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Raytheon Canada Limited

FINAL REPORT

Experiments with High Frequency Surface Wave Radar and Development of a Practical Ground Screen Method for HFSWR at Cape Bonavista

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1 Executive Summary

1.1 Introduction

Raytheon Canada Limited has been under contract to the Department of National Defence to develop and demonstrate Surface Wave Radar (SWR) for the surveillance of the Canadian Exclusive Economic Zone. Results, obtained from the experimental radar at Cape Bonavista Newfoundland, have been very promising with ships being detected and tracked to beyond 300 km and aircraft detected and tracked to beyond 200 km. However, before this technology can be considered mature enough for use as an operational sensor it is required that the problems associated with interference be addressed. In anticipation of an operational system Raytheon Canada Limited addressed these problems and propose and demonstrated solutions in a DREO contract entitled "Interference Suppression for Surface Wave Radar". This work was completed in March of 1995.

The proposal and subsequent contract detailed the dominant forms of interference experienced by SWR. Techniques were developed by Raytheon Canada Limited that both reduced the radars susceptibility to interference and cancelled any residue interference by the use of adaptive nulling.

Reducing the radars susceptibility to direct skywave interference was achieved through antenna design. Long range interference from other users of the HF spectrum was minimized by a combination of frequency management and the use of adaptive nulling techniques.

This report describes the High Frequency Surface Wave Radar (HFSWR) 1996 trials for the Interference suppression follow-up study. The primary goals of the trials were twofold: to further the design and evaluation of interference suppression techniques to be used in the 'Demonstration of HFSWR in a Coastal Surveillance Role', and to evaluate alternative methods of implementing a cost effective ground screen.

During the duration of the contract Raytheon was awarded two amendments. The first amendment was to evaluate clutter suppression techniques. The second amendment was to provide additional hardware.

1.2 Clutter Suppression

The clutter suppression work was subcontracted to Dr. Raafat Khan of C-CORE who has worked extensively in this field and is a consultant to Raytheon Canada on the East Coast Program. One of the objectives of the Canadian East Coast Program, which involves the construction of two (HFSWR) systems, is the operational surveillance of marine vessels. For HFSWR systems, radar energy reflected by the ocean waves (ocean clutter) is one of the main sources of interference which can mask the desired radar target signals; it is well known that the ocean clutter occupies certain regions of the radar Doppler spectrum, The HFSWR is a coherent device which is capable of discriminating target and clutter signals on the basis of their Doppler velocity. Thus, it is relatively easy to detect vessels travelling at velocities significantly different than the ocean waves responsible for the dominant components of the ocean clutter.

Unfortunately, these dominant clutter components, referred to as Bragg clutter, significantly overlap the typical operating speeds of marine vessels resulting in blind speed zones where ships cannot be detected.

A potential solution to this problem is the real-time implementation of clutter suppression techniques, developed by C-CORE, Memorial University of Newfoundland. These clutter suppression algorithms, based on a time-varying model of the ocean clutter, have demonstrated the enhancement of target detection with HFSWR systems. However, at the present time, these methods require intensive post-processing of the radar data.

The objective of the contract amendment was to investigate time-frequency signal processing methods to accurately approximate the C-CORE, clutter suppression algorithm. The outcome of this research and development work will be the implementation of the clutter suppression techniques in real-time, resulting in significant improvements in the target detection capability of HFSWR systems.

1.3 Additional Hardware

The existing four dual channel digital Data Acquisition System was enhanced by the addition of the further eight digital receiver units. Each unit consists of Antenna Interface Modules, RF-Digital Translator Units, and Complex Digital Filter Units. The additional hardware was housed within the existing VME Cage assembly.

Raytheon Canada took the opportunity to modify the previous generation receivers to improve their specification and make them compatible and interchangeable with the receivers developed for the Canadian East Coast System. These modifications were done at RCL expense with the pre-approval of the Scientific Authority.

Raytheon Canada in collaboration with DREO undertook again at RCL expense to house the new 16 channel data acquisition system in to a 14 foot box trailer. DREO supplied surplus equipment, including a 8 kW solid state amplifier to complete the test facility.

2 Technical Report

2.1 Introduction

The first trial was undertaken in March 1996. The trials collected data from a number of new antennas that were installed and the Raytheon Canada developed " Eight Channel Data Acquisition System" .

2.2 Antenna System

The antenna array at Cape Bonavista is a 4 by 4 array of Zentec whip antennas and one horizontally polarized cross-pole antenna.

The 4 by 4 array consists of HGF30, 10 metre, Zentec antennas. The antennas are spaced half-wavelength (at 4 MHz) apart in the azimuth dimension and one-quarter wavelength apart in the bore-sight direction. A group of four elements spaced one-quarter wavelengths are referred to as a quadlet. Each element of the 4 by 4 array is individually cabled to the equipment building. Within each of the four quadlets, the cables are of the same length. This allows a quadlet to be beamformed and added together using phase shifters and RF summing units. If a single quadlet is beamformed before the receiver, phase shifters are used so that the four element quadlet has maximum sensitivity along

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the bore-sight direction (end-fire to the quadlet). Since the individual quadlets have different lengths of cable, it was not feasible to beamform the entire array prior to the digital receivers.

