Research of Angle Measurement Technique in Transponder Landing System

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Abstract—**In this paper, a spatial smoothing technique based on MUSIC algorithm is introduced to substitute the traditional phase interferometer angle measurement algorithm of Transponder Landing System (TLS). It mainly researched the non-uniform linear receiving arrays design scheme under the new algorithm. This proposed algorithm aims to solve the multi-path or multi-targets interference problems of reply signal and eliminate the phase ambiguity caused by receiving arrays' baseline. It contrasted the feasibility, validity, resolving power and precision of the designed arrays with the uniform arrays in the same condition through computer simulation. The effectiveness and advantage of the proposed algorithm include the usability and reliability of the designed arrays is theoretically investigated. At last, we can obtain the real-time azimuth and elevation information relative to the touchdown point of landing aircraft through coordinate transformation.**

Index Terms—**Transponder landing system, angle measurement algorithm, arrays design, arrays capability, coordinate transformation**

I. INTRODUCTION

To meet the needs of airport in complex site condition and military mobility requirement, ANPC developed Transponder Landing System (TLS) [1, 2] in 1991. TLS obtains the aircraft's spatial location by measuring the carrier wave phase and TOA of the aircraft's reply signal, provides the guidance information to approach landing aircraft. It makes up for shortages of the instrument landing system (ILS), such as demanding installation sites or poor mobility. It only asks for ground equipments, using the airborne existing secondary radar equipments and ILS receiving equipment, to provide precision approach landing guidance to the aircraft in complex site conditions or provisional airports without any changes to the aircraft.

So far, the core journals home and abroad can hardly find the key technology and in-depth research articles about this system. At this point, we start the research of the system's key technology and correlative issue has the exploration significance to improve the key technology and optimize the performance of the system.

With the gradual opening up of lower space, air traffic capacity increases without cease. Due to great changes of battlefield condition and military field environment, the traditional phase interferometer angle measurement algorithm [3] cannot fully meet the needs of multi-targets resolution, wide range angle measurement, and multi-path interference suppression in harsh environments [4, 5, 6]. According to spatial spectrum estimating theory, these problems can be well solved by using high-precision, super-resolution spatial smoothing technique based on MUSIC algorithm [7, 8, 9, 10].

The spatial smoothing technique and MUSIC algorithm are all based on the principle of array signal processing, and each has a specific requirement for the design of antenna arrays. According to the characteristics of TLS system, it is more reasonable for one-dimensional linear arrays to measure the azimuth and elevation. Combined with the system's performance, the design scheme and the corresponding performance of TLS antenna arrays were discussed, then, compared them with the uniform arrays in the same condition.

II. TLS ANGLE MEASUREMENT ALGORITHM

To extend the system function and meet the needs of multi-purpose and multi-targets estimation, we can use S mode reply signal [11] shown in Fig. 1 to replace the original 3/A mode replay signal.

The reply data included in the data module follow the 4 replies steering pulses. Every datum is a 1µs "pulse and no-pulse" area. "no-pulse follow a pulse" denotes datum 1, "a pulse follow no-pulse" denotes datum 0.
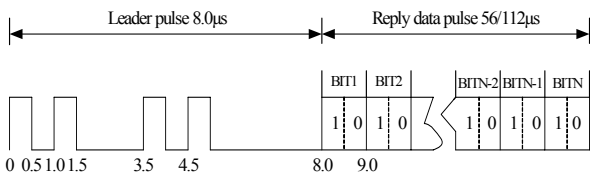
Figure 1. S mode replay signal format

Therefore, the mathematic module of the S mode reply signal can be demonstrated as:

$$s(t) = \sum_{i=0}^{3} \cos(2\pi f_c t) g_\tau (t - t_i)$$
$$+ \sum_{j=0}^{55/111} \cos(2\pi f_c t) g_{2\tau} (t - 8 - j2\tau - \frac{m}{2}\tau) \quad (1)$$

where f_c denotes carrier wave frequency, τ denotes the pulse width, t_i denotes the reply signal steering pulse's time delay. If a_n denotes the reply signal data sequence, m satisfied the equation2:

$$m = \begin{cases} 1, & a_n = 1 \\ 3, & a_n = 0 \end{cases} \quad (2)$$

The working condition of TLS is comparative poor. Due to topographical conditions and the impact of obstacles near the airport, it will be prone to reflection and scattering phenomena, and also form highly correlated multi-path and direct signals at the receiving arrays. At the same time, the landing aircrafts have the same signal formats. The receiving signals also have high correlation.

