Aircraft position estimation using angle of arrival of received radar signals

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Article Info

Article history:

Received Dec 10, 2019
Revised Feb 17, 2020
Accepted May 4, 2020

Keywords:

Angle of arrival estimation
Angulation
Position estimation
Position estimation error
Sensor array

ABSTRACT

With increasing demand of air traffic, there is a need to optimize the use of available airspace. Effective utilization of airspace relies on quality of aircraft surveillance. Active research is carried out for enhancements in surveillance techniques and various methods are evaluated for future use. This paper evaluates the use of multiple signal classification (MUSIC) based angle of arrival (AOA) estimation along with multiangulation for locating aircrafts from their electromagnetic wave emission. The performance evaluation of the system is presented by evaluating the AOA estimation errors and position estimation (PE) errors. The errors are evaluated by comparing the estimated value to the actual value. An analysis on the system parameters, AOA error and PE error are presented in the end. AOA errors are affected by the AOA value (emitter bearing), number of array elements, SNR and resolution of AOA estimation algorithm. Errors in AOA estimation lead to PE errors. The simulation results show small errors for short ranges. The system performance can be improved at the expense of computational time by using higher MUSIC resolution and larger antenna arrays.

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1. INTRODUCTION

Meeting the growing demand for air traffic largely depends on functionality of air traffic control (ATC) center which is responsible for locating aircraft accurately and updating each aircraft about the traffic in its surroundings [1]. Safety of air traffic flow depends on the quality of air traffic surveillance technique. Efficient surveillance can expedite the flow of air traffic and optimize the use of available airspace, hence allowing more aircrafts to fly simultaneously [2]. A typical air traffic control radar system consists of the primary surveillance radar (PSR) and secondary surveillance radar (SSR). The PSR estimates the target's position (bearing and range) by comparing the time difference between the transmitted and returned signal. With the use of SSR, the aircraft identity and altitude can be determined. The SSR sends an interrogation signal at an uplink frequency of 1030 MHz while the aircraft's transponder replies at downlink frequency of 1090 MHz [3]. There are 3 types of format used by SSR: mode A-identification, mode C-altitude and mode S-identification with altitude and position. Between the 3, Mode S is more advance to cater to the ever increase in air traffic intensity and to ensure navigation safety. Further enhancement comes with the introduction of ADS-B system which is a satellite based positioning system that utilizes GPS to estimate its current position (latitude and longitude) which is sent to the ground station along with other information such as velocity, altitude and 24 bits identification code. Aircrafts equipped with ADS-B transponders send signals periodically at 0.5 or 1 seconds at 1090 MHz using one of the formats used in mode S namely the mode S Extended

Squitter [4]. Thus, aircrafts are tracked at a more frequent rate compared to SSR at about 4 to 12 seconds which depends on the scan rate of the antenna [5]. Another technology to complement existing radar system is multilateration (MLAT) [6]. It estimates aircraft position by calculating the time difference of the aircraft transponder reply (mode A, C and S) detected at two spatial placed ground receiving stations (GRS)s. It requires a minimum of four GRSs which are all synchronized and connected to a command center via link infrastructure [7]. The ADS-B and SSR transponder transmit power for small aircraft is 125 W while for larger aircraft that flies at above 15,000 feet is 250 W [8]. Airborne weather radar is used by aircrafts to navigate and detect cloud formations. Since the radar operates in the X-band (8-12), it is possible to estimate the size and concentration of the atmospheric precipitation by measuring the energy difference of transmitted and returned signal [9]. The shorter wavelength allows the resolving smaller particles compared to the S-band [10]. The transmit power is lower at 500 Watts because of the shorter detection range and on board power constraint.

Search for both newer surveillance techniques and enhancements in the existing techniques is continuously going on. Although, Radar has been the conventional method for locating aircrafts, it requires high transmit power and high installation and maintenance cost, making it a costly surveillance technology. Furthermore, performance limitation due to distance, terrain and atmospheric condition and low update rate makes its functionality insufficient for surveillance in the current time [11]. Currently ADS-B alone suffers from security vulnerabilities due to its unauthenticated and unencrypted signals [12]. There are also chances of GPS device malfunction that would result in incorrect location [13]. Thus, there is a need to confirm the information provided by ADS-B system. In order to do so, time difference of arrival (TDOA) and angle of arrival (AOA) measurement based systems were suggested in [14]. An AOA based position estimation method is used as verification of ADS-B in [15]. A system based on MLAT is used to estimate 3D emitter position in [16]. A comparison of MLAT and multiangulation is carried out in [17]. Due to economic benefits of AOA, it is preferred over PSR, SSR, and MLAT.

