

Passive Geolocation with Unmanned Aerial Vehicles using TDOA-AOA Measurement Processing

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Abstract— Actual trends in current passive geolocation system development includes cooperation of flying segment based on receiver stations aboard Unmanned Aerial Vehicles (UAVs) with terrestrial segment including stationary ground receiver stations. Existing accuracy results achieves the order of tens and hundreds of meters in optimistic Line of Sight (LOS) conditions, however the problem of radio emission sources positioning with UAVs is especially relevant for search and rescue operations in heterogeneous terrain, when separate primary measurements obtained, for example, after reflections, could lead to a significant error. One possible way to improve the accuracy of positioning in such conditions is to use aerial passive geolocation based on UAVs with joint processing of Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) primary measurements. The contribution of the current investigation is the development of mathematical model for positioning of radio emission sources with UAVs using TDOA-AOA measurement processing and performance evaluation of hybrid measurement processing with handling AOA noise.

Keywords— Passive Geolocation, TDOA, AOA, RMSE, UAV, Measurement Processing

I. INTRODUCTION

Actual trends in current wireless networks development includes joint cooperation of flying segment based on transceiver stations aboard Unmanned Aerial Vehicles (UAVs) with terrestrial segment including stationary ground transceiver stations [1]. Location-based services in such networks could include both military applications, for example, in tactical wireless networks [2] or battlefield environments [3] and civil applications, for example, in ground-aerial surveillance [4], cognitive radio communications [5] or supporting search and rescue operations [6].

Passive geolocation is treated as position estimation of a stationary or mobile transmitter or radiating emitter from passive primary measurements of the arrival times, directions of arrival, or Doppler shifts of electromagnetic waves received at various sites [7]. In the context under consideration various sites are represented by ground and uav based receiver stations.

UAV based passive geolocation techniques had already got considerable attention in the past years and can be subdivided by primary measurements into Time Difference of Arrival (TDOA) [8]–[10], Frequency Difference of Arrival (FDOA)

[11], Angle of Arrival (AOA) [12]–[14] and Received Signal Strength Indication (RSSI) [15]–[17] positioning.

Every measurement processing technique based on TDOA, FDOA, AOA or RSSI has its advantages and shortcomings for a specific UAV based geolocation application scenario. While TDOA and FDOA measurement processing technique could achieve high location accuracy in optimistic Line of Sight (LOS) conditions, it requires precise sensors synchronization. If positioning is carried out by TDOA in three-dimensional space, at least four stationary receiving sensors are required. On the other hand, DOA measurement processing technique requires less number of receiving sensors and neither synchronization among them, however it needs an antenna array for each sensor and resulting location accuracy is highly dependent on the distance between the object of location and sensors. RSSI based localization is preferred in many applications including UAV based localization because of the simplicity in hardware and implementation, however its location accuracy degrades in large scale environments due to inherent variation of characteristics of the received signal strength (RSS).

To reduce the number of sensors required by TDOA processing technique, [8] proposed the use of UAVs as moving sensor platforms in conjunction with ship/land-based platforms to obtain multiple time difference of arrival measurements. Recursive location estimation of a stationary and moving emitter from a pair of unmanned aerial vehicles, using time difference of arrival measurements, formed by the correlation of signals received by two UAVs, is investigated for Kalman [9] and Gaussian [10] filtering techniques. Mobile emitter geolocation and tracking using TDOA and FDOA measurement fusion is considered in [11].

Hierarchical DOA estimation and the fusion of DOAs and the terrain map is proposed in [12] to reduce computational complexity of the near-real-time detection in unmanned airborne emitter monitoring system. A novel application of a common RF direction-finding technique called pseudo-Doppler using small, unmanned system is investigated in [13]. In [14] a series of both real-world flight testing and computer simulated scenarios were conducted to study the feasibility of a low-cost UAV DOA geolocation platform.

RSSI localization and tracking architecture, where a data driven neural network model is used for estimating the

unknown signal strength and extended Kalman filters are utilized for eliminating the RSS noise is presented in [15]. Work [16] investigates the impact of UAVs, equipped with RSSI sensors, formation and trajectory on the aerial RF source localization performance for Differential Received Signal Strength Indication (DRSSI) based approach in None LOS (NLOS) propagation conditions. Localization of a radio frequency (RF) transmitter with intermittent transmissions as quickly as possible via a group of UAVs equipped with omnidirectional RSS sensors is considered in [17].