In order to improve the accuracy of TLS angle measurement and enhance the system's ability to distinguish multiple targets, we can use the spatial smoothing technique based on Schmidt's MUSIC algorithm to obtain the angle information of the aircraft. The basic principle [12, 13] is as follow:
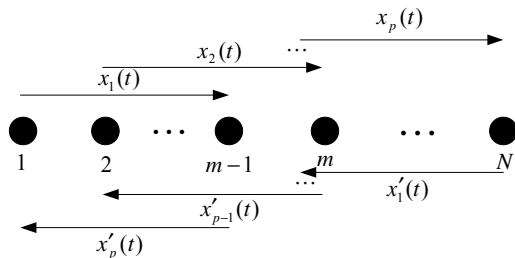

Figure 2. TLS angle measurement spatial smoothing principle

As shown in Fig. 2, if the total number of TLS receiving antenna array element is N and receiving signals is P, and $P < N$, we can divide the N elements antenna array into p sub-arrays, each sub-array has the same array elements number $m-1$. For the forward smoothing, considering the first array element as the reference array element of each sub-array, so the k sub-array data model can be demonstrated as:

$$x_k(t) = [x_k \quad x_{k+1} \quad \cdots \quad x_{k+m-1}]$$
$$= A(\theta) D^{(k-1)} s(t) + n_k(t) \quad (3)$$

where, $A(\theta) = [a(\theta_1), a(\theta_2), \cdots, a(\theta_P)]$ is array direction matrix of incident signals, $a(\theta_k)$ isarray steering vector, $s(t)$ is signal vector, $n_k(t)$ is white noise with the zero mean and variance σ^2, $x_k(t)$ is sub-array output vector.

$$D = \begin{bmatrix} e^{j\frac{2\pi l}{\lambda}\sin\theta_1} & 0 & \cdots & 0 \\ 0 & e^{j\frac{2\pi l}{\lambda}\sin\theta_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{j\frac{2\pi l}{\lambda}\sin\theta_P} \end{bmatrix} \quad (4)$$

Then the covariance matrix of each sub-array is:

$$R_k = AD^{(k-1)} R_S (D^{(k-1)})^H A^H + \sigma^2 I \quad (5)$$

The mean of all sub-array covariance matrixes is the forward smoothing covariance matrix:

$$R^f = \frac{1}{p} \sum_{k=1}^{p} R_k$$
$$= A(\theta) \left(\frac{1}{p} \sum_{k=1}^{p} D^{(k-1)} R_S (D^{(k-1)})^H \right) A^H(\theta) + \sigma^2 I \quad (6)$$

Similarly, the backward smoothing covariance matrix is:

$$R^b = \frac{1}{p} \sum_{k=1}^{p} R_{p-k+1}$$
$$= A(\theta) \left(\frac{1}{p} \sum_{k=1}^{p} D^{-(m+k-2)} R_S^* D^{(m+k-2)} \right) A^H(\theta) + \sigma^2 I \quad (7)$$

Then, the forward/backward smoothing covariance matrix can be demonstrated as:

$$R^{fb} = \frac{R^f + R^b}{2} \quad (8)$$

The characteristic decomposition [14] of covariance matrix R^{fb} is:

$$R^{fb} = U_S \Sigma_S U_S^H + U_N \Sigma_N U_N^H \quad (9)$$

To the characteristic decomposition of R^{fb}, there are P large eigenvalues and corresponding eigenvectors form the signal subspace U_S and $m-1-P$ small eigenvalues and corresponding eigenvectors form the noise subspace U_N, and both orthogonal to each other. The MUSIC spatial spectrum of the reply signals can be demonstrated as:

$$P_{MUSIC}(\theta) = \frac{1}{a^H(\theta) U_N U_N^H a(\theta)} \quad (10)$$

Making spectrum peak searching to equation (10), the peaks correspond to the angles are the azimuths or elevations of the landing aircrafts.