Phase and gain measurements of the individual antennas were previously recorded using an H.P. Model 4193A Vector Impedance Meter. The measurements were made at the base of the antennas with the Vector Impedance Meter powered by a portable power generator. Results are presented in Appendix A.

The horizontal cross-pole antenna was cabled such that both dimensions of the antenna could be individually sampled. The energy received on any of the cross pole antennas will be horizontally polarized and therefore consist strictly interference and noise. The cross-pole antenna was evaluated as a candidate auxiliary antennas for adaptive interference cancellation.

It was originally proposed to install and evaluate the performanceof two loop antennas. Considerable design effort went into the design of the loop antenna but this approach was evantually considered impractical and no loops were built. Examples of various loop antenna designs are included in Appendix B

2.3 Data Acquisition System

The original NORDCO developed HFSWR data collection system allows for four channels to be sampled and stored to tape simultaneously, or 8 channels to be multiplexed (four per pulse) on a pulse to pulse basis.

The preference when attempting adaptive interference suppression is to sample the array elements simultaneously, since external interference and noise will tend to de-correlate between pulses. This de-correlation prevents estimation of the channel covariance that is required with any adaptive interference suppression scheme. Multiplexed data, however, can still be used to evaluate nulling concepts which are designed to suppress interference that is coherent to the radar. Coherent interference is caused by an undesirable propagation path, and will not de-correlate significantly between pulses.

The new 8 channel data aquisistion system, developed by Raytheon Canada, allows for the simultaneous recording of 8 channels of data. The new data collection system is however, limited in the amount of data that it is able to be continuously recorded by the amount of memory available (presently 8 Mbytes). With 8 channels of data, a transmitted pulse repetition frequency (PRF) of 100 Hz and 150 samples per pulse per channel, the system is limited to about 15 seconds of recording time. After each collection period, the data in memory must be down-loaded to a hard disk resident on a Sun Workstation via Ethernet. The transfer operation takes about 2 minutes to complete.

2.4 Previous Results

Previous work performed by Raytheon identified adaptive interference suppression techniques that suppress both external and self-generated interference observed on data collected at the Cape Bonavista Radar Site. To-date, an array of monopoles spaced one quarter wavelength in the bore-sight direction (Quadlet), and a cross-polarized antenna system have been evaluated. Both the cross-polarized interference canceller and an adaptive quadlet have shown ability to suppress unwanted interference while retaining gain towards desired targets.

2.5 Ground Screen

Theft of the ground screen has occurred on two separate occasions in the past 10 years and will likely continue if measures are not taken. The copper ground screen used has considerable scrap value. An effective solution was to make the harvesting and resale of the ground screen economically unfeasible by choosing material that does not have significant scrap value. It is desirable to implement alternative solutions to ground screen that: 1): are cheaper to install, 2): are more difficult to harvest, 3): have lower salvage value and, 4): are effective radar ground screens. It is not possible to satisfy all of the above criteria simultaneously and a compromise between cost, effectiveness, and salvage economics must be made.

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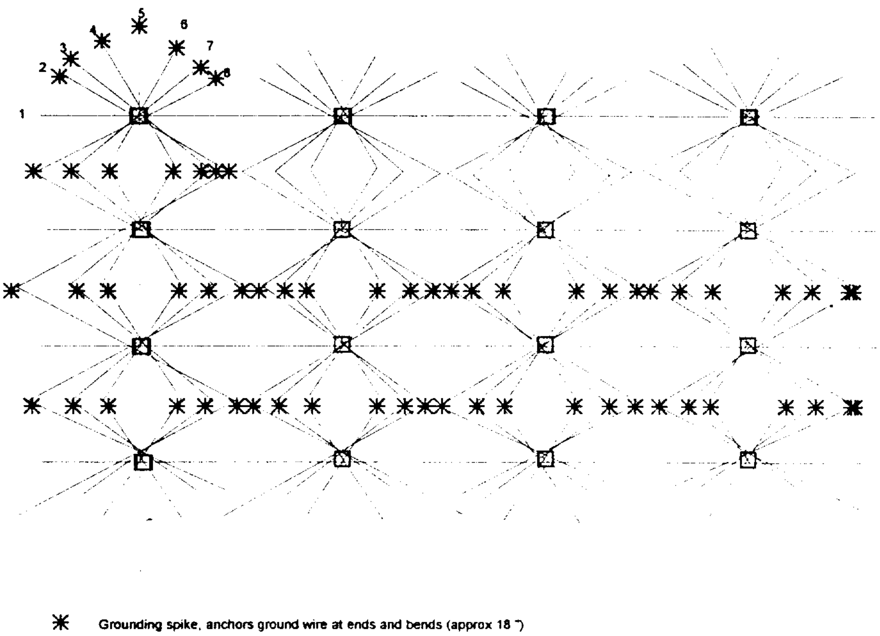
3 Results

3.1 Ground Screen Evaluation

An investigation into a cost-effective ground screen solutions for the Cape-Bonavista radar site was undertaken. Copper was selected as being the most effective ground screen material. Costs were minimised by reducing the amount of wire used in the installation. This was achieved by combining the element ground (required for impedance matching with the array ground. The ground wires were terminated where they intercepted. To minimise the antennas sensitivity to direct overhead interference the ground screen design maintained symmetry. An example of the antenna ground screen layout is presented in Figure 3.1.

