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Doppler rate estimation on coherent sinusoidal pulse train and its Cramer–Rao lower bound

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ABSTRACT

The Doppler rate estimation on coherent sinusoidal pulse train, which can be applied in the passive emitter location systems, is investigated in this paper. When the pulse repetition interval (PRI) is constant, a DFT-based Doppler rate estimation algorithm is proposed and its performance is briefly analyzed. In the case of non-constant PRI, a least-squares-fitting based Doppler rate estimator (LSFE) is proposed. The mean square error is computed in closed form and the threshold signal-to-noise ratio (SNR) is analyzed. The Cramer–Rao lower bound on Doppler rate estimation is derived whereafter, and is compared to the mean square error of the LSFE. Monte Carlo simulations show that when operating above the threshold SNR, the proposed approach achieves the CRLB. The threshold SNRs in the simulations are basically coincident with the theoretical values.

1. Introduction

The problem of locating an emitter from passive measurements is encountered in a variety of radar and sonar applications. The location can be performed either by a single sensor [1,2] or in an array of spatially distributed sensors [3–8]. The single sensor solution has the following advantages: (1) there is no need to synchronize and transfer data between sensors; (2) its system configuration is simple; (3) it is easy to implement in real applications. However, due to relatively few measured information, it is more difficult to design corresponding algorithms for positioning, tracking and parameter estimation. Array with multi-sensor methods can be divided into two types: uniform linear array (ULA) and non-uniform linear array (NULA). For ULA, the restrictive condition that the element distance d should be smaller than one half of the wavelength of the signal λ limits the size of the array. Consequently, antenna gain is limited and mutual couplings between the antenna elements significantly affect the performance. For NULA, when d is larger than $\lambda/2$, the measured results may be ambiguous and extra ambiguity resolution operation should be performed. Multi-sensor solutions and single sensor solutions have their own merits and drawbacks. The applications where the size of the passive location system is limited can be of major interest in single sensor solution.

There are several methods of position estimating. The standard method is based on bearing measurements at different points along the sensor trajectory, which is called the bearing method (BM) [9–13]. Another method is based on Doppler shift of the emitter frequency due to relative motion between the emitter and the observer. This method is called the frequency method (FM) [10,14]. If the motion locus is known, the position of a stationary emitter can be estimated from several frequency estimation values taken at different points in the sensor trajectory. The third method, which combines the BM and FM, is called the combined method (CM) [1,2] in the sequel. A research group of National University of Defense Technology of China investigates the single observer passive

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location algorithms and technologies in recent 20 years. Based on the conventional bearing method, they add new observed quantities, such as angle-of-arrival (AOA) rate and Doppler rate, and propose a novel method [15,16], which outperforms conventional methods in location and tracking accuracy and speed of convergence. With the continuous measured bearing and frequency parameters, the geolocalization is computed using conventional two-step methods (also known as decentralized methods) or one-step methods (also known as centralized methods). In this paper, we mainly focus on Doppler rate estimation used for geolocalization, detailed post-processing after parameter estimation can be found in [1,15] and other cross-citations of these two papers.

FM and CM methods all need to measure frequency. The accuracy of frequency estimation must be sufficiently high because the Doppler frequency and Doppler rate are usually small. Since the transmitted radar waves are generally pulsed waveform and the scales of pulse duration are commonly microsecond (μs), the estimated accuracy from single pulse can hardly fulfill the requirements of the passive emitter location systems. As we know, accumulation of multiple pulses can improve the performance of frequency estimation. Multi-pulse frequency estimation algorithms can be divided into two types: non-coherent [17] and coherent [18–21]. The non-coherent algorithm consists of averaging the frequency estimates of individual pulses. Its accuracy is inversely proportional to $\sqrt{N_p}$, where N_p denotes the observation time, or the number of pulses in this case. The non-coherent algorithm requires a long observation time before the emitter can be accurately located. When the number of pulses received by receiver is not so much or the emitter only transmits several pulses in one frequency point, the accuracy will be insufficient. This causes problems in practical application.

In order to estimate range, radial velocity, and acceleration of a target accurately, coherent technologies are widely used in modern radar systems. Coherent pulses are portions of a continuous wave and so the phases from pulse to pulse are in phase with the original wave. Parameters estimation on returned coherent pulse train has been investigated in previous works. For example, joint estimation of delay, Doppler, and Doppler rate [18], measurement of range, radial velocity, and acceleration [19,20], frequency estimation from short pulses of sinusoid signals [21], etc.

Since the carrier frequency and initial phase are prior parameters in radar, coherent accumulation can easily be implemented. In passive emitter location, however, these two parameters are unknown commonly. In order to use the coherent information in passive location, some extra processes should be taken. The Doppler rate-of-change (also called Doppler rate) of the signal received from remote emitter can be used for emitter location [15,16]. To this end very accurate frequency estimates are necessary.

Frequency estimation from short coherent pulses of a sinusoidal signal was investigated in [22]. The Cramer–Rao lower bound on differential Doppler frequency estimate was derived in [23], where the threshold SNR was also analyzed. Doppler shifted estimation can then be obtained from the difference of the adjacent Doppler estimations, which belongs to a kind of indirection method. In fact, the Doppler shifted frequency can be extracted directly. Since there is no prior knowledge, the frequency of each pulse should be estimated first, and a coherent accumulation can be performed subsequently. The accumulation results of successive pulse contain the information of Doppler rate, which can be extracted by parameters estimation methods, e.g., maximum likelihood estimation (MLE) [24], discrete polynomial-phase transform (DPT) [25,26], least mean square (LMS) [27], and others [28,29]. When the PRI is constant, MLE, DPT, and Kay estimator [28] can be used. However when the PRI is varying (e.g., stagger, jitter, sliding, etc), least-squares-fitting (LSF) will be a good choice.

In this paper, we investigate the Doppler rate estimation algorithm on coherent sinusoidal pulse train. First, we need to detect the pulses and measure the leading edge and trailing edge of each pulse. The methods proposed in [30,31] can estimate the leading and trailing edges under low SNR condition and can be used in our algorithm. When the PRI is constant, a Doppler rate estimation algorithm based on DPT is proposed, and the performance is briefly analyzed. In the case of non-constant PRI, a LSF based Doppler rate estimator is investigated. Then we derive the Cramer–Rao lower bound on Doppler rate estimation. Thereafter the mean square error of LSFE is computed in closed form and compared to the CRLB. The threshold signal-to-noise ratio (SNR) is also analyzed. In Section 4, we extend our algorithm to other forms of coherent pulse train. The coherent LFM (linear frequency modulated) pulse train is taken as an example. Finally Monte Carlo simulations are conducted to compare the performance of the LSF estimator against the CRLB for various signal-to-noise ratios. A typical non-rectangular pulse shape, i.e., Gaussian pulse, is used in simulations to demonstrate the performances for non-rectangular cases.

2. Mathematical model

Consider a stationary emitter with coordinates (0, 0) and a sensor is moving relative to the emitter (Fig. 1). In this case, the delay that signals propagate from the emitter

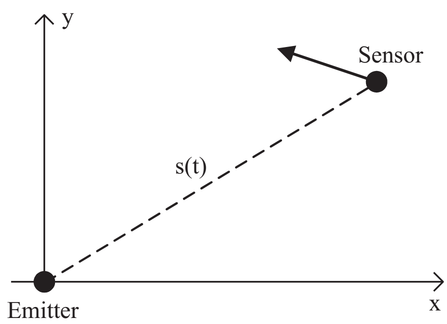

Fig. 1. Two-dimensional sensor-emitter geometry.