

Analysis and compensation of dual-channel IF response mismatch for passive coherent locator receivers

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ABSTRACT

This paper investigates the effect of inter-channel IF imbalance on interference cancellation performance in a frequency modulation-based passive radar receiver. Differences in the magnitude and phase responses of the reference and surveillance channels can significantly reduce the effectiveness of direct-signal interference cancellation. A least-squares-based extensive cancellation algorithm combined with frequency-domain channel equalization is investigated to compensate for these mismatches. Simulations are performed in MATLAB using a frequency modulation signal centered at 96 MHz with a bandwidth of approximately 180 kHz. The results show that a 3 dB channel mismatch reduces the direct signal interference cancellation depth from 62.18 dB to 15.33 dB and degrades the output signal to noise ratio from 6.71 dB to -40.24 dB. After channel-response equalization, the cancellation depth and output SINR are restored to 61.97 dB and 6.47 dB, respectively. These results demonstrate that intermediate-frequency channel equalization can effectively mitigate inter-channel mismatch and significantly improve interference cancellation performance in passive radar receivers.

Keywords: Passive coherent locator system; Clutter; Range - Doppler image; Direct-signal interference.

1. INTRODUCTION

Passive coherent locator systems have become increasingly important in modern electronic warfare due to several advantages over active traditional radar, particularly their ability to operate with a low probability of detection and improved operational security. Unlike active radar, passive coherent locator systems (PCL) do not transmit echo signals but only receives and processes electromagnetic signals available within the surveillance area [1–4]. A common approach is to exploit existing transmitters, such as frequency modulation (FM), digital video broadcasting – terrestrial (DVB-T), long – term evolution (LTE), and fifth generation (5G), as illuminators of opportunity and sources of reference signals [5].

A typical passive radar receiver consists of two receiving channels: a reference channel, which receives the direct signal from a known transmitter, and a surveillance channel, which receives signals reflected from targets within the surveillance area. In practice, the surveillance signal contains not only target echoes but also the direct signal from the transmitter, referred to as direct signal interference (DSI), unwanted reflections from the surrounding environment (clutter), and noise. The DSI and clutter components can be significantly stronger than the weak target echoes [6]. Therefore, suppressing these unwanted components in the surveillance channel is important for improving target detection and classification performance in passive radar systems.

Other studies [7–10] have proposed various signal-processing methods for DSI and clutter suppression, including the Extensive Cancellation Algorithm (ECA) and its variants. These methods use the reference-channel signal to estimate and remove correlated interference components from the surveillance signal. However, the effects of the amplitude and phase responses of the two receiver paths, particularly their complex frequency-response mismatch at

the intermediate-frequency (IF) stage, have not been sufficiently investigated. Therefore, this paper focuses on evaluating the effect of the complex frequency-response mismatch between the two receiving channels on DSI cancellation performance at the IF stage.

The remainder of this paper is organized as follows. Section 2 presents the theoretical background, signal model, and DSI cancellation method. Section 3 describes the simulation setup and presents the results used to evaluate the effect of inter-channel response mismatch on DSI cancellation performance. Finally, Section 4 summarizes the main conclusions and discusses directions for future work.

2. SIGNAL MODEL AND DIRECT SIGNAL INTEFERRENCE CANCELLATION

2.1. Dual-channel signal model

The transmitted signal from the broadcast source is defined by $x(t)$. The reference channel is mainly composed of DSI and receiver noise and can be expressed by (1).

$$r_0(t) = a_r x(t - \tau_r) + n_r(t) \quad (1)$$

where a_r and τ_r are the complex amplitude and propagation delay of the direct-path signal and $n(t)$ is the noise signal. The surveillance channel contains DSI, reflections from the ground environment, target echoes and noise signals. Its received signal is defined by (2).

$$s_0(t) = a_d x(t - \tau_d) + \sum_{l=1}^L a_l x(t - \tau_l) + a_l x(t - \tau_l) e^{j2\pi f_D t} + n_s(t) \quad (2)$$

where a_d and τ_d correspond to the DSI component. The l^{th} clutter component is described by a_l and τ_l while a_l, τ_l and f_D are the complex amplitude, propagation delay and Doppler frequency of the target echo. Since the two signals pass through separate receiver chains, their IF output is defined by (3).

