Positioning of radio emission sources with unmanned aerial vehicles using TDOA-AOA measurement processing

S V Bachevsky¹, G A Fokin¹, A N Simonov² and V V Sevidov²

¹The Bonch-Bruevich Saint-Petersburg State University of Telecommunications, Bolshevikov str. 22-1, Saint-Petersburg, Russia, 193232
²Military Academy of Communications named after S.M. Budyonny, Tikhoretskiy str. 3, Saint-Petersburg, Russia, 194064
e-mail: grihafokin@gmail.com

Abstract. Positioning of radio emission sources (RES) with ground and flying network segments exploits interaction of sensors aboard Unmanned Aerial Vehicles (UAVs) with terrestrial stationary ground sensors. Time Difference of Arrival (TDOA) and Angle of Arrival (AOA) measurements processing are the most wide-spread techniques for passive geolocation systems. Successful implementation of TDOA-AOA positioning in existing UAV based geolocation systems achieves accuracy results of tens and hundreds of meters for overoptimistic scenarios without reflections in so called Line of Sight (LOS) conditions. Prevailing application specific cases for UAV based positioning include search and rescue (S&R) operations in mountains, hills and other regions of irregular surface topography with Non-Line of Sight (NLOS) conditions, where radio waves could experience severe reflection and diffraction. For geolocation tasks NLOS problem usually leads to significant errors for both TDOA and AOA measurement processing techniques. Joint processing of TDOA and AOA primary measurements could partially overcome this problem by preliminary identification and exclusion of reflected signals. In current research we refine existing mathematical model and develop new simulation models to investigate NLOS tolerance during positioning with one stationary ground sensor and one sensor aboard flying UAV using joint TDOA-AOA measurement processing technique. The contribution of current research is performance evaluation of considered positioning system with AOA noise and confirmation of its practicability to handle NLOS problem, when AOA deviation is less than 10 degrees.

1. Introduction
Cooperation of transceiver stations aboard Unmanned Aerial Vehicles (UAVs) with widely deployed terrestrial ground transceiver stations [1] is becoming a common trend in current and future wireless networks development. Geolocation applications in such networks appear to be in demand for both military scenarios, such as tactical wireless networks [2] or battlefield environments [3] and civil scenarios, such as ground-aerial surveillance [4], cognitive radio communications [5] or supporting search and rescue operations [6].

Positioning of radio emission sources (RES) is termed passive geolocation if it is done from passive primary measurements of times of arrival, angles of arrival, or frequency (Doppler) shifts of radio waves
received at various sensors [7]. Considered positioning system consists of flying receiver stations or sensors aboard UAV and stationary ground-based sensors.

Positioning systems with cooperation of flying sensors aboard UAV and stationary ground-based sensors were already well studied and can be categorized by primary measurements into Time Difference of Arrival (TDOA) [8]–[10], Frequency Difference of Arrival (FDOA) [11], Angle of Arrival (AOA) or Direction of Arrival (DOA) [12]–[13] techniques.

Preferred geolocation technique, namely TDOA, FDOA, AOA or RSSI, depends on positioning scenario and has its advantages and disadvantages for particular UAV assisted positioning application. In optimistic Line of Sight (LOS) conditions TDOA positioning technique provides high location accuracy, however it requires accurate synchronization among sensors and in 3D at least four receivers are required to generate hyperboloids intersection. AOA or Direction Finding (DF) measurement requires only two receiving sensors for geolocation on the plane and works without synchronization among them, however its resulting accuracy diminish with the distance to RES. RSSI method of geolocation works by measuring the strength of the signal received from RES. RSSI benefit is that it is the most simple and easy in hardware and implementation, however its location accuracy is worst due to inherent exponential decay of received power when RES is far from sensor.

The use of UAVs as moving receiver in conjunction with ship/land-based platforms, reducing the number of sensors required to obtain multiple TDOA measurements, was proposed in [8]. Positioning of stationary and mobile RES with a pair of UAVs by TDOA technique with consecutive filtering was evaluated in [9] for Kalman and in [10] for Gaussian techniques. Evaluation of tracking performance by TDOA and FDOA measurement fusion was performed in [11].

Combination of AOA estimates with digital terrain map to perform the actual calculation or RES position with commercially available hardware was proposed in [12]. Investigation [13] dealt with geolocation of RES using low-cost UAV-based approach and contains several test cases, including UAV flight paths and AOA estimation uncertainties.