Existing accuracy results achieves the order of tens and hundreds of meters in optimistic LOS conditions. However, the problem of radio emission sources positioning with UAVs is especially relevant for search and rescue operations in heterogeneous terrain, when separate primary measurements obtained, for example, after reflections, could lead to a significant error with $RMSE > 10^3$ m [16], [26]. One possible way to improve the accuracy in such conditions is to use joint processing of TDOA and AOA primary measurements.

The problem of hybrid TDOA/AOA measurement processing to locate mobile station with stationary ground base stations on the plane was considered in [18] and demonstrated higher location accuracy than TDOA only location, when the number of base stations is small and/or when the TDOA measurements have a relatively poor accuracy. Localization of radar emitters from a single sensor using multipath and TDOA-AOA measurements in a naval context was investigated in [19]. Results of [18] and [19] are valid for the 2D scenario, however localization in 3D is much more challenging than in 2D. Especially for AOA technique we are not able to apply the 2D AOA method to the azimuth and the elevation angle separately to obtain the source location, because two angles have to be used jointly in their respective non-linear measurement equations in order to determine the position of the source [20].

Problem of passive geolocation radiating emitter source in the three-dimensional (3D) space, using hybrid TDOA-AOA measurements was investigated in [21], however it considered the case of two stationary ground stations. Case of UAV based passive geolocation, using a hybrid TDOA-AOA was simulated in [22], however no performance evaluation due to inherent TDOA and AOA noise variation was done. Thus, the aim of current research is to investigate the performance of hybrid measurement processing in handling TDOA and AOA noise for the case of UAV based passive geolocation.

The material in the paper is organized in the following order. Developed mathematical model for passive geolocation of radio emission sources with UAVs using TDOA-AOA measurement processing including UAV based passive geolocation system model, TDOA-AOA error-free model, Cramer-Rao Lower Bound (CRLB) for TDOA-AOA measurement processing model and TDOA-AOA noisy measurement processing model are presented in Section II. Developed simulation model, scenario of geolocation and numerical results for performance of hybrid measurement processing in handling TDOA and AOA noise are given in Section III. Finally, we draw the conclusions in Section IV.

II. TDOA-AOA MEASUREMENT

PROCESSING IN UAV BASED PASSIVE GEOLOCATION

In this section we present UAV based passive geolocation system model, TDOA-AOA error-free model, Cramer-Rao Lower Bound (CRLB) for TDOA-AOA measurement processing model and TDOA-AOA noisy measurement processing model.

A. UAV Based Passive Geolocation System Model

UAV based passive geolocation system under consideration, including flying segment based on transceiver stations aboard Unmanned Aerial Vehicles (UAVs) with terrestrial segment including stationary ground transceiver is shown in Figure 1.