In this paper, performance evaluation is carried out of an aircraft position estimation (PE) system based on a two stages process: 1) AOA estimation by multiple signal classification (MUSIC) algorithm, and 2) PE by angulation algorithm. Errors in each stage are analyzed. As for all wireless systems, noise is a major problem in aircraft surveillance. The received signals are corrupted by noise that leads to error in PE. If the maximum possible error in a system under a given operational condition (system coverage) is known, then this can be used to define a relationship between received signal quality and system performance. This relation can be used to identify the regions where the system will show promising results and where the system will fail. The errors in AOA estimation are evaluated by comparison of estimated AOA and actual AOA. The effect on the AOA errors is observed by variation in SNR values, number of array elements in receiver antenna and the resolution of MUSIC algorithm. Also, the effect on the computational time is examined. The AOA errors lead to PE errors in the second stage of system. A 2-D PE performance analysis of the system is presented to identify the range for which the system performs well.

2. RESEARCH METHOD

The system configuration is adopted from the previous works in [17, 18]. The system consists of four GRSs each equipped with a uniform linear array (ULA) all connected to the central unit as shown in Figure 1. The position coordinates of each GRS with a separation distance of 10 km are shown in Figure 2.

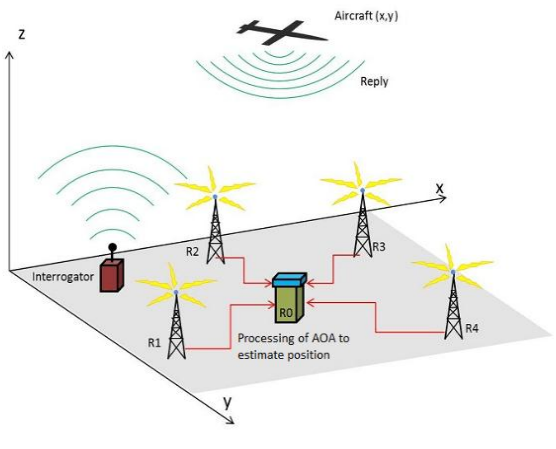


Figure 1. Working mechanism of AOA with maltiangulation

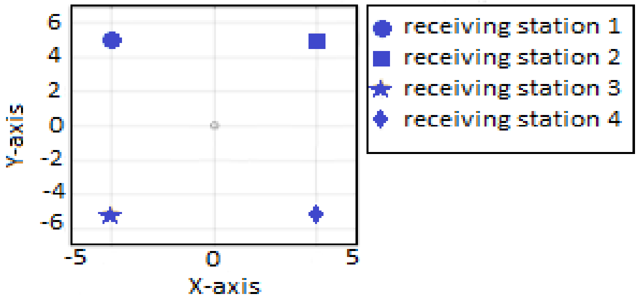


Figure 2. Receiving station configuration for 4 GRS

Simulation parameters used are based on true values used for aircraft surveillance. Signal with frequency of 1090 MHz, transmit power of 250 W and transmit antenna gain of 3 dBi is used to represent the SSR and ADS-B transponder signal. Receiver antenna gain of 18 dBi and 24 dBi is used for 8 and16 element arrays respectively. GRS receiver sensitivity is assumed to be -90 dBm. PE errors are calculated for emitter range 5 to 200 km and emitter bearing 0^o to 359^o. Signals transmitted by aircraft's transponder are received by each GRS simultaneously. Two variations of the MUSIC algorithm were used; one with 0.15^o resolution and the other with 0.25^o resolution. Root mean square error (RMSE) of position is used for comparison of PE error at various emitter positions. The PE process of the system is in two stages: 1) AOA estimation, and 2) PE using angulation algorithm. AOA estimation is carried out at each GRS while PE is done at the central unit. Firstly, signal received by each GRS is used for AOA estimation. In this system four AOAs are estimated for four GRSs. Next, the estimated AOAs along with the GRS position coordinates are used by the angulation algorithm to estimate the position of emitter.