Resulting upper accuracy limits for UAV-based positioning systems are summarized in table 1 and achieves the order of tens and hundreds of meters in optimistic LOS conditions and are far from high precision systems [26]–[31]. To validate hybrid TDOA-AOA measurement processing for UAV based positioning in heterogeneous terrain with NLOS conditions let's analyze existing accuracy results for TDOA, FDOA, AOA techniques described above.

| Ref. | Upper limit, m | Considered scenario | Primary measurements |
|------|---------------|---------------------|---------------------|
| [2]  | < 100        | Space (3D), 1 UAV, LOS | TDOA                |
| [3]  | < 99         | Space (3D), 1 UAV, LOS |                    |
| [8]  | < 2000       | Space (3D), 1 UAV, LOS | TDOA                |
| [9]  | < 1000       | Plane (2D), 2 UAVs, LOS, Kalman filtering | | |
| [10] | < 1000       | Plane (2D), 2 UAVs, LOS, Kalman filtering | TDOA–FDOA           |
| [20] | < 16         | Space (3D), 1 UAV, 5 Rx, LOS | AOA                 |
| [21] | < 3000       | Space (3D), 1 UAV, 5 sensors, NLOS | TDOA-AOA            |
| [11] | < 2000       | Plane (2D), 2 UAVs, LOS, Kalman filtering | TDOA–FDOA           |
| [12] | < 65         | Space (3D), 2 UAVs, LOS, | AOA                 |
| [13] | 20 – 200     | Plane (2D), 1 UAV, LOS |                    |
| [14] | <180         | Plane (2D), 4 sensors |                    |
| [15] | <102         | Plane (2D), 1 sensor, $\sigma_{\text{AOA}}=0.2^\circ$, $\sigma_{\text{TDOA}}=25\text{ns}$ | TDOA–AOA            |

Presented upper accuracy limits for positioning with unmanned aerial vehicles in table 1 result from simulation models, have a wide spread and come from a majority of model cases and parameters. However, we can draw the following conclusions. At first, larger number of sensors provides higher location accuracy. Then, positioning uncertainty on the plane (2D) is evidently lower than in space (3D)
simulation scenarios. Also, presented results hold for LOS scenarios and do not consider primary measurements variations due to possible reflections in irregular surface topography with hills and mountains. However, prevailing application specific cases for UAV based positioning include search and rescue (S&R) operations in mountains, hills and other regions of heterogeneous terrain with Non-Line of Sight (NLOS) conditions, where radio waves could experience severe reflection and diffraction. For geolocation tasks NLOS problem usually leads to significant errors for both TDOA and AOA measurement processing systems, as a result primary NLOS measurements, obtained after reflections, could lead to a significant Root Mean Square Error (RMSE) location accuracy final estimate exceeding $10^3$ m [21]–[23]. In current research we refine existing mathematical model and develop new simulation models to investigate NLOS tolerance during positioning with one stationary ground sensor and one sensor aboard flying UAV using joint TDOA-AOA measurement processing technique. Contribution of current investigation lies in the refinement of models [20], [21] and checking its robustness in handling AOA variance, encountering primary measurements disturbances after NLOS reflections.

Solution to joint TDOA-AOA technique on the plane was proposed in [14] and revealed substantial accuracy gain comparing to TDOA processing alone. Same task with single sensor was investigated for naval context in [15]. From [14] and [15] we can conclude, that joint TDOA-AOA measurement processing is preferred for the 2D scenario comparing to separate range difference and direction finding techniques. Solution to joint TDOA-AOA technique in 3D is more complex, because azimuth and the elevation angles need to be expressed and computed jointly during solving non-linear equations [16].

One of the approaches to handle TDOA-AOA measurement processing in 3D was proposed in [17], and supposed scenario with a couple of stationary ground sensors. Scenario with UAV based sensor and joint range difference and direction-finding processing was evaluated in [18] via simulation, which, however, had a lack of handling AOA variance encountering primary measurements disturbances after NLOS reflections. Current investigation aims to fill the gap in UAV based RES positioning systems using joint TDOA-AOA measurement processing technique and supply models in [20]–[23] with 3D AOA measurement processing technique by joint solving for azimuth and the elevation angle non-linear measurement equations.

