Efficient Direct Signal Cancellation for FM-based Passive Radar

Christof Schüpbach
armasuisse Science and Technology
Thun, Switzerland
christof.schuepbach@armasuisse.ch

Stephen Paine
armasuisse Science and Technology
Thun, Switzerland
stephen.paine@armasuisse.ch

Daniel O'Hagan
University of Cape Town
Cape Town, South Africa
daniel.ohagan@uct.ac.za

***Abstract*—The performance of an FM-based passive radar sensor is highly dependant on the level of suppression of direct signal interference. In this paper, we compare the performance of a selection of suppression algorithms in terms of detection performance and processing time. We show that the ECA-CD algorithm, even though originally designed for OFDM signals, can be applied to FM signals and that it performs well while being very computationally efficient.**

I. INTRODUCTION

Passive radar is a form of bistatic radar that uses existing transmitting infrastructure such as radio or cellular phone transmitters to detect and track targets of interest. Passive radar technology is starting to penetrate commercial and military markets as it matures. With the advancement in low-cost off-the-shelf computing devices it becomes feasible to build very cheap passive radar sensor networks. In [1] the authors demonstrated that a real-time implementation of a full passive radar processing chain is possible even on a very cheap Raspberry Pi 3B computer.

Irrespective of the computing platform used, mitigating direct signal interference (DSI) and other zero-Doppler clutter such as reflections from stationary objects, is among the most important challenges to the successful deployment of a passive radar sensor. Especially in the case of FM-based operation, detection of targets is only possible if the DSI is suppressed considerably and it has even been demonstrated in [2] and [3] that the DSI canceller can improve system performance in the presence of jamming by removing part of the jamming signal.

While significant work has been done in the area of DSI cancellation algorithms, many of the most common DSI suppression algorithms are computationally quite expensive and contribute a large portion of the overall processing time. Finding efficient algorithms is therefore crucial for the advancement of low-cost, low-power passive radar sensors.

Most FM based systems typically implement some form of least mean squares (LMS) based approach such as the extensive cancellation algorithm (ECA) or the conjugate gradient least squares (CGLS) algorithm [4], [5]. Palmer et al. demonstrated the effectiveness of various DSI cancellation algorithms applied to DVB-T passive radar data in [6] where it was found that optimisation of the Wiener-Hopf (WH) equations was able to achieve near-optimal performance with improved computational performance while LMS based filter approaches were able to achieve satisfactory performance with much improved computational performance, provided the cancellation region is not too large. An extension to this work was done by Garry et al. in [7] and [8] where the fast block least mean squares (FBLMS) algorithm was added to the comparison for DSI cancellation in DVB-T based passive radar. It was found that FBLMS provided strong DSI suppression while being significantly more computationally efficient than the WH filter approach.

In a paper by Schwark and Cristallini [9], the authors present an extension to the work done by Colone et al. [5] where the ECA algorithm is applied to OFDM-based signals such as DVB-T. This new approach, named extensive cancellation algorithm in carrier and Doppler (ECA-CD) was shown to provide a deep null with excellent computational efficiency when applied to OFDM-based signals.

The computational complexity of the described DSI suppression algorithms differs widely. Especially in the case of delay-Doppler processing via a 2-D FFT approach (batches algorithm [10], [11]), the cancellation stage of the algorithm can easily dominate the processing time per coherent processing interval (CPI). It is therefore desirable to choose algorithms that have strong suppression performance while being computationally efficient.

This paper investigates the performance of a selection of the current DSI algorithms applied to FM based passive radar. In particular, we demonstrate that the ECA-CD algorithm, which was originally conceived for OFDM signals, performs very well in conjunction with the batches algorithm while being computationally efficient.

The paper is organized as follows: Section II describes the overall processing chain that is assumed here, Section III gives an overview of the considered suppression algorithms. The results are presented in Section IV and Section V summarizes the findings.