$$\begin{cases} r(t) = h_r(t) * r_0(t) \\ s(t) = h_s(t) * s_0(t) \end{cases} \quad (3)$$

where $h_r(t)$ and $h_s(t)$ represent the IF responses of the reference and surveillance channels. In practice, these two responses are not identical because the receiver paths use separate analog components. To account for the effect of the receiver paths, the signals at the outputs of the two IF channels are expressed in the frequency domain as (4).

$$\begin{cases} R(f) = H_r(f) R_0(f) + N_r(f) \\ S(f) = H_s(f) S_0(f) + N_s(f) \end{cases} \quad (4)$$

where $H_r(f)$ and $H_s(f)$ are the frequency responses of the reference and surveillance IF channels $N_r(f)$ and $N_s(f)$ are the internal noise introduced by the two receiver paths [12].

2.2. Inter-channel IF response mismatch

The complex frequency responses of the reference and surveillance IF channels are defined by (5).

$$\begin{cases} H_r(f) = A_r(f) e^{j\phi_r(f)} \\ H_s(f) = A_s(f) e^{j\phi_s(f)} \end{cases} \quad (5)$$

where $A_r(f)$, $\phi_r(f)$ and $A_s(f)$, $\phi_s(f)$ are the amplitude and phase of the reference and surveillance IF channels. For ideally matched receiver channels.

$$H_r(f) = H_s(f) \quad (6)$$

In practice, differences in component tolerances, cables, filters, amplifiers and mixers introduce amplitude and phase differences between the two receiver paths. The relative response mismatch is therefore defined as (7).

$$\Delta H(f) = \frac{H_s(f)}{H_r(f)} = A_\Delta(f) e^{j\phi_\Delta(f)} \quad (7)$$

where $A_\Delta(f)$ and $\phi_\Delta(f)$ are the relative amplitude and phase responses between the two channels. For perfectly matched channels, $\Delta H(f)$ is expressed by (8).

$$\Delta H(f) = \frac{H_s(f)}{H_r(f)} = A_\Delta(f) e^{j\phi_\Delta(f)} = 1 \quad (8)$$

The amplitude, phase and corresponding group-delay mismatch are defined by (9).

$$\begin{cases} \Delta A(f) = 20 \log_{10} A_\Delta(f) \\ \Delta \phi(f) = \phi_s(f) - \phi_r(f) \\ \Delta \tau_g(f) = -\frac{1}{2\pi} \frac{d\Delta \phi(f)}{df} \end{cases} \quad (9)$$

Therefore, the simulations in Section 3 examine the cancellation performance as a function of both the inter-channel response mismatch and the cancellation-filter length K [13].

2.3. Direct signal interference and clutter cancellation and performance evaluation

After digitization, the reference and surveillance signals are defined by $r[n]$ and $s[n]$. DSI and correlated clutter are suppressed using LS/ECA canceller constructed from delayed replicas of the reference signal. For a filter length K , the reference matrix is defined by (10).

$$X_r = \begin{bmatrix} r[0] & r[-1] & \cdot & \cdot & r[-K] \\ r[1] & r[0] & \cdot & \cdot & r[1-K] \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ r[n-1] & r[n-2] & \cdot & \cdot & r[n-K-1] \end{bmatrix} \quad (10)$$

where each column represents a delayed version of $r[n]$. The cancellation weights are obtained by solving equation (11).

$$\begin{cases} \hat{w} = \arg \min \|s - X_r w\|^2 \\ \hat{w} = (X_r^H X_r)^{-1} X_r^H S \end{cases} \quad (11)$$

The estimated DSI/clutter component and the residual signal are then defined by (12)

$$\begin{cases} d = X_r w \\ y = s - d \end{cases} \quad (12)$$

In numerical implementation, (12) is solved using QR or SVD rather than by explicitly forming the matrix inverse. If $X_r^H X_r$ is poorly conditioned, Tikhonov regularization can be used (13)

$$w\lambda = \left(X_r^H X_r + \lambda I \right)^{-1} X_r^H S \quad (13)$$

Unless otherwise stated, K , the clutter-delay region, observation interval, and regularization parameter are kept fixed when comparing different mismatch conditions.