This work extends investigation [22], considering simulation model scenario explanation. The material in the paper is organized in the following order. Mathematical model for UAV based radio emission source positioning using TDOA-AOA measurement processing is presented in Section 2. Refined radio emission source positioning simulation model, positioning cases and NLOS tolerance results in handling AOA variance are given in Section 3. Conclusions is given in Section 4.

2. Mathematical model for RES positioning with UAV using TDOA-AOA technique

In this section we present mathematical model for UAV based positioning using TDOA-AOA measurement processing in the following order: 1) UAV based radio emission source positioning system model; 2) TDOA-AOA error-free radio emission source positioning model; 3) Cramer-Rao Lower Bound for TDOA-AOA radio emission source positioning model; 4) TDOA-AOA noisy radio emission source positioning model.

2.1. UAV Based Radio Emission Source Positioning System Model

Investigated radio emission source positioning system consists of flying sensor aboard UAV and stationary terrestrial sensor shown in figure 1.

Locations of terrestrial and flying receive sensors are available through Global Navigation Satellite Systems (GNSS). During positioning sensors gather primary Time of Arrival (TOA) and AOA measurements from packet transmissions of radio emission source. After each reception sensor records the time (TOA) and angle of arrival (AOA) for the received packet. Time fixing precision is defined by GNSS receiver capabilities. Recorded TOAs and AOAs are sent by sensors to the central measurement processing unit, which solves non-linear TDOA-AOA equations using known locations of terrestrial and flying receive sensors. Resulting solution contains radio emission source coordinates estimate $\hat{x}=(\hat{x}, \hat{y}, \hat{z})^T$. 

3
The use of UAVs as flying receive sensor in conjunction with terrestrial stationary ground-based receive sensor as a reference node, reducing the number of sensors required to obtain multiple TDOA measurements, is presented in figure 2.

\[ d_{i,0} = \frac{t_{i,0}}{c} \]

where \( c \) – speed of light and \( d_{i,0} \) is range difference between \( Rx_{UAV} \) and \( Rx_{GR} \) sensors.

**2.2. TDOA-AOA Error-Free Radio Emission Source Positioning Model**

Denote stationary terrestrial receive sensor \( Rx_{GR} \) with coordinates \( x_0=(x_0, y_0, z_0)^T \) as reference sensor and flying receive sensor \( Rx_{UAV} \) with coordinates \( x_i=(x_i, y_i, z_i)^T \), where time intervals \( i=1\ldots k \) correspond to synchronized reception records, \( k \) – the number of primary TOA/AOA measurements along UAV flight path. Denote \( TOA_i \) as packet time of arrival for the signal from radio emission source, then TDOA between flying \( Rx_{UAV} \) and reference terrestrial \( Rx_{GR} \) sensors is

\[ t_{i,0} = TOA_i - TOA_0 = \frac{d_{i,0}}{c}, \]
Error-free range difference is 
\[ d_{i,0} = d_i - d_0, \]  
where \( d_i \) is range between radio emission source with unknown coordinates \( x=(x,y,z)^T \) and receive sensor with available coordinates \( x_i=(x_i,y_i,z_i)^T \) calculated as 
\[ d_i = \| x - x_i \| = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}. \]  

Operator \( \| \cdot \| \) is a norm over a vector in 3D space [23]. TDOA-AOA positioning geometry for arbitrary time instant \( i \) is depicted in figure 3. Radio emission source transmissions, received by two sensors, give one TDOA \( t_{i,0} \) and two AOA pairs \( (\theta_0,\phi_0) \) and \( (\theta_i,\phi_i) \) of measurements every time instant \( i \).

Projection of range between radio emission source and receive sensor \( d_i \) on x-y plane follows from figure 3 and can be expressed by 
\[ d_{i,xy} = \sqrt{(x-x_i)^2 + (y-y_i)^2}. \]  

Error-free range difference measurements \( d_{0}(x) \in \mathbb{R}^{kx1} \) for \( i=1…k \) TOA measurements along UAV flight path with reference sensor \( R_{xGR} \) in matrix form can be expressed by 
\[
\begin{pmatrix}
\sqrt{(x-x_1)^2 + (y-y_1)^2} \\
\sqrt{(x-x_2)^2 + (y-y_2)^2} \\
\vdots \\
\sqrt{(x-x_k)^2 + (y-y_k)^2} 
\end{pmatrix}.
\]  

