

MATCHED WINDOW PROCESSING FOR MITIGATING OVER-THE-HORIZON RADAR SPREAD DOPPLER CLUTTER

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ABSTRACT

Ionospheric motion causes spreading of surface clutter in Doppler space which fundamentally limits the detection performance of skywave HF over-the-horizon radars. This paper presents a technique which reduces the effect of so-called “coincident” spread Doppler clutter, i.e. that which results from surface scattering from within the same range resolution cell as the target. The method exploits the spatial correlation of the ionospheric aberration along the geomagnetic field aligned irregularities to obtain a cross-relation between clutter in neighboring range bins. This cross relation is exploited to estimate the Doppler spreading sequence common to neighboring range bins by a technique adapted from blind multi-channel system identification. A Chebyshev Doppler window is then designed which is matched to the estimated ionospheric aberration. Simulation and real data results presented here indicate the proposed method provides as much as 10 dB improvement in side-lobe level using a 3 second coherent integration time radar waveform.

1. INTRODUCTION

Doppler processing is critical to target detection with skywave HF over-the-horizon radar (OTHR), since it discriminates moving aircraft from nominally stationary surface back-scatter [1, 2]. However, motion of the ionosphere, particularly in disturbed equatorial regions, can cause clutter return to be spread in Doppler space thereby obscuring the presence of targets. Several approaches have thus been proposed to mitigate different types of spread Doppler clutter [3, 4, 5].

Doppler spread clutter can be categorized according to the mechanisms by which it is caused, as depicted in Figure 1 [6]. The first type of clutter category is so-called “separated clutter” where the clutter return along path D is Doppler spread due to an ionospheric disturbance and has a slant range which coincides with the target in path B due to a range ambiguity. Mitigation techniques for such range-folded clutter include low waveform repetition frequency (WRF) signals and non-recurrent waveforms [5]. Separated spread Doppler clutter is often seen during normal mid-latitude OTHR operations where the first-hop ionosphere is well behaved but the range-folded second hop is through the disturbed equatorial region. The second type of clutter is “proximate” clutter since it occurs on the first-hop return, within the same dwell illumination region as the target, but arrives at a different elevation angle. This would be the case in Figure 1 when Doppler-spread clutter which arrives on raypath A is at the same slant-range as Target 1, which in turn arrives on raypath B. Selecting a frequency where only single-mode propagation to the desired ground range is

supported often mitigates proximate clutter. If this is not possible, then using a 2-D antenna array to spatially null out the Doppler spread arrivals in elevation has been proposed. Finally, the third type of clutter is known as “coincident” clutter because it results from spreading of the ground return in the same physical resolution cell as the target. Coincident clutter is illustrated in Figure 1 by clutter arriving on raypath C' which obscures the target on raypath C. Approaches proposed for mitigating coincident clutter typically involve some form of Bragg-line sharpening [5]. The difficulty with these approaches is that they require excessively long coherent integration times (CIT) (e.g. > 25 sec) in order to resolve the Bragg lines and further require that the frequency fluctuation within the CIT is fairly slow. Accordingly, such methods may be useful for surface-ship detection problems where the Doppler spreading is quite modest, but do not offer a solution for more typical operating conditions where CIT's on the order of 2-3 seconds are used.

The approach proposed here is designed to exploit the spatial correlation of the Doppler spreading sequence arising from ionospheric structure. In particular, by relating backscatter sounder data with air glow optical measurements, there is clear evidence that Doppler spreading is a result of electromagnetic scattering off of ionospheric depletion regions formed during day-night transitions [7]. These depletion regions form along the Earth's electromagnetic field lines and cause what are commonly known as field-aligned irregularities. Since the field lines run predominantly North-South, there should be a high degree of spatial correlation between Doppler spreading sequences affecting the radar signals received from neighboring range bins when looking in a southerly direction from a low latitude OTHR.

