PULSE COMPRESSION ECLIPSING REPAIR

Shannon D. Blunt

Electrical Engineering & Computer Science Department
University of Kansas, Lawrence, KS, USA

Karl Gerlach and Eric L. Mokole

Radar Division – US Naval Research Laboratory
Washington, DC, USA

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ABSTRACT

For radars operating with medium to high pulse repetition frequency (PRF), a loss in detection performance can result when the arrival of return echoes coincides with the transmission of a pulse, during which time the receiver is turned off. This so-called "eclipsing loss" is due to the partial reception of the reflected waveform corresponding to a given range cell. In this paper, the MMSE-based Adaptive Pulse Compression (APC) algorithm is modified to account for pulse eclipsing effects in order to improve the resolution accuracy of the eclipsed regions. Simulation results for the subsequent Eclipsing-Repair APC (APC-ER) are compared to results obtained from matched filtering and mismatched filtering, both of which are known to degrade in the presence of eclipsing, where it is found that APC-ER significantly improves the estimation of the eclipsed region.

1. INTRODUCTION

Eclipsing is the designation for the attendant loss that occurs for return echoes that arrive when the receiver is turned off during the transmission of a pulse [1,2]. As illustrated in Fig. 1, a return echo is eclipsed if it arrives in a time interval before pulse transmission is complete (echo (a)) or if it arrives in a time interval during which pulse transmission commences (echo (c)). For targets coinciding with the eclipsed regions, a signal-to-noise ratio (SNR) loss is experienced that is directly related to how far "into" the eclipsed region that the target lies as the degree of eclipsing for a given target corresponds to the amount of lost receive energy. Thus as the pulsewidth T_p increases relative to the pulse repetition interval (PRI) the likelihood and severity of eclipsing likewise increases. Also, as discussed in [3], for pulse compression radar waveforms such as chirps which garner bandwidth by sweeping across frequency, the loss of a portion of the reflected waveform via eclipsing can result in a significant reduction in range resolution within the eclipsed regions.

The eclipsing loss can likewise be viewed as a signal model mismatch. Least-Squares (LS) methods [4] for pulse compression do not model the eclipsed region to avoid rank deficiency in the LS formulation. Subsequently, LS approaches yield substantial degradation when targets lie in the eclipsed region. Furthermore, mismatched filters (for example [5,6,7]) which are generally based on some variation of the LS formulation likewise experience degradation due to this model mismatch.

Recently, a thresholded minimum mean-square error (MMSE-T) approach was proposed to alleviate the eclipsing problem [8]. When the eclipsed regions were properly accounted for, the MMSE-T approach was demonstrated to significantly improve detection performance for eclipsed targets. However, because it recursively inverts a matrix having dimensionality commensurate with the number of range cells in the receive window (potentially quite large), the computational requirements for this method tend to be significant.

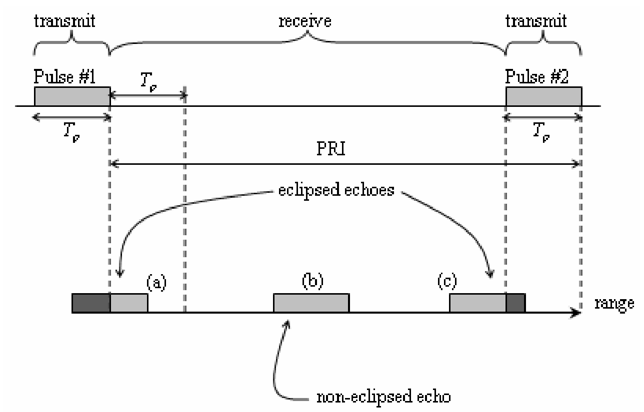

Figure 1. Example of eclipsed return echoes

In this paper, we examine the accurate resolution and resultant improved detection of targets that lie within the eclipsed region. Like [8], this estimation is performed on the basis of a minimum mean-square error (MMSE) criterion. However, the estimation here is performed locally by modifying the recently developed Adaptive Pulse Compression (APC) algorithm [9]. As such, the relative computational requirements can be much less than [8] with even lower complexity possible by utilizing the dimensionality reduction techniques discussed in [10]. The modification to the APC algorithm to accommodate eclipsing repair is in fact rather straight-forward. However, this modification enables the overall processing structure of APC to be altered and in so doing further improvement in estimation accuracy over the entire receive interval is obtained.