III. TLS ANTENNA ARRAYS DESIGN

To avoid the impact of phase ambiguity [15, 16], DOA estimation technique always adopts uniform equidistant arrays whose baseline is shorter than half wavelength. Actually, due to limitation of spatial location and arrays coupling, non-uniform arrays whose baseline is longer than half wavelength is more available. But, impact of phase ambiguity must be eliminated.

When set the array, assuming array element position is of 0.5λ units, and the array element position vector is $X = (x_1, x_2 \cdots x_N)$, so $X = 0.5\lambda[n_1, n_2, \cdots n_N]$, considering n_1 as the reference point ($n_1 = 0$), n_i is non-negative integer and $n_i > N - 1$ [17].

According to the definition of the steering vector, if the arrays are ambiguity, so has the equation (11):

$$e^{-j\frac{2\pi}{\lambda}x_n \sin\theta_i} = e^{-j\frac{2\pi}{\lambda}x_n \sin\theta_i'} \quad \theta_i \neq \theta_i' \quad (11)$$

Making the logarithm to equation (11):

$$n_i(\sin\theta_i - \sin\theta_i') = 2k_i \quad (12)$$

Where, k_i, n_i are corresponding positive integer. If $\rho = \sin\theta_i - \sin\theta_i'$, equation (12) can be rewritten as:

$$\rho = \frac{2k_i}{n_i} \quad i = 2,3,\cdots,M \quad (13)$$

Because the linear array's angle measurement range is $-90^0 \sim 90^0$, so $|\rho| < 2$, $k_i < n_i$, for each n_i, the equation (14) can exit.

$$\rho_{ij} = \left\{0, \pm\frac{2k_{ij}}{|n_i - n_j|}\right\} \quad k_{ij} < |n_i - n_j|, \ i \neq j \quad (14)$$

If n_i, n_j are prime numbers, the equation (15) can exit.

$$\rho = \{\rho_{12} \cap \rho_{23} \cap \cdots \cap \rho_{M-1,M}\} = \{0\} \quad (15)$$

That is to say, if n_i, n_j are prime numbers, parameter ρ has only 0 element satisfied equation (15), so as $\theta_i = \theta_i'$, the array has no ambiguity.

According to literature [18, 19], we can design the arrays like this:

Assuming the arrays $\Phi_i = \{d_1, d_2 \cdots d_{q-1}\}$ is the i sub-array which constitutes the entire TLS receiving antenna arrays, $i = 1,2,\cdots[(N-1)/(q-1)]$, $[\bullet]$ is integer operation. Then the TLS receiving arrays can be demonstrated as:

$$\Phi = \{\Phi_1, \Phi_2, \cdots \Phi_{[(N-1)/(q-1)]}, d_1, d_2, \cdots d_j\} \quad (16)$$

where, $d_1, d_2 \cdots d_{q-1}$ denotes the length of each sub-array's baseline, and they are mutual primes to each other, $j = (N-1) \bmod p$, p is the number of sub-array elements, N is the number of TLS receiving array element.

To ensure the simple, mobility and flexibility of the system, considering to the system's accuracy, we can respectively use one-dimensional non-uniform linear arrays with 2 sub-arrays and 6 total array elements and one-dimensional non-uniform linear arrays with 2 sub-arrays and 8 total array elements to denote the azimuth receiving antenna arrays and the elevation receiving antenna arrays. So the receiving antenna arrays can be demonstrated as:

$$\Phi_{AZ} = \{\Phi_1 \quad \Phi_2 \quad d_1\} \quad (16)$$

$$\Phi_{EL} = \{\Phi_1 \quad \Phi_2 \quad \Phi_3 \quad d_1\} \quad (17)$$

If $d_1 = 3$, $d_2 = 2$, array (16, 17) can be written as:

$$\Phi_{AZ} = \{3 \quad 2 \quad 3 \quad 2 \quad 3\} \quad (18)$$

$$\Phi_{EL} = \{3 \quad 2 \quad 3 \quad 2 \quad 3 \quad 2 \quad 3\} \quad (19)$$

The sensor position vector is:

$$X_{AZ} = 0.5\lambda[0 \quad 3 \quad 5 \quad 8 \quad 10 \quad 13] \quad (20)$$

$$X_{EL} = 0.5\lambda[0 \quad 3 \quad 5 \quad 8 \quad 10 \quad 13 \quad 15 \quad 18] \quad (21)$$