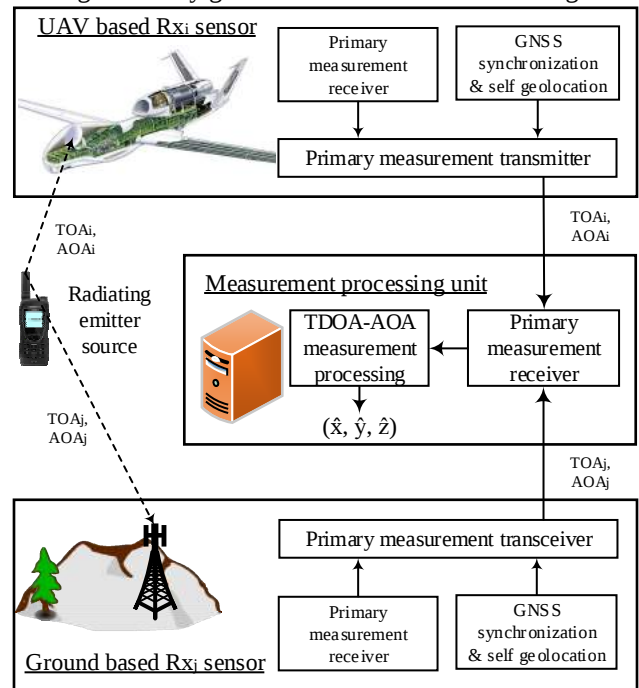


Figure 1. UAV based passive geolocation system

Ground and UAV based passive receive sensors whose positions are available with Global Navigation Satellite Systems (GNSS) carry out the task of receiving primary Time of Arrival (TOA) and AOA measurements from packets transmitted by radiating emitter source. Single passive sensor can record the time stamp and direction of the received packet. Accurate time stamping is possible since each sensor has a GNSS receiver for time synchronization. Then, TOAs (timestamps) and AOAs of each sensor are forwarded to the measurement processing unit, which in turn using known sensor locations and hybrid TDOA-AOA measurement processing, estimate radiating emitter coordinates $\hat{x} = (\hat{x}, \hat{y}, \hat{z})^T$.

If positioning is carried out by TDOA in three-dimensional space, at least four stationary receiving sensors are required to define three TDOA measurements from three pairs of sensors. Using of UAV as moving sensor cooperatively with ground based sensor as a reference node, as shown in Figure 2, allows to get multiple TDOA measurements along UAV flight path and hence reduce the number of required sensors to a pair.

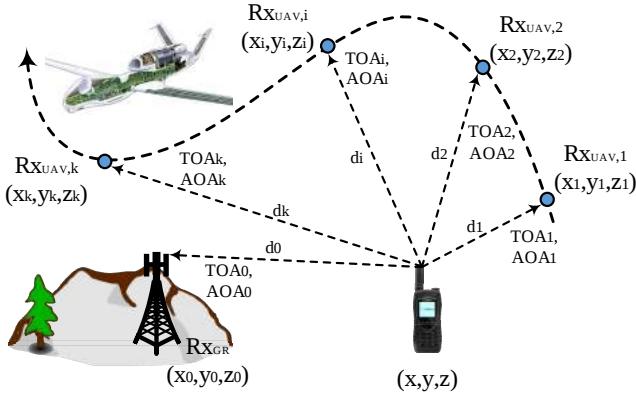


Figure 2. Using of UAV as moving sensor with ground based sensor

B. TDOA-AOA Error-Free Measurement Processing Model

Let denote ground based receive sensor Rx_{GR} with available coordinates $x_0=(x_0, y_0, z_0)^T$ as reference sensor and UAV based receive sensor Rx_{UAV} with available coordinates $x_i=(x_i, y_i, z_i)^T$, where time intervals $i=1\dots k$ correspond to synchronized timestamps, k – the number of primary measurements along UAV flight path. Let TOA_i be transmitted packet time of arrival for the signal radiating from the emitter, then TDOA between Rx_{UAV} and reference Rx_{GR} is defined by $t_{i,0}$ as

$$t_{i,0} = TOA_i - TOA_0 = d_{i,0}/c, \quad (1)$$

where c is speed of light and $d_{i,0}$ is range difference.

Actual error-free range difference is defined by

$$d_{i,0} = d_i - d_0, \quad (2)$$

where d_i is actual range between emitter with unknown coordinates $\mathbf{x}=(x, y, z)^T$ and sensor with available coordinates $\mathbf{x}_i=(x_i, y_i, z_i)^T$ defined as

$$d_i = \|\mathbf{x} - \mathbf{x}_i\|_2 = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}, \quad (3)$$

where $\|\cdot\|_2$ – norm operator over a vector in 3-D space [23].

Figure 3 shows TDOA-AOA geolocation geometry in the Cartesian coordinate system for the example time interval i . Emitter observation by two sensors results in one TDOA $t_{i,0}$ and two AOA pairs (θ_0, ϕ_0) and (θ_i, ϕ_i) of measurements.

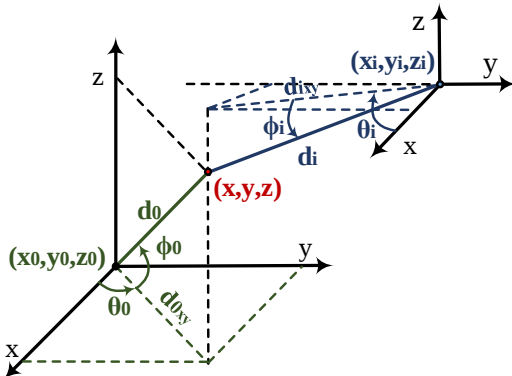


Figure 3. Geolocation geometry

As depicted in Figure 3, projection of the range d_i between emitter and sensor on x - y plane is denoted by d_{ixy} and defined by