Error-free bearing pair \( b_i \) with azimuth \( \theta_i \) and elevation \( \phi_i \) AOA from RES to receive sensor for \( i=1…k \) AOA measurements along UAV flight path in matrix form can be expressed by 
\[ b_i(x) = \begin{bmatrix} \theta_i \\ \phi_i \end{bmatrix}. \]  

To arrange equal number of primary TDOA and AOA measurements, assume RES to be stationary and bearing pair \( b_i \) is collected by terrestrial receive sensor \( R_{xGR} \) for \( i=1…k \) time intervals along UAV flight path. Then error-free bearing AOA measurement model \( b(x) \in \mathbb{R}^{2kx1} \) in matrix form can be expressed by 
\[ b(x) = \begin{bmatrix} b_1(x), b_2(x),...,b_k(x) \end{bmatrix}^T. \]
Error-free range difference (TDOA) and bearing (AOA) joint primary measurement model \( f_i(x) \) for \( i \)th time instant can be expressed by

\[
f_i(x) = [d_i(x), b_i(x)]^T.
\]  

(9)

In matrix form \( f_i(x) \) for \( i=1\ldots k \) primary measurements along UAV flight path is defined by

\[
f(x) = [d(x), b(x)]^T.
\]  

(10)

2.3. Cramer-Rao Lower Bound for TDOA-AOA Radio Emission Source Positioning Model

Cramer-Rao Lower Bound (CRLB) is a lower bound on variance of any unbiased estimator using the same primary measurements, and serves as a benchmark to compare with the root mean square error (RMSE) of positioning algorithms. To estimate CRLB one should build corresponding Fisher information matrix (FIM) \( I(x) \), computed at RES location \( x=(x,y,z)^T \). The diagonal elements of the FIM inverse are the minimum achievable variance values:

\[
\text{CRLB}(x) = \text{trace}(I^{-1}(x)).
\]  

(11)

For zero-mean Gaussian distributed primary measurement errors \( I(x) \) is [24]

\[
I(x) = \left[ \frac{\partial f(x)}{\partial x} \right]^T C^{-1} \left[ \frac{\partial f(x)}{\partial x} \right],
\]  

(12)

where \( C \) denotes TDOA and AOA noise covariance matrix, and \( \frac{\partial f(x)}{\partial x} \) is Jacobian matrix for joint TDOA-AOA measurement model \( f(x) \). Jacobian matrix \( \frac{\partial d_i(x)}{\partial x} \in \mathbb{R}^{k \times 3} \) for \( d_i(x) \) defined by

\[
\frac{\partial d_i(x)}{\partial x} = \begin{bmatrix}
\frac{x-x_i}{d_1} & \frac{x-x_0}{d_1} & \frac{y-y_i}{d_0} & \frac{y-y_0}{d_0} & \frac{z-z_i}{d_1} & \frac{z-z_0}{d_0} \\
\frac{x-x_2}{d_2} & \frac{x-x_0}{d_2} & \frac{y-y_2}{d_0} & \frac{y-y_0}{d_0} & \frac{z-z_2}{d_2} & \frac{z-z_0}{d_0} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\frac{x-x_k}{d_k} & \frac{x-x_0}{d_k} & \frac{y-y_k}{d_0} & \frac{y-y_0}{d_0} & \frac{z-z_k}{d_k} & \frac{z-z_0}{d_0}
\end{bmatrix},
\]  

(13)

where \( d_i \) is computed by (3). Jacobian matrix \( \frac{\partial b(x)}{\partial x} \in \mathbb{R}^{2k \times 3} \) can be expressed by

\[
\frac{\partial b(x)}{\partial x} = \begin{bmatrix}
\frac{(y-y_i)}{d_{i,y}^2} & \frac{(x-x_i)}{d_{i,y}^2} & 0 \\
\frac{(x-x_i)(z-z_i)}{d_{i,xy}^2} & \frac{(y-y_i)(z-z_i)}{d_{i,xy}^2} & \frac{d_{i,y}}{d_{i,x}} \\
\vdots & \vdots & \vdots \\
\frac{(y-y_k)}{d_{k,y}^2} & \frac{(x-x_k)}{d_{k,y}^2} & 0 \\
\frac{(x-x_k)(z-z_k)}{d_{k,xy}^2} & \frac{(y-y_k)(z-z_k)}{d_{k,xy}^2} & \frac{d_{k,y}}{d_{k,x}}
\end{bmatrix},
\]  

(14)

where \( d_{i,y} \) is computed by (4).