2. AN ABERRATED CLUTTER AND TARGET SIGNAL MODEL

During disturbed ionospheric conditions, the surface backscatter clutter received by an OTHR is modulated by an amplitude and phase-varying Doppler spreading sequence, $a(n)$, which can completely mask the targets. At range bin m , the Doppler spread clutter and noise return at the receiver for a sequence of waveform repetition intervals, $n = 1, \dots, N$, is

$$x_m(n) = a(n)c_m(n) + \epsilon_m(n). \quad (1)$$

In equation (1), $c_m(n)$ is the zero-mean unspread clutter backscatter return, assumed to be uncorrelated from one range bin to the next, and $\epsilon_m(n)$ is additive white Gaussian noise. In this work, because of its spatial correlation, the spreading sequence is assumed not to vary over a small neighborhood of range bins. The

signal component due to a target is also modulated by the aberration $a(n)$. Therefore, the return at the receiver in the presence of a target can be expressed as

$$x_{m_t}(n) = a(n)(c_{m_t}(n) + \alpha_t e^{j\omega_t n}) + \epsilon_{m_t}(n) \quad (2)$$

where m_t is the range bin of the target, α_t is the zero-mean complex Gaussian signal amplitude and ω_t is normalized target Doppler frequency.

Since the unspread clutter backscatter sequence $c_m(n)$ is commonly modeled by low Doppler frequency Bragg scattering of the sea surface [4], a low rank representation of $c_m(n)$ can be used,

$$c_m(n) = \sum_{l=1}^L \beta_{m,l} \psi_l(n) \quad (3)$$

where L is small and each sequence $\psi_l(n)$, $n = 1, \dots, N$ is defined by one of the first few dominant eigenvectors of the correlation matrix, $\mathbf{R}_c = E[\mathbf{c}_m \mathbf{c}_m^\dagger]$ where the n^{th} element of the vector $\mathbf{c}_m$ is $c_m(n)$.

3. DOPPLER SPREADING SEQUENCE ESTIMATION

The spatial correlation of the aberration due to field-aligned irregularities can be exploited by appropriate modification of a cross-correlation (CR) algorithm recently used in blind identification of multipath wireless communication channels [8]. In blind channel identification, the distinct impulse responses of two or more transmission paths are identified by taking advantage of the fact that the same signal was sent through multiple paths. Analogously, in the model of (1), clutter returns from different range bins undergo the same aberration. Thus, the ‘‘channel’’ in blind identification corresponds to the clutter and the transmitted ‘‘signal’’ sequence corresponds to the aberration sequence in the current problem. In the OTHR problem, however, note that the Doppler spreading sequence and ocean backscatter sequence are not convolved as in the communications problem, instead they are multiplied. Therefore here the aberration is estimated in the frequency domain where it can be expressed as a convolution with the clutter. Since in the proposed algorithm, the frequency domain is defined by the DFT, the use of circular convolution is required instead of linear convolution.

The Doppler spread clutter model, expressed in the Doppler frequency domain, is

$$x_m(u) = a(u) \otimes c_m(u) + \epsilon_m(u) \quad (4)$$

where $\otimes$ denotes circular convolution and $x_m(u)$ is the DFT of $x_m(n)$. Cross-correlation methods use the property that in the noiseless case,

$$\begin{aligned} c_{m'}(u) \otimes x_m(u) &= c_{m'}(u) \otimes c_m(u) \otimes a(u) = \\ c_m(u) \otimes c_{m'}(u) \otimes a(u) &= c_m(u) \otimes x_{m'}(u) \end{aligned} \quad (5)$$

in order to identify the clutter sequences. The cross-correlation in (5) can be expressed in matrix-vector form as

$$\mathbf{X}\mathbf{c} = \mathbf{0}. \quad (6)$$

where $\mathbf{c} = [\mathbf{c}_m^T \vdots \mathbf{c}_{m+1}^T]^T$ and $[\mathbf{c}_m]_u = c_m(u)$. If only two range bins, m and $m+1$, are used for CR,

$$\mathbf{X} = [\mathbf{X}_m \vdots -\mathbf{X}_{m+1}] \quad (7)$$

where $\mathbf{X}_m$ is matrix representation of circular convolution. In contrast with the linear convolution of [8], the $N \times N$ matrix for a circular convolution of length N used here is defined by