To reduce the computing complexity and difficulty of project implementation, we can only use the method of inserting 0 elements [20, 21, 22] to transform the non-uniform array (20, 21) into a uniform array to better satisfy the TLS angle measurement algorithm. So the $N = 6$ non-uniform arrays will be transformed into the $N' = 14$ virtual non-uniform arrays and the $N = 8$ non-uniform arrays will be transformed into the $N' = 19$ virtual non-uniform arrays. Then using spatial smoothing to the new virtual non-uniform arrays can realize the function of high-precision angle measurement. The array models are shown in Fig.3 and Fig.4:
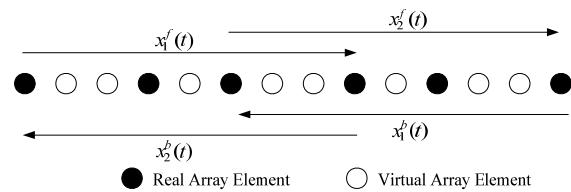

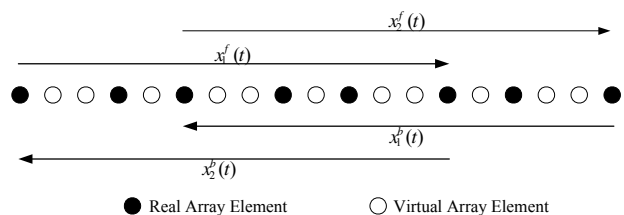**Figure 3.** TLS virtual arrays spatial smoothing model (Azimuth)

Figure 4. TLS virtual arrays spatial smoothing model (Elevation)

The new array steering vector $a_{TLS}^{AZ}(\theta_k)$ and $a_{TLS}^{EL}(\theta_k)$ are:

$$a_{TLS}^{AZ}(\theta_k) = [1,0,0,e^{-j3\beta_k},0,e^{-j5\beta_k},0,0,$$
$$e^{-j8\beta_k},0,e^{-j10\beta_k},0,0,e^{-j13\beta_k}]^T \quad (22)$$

$$a_{TLS}^{EL}(\theta_k) = [1,0,0,e^{-j3\beta_k},0,e^{-j5\beta_k},0,0,e^{-j8\beta_k},0,$$
$$e^{-j10\beta_k},0,0,e^{-j13\beta_k},0,e^{-j15\beta_k},0,0,e^{-j18\beta_k}]^T \quad (23)$$

where $\beta_k = \dfrac{2\pi d \sin\theta_k}{\lambda}$, $k = 1,2,\cdots,P$. The location of the virtual array element is with "0" compensation.

According to Fig.3 and Fig.4, we could firstly use forward/backward spatial smoothing algorithm to the two 9 elements sub-arrays and the two 14 elements sub-arrays respectively. Then the new covariance matrix $R_{TLS\_AZ}^{fb}$ and $R_{TLS\_EL}^{fb}$ can be obtained by taking the new array steering vector $a_{TLS}^{AZ}(\theta_k)$ and $a_{TLS}^{EL}(\theta_k)$ into equation (6, 7, 8). At last, the MUSIC spectrum will display the angles of the aircrafts.

In order to investigate the feasibility of the designed arrays, assumed that there were three aircrafts in close proximity at 5°, 9°, 14° azimuth directions, and the elevation directions were 3°, 6°, 8°, SNR = 10dB, the snapshots was 640. The azimuth and elevation angle estimating results of TLS arrays and ULA with same array element were shown in Fig.5 and Fig.6:
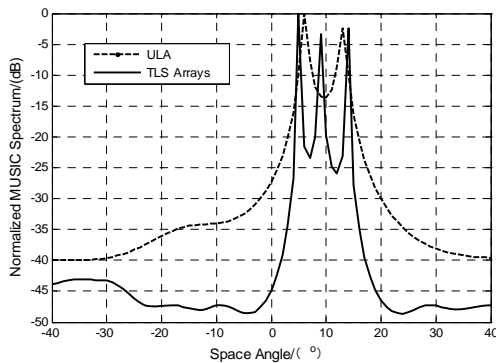
According to Fig.5 and Fig.6, when the aircrafts are in close proximity, TLS arrays can clearly distinguish the azimuth and elevation angles of the aircrafts, while the ULA with same array element can not accurately distinguish the azimuth and elevation angles of the aircrafts. It also shows the feasibility of the designed TLS arrays.

