A Strategy for Estimating Bistatic Range and Velocity in FM-radio-based Passive Bistatic Radar

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***Abstract*—The computation complexity of cross-ambiguity function (CAF) for an FM-radio signal based passive bistatic radar (PBR) is fairly huge. Since FM-radio signal has higher range resolution (about 1.5 km) compared to usual radar signals, its ambiguity function has wider width at the bistatic range axis. Fortunately, this feature makes it possible to coarsely calculate CAF, resulting in reduction of the computational amount of CAF at the bistatic range. Based in this inference, we propose a two-step algorithm using information of range resolution. In the first step, for the determination of the bistatic range interval in CAF, the range resolution is calculated. After interpolating signals, we derive certain section of the CAF with a fine range interval in second step. We show that the proposed method has lower computational load compared to the direct computation method. In addition, we also verify that the estimation accuracy of the proposed method is comparable to that of the direct computation method.**

Keywords—Passive bistatic radar; bistatic range; bistatic velocity; cross-ambiguity function

I. Introduction

A passive bistatic radar (PBR) tracks moving targets by exploiting uncooperative illuminators of opportunity such as FM (frequency modulation)-radio broadcasting [1], DVB-T (digital video broadcasting – terrestrial) [2], GSM (global system for mobile communication) and Wi-Fi access point [3]. The FM-radio-based PBR has been most extensively considered among many illuminators of opportunity since the FM-radio signal is transmitted as a satisfactory transmit power for the detection of uncooperative aircrafts. Due to its proper signal strength, the transmitted signal might be reflected from multiple moving targets. These target echo signals can be used to track the trajectory of fast moving aircrafts.

In order to derive a detection result of the target, a cross-ambiguity function (CAF) is calculated with a reference signal and a target echo signal. The CAF gives the estimation result of bistatic range and velocity, which provide the information of target location and velocity.

However, the computational complexity of the CAF is extremely large in itself. Furthermore, an FM-radio signal based PBR requires much more computation load compared to the traditional radar applications as the following reasons:

- As the FM-radio signal has poor range resolution and low signal-to-noise ratio (SNR), a coherent processing interval (CPI) of FM-radio-based PBR is generally a few seconds, at least a second. A few seconds of CPI is considerably long interval compared to the traditional radar signal processing. Since the number of observation samples is large, the computation of CAF takes long time in real-time implementation of PBR.
- A conventional PBR system is required to exploit at least three bistatic geometries for the exact estimation of the target location. The computation of the CAF should be performed in each bistatic geometry. Thus, the computational complexity increases with the number of bistatic geometries.

Due to the above two reasons, it is difficult to implement the PBR system in real-time.

To reduce the computational burden, Stein's fine mode algorithm [4] was proposed. By taking summation in each time window, the number of CAF points can be dramatically decreased. Since the Doppler frequency of the target is much smaller than the sampling frequency, Stein's fine mode algorithm is appropriate for our purpose. However, Stein's fine mode algorithm does not consider the characteristics of FM-radio signal such as poor range resolution property causing broad width of ambiguity function at the bistatic range axis.

By exploiting the characteristics of FM-radio signal such as the resolution of bistatic range and velocity in ambiguity function, the CAF can be computed efficiently while maintaining the estimation accuracy of the measurements. The information of the resolution can provide the proper interval of the CAF.

In this paper, a new strategy for efficient calculation of CAF is proposed by exploiting the resolution of bistatic velocity. In addition, the proposed algorithm derives the value of range resolution corresponding to each radio content. Since the coarse calculation of CAF causes poor estimation accuracy of the measurements, a second step to achieve the exact estimation of the bistatic range is also performed. From the analysis of the computational complexity, we show that the proposed method can reduce the computational complexity of the direct computation of CAF. From the simulation results, we also verify that the estimation accuracy is not affected by the reduced computational complexity.

II. Prerequisite

A. Signal model

A PBR has a reference channel and a surveillance channel for the reception of a reference signal and a target echo signal, respectively. When the transmitted FM-radio signal is denoted by $s(nf_s)$, the complex envelope of the reference channel output $y_r(nf_s)$ in discrete time domain can be written as

$$y_r(nf_s) = A_r s(nf_s) + v_r(nf_s), \quad n = 1,2,\dots,N, \tag{1}$$

where f_s is the sampling frequency, $v_r(nf_s)$ represents the noise signal in the reference channel and A_r denotes the complex amplitude of the reference signal. Note that the time delay of the direct-path signal is assumed to be zero for the convenience of derivation. The target echo signal can be obtained from the surveillance channel output signal $y_s(nf_s)$. Assuming that only one target echo signal is received, the complex envelope of the surveillance channel output signal is represented by

$$y_s(nf_s) = A_s s(nf_s - \tau_d) e^{j2\pi f_d n} + v_s(nf_s), \tag{2}$$

where $v_s(nf_s)$ represents the bandlimited noise signal in the surveillance channel, and A_s is the complex amplitude of the target echo signal. The bistatic velocity is represented by $V = (f_d c)/f_c$, where f_c is the carrier frequency of the FM-radio signal. When the speed of light is denoted by c, the bistatic range of the target is written by $R = \tau_d/c$. In (2), we also assume that DPI (direct-path interference) is removed by the interference mitigation algorithms such as extensive cancellation algorithm (ECA) [5] and its variation [6].