Jacobian matrix for joint measurement model \( f(x) \) in (13) and (14) can be expressed by

\[
\frac{\partial f(x)}{\partial x} = \left[ \frac{\partial d_i(x)}{\partial x}, \frac{\partial b(x)}{\partial x} \right]^T.
\]  

(15)
2.4. TDOA-AOA Noisy Radio Emission Source Positioning Model

Equations (2) and (6) give noiseless TDOA and AOA measurements. Noisy TDOA can be expressed by

\[ d_{i,0} = d_i - d_0 + n_{di} \]  

(16)

where \( n_{di} \) is TDOA measurement noise for \( d_{i,0} \) with standard deviation \( \sigma_{TDOA} \).

If we suppose that terrestrial receive sensor Rx_{GR} is in the Cartesian coordinate system origin [24], TDOA measurement processing model in matrix form can be expressed as [18]

\[ m_{TDOA} = g_{TDOA} X + n_{TDOA} \]

(17)

where

\[
\begin{bmatrix}
    d_{1,0} - K_1 \\
    d_{2,0} - K_2 \\
    \vdots \\
    d_{k,0} - K_k
\end{bmatrix},
\]

\[
\begin{bmatrix}
    -x_1 - y_1 - z_1 - d_{1,0} \\
    -x_2 - y_2 - z_2 - d_{2,0} \\
    \vdots \\
    -x_k - y_k - z_k - d_{k,0}
\end{bmatrix},
\]

\[ m_{TDOA} = \begin{bmatrix}
    d_{1,0} - K_1 \\
    d_{2,0} - K_2 \\
    \vdots \\
    d_{k,0} - K_k
\end{bmatrix},
\]

\[ g_{TDOA} = \begin{bmatrix}
    -x_1 - y_1 - z_1 - d_{1,0} \\
    -x_2 - y_2 - z_2 - d_{2,0} \\
    \vdots \\
    -x_k - y_k - z_k - d_{k,0}
\end{bmatrix},
\]

(18)

\[ n_{TDOA} = [n_{d1}, n_{d2}, \ldots, n_{dk}]^T, K_i = x_i^2 + y_i^2 + z_i^2, \]

and \( X = [x, y, z, d_o]^T \) is the vector of unknown variables.

In [18] only ground based sensor measured AOA. For our model with stationary emission source assumption, when Rx_{GR} measures single AOA pair \((\theta_0, \phi_0)\) and Rx_{UAV} measures \(k\) AOA pairs \((\theta_i, \phi_i)\), \(i=0\ldots k\) along UAV flight path, AOA measurement processing model in matrix form can be expressed as [18]

\[ m_{AOA} = g_{AOA} X + n_{AOA}, \]

(19)

where

\[
\begin{bmatrix}
    0 \\
    \vdots \\
    0 \\
    -\sin \theta_0 \cos \theta_0 \cos \phi_0 \cos \phi_0 \\
    \vdots \\
    -\sin \theta_k \cos \theta_k \cos \phi_k \cos \phi_k
\end{bmatrix},
\]

\[
\begin{bmatrix}
    -\sin \theta_0 \\
    \vdots \\
    -\sin \theta_k
\end{bmatrix},
\]

\[ m_{AOA} = \begin{bmatrix}
    0 \\
    \vdots \\
    0 \\
    -\sin \theta_0 \cos \theta_0 \cos \phi_0 \cos \phi_0 \\
    \vdots \\
    -\sin \theta_k \cos \theta_k \cos \phi_k \cos \phi_k
\end{bmatrix},
\]

(20)

\[ n_{AOA} = [d_{0xy}, n_{d0}, d_{n0}, \ldots, d_{0xy}, n_{d0}, d_{n0}]^T, \]

and \( n_{d0}, n_{\theta_i} \) is measurement noise for \((\theta_i, \phi_i), i=0\ldots k\), with AOA standard deviation \( \sigma_{AOA} \).

