar frequency of 3.1 MHz can be improved by 1.6 dB ($9.0^{o}/6.2^{o}$), and the SCR at the radar frequency of 4.1 MHz can be improved by 0.4 dB ($6.8^{o}/6.2^{o}$), if the spacing of the elements is optimum at the respective frequency. Unfortunately, in practice, this is impossible with a single receive array in a radar operating at two frequencies between 3 and 5 MHz.

7 Conclusions and Recommendations

The conclusions of the current study are that, in the detection of the large ships, the radar performance is independent of sea state, but in the detection of the small ships, the radar performance is dependent on sea state. This latter conclusion imposes a constraint on the aperture of the receive array. The target-signal-to-sea-clutter power ratio is directly proportional to the bandwidth of the radar and the aperture of the receive array. While the radar bandwidth cannot normally be increased due to channel congestion, there are economic incentives to reduce the aperture of the receive array. However, the results of the current study indicate that, if the aperture is reduced, there would be further degradation of the radar performance in the detection of ships with a GRT of about 1000 tons. If the radar, using the conventional Fourier beamforming technique, is to maintain the detection capability for ships with a GRT of about 1000 tons, then the aperture of the receive array cannot be reduced from its current value. This requires that the linear receive array must have at least 16 elements, with a nearly optimum spacing between the adjacent elements (i.e., half-wavelength apart).

The results here indicate that the radar performance can be improved if the sea clutter is suppressed. Hence, there are benefits in implementing an effective sea-clutter suppression algorithm in HFSWR.

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The effects of sea clutter on the performance of HF Surface Wave Radar (HFSWR) operating in the frequency band between 3 and 5 MHz are studied in this technical memorandum. The HFSWR is designed to detect two classes of ships: large freighters with a Gross Registered Tonnage (GRT) in the order of several tens of thousands of tons and small vessels with a GRT of about 1000 tons. Representative levels of the radar returns from the large and small targets are estimated from the HFSWR at Cape Race, Newfoundland. The estimated returns are then compared with the sea echoes measured from the same radar to assess the capability of the radar under different sea conditions. The conclusions of the study are that, in the detection of the large ships, the radar performance is independent of sea state, but in the detection of the small ships, the radar performance is dependent on sea state. It is shown that if a radar employing conventional linear beamforming methods is to maintain the detection capability for the small ships, then the aperture of the receive array cannot be reduced from its current value.

Le présent document technique traite de l'étude des effets de l'état de la mer sur l'efficacité du radar haute fréquence à ondes de surface (HFSWR) fonctionnant entre la bande de fréquence de 3 à 5 Mhz. Le radar est conçu pour détecter deux classes de navires : les gros navires de charge à jauge brute de l'ordre de plusieurs dizaines de milliers de tonneaux et les petits navires à jauge brute d'environ 1 000 tonneaux. Des niveaux représentatifs des échos radar produits par les grosses et les petites cibles sont estimés à l'aide du HFSWR de Cape Race (Terre-Neuve-et-Labrador). Les échos estimés sont ensuite comparés aux échos de mer mesurés avec le même radar afin d'évaluer la capacité de ce dernier à détecter les navires sous différentes conditions de mer. L'étude permet de conclure que pour la détection des gros navires, l'efficacité du radar est indépendante de l'état de la mer, mais que pour la détection des petits navires, elle dépend de l'état de la mer. Nous avons constaté que si le radar employant les méthodes de formateur de faisceau linéaire conventionnelles est pour conserver la capacité du radar à détecter les petits navires, il ne faut pas réduire l'ouverture du réseau de réception de sa valeur actuelle.

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