The effect of inter-channel mismatch depends on whether the resulting relative response $\Delta H(f)$ can be represented by the cancellation filter. A constant complex gain or a relative delay within the modeled delay span can generally be absorbed into the LS coefficients. In contrast, a frequency-dependent mismatch may require a longer equivalent impulse response. If this response cannot be represented by the selected K taps, part of the DSI/clutter remains in $s[n]$. Cancellation performance is quantified by the DSI cancellation depth (14).

$$C_{DSI} = 10 \log_{10} \left(\frac{P_{before}}{P_{after}} \right) \quad (14)$$

where P_{before} and P_{after} are the DSI/clutter powers before and after cancellation. The corresponding effect on target detection is evaluated using the output SINR (15).

$$SINR = 10 \log_{10} \left(\frac{P_t}{P_{res} + P_n} \right) \quad (15)$$

where P_t is the target power, P_r is the residual interference power, and P_n is the receiver noise power. After cancellation, the bistatic range–Doppler map is obtained from the cross-ambiguity function between $s[n]$ and $r[n]$ by (16)

$$\chi(\tau, f_D) = \sum s[n] r^*[n - \tau] \exp(-j2\pi f_D n / F_s) \quad (16)$$

here, τ and f_D denote the bistatic delay and Doppler frequency, respectively, and F_s is the sampling frequency. A target is expected to produce a peak near its corresponding delay–Doppler cell. Residual DSI/clutter raises the background level and can mask weak target returns. When measured responses $H_r(f)$ and $H_s(f)$ are available, the surveillance channel can be equalized before cancellation by (17) and (18).

$$\begin{cases} C(f) = \frac{H_r(f)}{H_s(f)} \\ S_{eq} = C(f) S(f) \end{cases} \quad (17)$$

$$C_\lambda(f) = \frac{H_r(f) H_s^*(f)}{|H_s(f)|^2 + \lambda} \quad (18)$$

where λ limits noise amplification. The equalized signal is transformed back to the time domain and processed using the same LS/ECA procedure.

3. RESULTS AND DISCUSSION

3.1. Input data

The input data are generated using a broadcast FM signal centered at $f_c = 96$ MHz with an occupied bandwidth of approximately $BW = 180$ kHz. The RF sampling frequency is set to $F_{s,RF} = 500$ MS/s. The same FM waveform is used as the common source for both the reference and surveillance channels. Controlled magnitude and phase differences are then introduced between the two IF-channel responses to investigate the effect of channel imbalance on interference

cancellation performance. The parameters for simulating are listed in Table 1.

3.2. Methods, simulation tools

The simulation was implemented in MATLAB using a broadcast FM signal centered at $f_c = 96$ MHz. The reference and surveillance channels were generated from the same FM waveform, with controlled magnitude and phase mismatches introduced between their IF responses. The LS/ECA algorithm and frequency-domain channel equalization were applied to investigate interference cancellation performance under different channel mismatch conditions. Performance was evaluated in terms of DSI cancellation depth, output SINR, and range–Doppler response. The simulation procedure is summarized in Figure 1.