Bonding techniques were evaluated. These included CadWeld, Crimp and Silver Solder. The silver solder approach was rejected due to the problems of ensuring consistentcy and quality standards in field conditions. Cadweld is a cold weld technique that has been used in the past at Bonavista. This technique has proved to be very reliable but is expensive. The cheaper crip techniques as used by the Telephone companies was selected as the preferred option based on the quality of the bond and low cost.



✳ Grounding spike, anchors ground wire at ends and bends (approx 18 ")

Figure 3–1 Combined Element and Array Ground Screen

3.2 Experimental Data

Experiments were conducted to assess the performance of different cross-polarized antenna systems.

Radar data was collected during both daytime and night time and a comparison between day and night performance made. All data was forwarded to DREO for analysis.

3.3 Configuration 1: Interference Cancellation with Multiple Cross-Polarization Antennas

This configuration uses four beamformed quadlets and two cross polarization antenna pairs, collected with the eight channel data acquisition unit. With this configuration, evaluation of the use of multiple polarization antennas is possible. It is also possible to combine azimuth and polarization nulling for suppression of both external and self-generated interference. The four quadlets are sampled simultaneously with the cross-polarized antennas, with this configuration cancellation of both self-and external interference is possible.

An alternative configuration used a loop antenna instead of cross polarized antennas as an alternate method to capture the horizontally polarized energy. Loop antennas have the potential to reduce the problem of picking up vertically polarized energy. This configuration was not implemented due to the complexity of installing the loop antenna (refer Appendix B)

4 Clutter Suppression

4.1 Introduction

This section documents the present status of a research project to investigate and develop new ocean clutter suppression techniques for a coastal surveillance radar system. This project was carried out under sub-contract to Raytheon Canada Limited; by Dr. Raafat Khan of C-CORE, Newfoundland.

An objective of the HFSWR project is the surveillance of marine vessels. Here, the radar returns are separated in radial speeds by Doppler processing. Ship detection is then performed. Sea clutter is an interference that cannot be ignored. The Doppler spectrum of this clutter is dominated by components centered at the advancing and receding Bragg frequencies. Hence there are two blind zones where ships cannot be detected and tracked. A potential solution to this problem of blind speed zones is the implementation of a sea clutter suppression method developed by C-CORE, Memorial University of Newfoundland. This method has demonstrated improved detection of a large ship in the

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blind speed zones. However, the computational load is too high for real-time implementation in the HFSWR. It is necessary to develop a method that can be implemented in real time and can approximate the theoretical performance of the C-CORE clutter suppression scheme.

The preliminary results reported here are based on viewing the ocean clutter problem from a new perspective. The clutter suppression can now be implemented with linear prediction filters, with a relatively lower computational effort. More importantly, the bulk of the processing needs to be performed on un-beamformed radar data, conforming to the channel data processing concept of operational radar systems. Target detection results are very encouraging. Considerable more effort is still required to optimize the processing parameters, validate the performance of the clutter suppression under different operating conditions and confirm the concept with data obtained from other radar systems.

4.2 Project Objectives

With the motivation of enhancing the surveillance performance of HFSWR systems, particularly for vessels, the following objectives were targeted for this project:

-further investigate the problem of ocean clutter and develop "linear" processing methods for suppressing the dominant components of the clutter;

-evaluate the performance of the new clutter suppression technique in detecting and tracking vessels masked by ocean clutter;

-using multiple radar data sets, optimize the processing parameters of the clutter suppression technique; and

-recommend a scheme for implementing the clutter suppression technique for real time operation in a radar system.

Significant progress has been achieved on the first two objectives. Brief details of the research progress, and preliminary results, are given in the next section. These preliminary results indicate that the main objective of developing a new processing strategy has almost been achieved. It is anticipated that all the project objectives will be met or exceeded during the next phase of this project.

4.3 Progress Report

It is well known that the ocean clutter in HFSWR systems is dominated by two "Bragg" peaks, corresponding to back-scattered energy from ocean waves having a wavelength half that of the radar wavelength. These clutter peaks occur at two distinct Doppler frequencies corresponding to the characteristic velocity of propagation of the two sets of ocean waves, propagating radically towards and away from the radar at 4 MHz. The characteristic propagation speed of about 6m/s (12knots) of these "Bragg" waves often overlaps the cruising speed of many marine targets. It is also important to note that the "Bragg" peaks are flanked by weaker, broader peaks which can also cause false target detections.