$$d_{ixy} = \sqrt{(x - x_i)^2 + (y - y_i)^2}, \quad (4)$$

In matrix form error-free range difference measurement model $\mathbf{d}_0(\mathbf{x}) \in \mathbb{R}^{k \times 1}$ for $i=1\dots k$ primary measurements along UAV flight path with reference sensor Rx_{GR} is defined by

$$\mathbf{d}_0(\mathbf{x}) = \begin{bmatrix} d_1 - d_0 \\ d_2 - d_0 \\ \vdots \\ d_k - d_0 \end{bmatrix}, \quad (5)$$

Actual error-free bearing pair b_i including azimuth θ_i and elevation ϕ_i AOAs from emitter with coordinates $\mathbf{x}=(x, y, z)^T$ to receiver sensor with coordinates $\mathbf{x}_i=(x_i, y_i, z_i)^T$, $i=1\dots k$ can be expressed as

$$b_i(\mathbf{x}) = \begin{bmatrix} \theta_i \\ \phi_i \end{bmatrix}, \quad (6)$$

$$\theta_i = \arctg\left(\frac{y - y_i}{x - x_i}\right), \quad (7)$$

$$\phi_i = \arctg\left(\frac{z - z_i}{\sqrt{(x - x_i)^2 + (y - y_i)^2}}\right).$$

For the sake of consistency in TDOAs and AOAs measurements, assume that emitter is stationary and bearing pair b_i is collected by UAV based receive sensor Rx_{UAV} for $i=1\dots k$ time intervals along UAV flight path. Then in matrix form error-free bearing AOA measurement model $\mathbf{b}(\mathbf{x}) \in \mathbb{R}^{2k \times 1}$ is

$$\mathbf{b}(\mathbf{x}) = \begin{bmatrix} b_1(\mathbf{x}) \\ b_2(\mathbf{x}) \\ \vdots \\ b_k(\mathbf{x}) \end{bmatrix}. \quad (8)$$

Actual error-free range difference (TDOA) and bearing (AOA) joint measurement model $\mathbf{f}_i(\mathbf{x})$ for i^{th} time interval is defined by

$$\mathbf{f}_i(\mathbf{x}) = \begin{bmatrix} d_{i,0}(\mathbf{x}) \\ b_i(\mathbf{x}) \end{bmatrix}. \quad (9)$$

In matrix form range difference (TDOA) and bearing (AOA) joint measurement model $\mathbf{f}(\mathbf{x}) \in \mathbb{R}^{3k \times 1}$ for $i=1\dots k$ primary measurements along UAV flight path is defined by

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{d}_0(\mathbf{x}) \\ \mathbf{b}(\mathbf{x}) \end{bmatrix}. \quad (10)$$

C. Cramer-Rao Lower Bound for TDOA-AOA Model

The CRLB gives a lower bound on variance attainable by any unbiased estimator using the same data, and thus it can be served as an important benchmark to compare with the root mean square error (RMSE) of positioning algorithms [23]. The key in producing the CRLB is to construct the corresponding Fisher information matrix (FIM) $\mathbf{I}(\mathbf{x})$, computed at emitter location with coordinates $\mathbf{x}=(x,y,z)^T$. The diagonal elements of the FIM inverse are the minimum achievable variance values:

$$\text{CRLB}(\mathbf{x}) = \text{trace}(\mathbf{I}^{-1}(\mathbf{x})). \quad (11)$$

When the primary measurement errors are zero-mean Gaussian distributed, $\mathbf{I}(\mathbf{x})$ can be computed as [24]

$$\mathbf{I}(\mathbf{x}) = \left[\frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}} \right]^T \mathbf{C}^{-1} \left[\frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}} \right]. \quad (12)$$

where $\mathbf{C}$ denotes TDOA and AOA noise covariance matrix, and $\frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}}$ is Jacobian matrix for joint measurement model