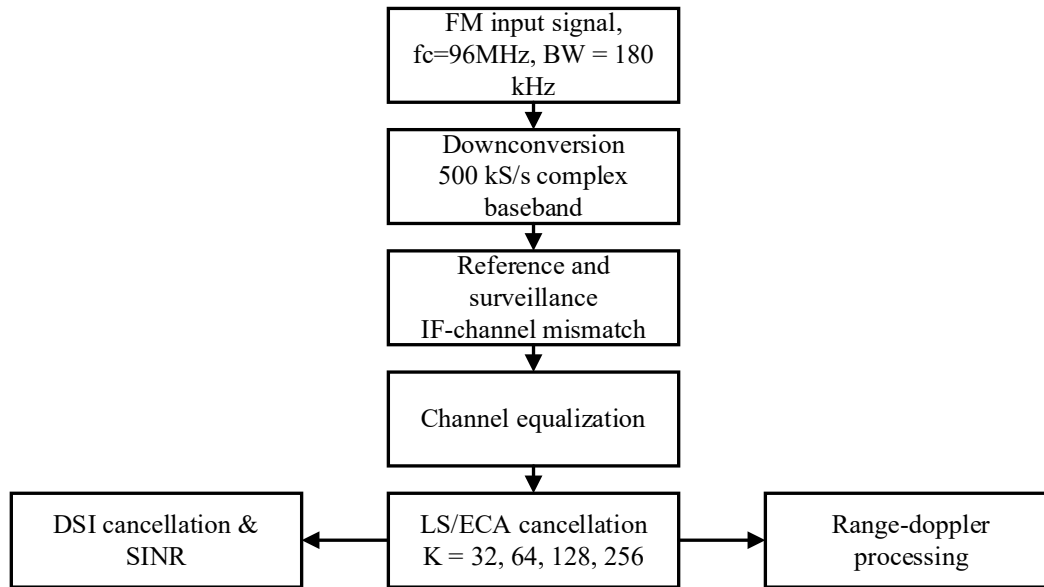


Figure 1. Simulation procedure for evaluating the effect of IF-channel imbalance on interference cancellation performance.

Table 1. FM signal and receiver parameters.

Parameter	Symbols	Value
FM carrier frequency	f_c	96 MHz
RF sampling frequency	$F_{s,RF}$	500 MS/s
FM signal bandwidth	BW	180 kHz
Maximum frequency deviation	Δf	± 75 kHz
Modulating signal bandwidth	B_m	15 kHz
Clutter relative power	P_c	-20 to -45 dBm
Target relative power	P_t	- 65 dBm
Target Doppler frequency	f_D	+ 80 Hz
Receiver noise power	P_n	- 75 dBm
LS/ECA filter length	K	32, 64, 128, 256
Maximum magnitude mismatch	ΔA	0 – 3 dB

3.3. Simulation results and comments

Figure 2 shows the spectra of the simulated reference and surveillance signals centered at $f_c = 96$ MHz with an occupied bandwidth of approximately $BW = 180$ kHz. Figure 2(b) shows that there is only a small change in the spectrum view. Figure 3(a) presents the frequency responses of the reference and surveillance channels, $H_r(f)$ (red line) and $H_s(f)$ (blue line) showing the response difference between the two IF paths (3 dB).

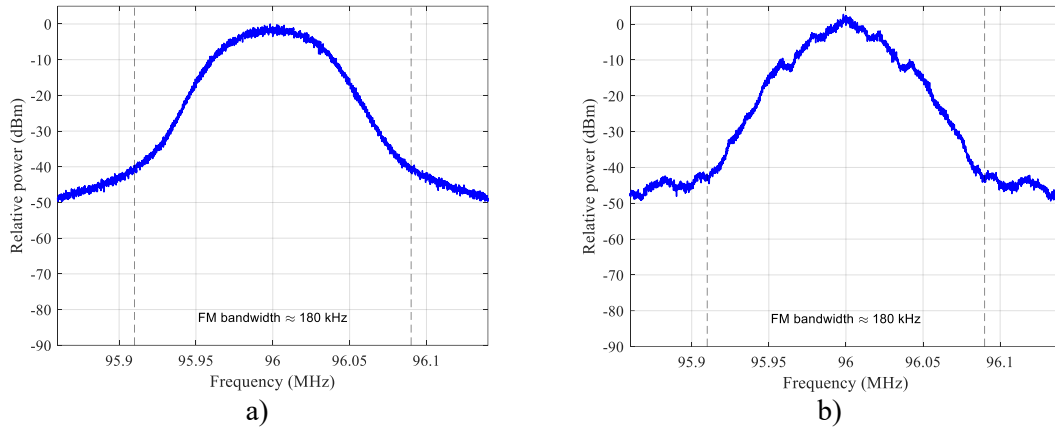


Figure 2. Received signal of passive system: a) Reference channel; b) Surveillance channel.

Figure 3(b) shows a range-Doppler map of the echo target. The range-Doppler map contains numerous false targets (yellow peaks), making the actual target difficult to identify. This result indicates that imbalance between the two receiver channels significantly degrades target detectability. Figure 4(a) illustrates the effect of inter-channel mismatch on the DSI cancellation performance of the LS/ECA algorithm. Under the ideal condition, the DSI cancellation depth reaches approximately $C_{DSI} = 62.18$ dB. As the mismatch increases, the cancellation performance of LS/ECA without channel equalization decreases to $C_{DSI} = 15.3$ dB at $C(f) = 3$ dB (blue line).