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It is clear that the selective suppression of ocean clutter signals is a very desirable feature that needs to be developed for HFSWR systems designed for surveillance operations. Towards this end, recent research work has investigated the characteristics of Bragg clutter signals with the objective of developing robust and reliable techniques to discriminate these signals from the desired target signals. Developments at C-CORE have shown that the main characteristics of the ocean clutter signal can be modelled using a low-order adaptive prediction filter. It is demonstrated that dominant clutter energy can be adequately modelled with two narrowband signals but with slowly varying frequencies. Allowing the narrowband signals to have a time-varying frequency also models part of the energy of the weaker, broader peaks flanking the main Bragg peaks. This approach has been extended, using eigen-analysis based time varying methods, to develop a clutter suppression technique which is capable of detecting and tracking ships masked by the "Bragg" clutter.

The main disadvantage of the present clutter suppression scheme is the fact that a time-varying clutter signal is being modelled and subsequently suppressed using processing methods which are capable of handling this non-stationary behaviour.

4.4 Physical Justification For New Clutter Suppression Scheme

The new clutter suppression approach described is based on studies to better understand the process with which the ocean clutter signals are received by the radar system. Consider a single omni-directional antenna element of a HFSWR receive array. At any time instant, after the transmission of a radar pulse, the ocean clutter signal at this element for a particular range cell represents a coherent summation of the total clutter energy originating in an annular region. Assuming that range gating has been performed, the range determines the radius of this annular region and the system range resolution determines its width.

Under the assumption that the dominant clutter signals consist of two narrowband "Bragg" signals, the principle of linear superposition indicates that the coherent summation of the clutter energy from the annular region will also contain only two narrowband signals at the same "Bragg" frequencies. However, the particular combination of magnitudes and phases over the annulus will result in an unpredictable signal level at each of the two frequencies. This behaviour is commonly observed and these time-varying characteristics make the modelling of the clutter signals difficult.

It is clear that the clutter time behaviour of the clutter signals in one ocean range cell are very difficult to predict. However, let us consider the relationship to the clutter signals in adjacent ocean range cells. Using the same argument as above, the time behaviour of the clutter signals cannot be independently predicted. But, considering the hydrodynamic properties of the ocean, it is reasonable to assume that there will be predictable variations between the individual components contributing to the total clutter signals in the adjacent range cells. The key point is that although the signals at an antenna exhibit a very non-linear variation over time, there is a strong linear relationship between the signals in neighbouring range cells. Thus the new clutter suppression scheme is based on the following hypothesis:

The instantaneous clutter signal level in any ocean range cell, for single radar antenna elements, can be predicted from the instantaneous clutter signal levels in neighbouring ocean range cells.

The eight frames in Figure 4.1 correspond to the clutter data received at a single antenna in time increments of about 7 seconds, i.e. the total time covered in the figure is a little under a minute. Each frame covers a range of 20 km to 30 km and the Doppler range of ie -9 to -16 knots is centered about the dominant Bragg frequency. Ten contour levels are plotted at 1 dB increments. This plot is typical of many plots that have been studied, and they all exhibit similar characteristics:

-at any instant, the clutter occurs as peaks in well defined locations;

-the clutter peaks are separated by relatively low signal levels;

-the locations and magnitudes of the peaks vary slowly; and

-different ranges exhibit different behaviour.

These observations support the above hypothesis and we are now in a position to specify a linear clutter suppression algorithm. The algorithm must contain the following:

a) forward as well as backward prediction is required as the Bragg waves are travelling both towards and away from the radar;

b) a gapped prediction is required, i.e. there must be a gap of a few range cells between the cell being predicted and the first cell of the set of ranges contributing to the prediction. This is required in order to prevent signal energy from a desired target from being suppressed; and

c) the operator is to be configured as a prediction error filter, which means that any signal energy which is predictable from neighbouring range cells is connected with an ocean process and should be subtracted out.

4.5 Mathematical Overview of New Technique

It is well known that the future value of an auto-regressive (AR) process can be predicted as a linear combination of its past L values:

$$s^f_L(n+1) = a^L_1 . s(n) + a^L_2 . s(n-1) + ... + a^L_L . s(n-L+1) \qquad (1)$$