$\mathbf{f}(\mathbf{x})$. Jacobian matrix $\frac{\partial \mathbf{d}_0(\mathbf{x})}{\partial \mathbf{x}} \in \mathbb{R}^{k \times 3}$ for $\mathbf{d}_0(\mathbf{x})$ is defined

$$\begin{aligned} \frac{\partial \mathbf{d}_0(\mathbf{x})}{\partial \mathbf{x}} &= \\ &= \begin{bmatrix} \frac{x-x_1}{d_1} - \frac{x-x_0}{d_0} & \frac{y-y_1}{d_1} - \frac{y-y_0}{d_0} & \frac{z-z_1}{d_1} - \frac{z-z_0}{d_0} \\ \frac{x-x_2}{d_2} - \frac{x-x_0}{d_0} & \frac{y-y_2}{d_2} - \frac{y-y_0}{d_0} & \frac{z-z_2}{d_2} - \frac{z-z_0}{d_0} \\ \vdots & \vdots & \vdots \\ \frac{x-x_k}{d_k} - \frac{x-x_0}{d_0} & \frac{y-y_k}{d_k} - \frac{y-y_0}{d_0} & \frac{z-z_k}{d_k} - \frac{z-z_0}{d_0} \end{bmatrix}. \end{aligned} \quad (13)$$

where d_i is computed according to (3). Jacobian matrix $\frac{\partial \mathbf{b}(\mathbf{x})}{\partial \mathbf{x}} \in \mathbb{R}^{2k \times 3}$ for $\mathbf{d}_0(\mathbf{x})$ is defined by

$$\frac{\partial \mathbf{b}(\mathbf{x})}{\partial \mathbf{x}} = \begin{bmatrix} -\frac{(y-y_1)}{d_{1xy}^2} & \frac{(x-x_1)}{d_{1xy}^2} & 0 \\ -\frac{(x-x_1)(z-z_1)}{d_1^2 d_{1xy}} & -\frac{(y-y_1)(z-z_1)}{d_1^2 d_{1xy}} & \frac{d_{1xy}}{d_1^2} \\ \vdots & \vdots & \vdots \\ -\frac{(y-y_k)}{d_{kxy}^2} & \frac{(x-x_k)}{d_{kxy}^2} & 0 \\ -\frac{(x-x_k)(z-z_k)}{d_k^2 d_{kxy}} & -\frac{(y-y_k)(z-z_k)}{d_k^2 d_{kxy}} & \frac{d_{kxy}}{d_k^2} \end{bmatrix}. \quad (14)$$

where d_i and d_{ixy} defined according to (3) and (4) respectively.

Jacobian matrix for joint measurement model $\mathbf{f}(\mathbf{x})$ is defined from (13) and (14) by

$$\frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial \mathbf{d}_0(\mathbf{x})}{\partial \mathbf{x}} \\ \frac{\partial \mathbf{b}(\mathbf{x})}{\partial \mathbf{x}} \end{bmatrix}. \quad (15)$$

D. TDOA-AOA Noisy Measurement Processing Model

Expressions (2) and (6) represent error-free values of TDOA and AOA, however in practice noise is always present in measurements. Noisy TDOA can be rewritten from (2) as

$$d_{i,0} = d_i - d_0 + n_{di}. \quad (16)$$

where n_{di} is measurement noise for $d_{i,0}$ with TDOA standard deviation σ_{TDOA} . Employing technique, proposed in [24], under the assumption that ground based receive sensor Rx_{GR} is in the Cartesian coordinate system origin, we can represent TDOA measurement processing model in matrix form as [22]

$$\mathbf{m}_{\text{TDOA}} = \mathbf{g}_{\text{TDOA}} \mathbf{X} + \mathbf{n}_{\text{TDOA}}. \quad (17)$$

where

$$\mathbf{m}_{\text{TDOA}} = \frac{1}{2} \begin{bmatrix} d_{1,0}^2 - K_1 \\ d_{2,0}^2 - K_2 \\ \vdots \\ d_{k,0}^2 - K_k \end{bmatrix}, \mathbf{g}_{\text{TDOA}} = \begin{bmatrix} -x_1 & -y_1 & -z_1 & -d_{1,0} \\ -x_2 & -y_2 & -z_2 & -d_{2,0} \\ \vdots & \vdots & \vdots & \vdots \\ -x_k & -y_k & -z_k & -d_{k,0} \end{bmatrix} \quad (18)$$

$$\mathbf{n}_{\text{TDOA}} = [n_{d1}, n_{d2}, \dots, n_{dk}]^T, K_i = x_i^2 + y_i^2 + z_i^2.$$

and $\mathbf{X} = [x, y, z, d_0]^T$ is the vector of unknown variables.