2.1. MUSIC algorithm for AOA estimation

Several AOA estimation algorithms are present in the literature. These can be classified into subspace methods and non-subspace methods [19]. Non-subspace estimation techniques like beam forming and Capon's minimum variance method yield poor resolution and can identify only a single source at a time. Therefore, these algorithms are not suitable for air traffic monitoring. Subspace estimation techniques like MUSIC and estimation of signal parameter via rotational invariance technique (ESPRIT) have high resolution and perform efficiently where angles are indicated to be closely spaced [20]. These techniques can identify multiple sources given that the number of sensor elements in the sensor array is more than the number of emitters. A comparison shows that ESPRIT requires less computation than MUSIC and has a higher resolution. MUSIC on the other hand performs better at low SNR [21]. ESPRIT can show better accuracy but it requires twice as many sensor elements as MUSIC [22].

The ULA at each GRS consists of M elements separated by a distance d. It receives the signal $s(t)$ from the emitter impinging the array at an angle θ. The array element closest to emitter receives the signal earlier then the other elements. As a result, the other array elements receive a delayed version of $s(t)$. The signal at the i-th element is represented as:

$$x_i(t) = e^{-j\omega(i-1)(\frac{d}{c})\sin(\theta)} s(t) \tag{1}$$

where $\omega=2\pi f$ is the angular frequency, and c is the speed of electromagnetic waves. Putting all the signals received at each GRS together with noise forms the input signal matrix X(t);

$$\mathrm{X}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ \cdot \\ \cdot \\ \cdot \\ x_M(t) \end{bmatrix} + \mathbf{n}(t) \quad = \begin{bmatrix} 1 \\ e^{-j\omega\left(\frac{d}{c}\right)sin(\theta)} \\ e^{-j\omega\left(\frac{d}{c}\right)sin(\theta)} \\ \cdot \\ \cdot \\ \cdot \\ e^{-j\omega(M-1)\frac{d}{c}sin(\theta)} \end{bmatrix} s(t) + \mathbf{n}(t) \tag{2}$$

$$\mathrm{X}(t) = \mathrm{a}(\theta)s(t) + \mathrm{n}(t) \tag{3}$$

where a (θ) is the steering vector that steers the received signal in the direction of the AOA [23]. Input signal matrix for K emitters is given as:

$$X(t) = A(\theta)s(t) + n(t) \tag{4}$$

where A (θ) = [a(θ_1), a(θ_2),a(θ_3),……,a(θ_K)]. The MUSIC algorithm computes the $M\times M$ correlation matrix R_x.

$$R_x = E\{\mathbf{x}(t)\mathbf{x}^H(t)\} \tag{5}$$

Eigenvalue decomposition of R_x results in M eigenvalues (λ_1, λ_2, λ_3,…, λ_K,…, λ_M,) and M associated eigenvectors (u_1, u_2, u_3,….., u_K,….,u_M). Eigenvectors associated to K smallest eigenvalues span the noise subspace U_N while the rest (M-K) eigenvectors span the signal subspace U_s.

$$U_N = [\, u_1, u_2, u_3, \ldots, u_K] \tag{6}$$

$$U_S = [\, u_K, u_{K+1}, \ldots, u_M] \tag{7}$$

Due to the orthogonality of the noise subspace and the array steering vector at the angles of arrival θ_1, θ_2,. . . θ_K, the matrix product $a^H(\theta)U_N U_N{}^H a(\theta)$ is zero for these angles. The reciprocal of this matrix product creates sharp peaks at the angle of arrival [24]. Thus, the MUSIC pseudospectrum is given by:

$$P(\theta) = \frac{1}{\left|\mathbf{a}^H(\theta)\mathbf{U}_N\mathbf{U}_N{}^H\mathbf{a}(\theta)\right|} \tag{8}$$