$$\mathbf{X}_m = \begin{bmatrix} x_m(0) & x_m(N) & \cdots & \cdots & x_m(1) \\ x_m(1) & x_m(0) & x_m(N) & \cdots & x_m(2) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_m(N) & x_m(N-1) & \cdots & x_m(1) & x_m(0) \end{bmatrix} \quad (8)$$

where the elements of the matrix $\mathbf{X}_m$ represent the received signal in the frequency domain. Note that the roles of $x_m(u)$ and $c_m(u)$ can be interchanged in the representation of circular convolution.

Since the clutter covariance is low rank, the unspread clutter $\mathbf{c}$ can be represented by a small number of parameters as

$$\mathbf{c} = \mathbf{\Psi} \bar{\beta} \quad (9)$$

where the $2N \times 2L$ matrix $\mathbf{\Psi}$ is block diagonal such that

$$\mathbf{\Psi} = \begin{bmatrix} \tilde{\mathbf{\Psi}} & \mathbf{0} \\ \mathbf{0} & \tilde{\mathbf{\Psi}} \end{bmatrix} \quad (10)$$

for which $[\tilde{\mathbf{\Psi}}]_{u,l} = \psi_l(u)$. Note that the basis functions $\psi_l(u)$ for the second order statistics of the frequency domain $c_m(u)$ are used here, and these are simply the DFT's of $\psi_l(n)$ defined in equation (3). Similarly, $\bar{\beta} = [\bar{\beta}_m^T \bar{\beta}_{m+1}^T]^T$ for which $[\bar{\beta}_m]_l = \beta_{m,l}$.

To estimate the unspread clutter vector $\mathbf{c}$ in the presence of noise, the equation $\mathbf{X}\mathbf{c} = \mathbf{0}$ can be replaced by the minimization of $\|\mathbf{X}\mathbf{c}\|^2$ as

$$\hat{\beta} = \arg \min_{\bar{\beta}} \bar{\beta}^\dagger \mathbf{\Psi}^\dagger \mathbf{X}^\dagger \mathbf{X} \mathbf{\Psi} \bar{\beta} \quad (11)$$

subject to the constraint $\bar{\beta}^\dagger \bar{\beta} = 1$. This minimization can be achieved by calculating the minimum eigenvector of $\mathbf{\Psi}^\dagger \mathbf{X}^\dagger \mathbf{X} \mathbf{\Psi}$.

Given $\hat{\beta}$, it follows from (9) that $\hat{\mathbf{c}} = \mathbf{\Psi} \hat{\beta}$. Consequently it is possible to calculate a least squares estimate of the Doppler spreading sequence, $\hat{\mathbf{a}}$. To do so, let the matrix $\hat{\mathbf{C}}$ be

$$\hat{\mathbf{C}} = [\bar{\mathbf{C}}_m^\dagger \vdots \bar{\mathbf{C}}_{m+1}^\dagger]^\dagger \quad (12)$$

where $\bar{\mathbf{C}}_m$ is the circulant matrix form of $\hat{\mathbf{c}}_m$ defined like $\mathbf{X}_m$ in equation (8) by replacing each element $x_m(u)$ replaced by $\hat{c}_m(u)$. With $\hat{\mathbf{C}}$ defined as in (12) the frequency domain Doppler spreading sequence is given by

$$\hat{\mathbf{a}} = (\hat{\mathbf{C}}^\dagger \hat{\mathbf{C}})^{-1} \hat{\mathbf{C}}^\dagger \mathbf{x} \quad (13)$$

where $[\hat{\mathbf{a}}]_u = \hat{a}(u)$ for $u = 1, \dots, N$, while $\mathbf{x} = [\mathbf{x}_m^\dagger \vdots \mathbf{x}_{m+1}^\dagger]^\dagger$ for which $[\mathbf{x}_m]_u = x_m(u)$ for $u = 1, \dots, N$.