II. OVERALL PROCESSING CHAIN

The processing chain used in FM passive radar is fairly mature, typically utilising two or more channels for data acquisition. Excluding the use of array based beamforming,

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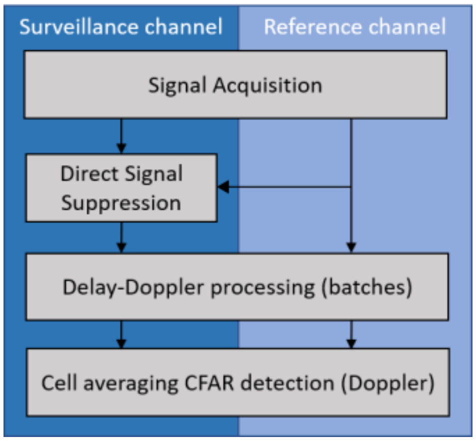

Figure 1: Block diagram of processing chain.

a typical FM passive radar consists of a reference antenna pointed directly towards the illuminator of opportunity (IoO) and a surveillance antenna, pointed away from the IoO and towards a surveillance volume. The signals are then coherently digitised before the DSI and strong zero-Doppler clutter is removed from the surveillance signal using the reference signal and an amplitude-range-Doppler (ARD) map is created using the reference signal and modified surveillance signal. The processing chain block diagram is illustrated in Figure 1. Since the goal is a computationally very efficient implementation, we use the 2-D FFT based batches approach for delay-Doppler processing [10].

III. OVERVIEW OF DSI ALGORITHMS

We assume a very simple model for the received surveillance signal:

$$S_{Surv} = S_{Tar} + S_{DSI}, \tag{1}$$

where S_{Tar} designates the desired part of the signal containing the target returns. To remove the DSI, S_{DSI}, from the surveillance signal, we need to subtract the interfering signal leaving (ideally) only the target echos. To produce an estimate of S_{DSI}, a matrix X can be constructed by building a matrix from the recorded reference signal and zero padding according to each bistatic range bin in which the DSI should be suppressed. We then require an estimate of the scaling coefficients, α, which are used to solve the equation $S_{DSI} = \alpha X$.

As the number of columns in X are made up of the number of delays and the rows represent the number of samples, the matrix A is typically not square and does therefore not have an inverse. This means that the equation $S_{DSI} = \alpha X$ is not directly solvable. The most common approach is therefore to minimise an error term given by $e = \alpha X - b$. This is simply the difference between the observed values, b, and the predicted values, αX. The least squares solution for calculating the filter coefficients α is that which minimises the error term:

$$min||\alpha X - b||^2 \tag{2}$$

A. Conjugate Gradient Least Squares

CGLS is an iterative least-squares algorithm that is efficient for well-defined matrices [12]. The method was explored as an adaptive filtering technique in 1992 by Boray et al. [13], who at the time wished to improve the performance of existing Least Mean Square techniques. As shown in [6], the CGLS algorithm is an extension of the conjugate gradient technique whereby with each iteration, the gradient is chosen to be conjugate to the previous gradient. This can then be used to determine $S_{DSI} = \alpha X$ using the least squares approach.

The CGLS algorithm achieves this by iteratively stepping towards a minimum value rather than performing a matrix inversion [14]. Once a satisfactory residual is achieved, the processing can be stopped. Alternatively, the algorithm can be run for a fixed number of iterations, regardless of whether a minimum has been achieved or not in order to maintain a fixed execution time. Performance can also be improved by priming the filter weights, α, from previous CPIs, provided the clutter scene is mostly stationary.

The number of iterations depends on the amount of computational power available as well as how small the error is required to be. The advantage of this approach over one shot algorithms such as ECA (discussed in the next section), is that it results in fixed execution times as well as a fixed memory footprint for a given cancellation matrix size.

