ADS-B Information Based Transmitter Localization in Passive Radar

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Abstract

Transmitters' locations are usually assumed to be known in passive radars that exploit the third-party radio sources as illuminators of opportunity to detect targets of interest. However, there are such cases where transmitters' locations are unavailable in advance, causing difficulties for target localization. To address the problem, this paper investigates a novel transmitter localization method that combines the decoded automatic dependent surveillance-broadcast (ADS-B) information and passive radar measurement information. The localization model is established at the first, followed by the discussion of localization uniqueness and accuracy. The feasibility of the proposed method is further verified by numerical analyses.

1. Introduction

Passive Radars, also known as passive coherent location, exploit the third-party radio sources as illuminators of opportunity to detect reflections from the environment and targets of interest. Passive radar is usually equipped with two type of receiving channels: reference and surveillance channels. The reference channel serves as a source of the original transmitted signal and the other one a source of the target echo signal. The noisy and multipath-polluted signal in the reference channel should be first purified as reference signal. Clutter rejection is executed in surveillance channel to cancel the clutters that may mask the target signals. Thereafter, by performing a 2-D cross correlation between the surveillance and reference signals, the echo can be detected by localizing the correlation peak in the range Doppler (RD) map. As no need for deployment of the dedicated transmitters, passive radars operate covertly, immune to anti-radiation missiles and active directional jamming inherently [1-3].

Passive radar often acquires the measurements about bistatic range and Doppler shift, direction of arrival (DOA) also included in some cases. Time-difference-of-arrival (TDOA) localization [4] is used for target localization. The prerequisite of TDOA localization is to know the Transmitter s' locations in advance. However, there are such cases where transmitters' locations are unavailable aforehand. It could occur when the system works in strange environment where the transmitter stations are not covered in our database or in a developing broadcast network where newly installed transmitter stations are also unknown, or the transmitter stations stay at a special region we cannot get access to. In this case, transmitter localization becomes a necessary step if we want to implement TDOA localization. To the best of the authors' knowledge, the transmitter localization problem has not been discussed in reported references. An in-depth study on this problem would improve the flexibility of passive radar in practical applications.

Different from the traditional passive ESM (Electronic Support Measurement) traker (PET) [5] where the source is usually moving, the transmitter localization herein usually faces static transmitter. Thus the tracking method used in PET is not applicable here. Besides, spectrum management monitoring vehicle also play the role of radio station localization. However, the time cost is usually high. In this paper we propose an alternative automatic dependent surveillance-broadcast (ADS-B) information based transmitter localization approach for aerial target detection passive radar, where ADS-B is a cooperative surveillance technology for tracking aircraft in which the aircraft determines its own position via GNSS and periodically broadcasts this via a radio frequency. The condition is that there exists aerial target equipped with ADS-B device, which is easy to reach since ADS-B devices are common in civil aviation aircrafts. Thus the proposed method works quickly and only an ADS-B receiver is required to be installed on the passive radar system.

2. System Overview

To interpret the problem discussed in this paper, we first take a look at the typical systematic architecture of passive radar and traditional PET systems. Passive radar system is sketched in Fig. 1(a). As mentioned in Section 1, both reference channel and surveillance channel are configured in the receiver. The dotted line denotes the motion trajectory of the target. The transmitter, target and receiver construct a bistatic triangle (i.e. ΔOAB). The TDOA obtained in the 2-D cross correlation step denotes the difference between transmitter-target-receiver path and transmitter-receiver path (baseline), i.e. bistatic range. Assuming the transmitter-to-receiver geometry is known, the TDOA indicates that the target is located in the ellipse/ellipsoid with transmitter and receiver as the focuses and with the sum of bistatic range and baseline as the major axis. Target location is determined by multiple such ellipses/ellipsoids that stem from multiple transmitter-receiver tuple. This is the basic principle of TDOA localization.

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In our topic, we want to find out the position of the transmitter to utilize the TDOA localization. The similar systems that fulfil source localization are PET system and spectrum management monitoring vehicle. As shown in Fig. 1(b), PET system involves just radio source and receiver, no third-party illuminator included. It tracks moving radio source with information of DOA, Doppler shift, and so on. The receiver needs to do maneuvering motion to accomplish observability under some cases. By means of DOA and/or received signal strength, the spectrum management monitoring vehicle approaches the radio source gradually, arriving at the target eventually, as shown in Fig. 1(c). Nevertheless, source localization with spectrum management monitoring vehicle usually requires high time cost.