Joint TDOA-AOA measurements can be expressed by combining (17) and (19) as a set of overdetermined non-linear equations

\[
\begin{bmatrix}
    m_{TDOA} \\
    m_{AOA}
\end{bmatrix} = \begin{bmatrix}
    g_{TDOA} \\
    g_{AOA}
\end{bmatrix} X + \begin{bmatrix}
    n_{TDOA} \\
    n_{AOA}
\end{bmatrix}.
\]

(21)

3. Simulation model for RES positioning with UAV using TDOA-AOA technique

Simulation model for RES positioning with UAV using TDOA-AOA technique aims to investigate NLOS tolerance during positioning with one stationary ground terrestrial sensor and one flying sensor aboard UAV using joint TDOA-AOA measurement processing technique. Simulation model assumes ideal synchronization, perfect self-geolocation of terrestrial and flying sensors aboard UAV, was realized in MatLab and included arrangement, estimation and visualization subsystems described in [20], [21].

Positioning of radio emission source was performed for scenario when RES is at the point \((5, 4, 1)\) km in an area with a size of \((10 \times 10 \times 5)\) km, stationary terrestrial receiver is at the origin point \((0, 0, 0)\) km, and sensor aboard UAV flies circumferentially over the area at constant altitude \(z = 4\) km, as depicted in figure 4.
Figure 4. Simulation scenario.

Figure 5. RES RMSE versus $\sigma_{\text{AOA}}$.

Circle trajectory choice of the UAV movement in simulation model can be explained because it is the most often analyzed trajectory for UAV based positioning [20]. Non-linear location equations were solved with Levenberg-Marquardt (LM) algorithm [24] and resulting estimates were compared with CRLB [17]. RES RMSE was calculated according to [25]

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

(22)

where $\hat{x} = [\hat{x}, \hat{y}, \hat{z}]$ is emitter LM location estimate.

Previous simulation results with six sensors and TDOA only measurement processing achieved RMSE of about 10 m [20]. Figure 5 shows performance of hybrid TDOA-AOA measurement processing location estimation in terms of RMSE versus the AOA standard deviation $\sigma_{\text{AOA}}$ computed during simulation when TDOA standard deviation $\sigma_{\text{TDOA}}$ is fixed at 10 m. From figure 5 we can conclude, that positioning performance with only two sensors is rather coarse comparing to the case of six sensors even with right primary AOA measurements acquisition [20]. However, gain from hybrid TDOA-AOA measurement processing could become clear, if we consider NLOS scenario.

In figure 6 we have illustrated scenario when moving receiver aboard UAV produces NLOS measurements because of mountain obstacle for a short time flight [21]. Resulting RMSE of current estimates in three axes according to UAV flight is provided in figure 7.

Figure 6. Example NLOS scenario.

Figure 7. RMSE for scenario in figure 6.

From figure 7 it follows that RMSE considerably increases in the interval from 42 s to 60 s, which is illustrated by reflected rays, when LOS between UAV and transmitter is absent and NLOS measurement comes after reflection from mountain during the UAV flight behind the obstacle.

Turning back to figure 5 with resulting location RMSE versus AOA standard deviation $\sigma_{\text{AOA}}$ for azimuth and elevation angles, it follows, that RMSE quickly degrades with the increase of AOA noise and reaches the order of $10^3$ m, when AOA deviation $\sigma_{\text{AOA}}$ approaches 10 degrees.
RMSE order of $10^3$ m is considerably higher, than LOS [20], but lower, than NLOS RES location error [21]. Approach to identify and exclude NLOS error, validated in [21], uses RMSE threshold, which is higher than LOS error for worst SNR values and, at the same time, lower than location error for NLOS scenario. Practical relevance of the obtained results lies in the choice of $\sigma_{\text{thres}}=10^3$ for TDOA-AOA measurement processing which is reasonable in three-dimensional space case.

4. Conclusion

In this paper we evaluated the positioning accuracy of hybrid TDOA-AOA measurement processing location estimation with handling TDOA and AOA noise. Simulation results in terms of RMSE versus the AOA standard deviation $\sigma_{\text{AOA}}$ demonstrated that positioning performance with only two sensors is rather coarse comparing to the case of six sensors even with right primary AOA measurements acquisition. However, performed simulation results confirm possibility to handle NLOS with just two sensors, because even coarse AOA with $\sigma_{\text{AOA}}<10^\circ$ can contribute to NLOS measurements identifying. Contribution of validated joint TDOA-AOA measurement processing technique lies in accounting of NLOS effect in three-dimensional space by means of simulation which demonstrated possibility to reliably identify and temporarily exclude NLOS measurements during UAV flight by means of TDOA-AOA measurement processing when AOA deviation is less than 10 degrees.

5. References

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