B. Extensive Cancellation Algorithm

ECA proposed by Colone et al. in [5] assumes a clutter distribution up to the K^{th} range bin and in $2P{+}1$ Doppler bins centered around the zero-Doppler bin. ECA then attempts to remove the DSI from the surveillance channel based on a one-shot least-square minimisation. The output of the canceller, S_{ECA}, can be expressed mathematically as:

$$\begin{aligned} S_{ECA} &= S_{Surv} - S_{DSI} \\ &= S_{Surv} - \alpha X \end{aligned} \tag{3}$$

where S_{Surv} is the raw surveillance data and X represents the clutter subspace matrix. Each row in X is comprised of time and Doppler shifted replicas of the reference signal S_{Ref} where the parameter α is a column vector which applies a set of weights to each of the rows of X. The calculation of these weights is computationally expensive and is based on least-square theory where the residual energy in the surveillance channel, S_{Surv}, is minimised according to:

$$min||S_{Surv} - \alpha X||^2 \tag{4}$$

Solving (4) yields:

$$\alpha = (X^H X)^{-1} X^H \tag{5}$$

The resulting matrix X is a basis of the $K(2P{+}1)$ dimensional interference subspace where K represents the maximum discretised time delay (corresponding to the maximum range of DSI and zero-Doppler clutter) and P represents the maximum discretised Doppler shift to be cancelled. As a result, the computational requirements increase drastically as the cancellation subspace matrix X increases, leading to slow execution times.

C. Extensive Cancellation Algorithm by Carrier and Doppler

The primary limitation of the base implementations of the ECA algorithm is its time domain implementation. This makes the base ECA algorithm computationally and memory intensive due to the matrix scaling mentioned in the previous section.

Applying the ECA algorithm in the frequency domain rather than the time domain as demonstrated by Zhao et al. [15], can lead to a significant reduction in computational and memory requirements. In order to achieve the frequency domain implementation, an FMCW-like batches approach needs to be taken [10]. Known as ECA by carrier or ECA-C, the clutter subspace matrix, X, is then composed using each frequency carrier as follows:

$$X_{zero-Doppler} = Q_k = \begin{bmatrix} C_{k,1} & C_{k,2} & \ldots & C_{k,L} \end{bmatrix}^T$$

where $C_{k,i}$ represents the complex amplitude of the k^{th} carrier within the i^{th} batch. As a result, the ECA-C clutter subspace matrix need not account for delayed replicas of the reference signal in order to cancel each range bin, since a delay in the time domain applies only a phase shift in the frequency domain. This significantly reduces the dynamic memory requirements of the system by making it completely independent of the number of range bins to be canceled.

ECA-C was further extended by Schwark and Cristallini [9] to ECA by carrier and Doppler or ECA-CD to include Doppler shifted DSI. To account for non-stationary clutter, the final X matrix is constructed by applying p frequency shifts to each column of the $X_{zero-Doppler}$ matrix:

$$X = \begin{bmatrix} \Delta_{-p} Q_k & \ldots & Q_k & \ldots & \Delta_p Q_k \end{bmatrix}$$

The overall size of the X matrix is therefore reduced from $K(2P+1)$ for standard ECA to $(2P+1)$ for ECA-CD, leading to significantly reduced computational requirements. To apply ECA-CD to FM signals, the signal is treated as an OFDM signal and split into batches as described in [10]. Each batch is then treated as an OFDM symbol and processed as such without requiring any additional changes to the processing chain.

D. Fast Block Least Mean Squares

FBLMS was first demonstrated by Attalah et al. [16] as a means to suppress DSI in DVB-T based passive radar where it was shown to be highly efficient. As the name suggests, the FBLMS algorithm is a modified version of the LMS algorithm working on a batches-like approach. Like ECA-CD, FBLMS is implemented in the frequency domain, therefore providing increased computational performance compared to other time based approaches. Its implementation in the frequency domain makes it perfectly suited for the application in conjunction with delay-Doppler processing based on batches.

