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Joint TDOA, FDOA and differential Doppler rate estimation: Method and its performance analysis

Dexiu HU [a,b], Zhen HUANG [a,*], Shangyu ZHANG [a], Jianhua LU [a]

[a] Space Technology Research Center, Tsinghua University, Beijing 100084, China
[b] Zhengzhou Information Technology Institute, Zhengzhou 450002, China

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Abstract Considering the estimation accuracy reduction of Frequency Difference of Arrival (FDOA) caused by relative Doppler companding, a joint Time Difference of Arrival (TDOA), FDOA and differential Doppler rate estimation method is proposed and its Cramer-Rao low bound is derived in this paper. Firstly, second-order ambiguity function is utilized to reduce the dimensionality and estimate initial TDOA and differential Doppler rate. Secondly, the TDOA estimation is updated and FDOA is obtained using cross ambiguity function, in which relative Doppler companding is compensated by the existing differential Doppler rate. Thirdly, differential Doppler rate estimation is updated using cross estimator. Theoretical analysis on estimation variance and Cramer-Rao low bound shows that the final estimation of TDOA, FDOA and differential Doppler rate performs well at both low and high signal–noise ratio, although the initial estimation accuracy of TDOA and differential Doppler rate is relatively poor under low signal–noise ratio conditions. Simulation results finally verify the theoretical analysis and show that the proposed method can overcome relative Doppler companding problem and performs well for all TDOA, FDOA and differential Doppler rate estimation.

1. Introduction

In several areas including passive radar, sonar, communications, etc., the signal received by two observation sensors often contains corresponding parameters such as Time Difference of Arrival (TDOA), Frequency Difference of Arrival (FDOA), etc., which carry the information of the relative range and velocity for the target. Many practical applications can be realized using these parameters. In passive location for instance, two satellites or aircraft can locate emitter sources using time and frequency difference.[1,2] One class of source location methods are based on TDOA/FDOA.[3–7] The estimation accuracy of these parameters can be very important in these applications.

The estimation of TDOA and FDOA has been intensively studied in the past many years. For TDOA estimation, a lot

* Corresponding author.
E-mail address: huangzhen@tsinghua.edu.cn (Z. HUANG).

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of methods based on cross-correlation have been developed.[8] To further improve its accuracy, interpolation algorithms and window functions[9,10] can be utilized. As the estimation of FDOA can be viewed as a dual problem of time delay estimation, it does not attract so mush interest. The problem of joint TDOA/FDOA estimation, however, is widely studied.[11–15]Cross Ambiguity Function (CAF) may be the most well-known method in this area,[12,13] although other modified methods also have been presented for some special cases, such as non-stationary higher order cumulant for correlative noises.[16] These methods model TDOA and FDOA to be constant parameters over the correlation aperture time.[11] Under this model assumption, the CAF method works well.

However, there is a contradiction between the estimation accuracy and model assumption using CAF. According to the estimation accuracy,[13] it is very important to enlarge correlation aperture time T in cross ambiguity function for a better parameter estimation accuracy and location performance. When T becomes large, however, other problems will happen. Time and frequency differences can be no more viewed as constant in this condition. Namely, Relative Time Companding (RTC) and Relative Doppler Companding (RDC) effects would deteriorate estimation accuracy distinctly.[17,18] This is because these two types of companding would not only reduce the output Signal-Noise Ratio (SNR), but also produce distortion on the shape of CAF. Specifically, RTC is mainly related to time difference and RDC is mainly related to frequency difference. The influence of these two types of companding should be discriminatively considered for different types of signals in passive location.For wideband signal, such as the wireless video or other data signals whose bandwidth is many MHz or more, RTC problem has to be mainly concerned. This is because wideband signal has a fairly high time delay resolution and relative time companding would be very sensitive relatively. Ref.[19] has analyzed the effects of RTC on time delay estimation and given the decreasing factor on the accuracy of time delay by $\Omega(\pi\dot{R}BT/c)/3$, where $\Omega(x)=|x^3(\sin x - x\cos x)^{-1}|$, $\dot{R}$ is relative velocity, T is the correlation aperture time c is the light velocity and B is signal bandwidth. This factor is useful for the case of $\dot{R}BT/c \leqslant 4$. For the case of $\dot{R}BT/c > 4$, the TDOA accuracy decreases drastically and the CAF method would become invalid. Many works have been published to solve the RTC problem, such as short-CAFs[20] and maximum likelihood correlator.[21]