4. MATCHED WINDOW PROCESSING

Once the aberration sequence is estimated from clutter return, it can be used to design a window that compensates for the Doppler spreading of both point targets and clutter. This design method is referred to here as matched window processing (MWP) due to its resemblance to matched field processing (MFP). While in MFP, a beamformer $\mathbf{w}$ is designed to match a complex multipath wavefront $\mathbf{d}$ produced at a sensor array, in MWP a window $\mathbf{w}_m(n)$ is designed to match the aberration sequence, $a(n)$, produced at the

radar receiver by complex multipath propagation through the ionosphere.

For a return from a point target with Doppler frequency ω_d and aberration $a(n)$, the response of a windowed DFT is

$$\Gamma(\omega_d) = \sum_{n=1}^N w_m^*(n) a(n) e^{j\omega_d n} \quad (14)$$

In MWP, Chebyshev filter weights $\hat{w}_m(n)$ are designed to minimize the maximum value of $|\Gamma(\omega_d)|$ in the sidelobe region such that $\Gamma(0) = 1$ and $\frac{d\Gamma}{d\omega}(0) = 0$. In this paper, the method implemented to obtain $\hat{w}_m(n)$ is a computationally efficient numerical iterative design technique [9]. To design the Doppler window in this paper, an estimate, $\hat{a}(n)$ is inserted instead of known $a(n)$. Finally, given the Chebyshev Doppler window designed to account for the ionospheric aberration, the Doppler spectrum of the data is obtained by

$$P_m(\omega_d) = \left| \sum_{n=1}^N \hat{w}_m^*(n) e^{j\omega_d n} x_m(n) \right|^2 \quad (15)$$

for range bin m . Note that the window $\hat{w}_m(n)$ and the data $x_m(n)$ are all given in the time domain. In practice, because the aberration is constant only over a small neighborhood of range bins, $\hat{w}_m(n)$ must be estimated for each m using a sliding window across slant range.

5. SIMULATIONS AND REAL DATA RESULTS

The capability of the proposed method to mitigate spread Doppler clutter is illustrated both by simulation and real data results. For the simulations, a typical 2-second CIT radar waveform is considered with a nominal 70 dB maximum sidelobe level, defined in the absence of Doppler spreading. The data consists of first-order Bragg line sea backscatter clutter and a target at 50-knot radial velocity with 20 dB SNR. SNR is defined with respect to the sidelobe plus noise level of the unspread clutter. The Doppler spreading sequence is complex unit mean and variance Gaussian with a 4 Hz low-pass spectrum and -40 dB sidelobes. The spreading sequence was estimated from 4 neighboring range bins containing no target. Conventional Doppler processing includes the use of a Taylor window designed to have -70 dB sidelobes [10]. Figure 2 shows the conventional Doppler spectrum of the unspread clutter plus target (dashed line) and compares it with the conventional results when the clutter is Doppler spread (solid line). In the latter case, the weak target at Doppler frequency of 4.37 Hz is completely masked. Figure 3 contains the MWP Doppler spectrum in which the weak target can be clearly observed around 4 Hz.

In addition, MWP has been applied to real data, collected from a mid-latitude OTHR. The CIT is 3.1 seconds and bandwidth is 16 kHz. Figure 4 shows an example in which a 10dB improvement in sidelobe suppression is achieved by MWP.

6. CONCLUSIONS

In this paper, a Doppler spread mitigation method is proposed for OTHR Doppler processing. The ability of the method to increase the subclutter visibility by as much as 10 dB with respect to conventional processing is illustrated both with simulations and real data. This is achieved by exploiting the high degree of correlation

of the Doppler spreading sequence across range bins which can occur when the radar look direction is similar to the orientation of magnetic field aligned ionospheric irregularities.