The FBLMS algorithm can be described as follows: Assume the complex surveillance signal, $S_{Surv}[n]$, is expressed as:

$$S_{Surv}[n] = \sum_{m=0}^{M-1} w_m S_{Ref}[n-m] + v[n] \tag{6}$$

where $S_{Ref}[n]$ is the complex reference signal, $v[i]$ is random noise, w_m is the filter tap coefficients representing the propagation channel and multipath components and M is the filter length. FBLMS is then used to determine an estimate $w[k]$ of the filter tap vector

$$w[k] = \begin{bmatrix} w_1[k] & \ldots & w_{M-1}[k] \end{bmatrix}^T$$

at block number k. The fundamental form of the update equation of the FBLMS for complex signals is therefore:

$$\begin{aligned} w[k+1] =& w[k] + \mu A^T[k] e^*[k] \\ =& w[k] + \mu \sum_{l=0}^{L-1} e^*[kL+l] S_{Ref}[kL+l] \end{aligned} \tag{7}$$

where k is the block number, L is the block length, μ is a step size and $A^T[k]$ is a data matrix. The estimation error vector $e[k]$ on the left-hand side of (7), given as:

$$e[k] = \begin{bmatrix} e[kL] & \ldots & e[kL+L-1] \end{bmatrix}^T$$

with the error:

$$e[kL+i] = S_{Surv}[kL+i] - w^H[k] S_{Ref}[kL+i] \tag{8}$$

where $e[n]$ on the right-hand side is the error at sample n. Note that the error signal, $e[n]$ is the actual output signal for the interference cancellation case.

IV. RESULTS

In literature, there are many different approaches taken when comparing the performance of DSI suppression algorithms. Since the overall performance of the passive radar system depends on the detection performance, we choose to compare the output of the detector. Additionally, the overall power in the ARD map is compared as well as relative compute times for each.

Algorithm	Processing Time [s]	relative duration
none	0.3	1.0
FBLMS	0.8	2.7
ECA	10.5	33.3
CGLS	6.4	21.3
ECA-CD	1.6	5.3

Table I: Absolute and relative processing times per CPI.

The algorithms are applied to a 300 s recording of an FM station close to the international airport of Zurich, Switzerland. Two directional antennas were used for the phase-coherent reference and surveillance channels. The recording was done on a PXI-based RF signal analyzer by National Instruments at a complex sampling rate of 240 kS/s. An integration time of 1 s was used and the signal was cut into 500 batches for delay-Doppler processing.

Table II summarises the processing parameters used for each cancellation algorithm in this comparison. The OFDM based algorithms inherently cancel the entire bistatic range profile while the analogue based algorithms can be tuned based on the clutter present in the signal.

The detection is based on a CA-CFAR detector in the Doppler domain with 4 training cells and 5 guard cells on

Cancellation Parameters	FBLMS	ECA	CGLS	ECA-CD
Range Bins	100	70	70	100
Doppler Bins	1	3	3	3
Segments	1	1	16	1
Iterations	-	-	30	-

Table II: Processing parameters for each cancellation algorithm (1.5 km per range bin with a total bistatic range of 150 km)

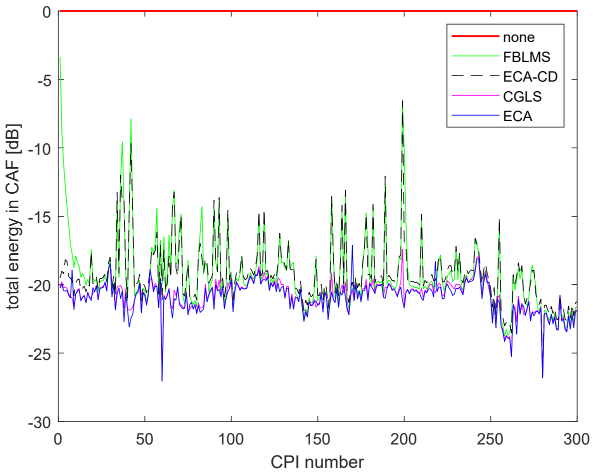

Figure 2: Relative total energy in ARD map for evaluated algorithms.

either side of the cell under test and a probability of false alarm of 10^{-5}. At the output of the CA-CFAR, only detections that correspond to local maxima in the original ARD map are kept and all others discarded.