The forward prediction error is defined as:

$$e^f_L(n) = s(n) - s^f_L(n) \qquad (2)$$

In a similar manner, the backward prediction operates on a linear combination of future values:

$$s^b_L(n) = b^L_1 . s(n+1) + b^L_2 . s(n+2) + ... + b^L_L . s(n+L) \qquad (3)$$

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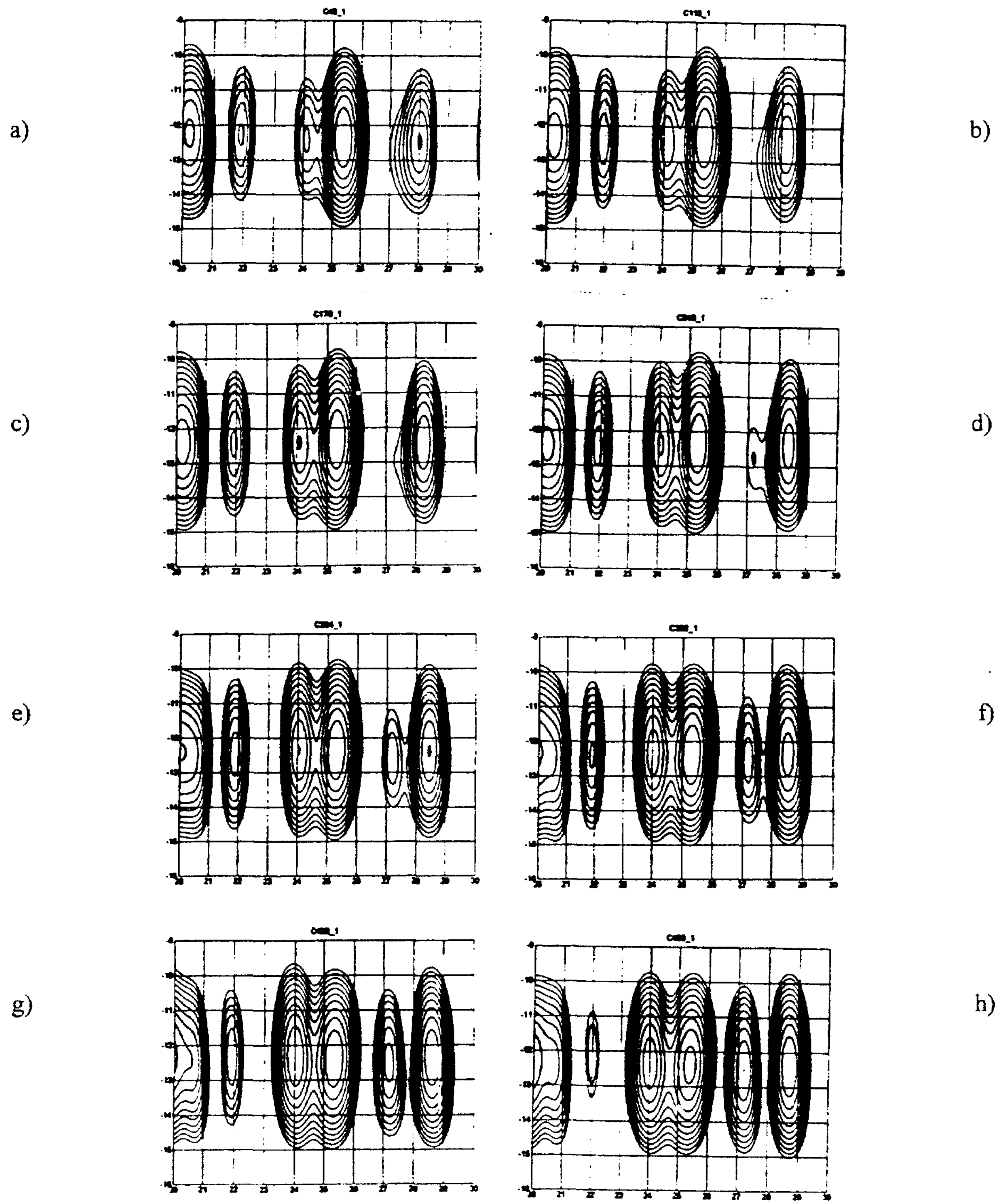

Figure 4.1 Time-varying behavior of dominant Bragg clutter signal received at a signal antenna.

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For a time series with N samples, the forward prediction coefficients can be determined from the data by solving the following matrix equation:

$$\begin{bmatrix} s(L) & s(L-1) & \cdots & s(2) & s(1) \\ s(L+1) & s(L) & \cdots & s(3) & s(2) \\ \cdot & \cdot & \cdots & \cdot & \cdot \\ \cdot & \cdot & \cdots & \cdot & \cdot \\ s(N-G-1) & s(N-G-2) & \cdots & s(N-G-L+1) & s(N-G-L) \end{bmatrix} \cdot \begin{bmatrix} a_1^L \\ a_2^L \\ \cdot \\ \cdot \\ a_L^L \end{bmatrix} = \begin{bmatrix} s(L+G+1) \\ s(L+G+2) \\ \cdot \\ \cdot \\ s(N) \end{bmatrix} \quad (4)$$

This and a similar matrix equation for the backward prediction filter coefficients can be easily solved using standard routines. Note that the first row of the matrix equation uses the first L values of the sequence to predict the (L+G) value; there is a gap G between the last value L in the prediction set and the predicted value.

