A Sidelobe Mitigation Method for an FM-radio-based PCL System

So-Young Son, Geun-Ho Park and Hyoung-Nam Kim
Department of Electronics Engineering
Pusan National University
Busan, Republic of Korea
hnkim@pusan.ac.kr

Kyu-Ha Song, and Jun-Il Ahn
Agency for Defense Development
Daejeon, Republic of Korea
junilahn98@gmail.com

***Abstract*—A passive coherent location (PCL) system is a passive radar system, where frequency modulation (FM) stereo signals are commonly used. This system detects targets by calculating the cross-ambiguity function (CAF) between the direct-path signal and the target echo signal. Due to the structure of the FM stereo signal, however, several sidelobes occur in the result of the CAF. These sidelobes may degrade the target detection performance by increasing the false alarm rate in the detection process. In this paper, we show that the sidelobes are generated in the CAF due to a characteristic of the FM stereo signal. Then, we apply a mismatched filtering algorithm to reduce the sidelobe level in the CAF and analyze the amount of sidelobe reduction.**

***Keywords*—FM stereo signal; passive coherent location; sidelobe mitigation; mismatched filtering**

I. Introduction

An FM-radio-based PCL system is a passive radar that tracks the position and the velocity of a target by using commercial FM broadcasting signals [1, 2]. The PCL system operates two channels of a reference channel and a surveillance channel. The reference channel is designed to obtain a direct-path signal propagating along the straight path between the FM transmitter and the receiver. The surveillance channel aims to receive a target echo signal. The position and the velocity of the target can be estimated by using the time difference of arrival (TDOA) and the frequency difference of arrival (FDOA) between the direct-path signal and the target echo signal. This information can be obtained by calculating the cross-ambiguity function (CAF) [1].

Due to the structure of the commercial FM broadcasting signal, however, multiple sidelobes appear in the FDOA axis of the CAF [3]. These sidelobes degrade the target detection performance by increasing the false alarm rate in the detection process. In order to solve this problem, the side peaks identification (SPI) method was proposed [3]. Using the symmetry of the sidelobes, this method excludes asymmetric detection results from the entire detection results. However, this method cannot reduce the sidelobe level in the CAF, and also cannot be used when the detection result of the sidelobes is not symmetric. Therefore, it is necessary to reduce the sidelobe level in the CAF. The mismatched filtering was proposed to mitigate the sidelobe of the CAF in an ATV (analog television)-based PCL system [4]. However, this algorithm has never been applied to the FM-radio-signal-based PCL system.

Therefore, in this paper, we analyze the tendency of the sidelobes in the FDOA axis due to the structure of the FM stereo signal. After generating the FM stereo signal, the sidelobes in the FDOA axis generated in the CAF are verified through computer simulations. Then, we apply the mismatched filtering algorithm to the FM-based PCL system and show that the sidelobe level can be reduced in the CAF.

II. FM Stereo Signal and Analysis of Sidelobe

A. FM stereo signal

The FM stereo signal contains the left channel signal (L) and the right channel signal (R). Each channel signal is produced by two speakers, respectively. The message signal of the FM stereo signal also includes a pilot tone of 19 kHz. (L+R) signal is placed at baseband, and (L-R) signal has a center frequency of 38 kHz. The message signal of the FM stereo signal is written as

$$m(t) = 0.9\left[\frac{L+R}{2} + \frac{L-R}{2}sin\left(4\pi f_p t\right)\right] + 0.1\,sin\left(2\pi f_p t\right), \quad (1)$$

where f_p represents pilot tone of 19 kHz.

The transmitted FM stereo signal is generated as a complex baseband signal using (1). The transmitted FM stereo signal is written as

$$s(t) = exp\left\{j2\pi k_f \int_0^t m(\tau)\,d\tau\right\}, \quad (2)$$

where k_f denotes the maximum frequency deviation of 75 kHz.

B. Analysis of sidelobe in cross-ambiguity function [3]

As mentioned in Introduction, the sidelobes of the FDOA axis are caused by the structure of the FM stereo signal. This section reviews the characteristic of the sidelobes.