Noisy AOA was also considered in [22], however only ground based sensor measured AOA. Consider the case of stationary emitter, illustrated in figure 3, where Rx_{GR} measures single AOA pair (θ_0, ϕ_0) and Rx_{UAV} measures k AOA pairs (θ_i, ϕ_i) , $i=1 \dots k$ along UAV flight path. Then we can represent AOA measurement processing model in matrix form as [22]

$$\mathbf{m}_{\text{AOA}} = \mathbf{g}_{\text{AOA}} \mathbf{X} + \mathbf{n}_{\text{AOA}}. \quad (19)$$

where

$$\mathbf{m}_{\text{AOA}} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}, \mathbf{g}_{\text{AOA}} = \begin{bmatrix} -\sin \theta_0 & \cos \theta_0 & 0 & 0 \\ -\sin \phi_0 / \cos \theta_0 & 0 & \cos \phi_0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -\sin \theta_k & \cos \theta_k & 0 & 0 \\ -\sin \phi_k / \cos \theta_k & 0 & \cos \phi_k & 0 \end{bmatrix} \quad (20)$$

$$\mathbf{n}_{\text{AOA}} = [d_{0xy} n_{\theta_0}, d_0 n_{\phi_0}, \dots, d_{kxy} n_{\theta_k}, d_k n_{\phi_k}]^T.$$

where $(n_{\theta_i}, n_{\phi_i})$ is measurement noise for (θ_i, ϕ_i) , $i=0 \dots k$, with AOA standard deviation σ_{AOA} . Joint processing of TDOA and AOA primary measurements by combining (17) and (19) gives a set of overdetermined location equations

$$\begin{bmatrix} \mathbf{m}_{\text{TDOA}} \\ \mathbf{m}_{\text{AOA}} \end{bmatrix} = \begin{bmatrix} \mathbf{g}_{\text{TDOA}} \\ \mathbf{g}_{\text{AOA}} \end{bmatrix} \mathbf{X} + \begin{bmatrix} \mathbf{n}_{\text{TDOA}} \\ \mathbf{n}_{\text{AOA}} \end{bmatrix}. \quad (21)$$

III. SIMULATION SCENARIO AND RESULTS

Simulation scenario described further is based on the assumption of ideal synchronization between sensors of the terrestrial and flying segments aboard UAV. Simulation model included arrangement, estimation and visualization subsystems [25]–[29]. The positioning of the emitter was performed for scenario when it is located in three-dimensional space at the point (5, 4.0, 1.0) km in an area with a size of (10 km × 10 km × 5 km) as depicted in Figure 4 [26].

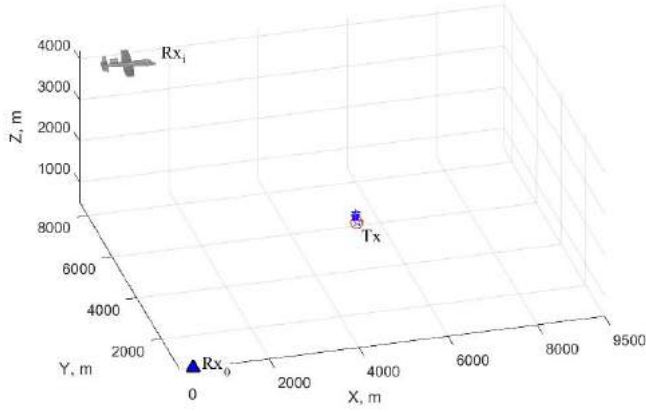


Figure 4. Simulation scenario

UAV flies circumferentially over the working area at a constant altitude $z = 4$ km [26]. A set of overdetermined location equations (21) was solved with Levenberg-Marquardt (LM) positioning algorithm [30] and compared with CRLB (11). The root-mean-square error (RMSE) of coordinates estimate of the emitter source is [31]

$$\text{RMSE} = \sqrt{E \left\{ \sqrt{(\hat{x} - \hat{x})^2 + (\hat{y} - \hat{y})^2 + (\hat{z} - \hat{z})^2} \right\}}. \quad (22)$$

where $\hat{\mathbf{x}} = [\hat{x}, \hat{y}, \hat{z}]$ is emitter LM location estimate. Figure 5 shows performance of hybrid TDOA-AOA measurement processing location estimation in terms of RMSE versus the AOA standard deviation σ_{AOA} computed during simulation when TDOA standard deviation σ_{TDOA} is fixed at 10 m.