2. RECEIVED SIGNAL MODEL

Considering first the non-eclipsed region, a received radar return for the ℓ^{th} range cell can be defined as [5]

$$y(\ell) = \mathbf{x}^T(\ell)\mathbf{s} + v(\ell) \tag{1}$$

where $\mathbf{s} = [s_0\ s_1\ \cdots\ s_{N-1}]^T$ is the length-N sampled transmit waveform, $\mathbf{x}(\ell) = [x(\ell)\ x(\ell-1)\ \cdots\ x(\ell-N+1)]^T$ is the portion of the range profile that the transmitted waveform $\mathbf{s}$ convolves with at delay ℓ, $v(\ell)$ is additive noise, and $(\bullet)^T$ is the transpose operation. Collecting N samples of the received radar return signal, the received signal model can be expressed as

$$\mathbf{y}(\ell) = \mathbf{X}^T(\ell)\,\mathbf{s} + \mathbf{v}(\ell) \tag{2}$$

where $\mathbf{v}(\ell) = [v(\ell)\ v(\ell+1)\ \cdots\ v(\ell+N-1)]^T$ and

$$\mathbf{X}(\ell) = [\mathbf{x}(\ell)\ \ \mathbf{x}(\ell{+}1)\ \ \cdots\ \ \mathbf{x}(\ell{+}N{-}1)] = \begin{bmatrix} x(\ell) & x(\ell+1) & \cdots & x(\ell+N-1) \\ x(\ell-1) & x(\ell) & \cdots & x(\ell+N-2) \\ \vdots & \vdots & \ddots & \vdots \\ x(\ell-N+1) & \cdots & x(\ell-1) & x(\ell) \end{bmatrix}. \tag{3}$$

It is the received signal in (2) from which the standard matched filter estimate can be obtained as

$$\hat{x}_{MF}(\ell) = \mathbf{s}^H\,\mathbf{y}(\ell). \tag{4}$$

Combining equations (2) and (4) as

$$\mathbf{s}^H\mathbf{y}(\ell) = \mathbf{s}^H\mathbf{X}^T(\ell)\,\mathbf{s} + \mathbf{s}^H\mathbf{v}(\ell) \tag{5}$$

and using equation (3), it is observed that the application of the matched filter as in (4) has the effect of coherently matching to the portion of each received sample that corresponds to the main diagonal term in $\mathbf{X}(\ell)$, namely $x(\ell)$. However, in the eclipsed regions, the complete set of N receive samples in $\mathbf{y}(\ell)$ is not available. Hence, the receive vector to which the matched filter $\mathbf{s}^H$ is applied can be modelled as

$$\tilde{\mathbf{y}}_{n,1}(\ell) = [0\ \cdots\ 0\ \ y(\ell+n)\ \cdots\ y(\ell+N-1)]^T \tag{6}$$

for the first eclipsed region (at the beginning of the range window) and

$$\tilde{\mathbf{y}}_{n,2}(\ell) = [y(\ell)\ \cdots\ y(\ell+N-1-n)\ \ 0\ \cdots\ 0]^T \tag{7}$$

for the second eclipsed region (at the end of the range window) during a single PRI where $n \in \{1, 2, \ldots, N-1\}$ with n preceding and trailing zeros for (6) and (7), respectively.