To investigate the effectiveness of multi-targets estimating of TLS arrays: assumed that the azimuth angles of two targets were 10° and 15°, the elevation angles of the two targets were 3° and 6° , the snapshots was 640, set the successful estimation threshold according to TLS accuracy, make 1000 times Monte Carlo experiments on each SNR. The angle estimation successful probabilities of TLS arrays and ULA with the same array element were shown in Fig.7, Fig.8, Fig.9 and Fig.10:
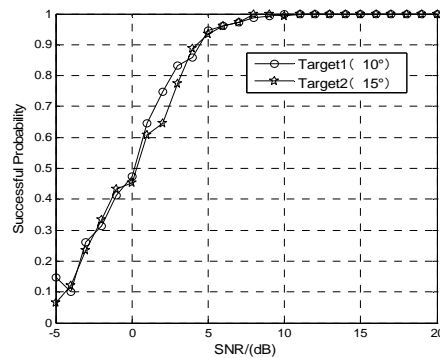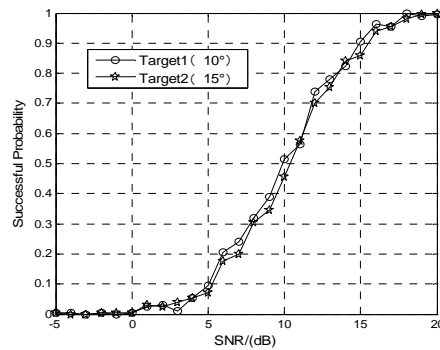

Figure 7. Successful probability of TLS arrays (Azimuth)

Figure 5. Angle spectrum of different array models (Azimuth)

Figure 8. Successful probability of ULA (Azimuth)

Figure 6. Angle spectrum of different array models (Elevation)
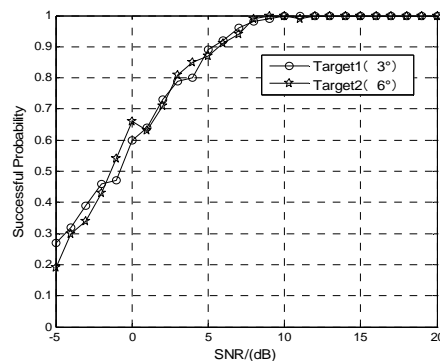

Figure 9. Successful probability of TLS arrays (Elevation)

Figure 10. Successful probability of ULA (Elevation)

Figure 11. Array resolution of different array models (Azimuth)
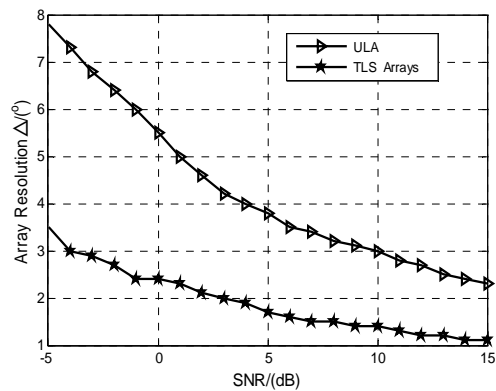
Figure 12. Array resolution of different array models (Elevation)
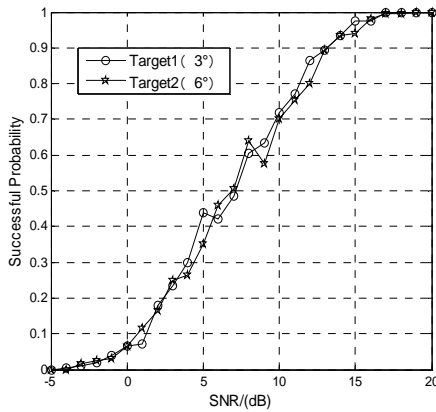
According to simulations from Fig.7 to Fig.10, we can see that the angle estimation effectiveness of TLS arrays is stronger than the uniform arrays with the same array element for multi-targets estimation; it fatherly validated the feasibility of the designed TLS arrays even at a lower SNR.