Substituting (1) into (2), the transmitted FM stereo signal in (2) can be rewritten as

$$\begin{aligned} s(t) = {} & exp\left\{j2\pi k_f \times \frac{0.9}{2}\int_0^t [L(\tau)+R(\tau)]\,d\tau\right\} \\ & \times exp\left\{j2\pi k_f \times \frac{0.9}{2}\int_0^t [L(\tau)-R(\tau)]\,sin\left(4\pi f_p \tau\right)d\tau\right\} \\ & \times exp\left\{j2\pi k_f \times 0.1\int_0^t sin\left(2\pi f_p \tau\right)d\tau\right\}. \quad (3) \end{aligned}$$

In (3), the integral term of the (L+R) signal can be defined by

$$S_{int}(t) = \int_0^t [L(\tau) + R(\tau)]\, d\tau. \quad (4)$$

Through more detailed discussions in [3], we can notice that the sidelobes appear in the value of the FDOA axis of $f_d{}'$ which can be written as [3]

$$f_d' = f_d \pm m f_p \pm n f_i, \quad (5)$$

where f_d represents the Doppler frequency of the target, f_i denotes high frequency component in (4), and m, k are positive integers including 0 that satisfy $m + n \neq 0$. Considering the FDOA of the target is within $\pm$ 450 Hz, the multiples of the pilot tone, $\pm m f_p$, exceeds this range. Thus, within the Doppler frequency of interest, (5) can be simplified as

$$f_d' = f_d \pm k f_i. \quad (6)$$

III. Mismatched Filtering

In an FM-based PCL system, the location and the velocity of the target can be estimated by calculating the CAF. The CAF is defined as

$$\chi(\tau, f) = \int_{-\infty}^{\infty} s_{ref}(t) s_{surv}^{*}(t + \tau) e^{-j2\pi f t}\, dt, \quad (7)$$

where s_{ref} represents the reference channel containing the direct-path signal, $s_{surv}(t)$ denotes the surveillance channel including the target echo signal.

As analyzed in Section II, the sidelobes occur in the FDOA axis of the CAF due to the structure of the FM stereo signal. The mismatched filtering was proposed to mitigate the sidelobe of the CAF in an ATV-based PCL system [4]. However, due to some differences between the ATV signal and the FM stereo signal, the mismatched filtering in [4] needs to be modified to apply to the FM-radio-based PCL.

The mismatched filtering uses a factor instead of the reference channel in deriving the CAF. Therefore, the CAF of the mismatched filtering is defined as

$$\chi_{mis}(\tau, f) = \int_{-\infty}^{\infty} w(t) s_{surv}^{*}(t + \tau) e^{-j2\pi f t}\, dt, \quad (8)$$

where $w(t)$ is a factor of mismatched filtering derived from a cost function that minimizes the total energy of the sidelobes. Although ATV signal has the sidelobes of the TDOA and FDOA axis in the CAF [4], the FM stereo signal only considers the sidelobes of the FDOA axis.

The sampled versions of the reference channel and the surveillance channel are written as

$$\mathbf{s}_{ref} = [s_{ref}[0], s_{ref}[1], \cdots, s_{ref}[N-1]]^T, \quad (9)$$

$$\mathbf{s}_{surv} = [s_{surv}[0], s_{surv}[1], \cdots, s_{surv}[N-1]]^T, \quad (10)$$

where N is the number of observation samples. Using these discrete-time representations, (8) can be expressed as

$$\chi_{mis}[l, p] = \sum_{i=0}^{N-1} w[i] s_{surv}^{*}[i + l] e^{-j2\pi p i/N}, \quad (11)$$

where $w[i]$ is a factor of mismatched filtering. This factor can be obtained as

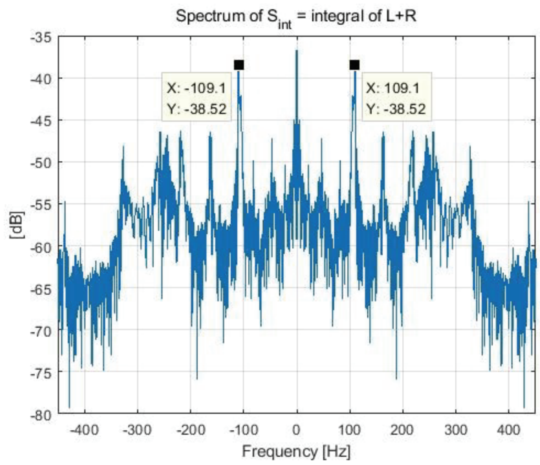

Fig. 1. Power spectrum of $\boldsymbol{S_{int}}$.