For ocean clutter prediction a somewhat different matrix equation is used. This is because we are combining spatial and temporal information in setting up the matrix equation to solve for the prediction coefficients. For forward prediction, a set of ocean range cells, at a particular time instant, is used to predict the clutter value for a cell at a further range but at the same time:

Each column of the (L x N) matrix represents N time samples from an ocean range cell. The first argument refers to the range cell number and the second argument refers to the time index. The solution of equation (4) for a particular value of k will allow us to predict the clutter signal values in range cell k as a linear combination of the values in a set of L ranges, starting after a gap G. It is important to note that the prediction is based on signal values of the same time index only.

A similar procedure can be followed for the backward prediction procedure. Again, a gap must be provided between the range cell to be predicted and the nearest neighbour in the prediction set. In practice, both forward and backward prediction equations are set up simultaneously and solved in a single step.

It is important to remember that, when a prediction error filter is applied to an AR process, the output of the filter is white noise. Thus it is to be expected that the application of the clutter suppression scheme will result in a slight increase in the noise floor. However, the output of the prediction error filter can be input into an AR spectral estimation process, instead of the usual Doppler Fast Fourier Transform to achieve an enhanced spectral estimate.

4.6 Selection of Prediction Parameters

Model based estimation schemes, such as the one proposed here, are fairly sensitive to the process parameters. In this case the prediction length L and the prediction gap G must be selected such that desired target signals are not affected by the prediction error filter, and a maximum suppression of the clutter signal energy is achieved. A preliminary test procedure has yielded the following parameter values:

Prediction length	10

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Prediction gap 3

These values are not expected to be accurate. Testing with a number of different radar data sets is required to validate or modify these values.

4.7 Preliminary Clutter Suppression Results

The first example deals with the case where the target Doppler is sufficiently removed from the clutter Doppler so that in this case other Doppler discrimination techniques can also be equally effective. Figure 4.2 shows the Doppler spectrum plot for an ocean range cell with a ship target. It is seen that both Bragg peaks are at a higher level than the ship signal at around 5 knots. This is not surprising as the Bragg signals are summed over a large annular region as explained in the previous section. The half beam width of the antenna element is about 30 degrees. Figure 4.3 shows the Doppler spectrum for the same range cell after clutter suppression. The ship signal has remained unchanged. The negative Bragg has been attenuated by about 40 dB and the positive Bragg by about 25 dB. It is also clear that the overall noise level is somewhat elevated. As discussed before, this is expected due to the "white noise" output of the prediction error filter. Methods are currently being investigated to improve the output signal to noise ratio.

Figure 4.4 shows an example where the ship is very close to the positive Bragg signal. This is the case where conventional processing is not able to detect the target signal. The shape of the Bragg peak gives an indication that a target may be present, but normal target detection is not possible. The Doppler spectrum in Figure 4.5, after clutter suppression shows the ship target clearly and detection is obviously possible.

The above examples were for single channel data. Figures 4.6 and 4.7 show the target data corresponding to Figures 4.4 and 4.5 after beam-forming. Figure 4.6 shows a significant reduction in the level of the negative Bragg indicating that the dominant energy of this clutter is not in the target direction. The ship target is again clearly detectable.

4.5 Real-Time Implementation of Bragg Suppression Technique

The Bragg clutter suppression technique developed here can be implemented in real-time. All the results reported here were obtained by performing clutter suppression operations on data from single radar channels. For the beam-formed example of Figure 4.7, the clutter suppression was performed before the beam-forming operation.

The main computational load in the clutter suppression scheme is shared by two operations:

a) dot product operations on pairs of time series corresponding to two ocean range cells; this length corresponds to the coherent integration period of the radar. These dot products fill a L x L square matrix, where L is the length of the prediction filter; and

b) inversion of the L x L matrix to solve for the prediction coefficients.

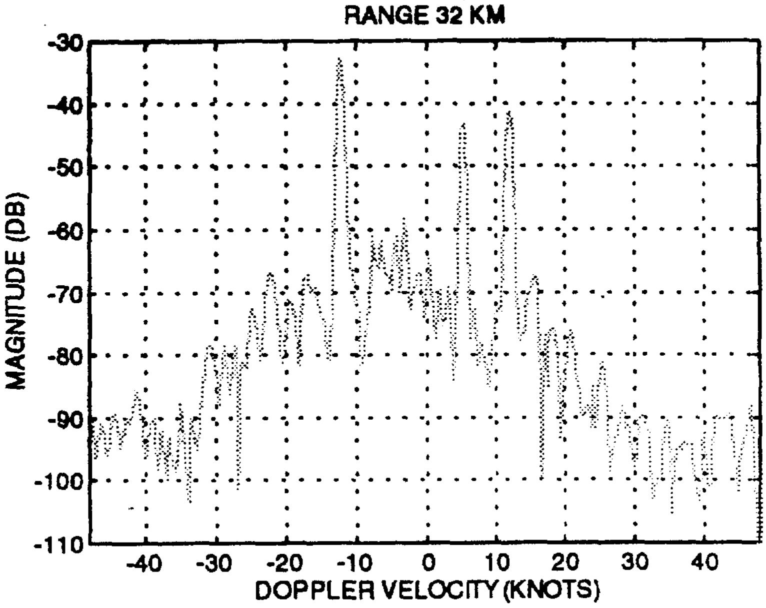

Figure 4.2 Radar Doppler spectrum with ship target well removed from the Bragg clutter signals. Ship velocity is about 5 knots.