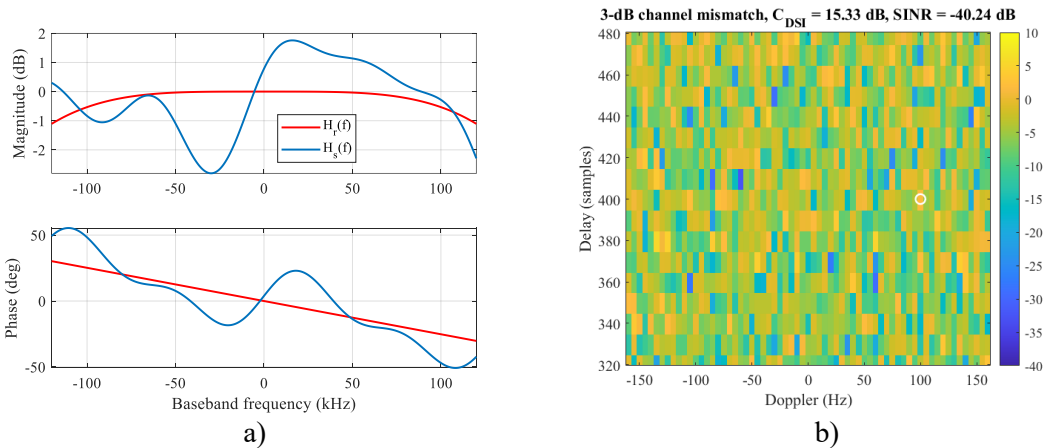


Figure 3. Simulation results: a) Frequency responses; b) Range-Doppler map.

As shown by the blue line, increasing the LS/ECA filter length alone provides only marginal improvement, with the cancellation depth remaining around $C_{DSI} = 15$ dB. In contrast, when channel equalization is applied before LS/ECA, the cancellation depth increases from approximately $C_{DSI} = 24$ dB at $K = 32$ to $C_{DSI} = 61.97$ dB at $K = 128$ and remains stable thereafter (red line, Figure 4(b)). These results demonstrate that channel equalization is essential

for mitigating inter-channel response mismatch, whereas simply increasing the LS/ECA filter length is insufficient.

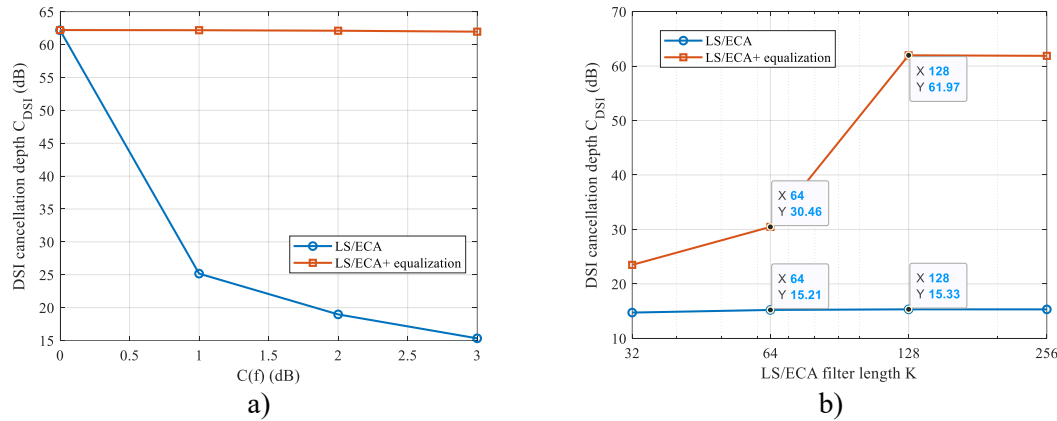


Figure 4. Simulation results: a) DSI cancellation vs IF mismatch; b) DSI cancellation vs K .