$$\mathbf{w} = (\mathbf{I}_N + c \textstyle\sum_d \mathbf{S}_{shift,d} \mathbf{S}_{shift,d}^H)^{-1} \mathbf{s}_{ref}, \quad (12)$$

where c is the coefficient for the adjusting the suppression level of the sidelobe. $\boldsymbol{S_{shift}}$ is the time and the frequency shifted reference signal:

$$\boldsymbol{S}_{shift} = \mathbf{s}_{ref}^{d} e^{j2\pi f_i t}, \quad (13)$$

where $\mathbf{s}_{ref}^{d}$ represents d samples delayed version of the reference channel. The sidelobe caused by the FM stereo signal is slightly off-centered from the mainlobe [3]. Thus, we propose to use a delayed version of the reference channel for the derivation of the factor in the mismatched filtering. We verify the sidelobe suppression performance of the proposed method in Section IV.

The inverse of the $N \times N$ matrix in (12) requires high computational complexity. Thus, instead of computing the whole inverse matrix, the whole signal is divided into several small batches to obtain the factor of mismatched filtering with relatively low computational burden. A detailed discussion of the batch version algorithm is described in [4].

IV. Simulation Results

The FM stereo signal is generated from the source file of the rock music. The number of samples of the FM stereo signal used in the simulation is 220,500. It is assumed that the reference channel receives the direct-path signal of 90 dB and the surveillance channel obtains the target echo signal of -10 dB. In addition, the target echo signal is assumed to be delayed by 15 samples. In order to concentrate on the values of f_i in (6), we assume that $f_d = 0$ Hz satisfies.

The spectrum of (4) is shown in Fig. 2. This figure shows $f_i =$ 109.1 Hz. Fig. 3 represents the results of the conventional CAF. From Figs. 2 and 3, we can see that f_i in the spectrum of (6) appears as the sidelobes. Fig. 4 shows the CAF centered on the Doppler frequency axis for more detailed view of the sidelobes. The peak of the mainlobe is normalized to 1 in Fig. 4.

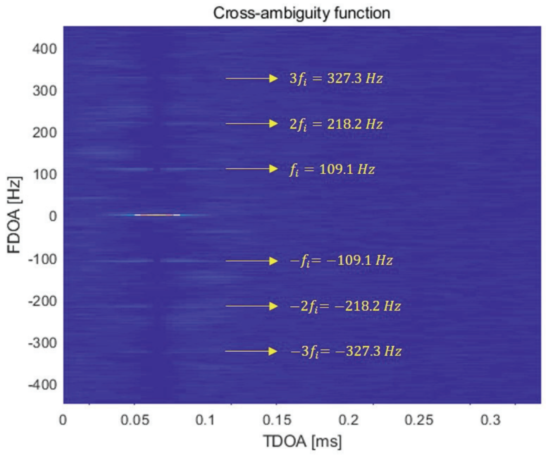

Fig. 2. Cross-ambiguity function using reference channel.

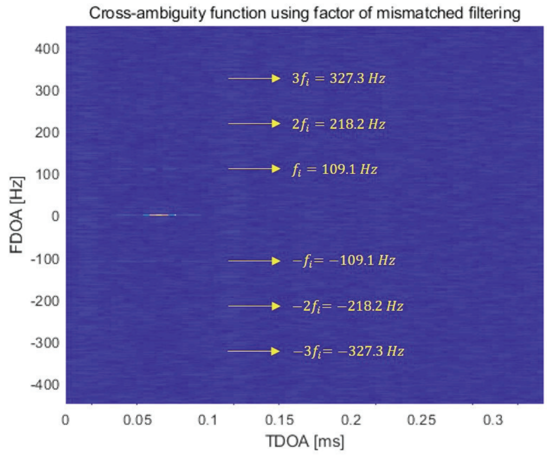

Fig. 4. Cross-ambiguity function using factor of mismatched filtering.