2.2. Multiangulation position estimation methodology

Multiangulation is a method of estimating coordinates of emitter using AOAs and coordinates of GRS [8]. The point of intersection of line of bearings (LOB) is the position of emitter. Equation of LOB for the i-th GRS is:

$$yi = mi\ xi + ci \tag{9}$$

where (xi,yi) are the coordinates of i-th GRS. The slope and the y-intercept for (9) are given as:

$$m_i = \tan(90 - \theta_i) \tag{10}$$

$$c_i = y_i - x_i \tan(90 - \theta_i) \tag{11}$$

The multiangulation system consisting of four GRS results in four LOB equations which can be expressed in matrix form as:

$$Ax = b \tag{12}$$

where,

$$\mathbf{A} = \begin{bmatrix} -\tan(90-\theta_1) & 1 \\ -\tan(90-\theta_2) & 1 \\ -\tan(90-\theta_3) & 1 \\ -\tan(90-\theta_4) & 1 \end{bmatrix}, \mathbf{x} = \begin{bmatrix} x \\ y \end{bmatrix}, \ \mathbf{b} = \begin{bmatrix} y_1 - x_1\tan(90-\theta_1) \\ y_2 - x_2\tan(90-\theta_2) \\ y_3 - x_3\tan(90-\theta_3) \\ y_4 - x_4\tan(90-\theta_4) \end{bmatrix}$$

Since the number of equations is more than the unknowns, the matrix inverse does not exist. The over-determined least squares approach can be utilized [25]. Equation (12) can be represented as:

$$A^T A\ x = A^T b \tag{13}$$

The solution to the position estimate is found by:

$$x = (A^T A)^{-1} A^T b \tag{14}$$

For N-realization Monte Carlo simulation, RMSE for position is given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{M}\left[(x_i - x)^2 + (y_i - y)^2\right]}{N}} \qquad (15)$$

where (x,y) are the actual position coordinates of emitter and (x_i,y_i) are the position coordinates estimated at the i-th iteration.

3. RESULTS AND DISCUSSION

The evaluation of system performance is based on errors in AOA estimation and PE estimation.

3.1. Effect of varying SNR on AOA estimation error

The MUSIC algorithm was tested for various angles using Monte Carlo simulation for SNR values ranging from 25 to 55 dB. Standard deviation of estimated angles is shown in Tables 1 and 2 for 8 and 16 elements array respectively. At low SNR AOA estimation degrades producing high unacceptable errors for AOA values closer to the edge of array shown by angles closer to 90^o. Therefore, MUSIC algorithm will not be able to detect emitter at the edges of array at low SNR.

Table 1. AOA standard deviation for 8 elements array

M = 8		SNR (dB)						
		25	30	35	40	45	50	55
AOA	88	**35**	0.40	0.21	0.13	0.05	0	0
(^{o})	89	**84**	**70**	**70**	**31**	0.15	0.07	0.02
	90	**89**	**88**	**89**	**87**	**86**	**82**	**74**

Table 2. AOA standard deviation for 16 elements array

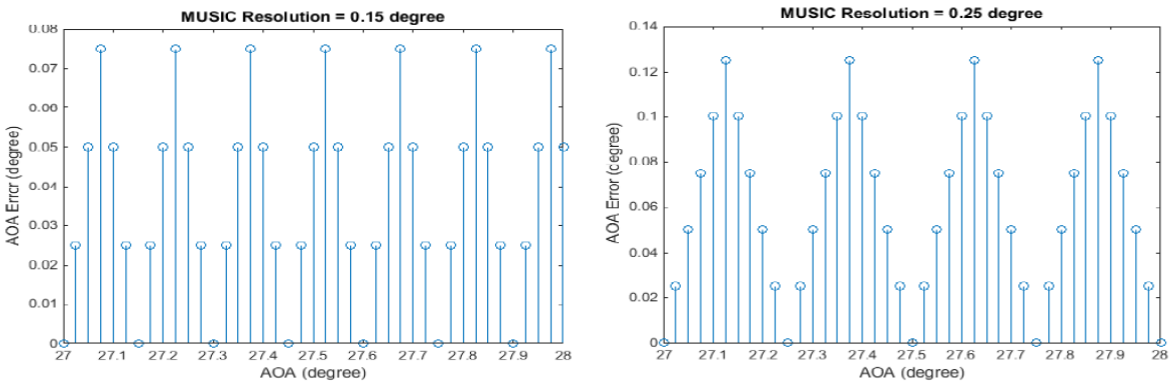
M = 15		SNR (dB)						
		25	30	35	40	45	50	55
AOA	88	0.02	0.14	0.07	0	0	0	0
(^{o})	89	**66**	**38**	0.16	0.07	0	0	0
	90	**90**	**88**	**88**	**85**	**83**	**75**	**66**