B. Cross-ambiguity function (CAF)

The primary aim of PBR is to estimate the bistatic range and the velocity, which can be attained from a peak of CAF. The CAF is written as

$$C(l,p) = \sum_{n=0}^{N-1} y_s(nf_s) y_r^*(nf_s - l) e^{-j2\pi pnf_s/N}. \tag{3}$$

From a maximum value of $|C(l,p)|$, the bistatic range and velocity can be estimated.

III. Range and Doppler Frequency Resolution of FM-radio Signal

From the direct computation of (3) and the detection process, the bistatic range and velocity can be estimated. However, the computational complexity of (3) is extremely high for the real-time implementation. In this section, the Doppler frequency resolution and the bistatic range resolution of the FM signal is derived for the efficient calculation of CAF. The information of the resolution is used to determine the interval of the CAF.

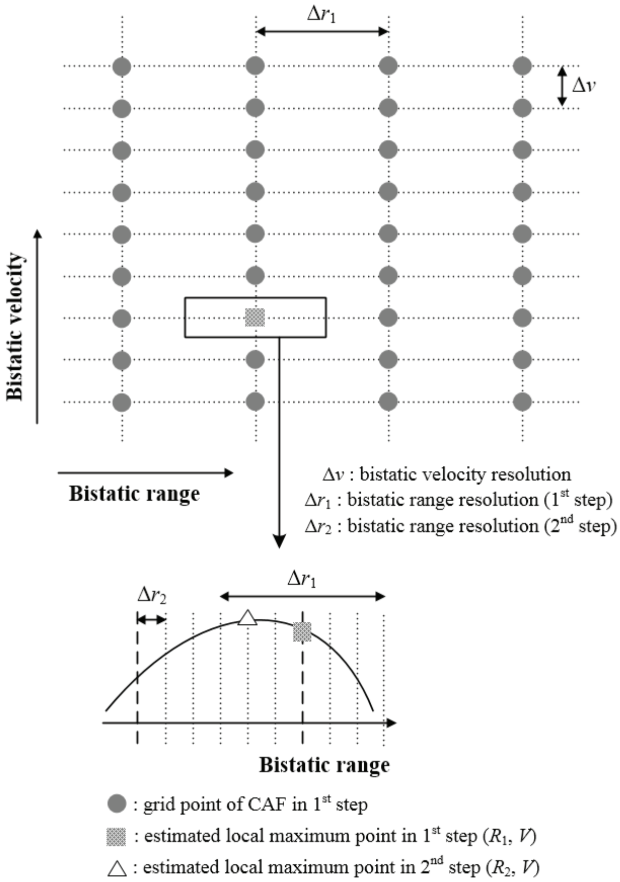

Fig. 1. A strategy for efficient computation of CAF by processing signals in 2-step.

A. Doppler frequency resolution

The Doppler frequency resolution is calculated by $\Delta f = 1/T$, where T denotes the integration time. The observation time in FM-radio-based PBR is generally a few seconds. When the observation time is 1 second, then the Doppler frequency resolution is 1 Hz. Thus, the Doppler frequency interval in CAF should be less than 1 Hz for the target detection. The bistatic velocity resolution Δv should be below $c/(Tf_c)$.

B. Range resolution

The Doppler frequency resolution Δf is determined only by the integration time T. Thus, when the integration time is assumed to be a constant value, then Δf is also a constant. On the other hand, the range resolution varies with the FM-radio program content. The range resolution Δr is calculated by $1/B$, where B denotes the effective bandwidth of the reference signal. The effective bandwidth of the FM-radio signal is associated with the message signal. As described in [1], the bandwidth of a speech type signal lies between 500 Hz and 22.2 kHz and the bandwidth of fast tempo jazz may vary from 13.8 to 35.1 kHz.

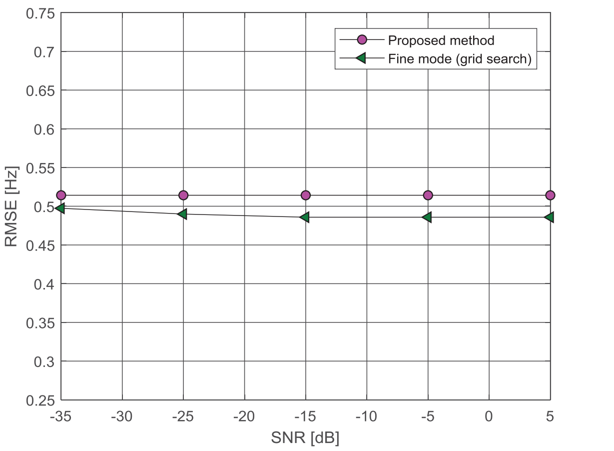

Fig. 2. Root-mean-square error of Doppler frequency in the fine mode and the proposed method according to the signal-to-noise ratio of the target echo signal.