7. ACKNOWLEDGEMENT

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8. REFERENCES

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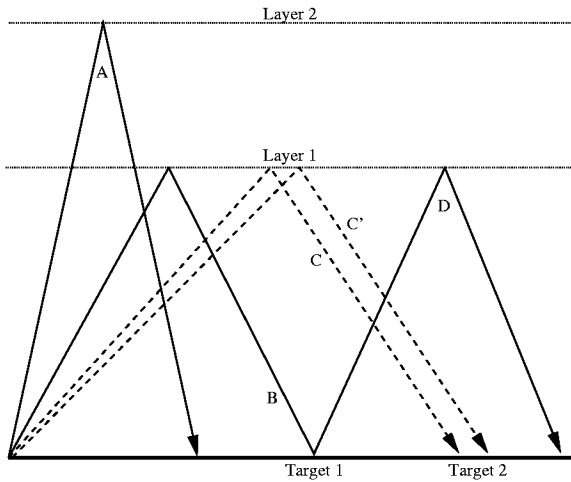


Figure 1: Illustration for mechanisms of spread Doppler clutter. (A) is the path for “proximate” clutter for target 1, (D) is the second-hop path for “separated” clutter for target 1 and (C’) is the path for “coincident” clutter for target 2.

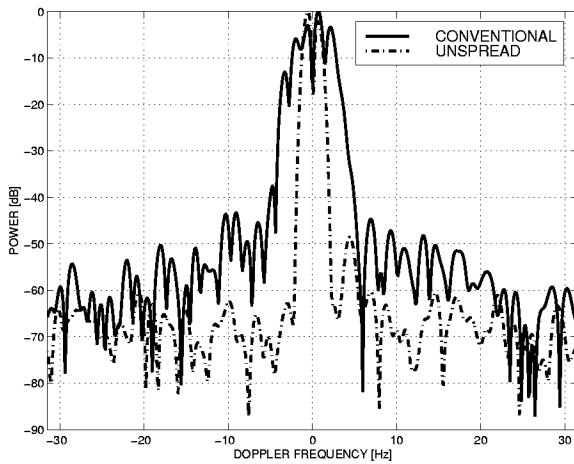


Figure 2: Simulated Doppler spectrum of spread versus unspread clutter and target.

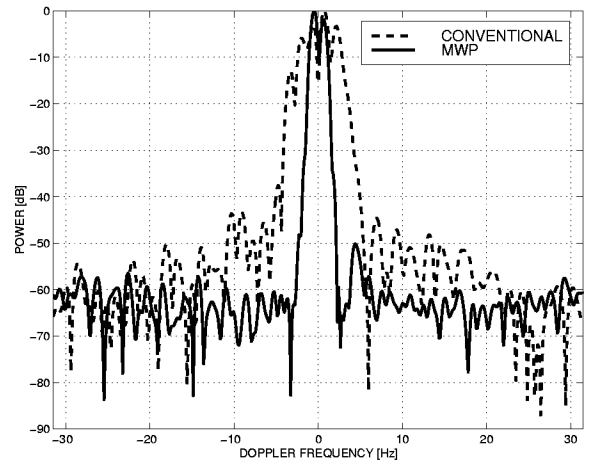


Figure 3: Simulated Doppler spectrum of aberration-matched Chebyshev window compared with conventional processing.

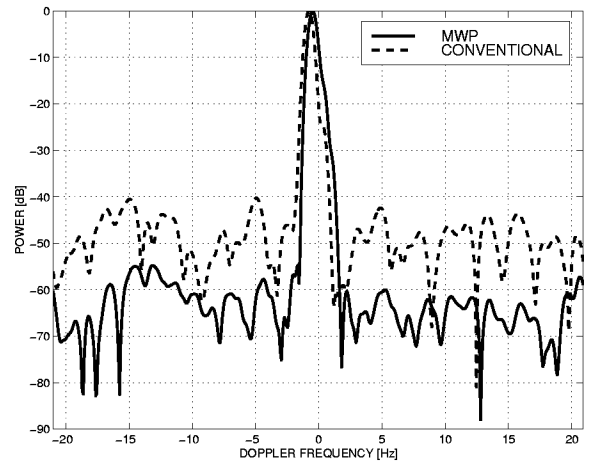


Figure 4: Experimental Doppler spectrum obtained with conventional processing with Taylor window. CIT is 3.1 sec and the data is from dwell at time 17:29:43.27 of November 4, 1997 at range 2775 km. Data length is 128.