3.2. Effect of varying number of array elements on AOA estimation error

Tables 1 and 2 showed the performance of MUSIC algorithm is affected by the number of elements in the array. The 8 elements array is not able to estimate AOA of 88^o below 25 dB and 89^o below 40 dB. However, the 16 elements array is able to estimate 88^o at any SNR value in the given range but cannot estimate 89^o below 30 dB. The results also show that both the arrays cannot estimate AOA of 90^o at any SNR value. Therefore, at low SNR, increasing the number of array elements will improve the system performance

3.3. Effect of varying MUSIC resolution on AOA estimation error

MUSIC algorithm scans the spectrum for a range of -90^o to 90^o with fixed interval defined by t he resolution of algorithm. Smaller the interval higher is the resolution. For instance MUSIC with resolution of 1^o scans the spectrum at -90^o, -89^o, -88^o,……, 89^o, 90^o whereas MUSIC with a resolution of 5^o scans the spectrum at -90^o, -85^o, -80^o,……, 85^o, 90^o. Resolution of MUSIC algorithm affects the performance of the system. A comparison of AOA RMSE for 0.15^o and 0.25^o resolution at angles between 27^o to 28^o is shown in Figure 3.



(a) (b)

Figure 3. RMSE comparison for AOA estimation error, (a) AOA error for 0.15^o resolution, (b) AOA error for 0.25^o resolution

From Figure 3 it can be seen that the error is zero for AOAs that are multiples of the resolution value such as at 27°, 27.15°, 27.30° and 27.45° for 0.15° and at 27°, 27.25°, 27.50° and 27.75° for 0.25°. Amount of error at angles between the multiples of resolution value shows a symmetrical and periodic trend. Angles those are closer to the multiple of resolution value show low error.

3.4. Effect of varying array elements on PE estimation error

From the estimated AOA and the coordinates of all the four GRSs, the multiangulation algorithm is used to estimate the position of the emitter. The PE errors for various emitter positions are listed in Tables 3 and 4. The PE error that is less than 1.5 km satisfies Federal Aviation Administration (FAA) horizontal separation [16]. Both 8 and 16 element arrays show compliance with FAA horizontal separation for a range of 150 km. Certain positions show high unacceptable errors and emitter at these positions cannot be detected by the multiangulation system with single ULA. At 0° bearing and 5 km range, the actual AOA of the emitter at GRS-1 and GRS-2 are 90° and -90° respectively. Since the actual AOA of 90° cannot be estimated by MUSIC as shown in Table 1, a high PE error occurs at this position as shown in Tables 3 and 4 and the emitter cannot be detected by both 8 and 16 element arrays. It can be seen in Table 3 that high PE errors also occur at 90° bearing for range beyond 150 km when using 8 elements array. The actual AOA at each GRS for these locations are above 88° and SNR values are below 28 dB. Table 1 shows high AOA errors for AOA above 88° at SNR below 40 dB. High AOA errors consecutively result in high PE errors.

3.5. Effect of varying MUSIC elements on PE estimation error

Figure 4(a)-(b) shows contour plot of PE errors for 16 array elements for 0.15° and 0.25° resolution respectively. The plots show that errors for 0.15° resolution are lower than errors for 0.25°. This proves that MUSIC with higher resolution performs better. The errors increase as the range increases. It can also be seen that in Figure 4(b) there are certain positions with very high PE errors surrounded by positions with low PE errors. This is the result of variations in AOA errors by MUSIC resolution as shown in Figure 3. For 30° bearing PE error at 50 km is 0.0244 km and at 150 km is 0.3412 km. The PE error at 100 km is expected to be between 0.0244 and 0.3412 km. However, the error at 100 km is 1.8552 km. This is because emitter makes an angle of 26.16° and 27.42° with GRS-4 at 100 km and 150 km respectively. The AOA error for 26.16° is higher than that for 27.42° using a resolution of 0.15°. Thus, PE error at 100 km is higher than that at 150 km.