The processing is done in MATLAB without any parallelisation or other optimisations, using a standard laptop computer with an Intel Core i7-7700HQ CPU. The average processing times per CPI are shown in Table I for the evaluated DSI algorithms where it is clear that there are significant differences. Compared to the CPI duration of 1 s, the FBLMS algorithm is by far the fastest and only adds very little to the overall processing time. This is followed by the ECA-CD algorithm that increases the duration of the processing just slightly over the requirement for real time processing. Both ECA and CGLS are computationally significantly more demanding.

Figure 2 shows the total energy of the ARD maps for the different algorithms compared to the energy of the same CPI without any DSI suppression. On average, all the algorithms suppress the energy by approximately 20 dB. The best suppression performance in this metric is exhibited by the ECA and CGLS algorithms. Both ECA-CD and FBLMS show very similar spikiness and almost identical values, except for the early CPIs where the FBLMS filter needs some time to converge.

The full measure of how well an algorithm performs is only revealed after evaluating the subsequent detection performance. As a baseline, we look at the accumulated detector output from 0 to 150 km bistatic range when no suppression is applied, shown in Figure 3. There are only false alarms and no clear target tracks. Clearly, the direct signal masks all the targets.

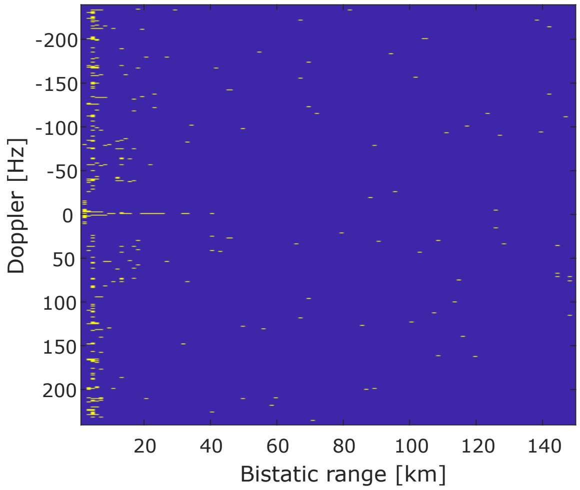

Figure 3: Accumulated CFAR output without DSI cancellation.

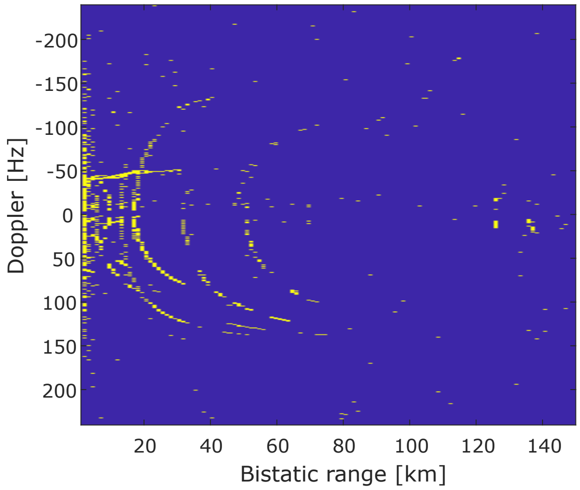

Figure 4: Accumulated CFAR output after CGLS cancellation.

Figures 4 and 5 show the results using the CGLS and ECA cancellation, respectively. As expected, these perform very similarly.

Figure 6 shows the results after FBLMS cancellation. Here, the zero-Doppler notch is very narrow compared to a relatively wide notch produced by the CGLS and ECA algorithms which results in the detector picking up targets at very low Doppler values. The overall performance, however, is clearly not as good as the CGLS and ECA algorithms.