It is noticed that the passive radar itself is a receiving devise. The method with less additional equipment and low-cost operation would possess good practicality and flexibility. Observing the passive radar system, in the bistatic triangle, if transmitter and receiver are known, then we can localize the target with TDOA information. An alternative idea is that we can localize the transmitter with TDOA information if the target's position is known. Moreover, we notice that modern civil aircraft carries ADS-B system which broadcasts its position and velocity information. Thus, if there are civil aircrafts in the passive radar coverage, ADS-B information based transmitter localization would be a promising approach.

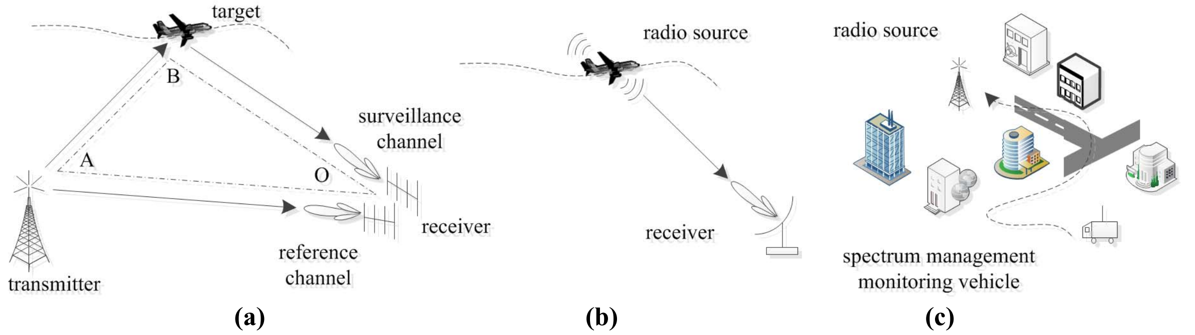

Fig. 1. System sketch map of passive radar, PET and spectrum management monitoring. (a) Passive radar. (b) PET. (c) Spectrum management monitoring.

3. Localization model and method

According to the bistatic geometry illustrated in Fig.1 (a), the bistatic range measured by passive radar can be expressed as

$$r = \mathrm{AB} + \mathrm{OB} - \mathrm{OA} + e , \tag{1}$$

where e denotes measurement noise. With the aid of ADS-B information, then point B is known. Thus $\mathrm{AB} - \mathrm{OA}$ can be obtained, indicating that point A is located on the hyperbola with O and B as focuses and with $\mathrm{AB} - \mathrm{OA}$ as the real axis. The common intersection of multiple such hyperbolas is the position of transmitter.

Multiple such hyperbolas require multiple bistatic range measurements. The multiple bistatic range measurements can be provided by multiple targets, or by measurement sequence of single target, or the combination of them. When multiple targets are involved, it should be assured that the measurements of the multiple targets stem from the same transmitter. It is intuitive in multiple frequency network (MFN) where each transmitter works on a unique frequency. However, it is difficult to achieve in single frequency network (SFN) where the measurement to transmitter association is ambiguous since all the transmitters in the SFN broadcast the same signal at the same frequency simultaneously. Thus measurement sequence of single target will be the first choice in the SFN scenario because the measurement sequence of single target can be associated in the RD domain.

Moreover, in the SFN scenario, the extracted reference signal usually corresponds to a certain transmitter that maybe different from the considered one. Thus there is a constant factor difference between the estimated bistatic range and $\mathrm{AB} + \mathrm{OB} - \mathrm{OA}$ in practice. To include more cases, we extend model (1) to a general one, that is

$$r_k = \mathrm{AB}_k + \mathrm{OB}_k - \mathrm{OA} + u + e_k , \ k = 1, 2, \cdots, N , \tag{2}$$

where u denotes the constant factor that is related to the transmitter. N denotes the number of measurements. The measurement noise e_k is assumed to be independent with each other and follows Gaussian distribution with zero mean and variance σ_k^2.

TDOA localization method cannot apply to model (2) directly as there is the constant factor. Single differencing can solve this problem. By choosing r_k as a reference, subtracting it from all other $N-1$ bistatic ranges gives

$$r_k - r_N = \mathrm{AB}_k - \mathrm{AB}_N + \mathrm{OB}_k - \mathrm{OB}_N + e_k - e_N , \ k = 1, 2, \cdots, N-1 . \tag{3}$$

It indicates that point A is located on the hyperbola with B_k and B_N as focuses and with $\mathrm{AB}_k - \mathrm{AB}_N$ as the real axis. If $N \geq M + 2$, where M is the coordinate dimension of A, and B_k ($k = 1, 2, \cdots, N$) are non-collinear, it can be concluded that the equation set (3) is solvable and the solution is unique. If $N \geq M + 2$ and B_k ($k = 1, 2, \cdots, N$) are collinear, the equation set (3) has two symmetrical solutions with the line, even unsolvable if A is collinear with B_k. If the solution is unique, it can be solved with least square (LS) or maximum likelihood (ML) method.