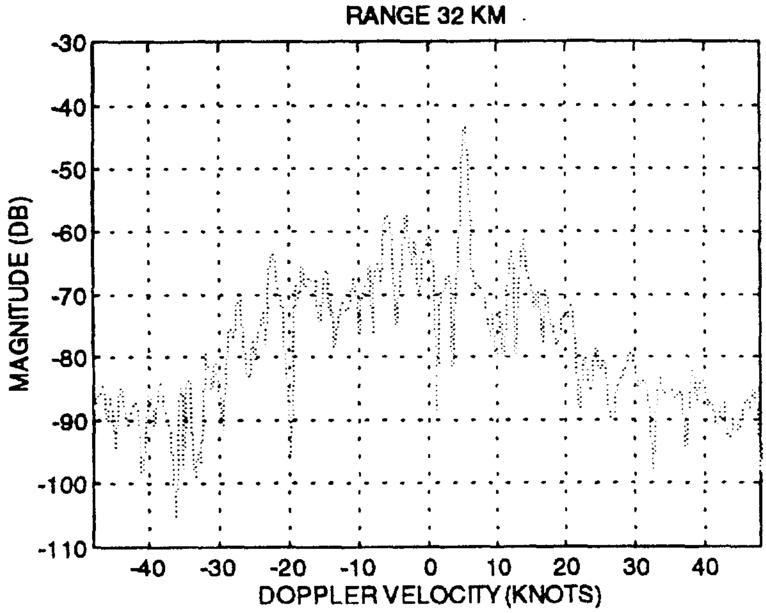

Figure 4.3 Radar Doppler spectrum after clutter suppression. Ship signal has not been affected.

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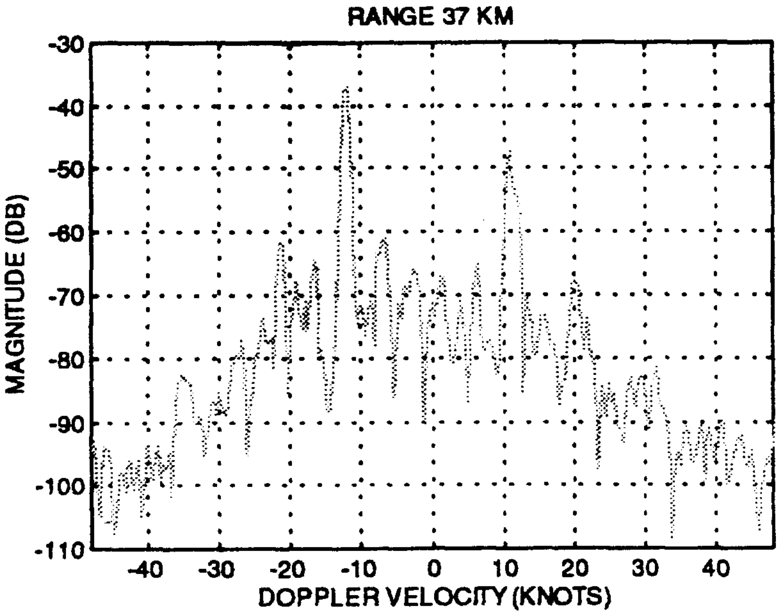

Figure 4.4 Radar Doppler spectrum with ships target close to positive Bragg signal. Ship velocity is about 10.5 knots.

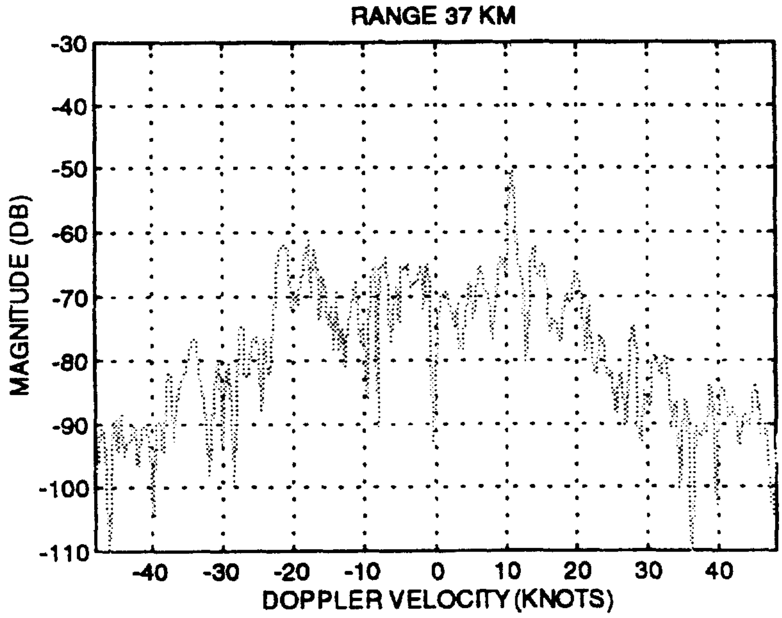

Figure 4.5 Radar Doppler spectrum of Figure 4 after clutter suppression. Ship signal strength appears to have decreased by about 2 dB.