IV. PERFORMANCES OF TLS ANTENNA ARRAYS

The performances of TLS arrays are mainly scaled by the resolving power, the angle measurement error and mean square error of the antenna arrays.

Array resolution mainly investigates the ability to distinguish two close signals or targets. In the TLS working environment, TLS receiving antenna arrays must need high array resolution because of the requirements of multi-path effects or the approaching of multiple aircrafts at the same time.

If $P(\theta) = a^H(\theta)U_S U_S^H a(\theta)$ is signal spectrum, make the following definitions:

$$P_{pezk} = \frac{P(\theta_1) + P(\theta_2)}{2} \tag{24}$$

$$\theta_m = \frac{\theta_1 + \theta_2}{2} \tag{25}$$

$$Q(\Delta) = P_{peak} - P(\theta_m) \tag{26}$$

where $\Delta = \theta_1 - \theta_2$, if $Q(\Delta) > 0$, $Q(\Delta)$ is distinguished. Δ is the array resolution, smaller Δ means higher resolution.

According to the definition of array resolution, make 1000 times Monte Carlo experiments on each SNR to TLS arrays and ULA with the same array element. The relationship between array resolution and SNR were shown in Fig. 11 and Fig.12. We can clearly see that TLS array resolution is better than ULA with the same array element. At the same time, it reveals that the designed TLS receiving antenna arrays can be better used for precision angle measurement and multi-targets resolution in complex environment theoretically.
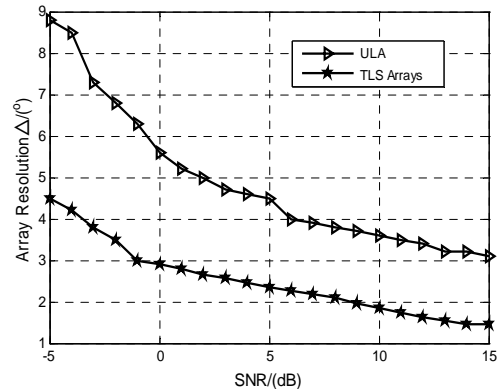
The error and mean square error mainly appraise the accuracy and stability of the receiving antenna arrays. Typically, the angle corresponding to the spatial spectrum peak is not the aircraft real angle θ, but the maximum likelihood estimation angle $\hat{\theta}$. To a certain array model, angle measurement accuracy can be appraised by the angle measurement error γ and the mean square error *RMSE* as the following equations:

$$\gamma_i = \hat{\theta}^i - \theta \tag{27}$$

$$RMSE(\theta) = \sqrt{\frac{1}{L} \sum_{i=1}^{L} \gamma_i^2} \tag{28}$$

where $\hat{\theta}^i$ is the estimated angle at the i time, γ_i is angle estimation error, L is estimation times.

To verify angle estimation accuracy of the designed TLS antenna arrays, according to equation (27, 28), make the following simulations to TLS arrays and the ULA with the same array element: two targets were at 10°,15° azimuth directions and 3°,6° elevation directions, snapshots was 640, make 1000 times Monte Carlo experiments on each SNR. The simulation results were shown in Fig.13, Fig.14, Fig.15 and Fig.16.
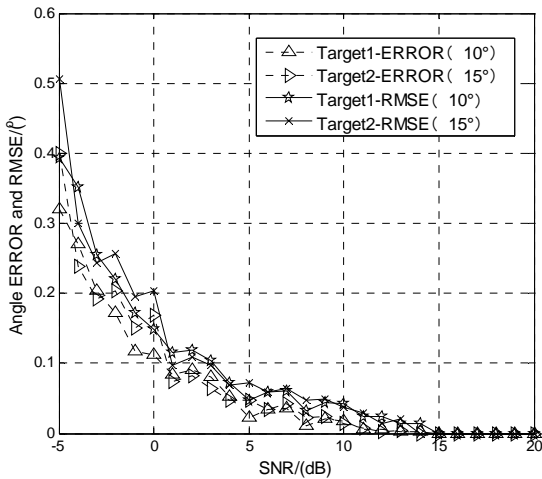
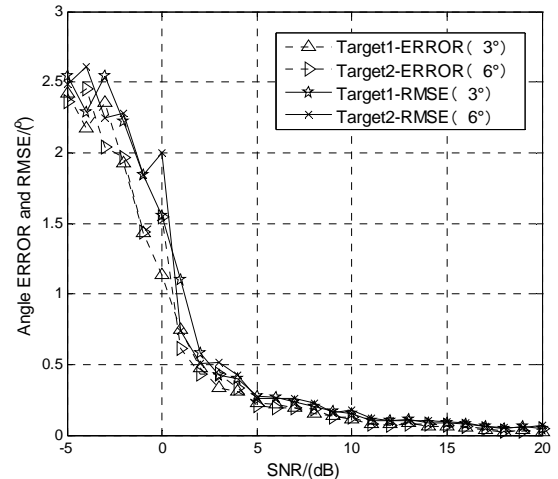**Figure 13.** TLS arrays angle estimating accuracy (Azimuth)