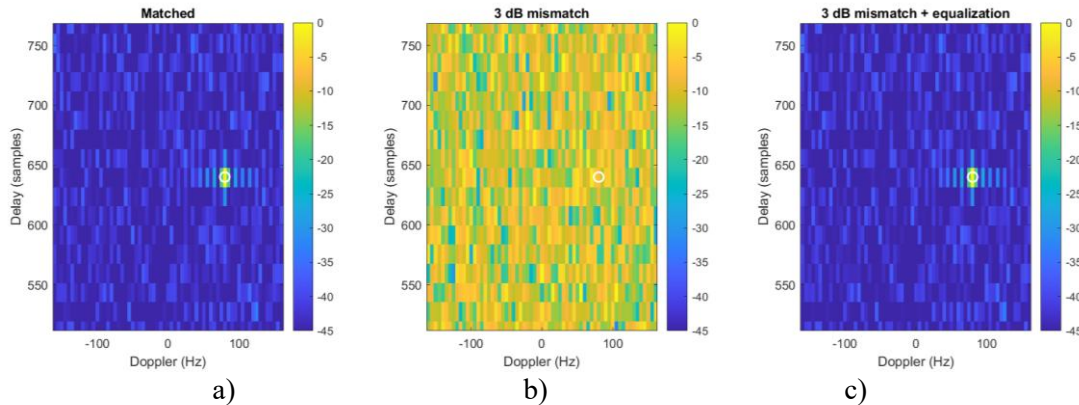


Figure 5. Range-Doppler maps: a) Matched; b) Mismatch; c) Mismatch + EQ.

Figure 5 shows that the matched-channel case shows a clear target peak at the expected delay–Doppler position. A 3 dB channel mismatch significantly raises the background level and masks the target, whereas channel equalization suppresses the residual interference and restores the target peak.

4. CONCLUSIONS

This paper investigated the effect of inter-channel IF imbalance on interference cancellation performance in a passive coherent locator receiver using an FM signal. Simulation results showed that frequency-dependent channel mismatch significantly degraded LS/ECA performance. For a $C(f) = 3$ dB mismatch, the DSI cancellation depth decreased from $C_{DSI} = 62.18$ dB in the matched-channel case to $C_{DSI} = 15.33$ dB, while the output SINR decreased from $\text{SINR} = 6.71$ dB to $\text{SINR} = -40.24$ dB. Increasing the LS/ECA filter length alone provided only limited improvement. By applying channel-response equalization, the cancellation depth was restored to $C_{DSI} = 61.97$ dB and the output SINR improved to $\text{SINR} = 6.49$ dB, approaching the matched-channel performance. These results demonstrate the importance of IF-channel balance and channel-response compensation for effective interference suppression in passive coherent locator receivers.

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TÓM TẮT

Nghiên cứu và đánh giá bù sai lệch đáp ứng tuyến trung tần giữa hai kênh trong máy thu radar thụ động

Bài báo nghiên cứu ảnh hưởng của sự mất cân bằng giữa các kênh trung tần đến hiệu quả triệt nhiễu trong hệ thống radar thụ động sử dụng tín hiệu FM. Sự sai khác về đáp ứng biên độ và pha giữa kênh tham chiếu và kênh giám sát có thể làm suy giảm đáng kể khả năng triệt nhiễu tín hiệu trực tiếp. Phương pháp triệt nhiễu LS/ECA kết hợp với cân bằng đáp ứng kênh trong miền tần số được sử dụng nhằm bù sai lệch giữa hai kênh. Mô phỏng được thực hiện trên MATLAB với tín hiệu FM có tần số trung tâm 96 MHz và băng thông xấp xỉ 180 kHz. Kết quả cho thấy khi sai lệch biên độ giữa hai kênh là 3 dB, độ sâu triệt DSI giảm từ 62,18 dB xuống 15,33 dB và SINR đầu ra giảm từ 6,71 dB xuống -40,24 dB. Sau khi cân bằng đáp ứng kênh, độ sâu triệt DSI và SINR đầu ra được phục hồi tương ứng lên 61,97 dB và 6,49 dB. Kết quả cho thấy cân bằng kênh IF có khả năng bù hiệu quả sai lệch giữa hai kênh và cải thiện đáng kể hiệu quả triệt nhiễu trong hệ thống radar thụ động.

Từ khoá: Radar thụ động; Nhiễu; Ảnh cự ly – Doppler; Tín hiệu trực tiếp.