In addition, point B is assumed to be known in accordance with ADS-B information in the above model and method. In practice, this assumption needs to resolve the association between radar measurement and ADS-B information, namely determining the radar measurement corresponding to which target in ADS-B information. A feasible way is to exploit the DOA measurement which is a parameter independent to transmitter's position.

Finally, the practicality of the proposed transmitter localization method depends on its positioning accuracy. Cramer-Rao bound (CRB) is derived here to represent the positioning accuracy. Record $\boldsymbol{m} = [r_1 - \mathrm{OB}_k, \cdots, r_N - \mathrm{OB}_k]^{\mathrm{T}}$, where superscript "T" denotes transpose operation, $\boldsymbol{r}$, $\boldsymbol{r}_{\mathrm{R}}$ and $\boldsymbol{s}_k$ denotes the position of the transmitter, receiver and B_k, respectively. The Fisher information matrix with respect to $\boldsymbol{r}$ and u conforms to

$$\boldsymbol{I}(\boldsymbol{r},u) = \sum_{k=1}^{N} \frac{1}{\sigma_k^2} \boldsymbol{a}_k \boldsymbol{a}_k^{\mathrm{T}} , \tag{4}$$

where $\boldsymbol{a}_k = \begin{bmatrix} (\boldsymbol{r}-\boldsymbol{r}_{\mathrm{R}})/\|\boldsymbol{r}-\boldsymbol{r}_{\mathrm{R}}\| - (\boldsymbol{r}-\boldsymbol{s}_k)/\|\boldsymbol{r}-\boldsymbol{s}_k\| \\ -1 \end{bmatrix}$. Then CRB can be obtained from the diagonal elements of $\boldsymbol{I}^{-1}(\boldsymbol{r},u)$.

Interestingly, if we draw the vectors $\frac{\boldsymbol{r}-\boldsymbol{r}_{\mathrm{R}}}{\|\boldsymbol{r}-\boldsymbol{r}_{\mathrm{R}}\|} - \frac{\boldsymbol{r}-\boldsymbol{s}_k}{\|\boldsymbol{r}-\boldsymbol{s}_k\|}$ ($k = 1,2,\cdots,N$) together, it will manifest as Fig. 2 where 2-dimensional case is considered. It shows that the support domain of $\frac{\boldsymbol{r}-\boldsymbol{r}_{\mathrm{R}}}{\|\boldsymbol{r}-\boldsymbol{r}_{\mathrm{R}}\|} - \frac{\boldsymbol{r}-\boldsymbol{s}_k}{\|\boldsymbol{r}-\boldsymbol{s}_k\|}$ ($k = 1,2,\cdots,N$) increases with the increase of the view angle of target trajectory with respect to transmitter. According to the eigenvalue decomposition characteristics of $\boldsymbol{I}(\boldsymbol{r},u)$, bigger support domain indicates lower CRB, namely higher positioning accuracy. Thus, wider view angle provides better positioning accuracy under the condition of same number of measurement. In addition, more independent measurements will improve the positioning accuracy under the same view angle case.

4. Numerical Analyses

To verify the proposed method more intuitively, we do several numerical analyses in this section. The scenario of the numerical analyses is sketched in Fig. 3. There are two aircraft trajectories that represent two different cases. Both the two trajectories are $\pi/2$ arc with common focus at A_2. 300 aircraft measurements are uniformly distributed on each trajectory. The accuracy of bistatic range measurement is assumed to be 30m, i.e. $\sigma_1 = \cdots = \sigma_N = 30\mathrm{m}$. A_1, A_2 and A_3 are three selected points for CRB comparison. 2-dimensional case for transmitter is considered.

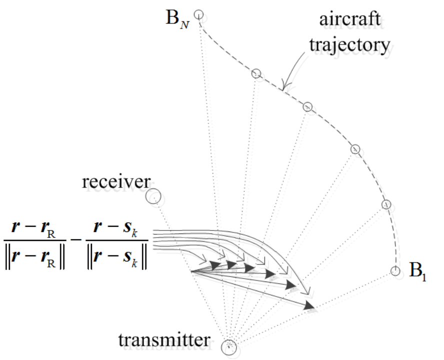

Fig. 2. Geometric interpretation of the CRB.