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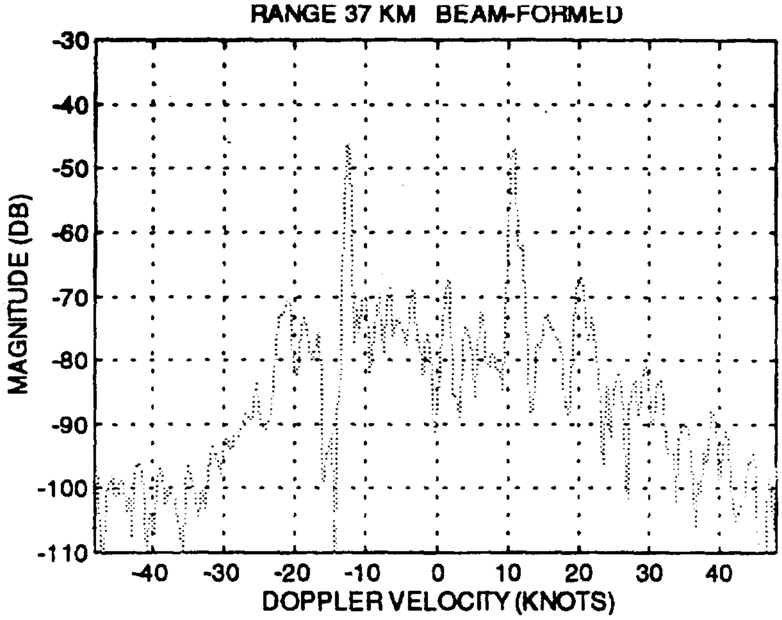

Figure 4.6 Radar Doppler spectrum after beam-forming. Note that the relative levels of the Bragg signals are different as compared to Figure 4.4.

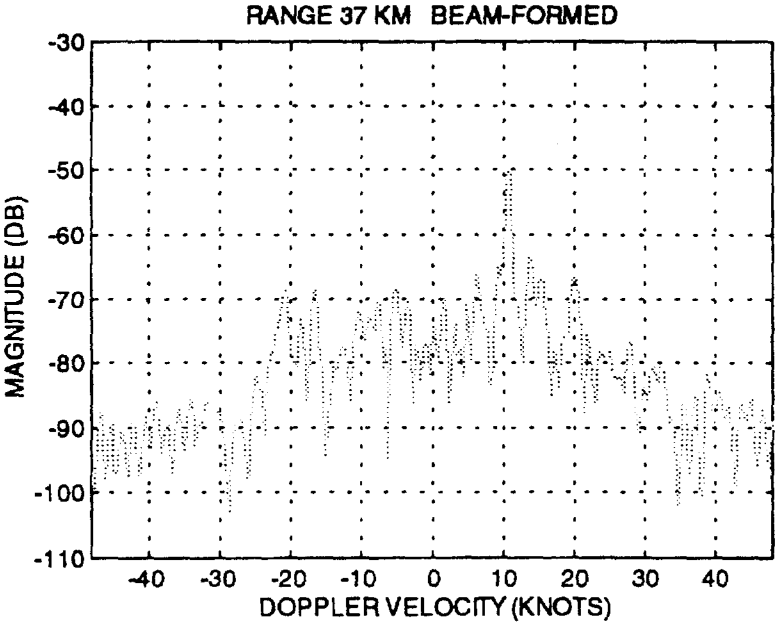

Figure 4.7 Beam-formed Doppler spectrum after clutter suppression. There is a noticeable increase in the noise floor level.

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These operations are well within the capability of a modest processor.

4.6 Conclusions and Proposed Work for Next Phase

The new clutter suppression scheme looks very promising and it is anticipated that it will supercede the previous Singular Value Decomposition (SVD) based scheme.

There is still a significant research and development required to validate this scheme and optimize the operational parameters. The new technique has demonstrated a performance matching that of the SVD technique for one radar data set. It is essential that additional data sets be tested. The Department of National Defence has collected a further data set in November 1996 and the technique will be tested with this data as soon as it is available. It would also be desirable to test the clutter suppression on pulsed radar data from the Cape Bonavista system. Processing these two additional data sets will also help in determining the optimal operational parameters for the clutter suppression.

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Raytheon Canada Limited and the Department of National Defence have jointly funded a project to develop a high frequency surface wave radar (HFSWR) for coastal surveillance. This report describes some experiments with the HFSWR and the construction of a practical ground screen for the receive array elements in the HFSWR.

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High frequency surface wave radar

Coastal surveillance

Experiments

Ground screen

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