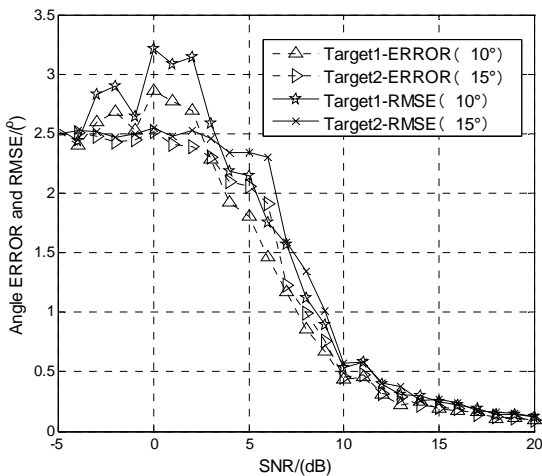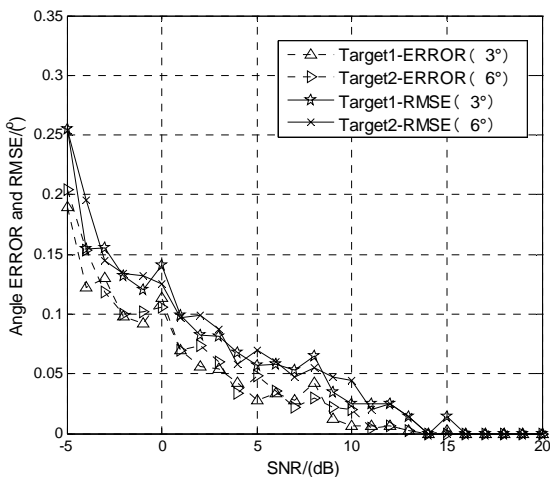**Figure 16.** ULA angle estimating accuracy (Elevation)

According to the simulations from Fig.13 to Fig.16, we can clearly see that the designed TLS receiving antenna arrays have higher estimation accuracy and better effect for multi-targets estimation, and the estimation accuracy has no relationship with the targets angles. It can also carry out the correct angle estimation even at a lower SNR and provide a good theoretical basis to design or realize the system.

Figure 14. ULA angle estimating accuracy (Azimuth)

V. COORDINATE TRANSFORMATION

Measurements of angles and range are derived from signals received by the designed TLS antenna arrays respectively. However, during the period of approaching, the aircraft's position information provided by ground equipment must base on the touchdown point as origin. So, the aircraft's available location data can only be derived after coordinate transformation of the measured information.
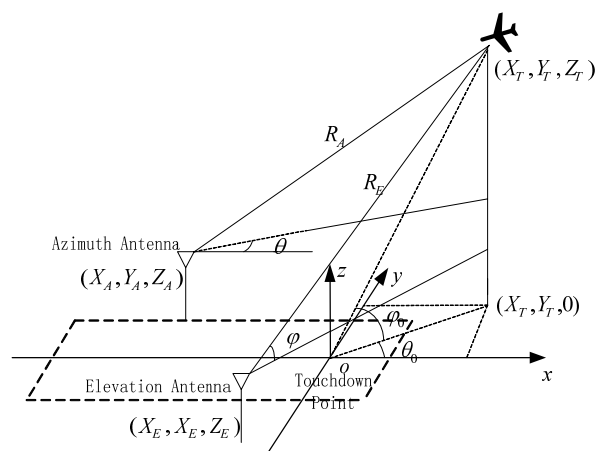
Figure17. Geometry relationship between the aircraft's position and measurements