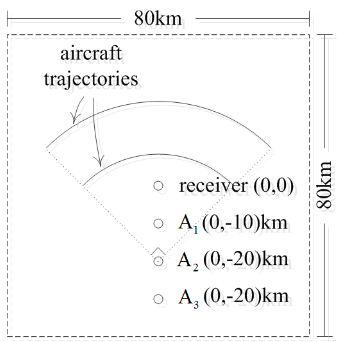

Fig. 3. The scenario of the numerical analyses.

The CRBs of the selected points are presented in Table I. The CRBs of point A_2 in both cases are the same. The CRB of point A_1 in the small arc case is less than the big arc case since there is wider view angle in the small arc case. The CRB of point A_3 can be explained with the same way. All these are consisted with the theoretical CRB analysis in Section 3. The contours of the CRB in the whole 80km×80km area are shown in Fig. 4. In practice, if the positioning accuracy is on the same level of bistatic range measurement, the target localization performance degradation caused by non-ideal transmitters' position can be ignored. Specifically, in the considered case, the area that the root squared CRB is less than 30m could be thought as good transmitter localization area. It can be observed in Fig. 4 that the good transmitter localization area is relatively large. More importantly, the good transmitter localization area can be predicted according to the geometry. Thus the proposed ADS-B information based transmitter localization approach is feasible.

Table I CRBs of the selected points.

class	points	$\sqrt{\mathrm{CRB}(x)}$ (m)	$\sqrt{\mathrm{CRB}(y)}$ (m)	$\sqrt{\mathrm{CRB}(x)+\mathrm{CRB}(y)}$ (m)
Small arc	A_1	3.0	10.3	10.7
	A_2	4.1	19.7	20.1
	A_3	5.3	34.4	34.8
Big arc	A_1	3.3	12.8	13.2
	A_2	4.1	19.6	20.0
	A_3	4.9	28.8	29.3

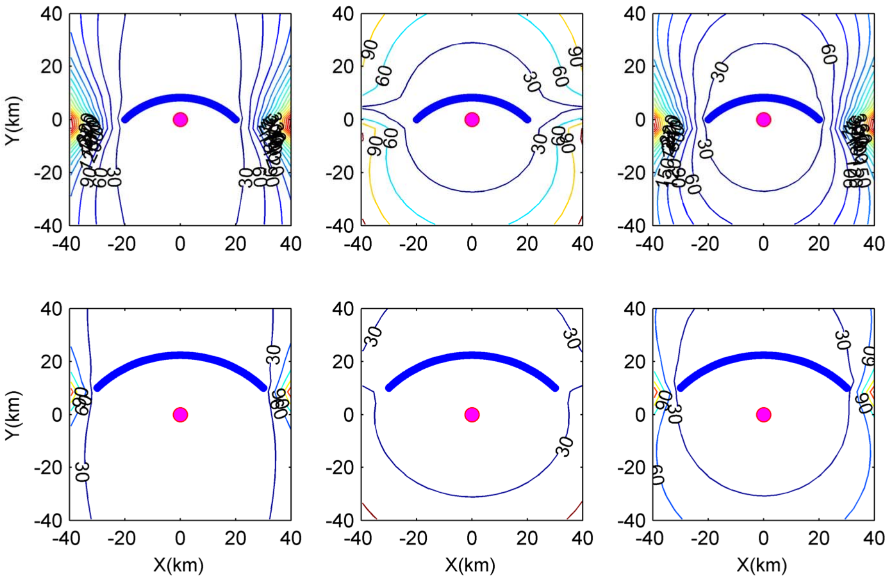

Fig.4. Contours of the CRB. The three columns correspond to $\sqrt{\mathrm{CRB}(x)}$, $\sqrt{\mathrm{CRB}(y)}$ and $\sqrt{\mathrm{CRB}(x)+\mathrm{CRB}(y)}$.

5. Conclusion

This paper has discussed a novel transmitter localization method by combining the ADS-B information and passive radar measurements. Its feasibility and performance has been demonstrated through theoretical and numerical analyses. As only a portable ADS-B receiver is needed to be installed on the passive radar, it will greatly improve the flexibility of passive radar in practical applications. Although the proposed method has been verified by real-life data, the result with real-life data is not presented in the paper because of the limited paper length.

6. Acknowledgments

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