Alternatively, an equivalent formulation for the eclipsed-region matched filter operation is to employ the set of N received signal samples adjacent to the given eclipsed region as

$$\mathbf{y}(\ell) = [y(\ell)\ y(\ell+1)\ \cdots\ y(\ell+N-1)]^T \tag{8}$$

and apply a shifted version of the matched filter denoted as $\mathbf{s}_n$ for $n \in \{1, 2, \ldots, N-1\}$ where

$$\mathbf{s}_{n,1} = [s_n\ \cdots\ s_{N-1}\ \ 0\ \cdots\ 0]^T \tag{9}$$

with n trailing zeros is applied to (8) for the range cells corresponding to the first eclipsed region and

$$\mathbf{s}_{n,2} = [0\ \cdots\ 0\ \ s_0\ \ s_1\ \cdots\ s_{N-n-1}]^T \tag{10}$$

with n preceding zeros is applied to (8) for the range cells corresponding to the second eclipsed region. By replacing either (9) or (10) as the matching filter in (5), it can be seen by referring to (3) that the shifted matched filter has the effect of coherently matching to the portion of each received sample that corresponds to the associated term on a given off-diagonal of $\mathbf{X}(\ell)$. It is this shifted matched filter formulation using (9) and (10) that we shall use to modify the APC algorithm to operate in the eclipsed regions.

3. ADAPTIVE ECLIPSING REPAIR

Using the signal model of (2), the APC algorithm was previously derived [5] to have the form

$$\mathbf{w}(\ell) = \hat{\rho}(\ell)\left(\hat{\mathbf{C}}(\ell) + \mathbf{R}\right)^{-1}\mathbf{s} \tag{11}$$

where $\hat{\rho}(\ell) = |\hat{x}(\ell)|^2$ is the current power estimate of $x(\ell)$, $\mathbf{R} = E[\mathbf{v}(\ell)\ \mathbf{v}^H(\ell)]$ is the noise covariance matrix. The structured signal correlation matrix estimate $\hat{\mathbf{C}}(\ell)$ is

$$\hat{\mathbf{C}}(\ell) = \sum_{m=-N+1}^{N-1} \hat{\rho}(\ell{+}m)\ \mathbf{s}_m\ \mathbf{s}_m^H \tag{12}$$

in which $\mathbf{s}_m$ is defined as $\mathbf{s}_m = [0\ \cdots\ 0\ \ s_0\ \ s_1\ \cdots\ s_{N-m-1}]^T$ with m preceding zeros for $m \geq 0$ and $\mathbf{s}_m = [s_{-m}\ \cdots\ s_{N-1}\ \ 0\ \cdots\ 0]^T$ with $|m|$ trailing zeros for $m \leq 0$. The power estimates $\hat{\rho}(\ell)$ can be initially obtained using a normalized version of the matched filter and are subsequently updated after each recursive stage of APC.

From (11) it is observed that the radar waveform $\mathbf{s}$ acts as the desired steering vector while the inverted matrix term $\left(\hat{\mathbf{C}}(\ell) + \mathbf{R}\right)^{-1}$ effectively places nulls in the range domain to suppress the sidelobe interference induced by nearby large scatterers. Also, the term $\hat{\rho}(\ell)$ in front acts to normalize the associated ℓ^{th} term in (12) so that a near-unity gain is achieved for the range cell being estimated. Based on these observations, we may modify the APC filter in (12) to estimate the range cells in the eclipsed regions. This modification is rather straight-forward and requires only that 1) the $\hat{\rho}(\ell)$ term in front be replaced with the current power estimate of the given eclipsed-region range cell $\hat{\rho}(\ell - n)$ or $\hat{\rho}(\ell + n)$ for the first or second eclipsed region, respectively, and 2) the waveform steering vector $\mathbf{s}$ be replaced with the shifted waveform $\mathbf{s}_{n,1}$ from (9) or $\mathbf{s}_{n,2}$ from (10) for $n \in \{1, 2, \ldots, N-1\}$ for the first or second eclipsed region, respectively. Hence, the Eclipsing-Repair APC (APC-ER) filter for the $N-1$ range cells in the first eclipsed region is

$$\mathbf{w}(\ell - n) = \hat{\rho}(\ell - n)\left(\hat{\mathbf{C}}(\ell) + \mathbf{R}\right)^{-1} \mathbf{s}_{n,1} \tag{13}$$

for $n \in \{1, 2, \ldots, N-1\}$ and the APC-ER filter for the second eclipsed region is

$$\mathbf{w}(\ell + n) = \hat{\rho}(\ell + n)\left(\hat{\mathbf{C}}(\ell) + \mathbf{R}\right)^{-1} \mathbf{s}_{n,2} \tag{14}$$

for $n \in \{1, 2, \ldots, N-1\}$.