For narrowband signal, such as the tactical radio signal whose bandwidth is only several kHz, however, RDC problem has to be mainly concerned. TDOA accuracy is relatively low and it needs an accurate FDOA estimation to ensure the location accuracy. In this way, it needs a much larger T compared with wideband signal, which results in a higher FDOA resolution. As a consequence, the change of FDOA would be more obvious and RDC problem is more likely to happen in this condition.[22] Since the frequency difference is dual with time difference, the decreasing factor for TDOA can be also used for FDOA, which can be given by $\Omega(\pi\ddot{R}T^2/\lambda)/3$, where $\ddot{R}$ denotes relative acceleration and λ denotes wavelength. Similarly, this factor is useful for the case of $\ddot{R}T^2/\lambda \leqslant 4$. Otherwise, the FDOA accuracy decreases drastically and the CAF method would become invalid.

To deal with RDC problem, differential Doppler rate has to be considered,[22] because the companding is caused by it. Therefore, the joint estimation of TDOA, FDOA and differential Doppler rate is needed. Compared with conventional estimation of differential time and frequency, the additional parameter of differential Doppler rate is included. It can be used to not only compensate relative Doppler companding, but also supply a new measurement for passive location.[23–25] Ref.[23] has shown that the location accuracy increases significantly by using additional parameter of differential Doppler rate.

The estimation of TDOA, FDOA and differential Doppler rate is a high-order problem for maneuvering target passive location. For the similar problem of maneuvering target detection and high-order target motion parameter estimation in active radar area, Refs.[26–28] proposed Radon-Fourier transform and generalized Radon-Fourier transform method. Besides, Refs.[29–31] also modeled radar target as fast high-order maneuvering mode and proposed fast calculation methods including the fast implementation of RFT, the Chirp-Z transform based method and particle swarm optimization. All these methods have obtained excellent results for high-order maneuvering target parameter estimation in radar area. Unfortunately, the joint estimation of TDOA, FDOA and differential Doppler rate in passive location area has not been studied comprehensively yet.

Motivated by the above facts in narrowband signal location, this paper focuses on the joint estimation of TDOA, FDOA and differential Doppler rate. We shall introduce a joint estimation method, derive the CRLB and analyze the performance of the method. The contribution of the paper includes:

(1) An estimation method for joint TDOA, FDOA and differential Doppler rate is proposed. This joint estimation is a three-dimensional problem and consequently has to be solved efficiently. Besides, the estimation accuracy is very important in this problem. To solve the above two difficulties, a three-step estimation method is proposed in this paper. The first step obtains an initial estimation of TDOA and differential Doppler rate. The second step obtains the estimation of FDOA and updates the estimation of TDOA. The third step updates differential Doppler rate estimation.
(2) The CRLB for the joint estimation is derived. The CRLB is useful to evaluate parameter estimation accuracy and forecast location precision. The derivation of CRLB is quite complicated as the source signal is unknown and non-cooperative.
(3) The performance of the proposed method is analyzed. The estimation variance of differential Doppler rate obtained by the first step is derived and compared with CRLB, showing that the variance cannot reach its CRLB in low SNR condition. Therefore, differential Doppler rate is updated in the following step and its accuracy reaches its CRLB finally.

The remainder of this paper is organized as follows. The signal model is introduced in Section 2, the proposed method is described in Section 3, the CRLB is given in Section 4, and the simulation is shown in Section 5. Finally, a brief conclusion is given in Section 6.