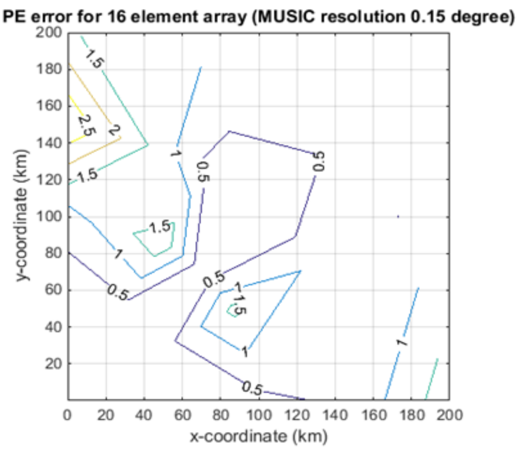
Table 3. AOA standard deviation for 8 elements array

M = 8		Bearing				
		0°	30°	45°	60°	90°
Range	5	13.3029*	0.0063	0.0026	0.0049	0
(km)	50	0.1479	0.0244	0.3152	0.0284	0.0528
	100	0.7152	0.8982	0.1315	0.4224	0.4814
	150	**2.6924**	0.2563	0.0592	0.3731	107.4*
	200	0.8114	0.6037	0.6773	0.6881	193.5*

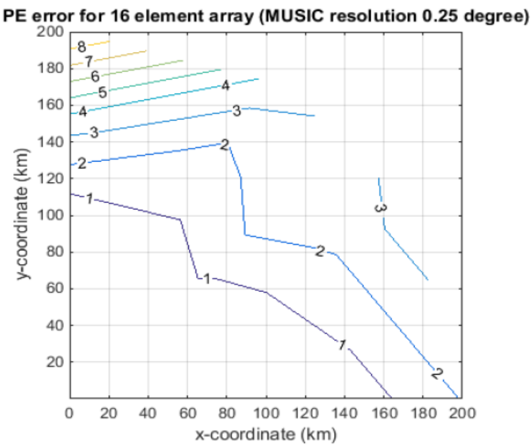
Table 4. AOA standard deviation for 16 elements array

M = 16		Bearing				
		0°	30°	45°	60°	90°
Range	5	12.2129*	0.0063	0.0026	0.0049	0
(km)	50	0.1479	0.0244	0.3160	0.0284	0.0354
	100	0.7152	**1.8552**	0.1315	**1.6183**	0.0344
	150	**2.9790**	0.3422	0.0583	0.8611	0.6230
	200	**1.5548**	0.7601	0.6376	0.4988	**1.8014**

Note: (*)=emitter undetectable, (bold)=exceeding FAA horizontal separation, (no mark)=compliance with the FAA horizontal separation



(a)



(b)

Figure 4. PE error comparison for MUSIC resolutions, (a) 0.15° resolution, (b) 0.25° resolution

4. CONCLUSION

A performance evaluation of system for estimating the position of aircraft using the radar signals of aircraft transponder was presented. The system is based on AOA estimation combined with multiangultion algorithm to estimate the position. Errors in estimated AOA were observed by varying the number of elements in ULA, the SNR values of the received signal and the resolution of MUSIC algorithm. Lower number of array elements produces low receiver antenna gain. Thus, more AOA errors were observed using lesser number of array elements compared to higher number of array elements at a particular SNR. It was also observed that the angles closer to the edge of the array produce large AOA errors. This is due to the inability of MUSIC algorithm to detect AOA closer to the edge. A comparison was also made of the effect of resolution of MUSIC on AOA errors. A higher resolution produces lower AOA errors as compared to lower resolution. On the contrary it requires longer computational time. There is always a tradeoff between system performance and computational time based on MUSIC resolution. Errors in the estimated position depend on AOA errors and the range of emitter. Larger number of array elements and higher resolution of MUSIC algorithm result in lower PE errors. Position of aircraft closer to the system can be estimated with higher accuracy.

ACKNOWLEDGEMENTS

The authors would like to thank the authorities of Digital Signal Processing (DSP) lab, Universiti Teknologi Malaysia (UTM) for providing the tools to carry out this research.

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