By modifying the APC algorithm in this manner, estimates of the eclipsed-region range cells can be obtained with higher accuracy than can be achieved with the standard matched filter. However, this simple change also enables the general structure of the operation of APC to be altered. In Fig. 2 the updated range cell estimates for each stage of APC are illustrated. Note that, because the APC filter formulation in (12) is a function of the proximate $2N-1$ previous power estimates $\hat{\rho}(\ell)$ centered on the given range cell of interest, each successive stage of APC updates the estimate of $2(N-1)$ fewer range cells than the previous stage. As a result, the range cells on the outer edges have matched filter accuracy with the estimation accuracy improving for each multiple of $N-1$ range cells from the edge.

In contrast, because the APC-ER modification estimates "into" the eclipsed regions no reduction in the number of updated range cells is required since the proximate $2N-1$ previous power estimates are always available for the outermost range cells not in the eclipsed regions. Thus, as Fig. 3 illustrates, the APC-ER algorithm can achieve estimation accuracy better than APC in the outer regions of the range window including even the eclipsed regions.

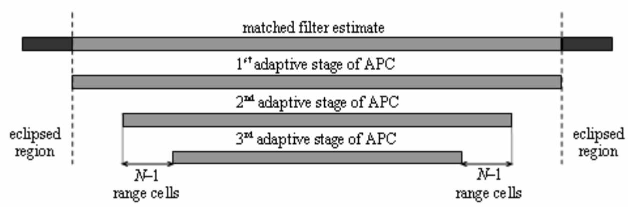

Figure 2. Swath of range cell estimates for each stage of APC

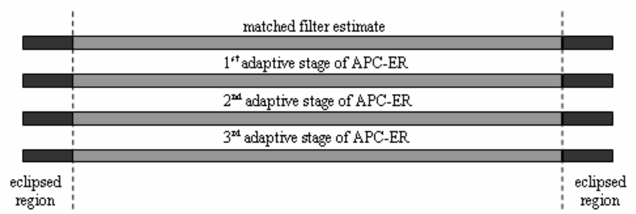

Figure 3. Swath of range cell estimates for each stage of APC-ER

4. SIMULATION RESULTS

To demonstrate the performance of the APC-ER algorithm, we consider two scenarios: a sparsely-populated range profile in which large scatterers reside in the eclipsed region and a more densely-populated range profile where scatterers are randomly distributed. For the radar waveform we select the first code in Table 1 of [7] which is a $N = 32$ length loss-constrained waveform optimized for the mismatched filter. The range window between eclipsed regions contains $L = 200$ range cells with each eclipsed regions (prior to range index 0 and after range index 200) each containing $N-1 = 31$ range cells.

For both scenarios, the matched filter, a LS-based mismatched filter of length $N_{\text{MMF}} = 100$, and the APC-ER algorithm are applied. The APC-ER algorithm is applied for 4 stages (the matched filter followed by 3 adaptive stages) with the α parameter in $\hat{\rho}(\ell) = |\hat{x}(\ell)|^{\alpha}$ set to 1.7, 1.4, and 1.4 for the three adaptive stages to prevent ill-conditioning (see [9] for details).

For the first scenario there are two large scatterers at range indices –10 and 117 that each possess a signal-to-noise ratio (SNR) of 60 dB. A third scatterer with SNR of 40 dB is also present in the eclipsed region at range index –20. For the simulation, the additive noise is white Gaussian. Additionally, to model the realistic dynamic range of the radar a random error floor (also white Gaussian) is set 70 dB below the large scatterers.