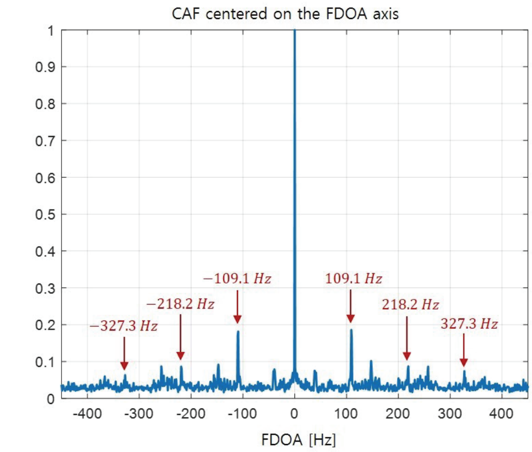

Fig. 3. Cross-ambiguity function centered on the Doppler frequency axis (reference channel).

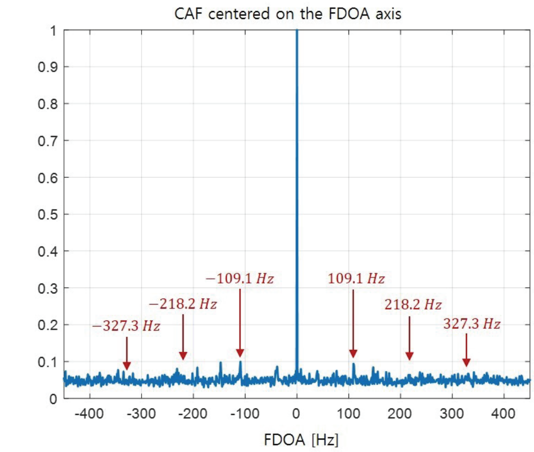

Fig. 5. Cross-ambiguity function centered on the Doppler frequency axis (factor of mismatched filtering).

The mismatched filtering algorithm is applied to mitigate the sidelobes shown in Fig. 3. The batch version of the algorithm was applied for fast computation of the factor of mismatched filtering. The number of observation samples per one batch is 150 samples and the number of batches is 1470. The coefficient c is set to 100. For the sidelobe mitigation, the reference channel is delayed by ± 3 samples. Fig 5 shows the CAF of the factor of mismatched filtering and the surveillance channel. Comparing Figs. 3 and 4, it can be seen that the sidelobes corresponding to multiples of ± 109.6 Hz are mitigated. Fig. 6 shows the CAF centered on the Doppler frequency axis for more detailed view of the sidelobe.

To analyze the performance of the sidelobe mitigation, we define the mainlobe-to-sidelobe ratio (MSR). The MSR is the ratio of the amplitudes of the mainlobe and the sidelobe in the CAF centered of the Doppler frequency axis. Since the amplitude of the mainlobe is normalized to 1, the amplitude of the sidelobe becomes a measure of the MSR.

Table I shows the amplitude of sidelobe in the CAF using reference channel and the factor of mismatched filtering, respectively. We can see that the amplitude of sidelobe is reduced.

TABLE I. AMPLITUDE OF SIDELOBE

f'_d	**Amplitude of sidelobe in the cross-ambiguity function**		
	Reference channel (A)	***Factor (B)***	***Difference (B-A)***
109.1 Hz	0.1854	0.1052	-0.0802
218.2 Hz	0.0808	0.0636	-0.0172
327.3 Hz	0.0622	0.0539	-0.0083
-109.1 Hz	0.1849	0.0932	-0.0917
-218.2 Hz	0.0839	0.0665	-0.0174
-327.3 Hz	0.0656	0.0510	-0.0146

V. CONCLUSION

We analyzed the tendency of the sidelobe in the FDOA axis due to the structure of the FM stereo signal. In order to verify this, we generated an FM stereo signal using sound source file. Then, the sidelobes of the CAF were derived through computer simulations.

To reduce sidelobe level in the CAF, we applied the mismatched filtering by modifying the ATV-based algorithm for the FM stereo signal. Then, we compared the MSRs of the mismatched filtering and that of the matched filtering to analyze the performance of the sidelobe mitigation. From the simulation results, it can be seen that the MSR of the mismatched filtering is smaller than that of matched filtering. From this, we verified that the modified form of the mismatched filtering can be effectively applied to the FM-based PCL system.

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