Finally, Figure 7 shows the output of the ECA-CD algorithm. It appears to perform at least as good as the ECA and CGLS algorithms while having a narrower zero-Doppler notch, allowing for more consistent tracking when targets cross zero-Doppler. The slightly increased false alarm rate in the bands above and below zero-Doppler are due to the very deep zero-Doppler notch. This can easily be mitigated by filling in the notch with an interpolation of the neighboring cells or by using a greater-of CFAR approach that accounts for the artificially

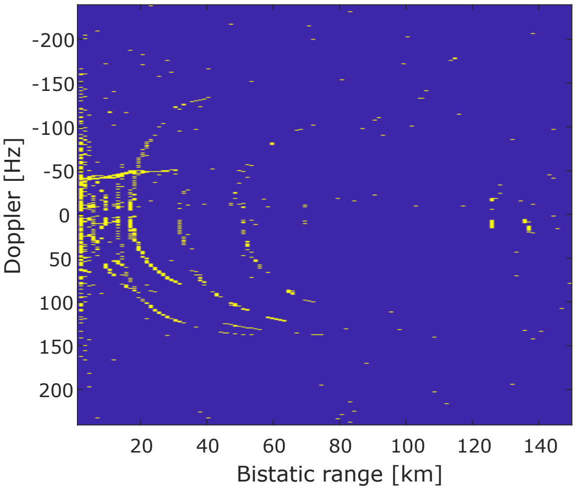

Figure 5: Accumulated CFAR output after ECA cancellation.

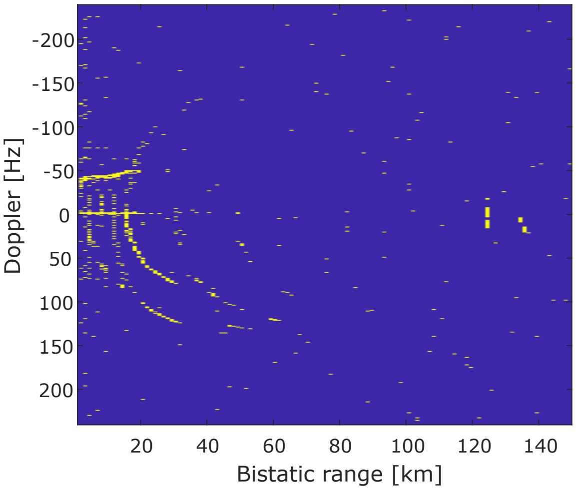

Figure 6: Accumulated CFAR output after FBLMS cancellation.

low threshold as a result of the zero-Doppler notch.

V. Conclusion

We showed that the ECA-CD suppression algorithm, which was previously only used for OFDM signals, can be applied to FM signals and ties into the processing chain very well if the delay-Doppler processing is done in batches and using a 2-D FFT approach. We compared the results to three commonly used suppression algorithms with respect to detection performance and relative processing time. The ECA-CD algorithm is shown to be significantly faster than ECA and CGLS while maintaining similar CFAR performance. While FBLMS is faster than ECA-CD, the CFAR detection performance is not as robust as when using ECA-CD. It is therefore concluded that ECA-CD offers an excellent balance between suppression performance and computational load.

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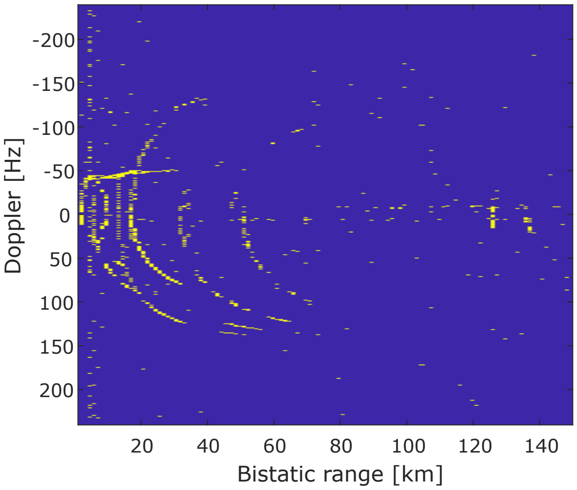

Figure 7: Accumulated CFAR output after ECA-CD cancellation.

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