Figure 15. TLS arrays angle estimating accuracy (Elevation)

The configuration of ground equipment of TLS is very flexible. The Cartesian coordinate system as shown in Fig.17 can be established on touchdown point as origin

[23]. Assumed that the phase centers of azimuth antenna arrays and elevation antenna arrays are (X_A, Y_A, Z_A) and (X_E, Y_E, Z_E) respectively. The position of approaching aircraft is (X_T, Y_T, Z_T).

Based on Fig.17, the aircraft's position equation can be obtained by:

$$\begin{cases} \sin\theta = \dfrac{Y_T - Y_A}{\sqrt{R_A^2 - (Z_T - Z_A)^2}} \\ \cos\theta = \dfrac{X_T - X_A}{\sqrt{R_A^2 - (Z_T - Z_A)^2}} \\ \sin\varphi = \dfrac{Z_T - Z_E}{R_E} \end{cases} \quad (29)$$

where θ, φ denotes the azimuth and elevation measurement respectively; θ_0, φ_0 denotes the azimuth and elevation relatives to the touchdown point; R_A, R_E which can be obtained by ask/answer range measurement algorithm [24] denotes the distance from azimuth antenna arrays and elevation antenna arrays to the approaching aircraft respectively.

Equation (29) can also be expressed as:

$$\begin{cases} Z_T = Z_E + R_E \sin\varphi \\ X_T = X_A + \sqrt{R_A^2 - (Z_E - Z_A + R_E \sin\varphi)^2}\cos\theta \\ Y_T = Y_A + \sqrt{R_A^2 - (Z_E - Z_A + R_E \sin\varphi)^2}\sin\theta \end{cases} \quad (30)$$

So, we can simply obtain the aircraft's angles relative to touchdown according to the geometry relationship in Fig.17:

Azimuth:

$$\begin{aligned} \theta_0 &= \arctan\frac{Y_T}{X_T} \\ &= \arctan\frac{Y_A + \sqrt{R_A^2 - (Z_E - Z_A + R_E \sin\varphi)^2}\sin\theta}{X_A + \sqrt{R_A^2 - (Z_E - Z_A + R_E \sin\varphi)^2}\cos\theta} \end{aligned} \quad (31)$$

Elevation:

$$\begin{aligned} \varphi_0 &= \arctan\frac{Z_T}{\sqrt{X_T^2 + Y_T^2}} \\ &= \arctan\frac{Z_E + R_E \sin\varphi}{\sqrt{(X_A + \sqrt{R_A^2 - R^2}\cos\theta)^2 + (Y_A + \sqrt{R_A^2 - R^2}\sin\theta)^2}} \end{aligned} \quad (32)$$

where $R = Z_E - Z_A + R_E \sin\varphi$.

The objective of coordinate transformation is to utilize the measured azimuth θ, elevation φ and rang R_A, R_E of real time to update the aircraft's real-time spatial location coordinate bases on those equations above.

VI. CONCLUSION

The paper simply introduced the traditional TLS angle measurement principle. According to the requirement of current actual military and civilian airport environment, it used spatial smoothing technique based on MUSIC algorithm to substitute the traditional angle measurement algorithm of TLS. The new angle measurement algorithm was briefly introduced, but the TLS receiving antenna arrays scheme was mainly designed. Then, the paper analyzed the feasibility, effectiveness, array resolution and accuracy of the designed TLS receiving antenna arrays and the ULA in the same condition through computer simulation. It strongly validated the availability and reliability of the designed TLS receiving antenna arrays based on the new angle measurement algorithm. At last, the paper carried out the aircraft's real-time position through coordinate transformation with the measured azimuth, elevation and rang of real time. It also provided the theoretical foundation to design and realize the whole system.

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