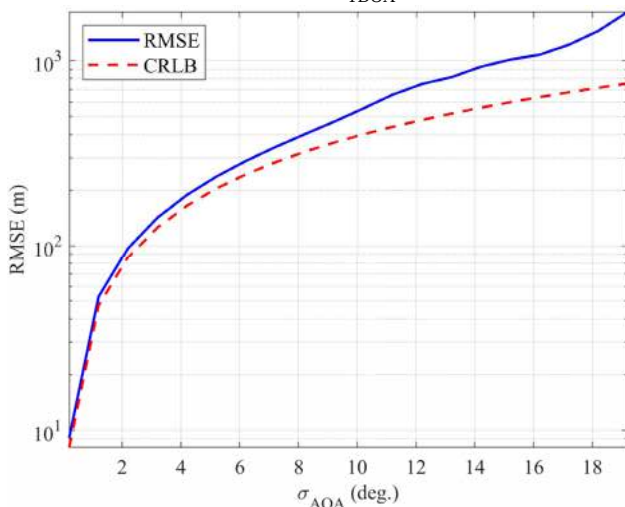


Figure 5. Emitter location RMSE versus AOA standard deviation σ_{AOA}

Previous simulation results in [25]–[29] with TDOA only measurement processing achieved RMSE of approximately 10 m in LOS conditions, that's why $\sigma_{\text{TDOA}}=10\text{m}$ was chosen as a reference for hybrid TDOA-AOA measurement processing with handling AOA noise.

It can be seen from Figure 5, that positioning accuracy performance with only two sensors quickly degrades with the increase of AOA noise and looks rather coarse comparing to the cases in [25]–[29] with five ground based receive sensors Rx_{GR} and one UAV based receive sensor Rx_{UAV} . To prove practicability of hybrid TDOA-AOA measurement processing let's observe existing accuracy results for passive geolocation with TDOA, FDOA, AOA or RSSI measurement processing, including UAV based passive geolocation, shown in Table 1.

TABLE 1. ACCURACY RESULTS FOR PASSIVE GEOLOCATION WITH UAVS

Ref.	Accuracy bounds, m	Assumptions	Primary Measurements
[2]	21 – 100	3D, 1 UAV, LOS	TDOA
[3]	16 - 99	3D, 1 UAV, LOS	
[8]	500 – 2000	3D, 1 UAV, LOS	
[9]	10 – 1000	2D, 2 UAVs, LOS, Kalman filtering	
[10]	100 – 1000	2D, 2 UAVs, LOS, Kalman filtering	
[25] [28]	9 – 16	3D, 1 UAV, 5 Rx_{GR} , LOS	TDOA
[26]	20 – 3000	3D, 1 UAV, 5 Rx_{GR} , NLOS	
[11]	10-2000	2D, 2 UAVs, LOS, Kalman filtering	TDOA–FDOA
[12]	15 – 65	3D, 2 UAVs, LOS,	AOA
[14]	20 – 200	2D, 1 UAV, LOS	
[15]	28 - 57	3D, 3 UAVs, LOS, Kalman filtering	RSSI
[17]	30 – 200	2D, 2 UAVs, LOS	
[18]	22 – 180	2D, 4 Rx_{GR}	TDOA-AOA
[19]	~102	2D, 1 Rx_{GR} , $\sigma_{\text{AOA}}=0.2^\circ$, $\sigma_{\text{TDOA}}=25\text{ns}$	

Results in Table 1 are simulation based and depend on a plenty of factors, including model setup and parameters. However, for the case of passive geolocation in 3D space in NLOS conditions with only one ground and one UAV based sensor hybrid TDOA-AOA measurement processing appears to be practicable because even coarse AOA with σ_{AOA} up to 20° can straightforwardly contribute to NLOS measurements excluding [26] which in 3D space lead to $\text{RMSE} > 10^3$.

IV. CONCLUSIONS

In this paper we developed mathematical model for positioning of radio emission sources with UAVs using hybrid TDOA-AOA measurement processing and verified its practicability in NLOS conditions with only two sensors.

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