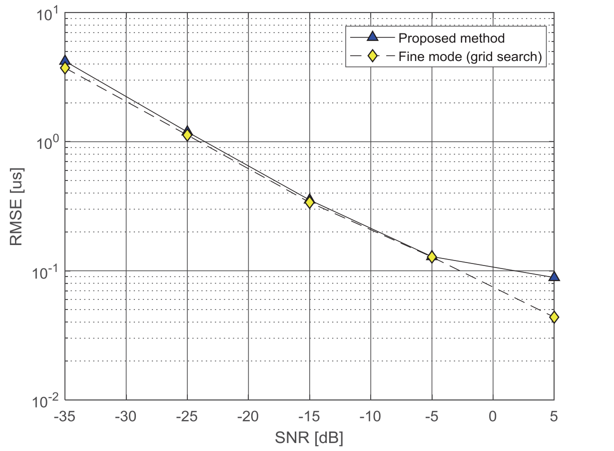

Fig. 3. Root-mean-square error of bistatic range in the fine mode and the proposed method according to the signal-to-noise ratio of the target echo signal.

IV. A Strategy for Efficient Computation of Cross-Ambiguity Function

In this section, a strategy for CAF computation is proposed based on the following two characteristics of an FM-radio signal:

- When the integration time is 1 second, the Doppler frequency resolution is 1 Hz. The Doppler frequency of 1 Hz is much less than the searching range at the Doppler frequency axis of CAF. Thus, for the robust detection in CAF, the interval of the Doppler frequency axis should be fine.
- The complex envelope of the FM-radio signal has narrow bandwidth, resulting in poor range resolution. Compared to the searching range in the axis of bistatic range, the range resolution is fairly large. Thus, the coarse interval can be used to detect targets at the bistatic range axis.

From the characteristics of an FM-radio signal, we propose a two-step process of CAF calculation. The basic concept of the proposed method is depicted in Fig. 1. In the first step, the bistatic range resolution Δr_1 is used to determine the initial interval at the bistatic range axis. Δr_1 is calculated by

$$\Delta r_1 = c \cdot \arg_{\tau} \left\{ |y_r(nf_s) y_r^*(nf_s - \tau)|^2 = \frac{1}{2} \right\}. \quad (4)$$

Since Δr_1 varies with radio program content, the interval of the CAF at the bistatic range axis also changes in each integration time.

After detecting a peak point in the first step, $y_s(nf_s)$ and $y_r(nf_s)$ is interpolated to f_{s2}. Then the bistatic range interval in the second step is calculated by $\Delta r_2 = c/f_{s2}$. From the interpolation, the estimation error of the bistatic range can be decreased because the fine interval provides a chance to find exact peak of CAF. As depicted in Fig. 1, the estimated peak point in the second step R_2 has much lower error than that of R_1.

When we consider only the computation number of the grid points in CAF, the computational complexity is simply derived in both the fine mode and the proposed method. Note that the fine mode represents the direct computation of CAF with range interval Δr_2. The computation number of grid points in the fine mode is computed by $M_{\text{fine}} = N_R N_I N_D$, where N_R denotes the number of range bins in the first step, N_I represents the interpolation factor, and N_D is the number of bistatic velocity bins. On the other hand, the computation number of the proposed method is written as $M_{\text{prop}} = N_R N_D + N_I$. As N_I is generally much smaller than $N_R N_D$, $M_{\text{prop}} \approx N_R N_D$ satisfies. Since $M_{\text{fine}}/M_{\text{prop}} \approx N_I$ satisfies, the computational complexity in the fine mode is approximately N_I times of the proposed method.

V. Simulation Results

The bandwidth of the complex envelope in a single FM-radio channel is 200 kHz. The surveillance and reference channel output signals are also sampled with the sampling frequency of 200 kHz. Each signal is observed for 1 second. The CAF is calculated with the Doppler frequency interval of 1 Hz and the TDOA interval of 5 μs. For the proposed method, each signal is interpolated with a factor of $N_I = 30$. The bistatic range is considered from 0 to 300 km. The Doppler frequency is between -500 and 500 Hz.

The root-mean-square error (RMSE) of the Doppler frequency and time-difference of arrival (TDOA) according to signal-to-noise ratio (SNR) of the target echo signal is derived in Figs. 2 and 3, respectively. As shown in Fig. 2, the proposed method has slightly higher RMSE than that of fine mode. As also in Fig. 3, each RMSE graph shows the similar estimation performance except for the case of SNR of 5 dB.

VI. Conclusions

A new strategy for an efficient computation of an FM-radio signal based CAF was proposed. From the information of the range and the Doppler frequency resolution, we reduced the computational points of the CAF. The effectiveness of the proposed approach has been verified with both the mathematical analysis and the computation simulations. In addition, the experimental results show that the estimation accuracy of the proposed method is comparable to that of the grid search method. Therefore, the proposed method can be regarded as an effective method for a real-time-based-PBR applications.

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