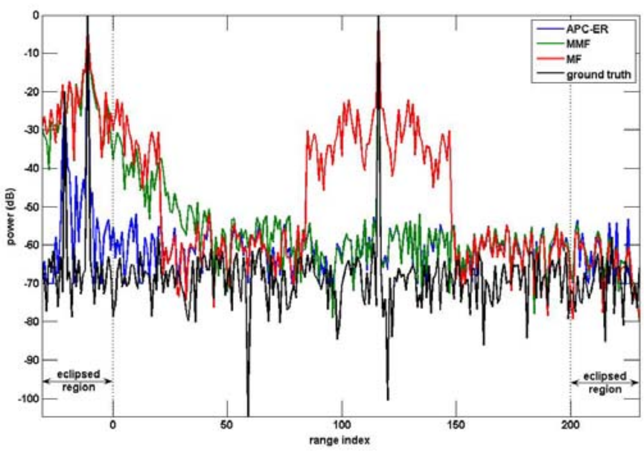

Figure 4. Range cell estimation performance for eclipsing in a sparsely-populated environment

It is observed in Fig. 4 that the matched filter (MF) induces sidelobes around the large scatterers as expected. By using a waveform optimized for the mismatch filter (MMF), the sidelobes around the large scatterer in the center are essentially suppressed into the noise. However, in the first eclipsed region the mismatch filter suffers from model mismatch effects resulting in performance on par with the matched filter. In contrast, the APC-ER algorithm suppresses the sidelobes from the large scatterer in the center and significantly reduces the sidelobes for the scatterers in the eclipsed region, enough so that the 40 dB SNR scatterer is easily detectable. In regard to relative mean-square error (MSE) performance over the range window and the eclipsed regions, the matched filter and mismatched filter achieve –27 dB and –28 dB, respectively, while the three adaptive stages of APC-ER yield MSE values of –42 dB, –44 dB, and –50 dB.

For the second scenario, multiple scatterers are randomly distributed throughout the entire range profile with randomly assigned power levels. Relative to the largest (randomly determined) scatterer power, the SNR is now 80 dB with the error floor set 90 dB below the largest scatterer. Similar to the previous scenario, in Fig. 5 the matched filter (MF) exhibits sidelobe effects while, at least in the center of the range window, the mismatch filter (MMF) significantly reduces the sidelobes. Both within and near the eclipsed regions the mismatch filter experiences degradation due to model mismatch. Also, the length ($N_{\text{MMF}} = 100$) of the mismatch filter causes the model-mismatch-induced sidelobes to spread into the range window (between range indices 0 and 200). As before, the APC-ER algorithm effectively suppresses the range sidelobes both within the range window and within the eclipsed regions. The relative MSE values over the entire range interval for the matched filter and mismatched filter is found to be –3 dB and –4 dB while the three adaptive stages of APC-ER yield relative MSE values of –14 dB, –29 dB, and –41 dB.

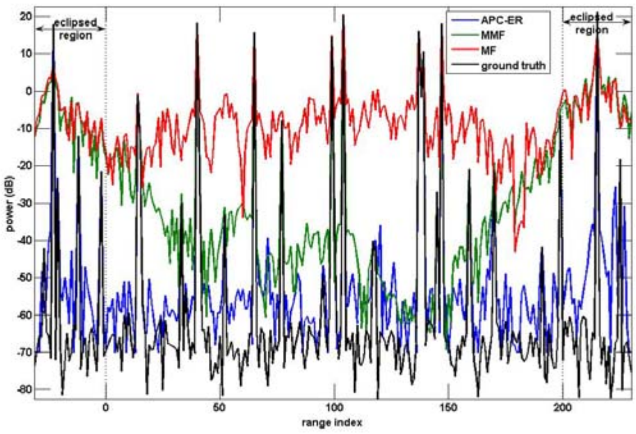

Figure 5. Range cell estimation performance for eclipsing in a densely-populated environment

CONCLUSIONS

Radar eclipsing poses a significant problem for medium to high PRF radars due to the intrinsic loss that occurs by not receiving the entire extent of the reflected signal for a given range cell. While optimum (in the LS sense) mismatch filters can significantly reduce range sidelobes, they are found to degrade in the eclipsed region due to model mismatch effects. In contrast, it has been demonstrated how a straightforward modification to the implementation of the Adaptive Pulse Compression (APC) algorithm, denoted as Eclipsing-Repair APC (APC-ER) enables relatively accurate estimation of the eclipsed region. In so doing, the general structure of the APC implementation is altered thereby yielding accurate estimation and resolution of targets over the entire range window inclusive of the eclipsed regions.

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