Simulation Analysis of Signal Coverage of ADS-B Base Station Based on DEM

Bo Cao¹, Wenping Liu¹*, Liang Zhang¹, Zhihu Tang², Kun Liu³

¹Guang zhou Civil Aviation College, Guang zhou 51040; ²Air Traffic Management Bureau of Middle& Southern Region Hubei CAAC, Wuhan, 430000 ³China Academy of Civil Aviation Science and Technology Beijing 100028

*Corresponding author: liuwenping@caac.edu.cn

Abstract. The most basic requirement is to provide continuous and reliable flight dynamic information for monitoring equipment within the range of air traffic control. ADS-B is the future major surveillance technology determined by the International Civil Aviation Organization. Based on the theory of electromagnetic wave and electromagnetic field, this paper analyzes the influence of space propagation on ADS-B signal coverage. Combined with DEM topography, the sightline range cut-off distance of ADS-B was calculated. The base station antenna is simulated and the antenna radiation performance is calculated. In this paper, the actual application of ADS-B base station signal coverage is simulated and the methods and measures to improve the signal coverage of base station is put forward. According to the experiment results, this method meets the needs of engineering application, has certain practical value, and provides a basis for the site selection of base stations.

Keywords: ADS-B DEM coverage terrain masking.

1. Preface

As an important part of the new navigation system (CNS/ATM) of the International Civil Aviation Organization (ICAO), surveillance technology is the combination of various advanced technologies such as satellite-based positioning and navigation, airborne equipment and ground equipment, etc. It provides required aviation operation situational awareness information for controllers and pilots. Surveillance technology is the foundation of modern air traffic management. Reasonable use of various surveillance technologies can provide more abundant, safe and efficient means of air traffic surveillance. Thus, it can effectively improve the level of air traffic safety, airspace capacity and operational efficiency [1, 2].

ADS-B technology is an air or ground traffic surveillance application. It periodically broadcasts its state vectors, such as horizontal and vertical positions, heights, and other messages. ADS-B is characterized by fast data update, high accuracy and large amount of information. ADS-B system is the main development direction of global new navigation technology. The base station is the core of the system, which can not only receive messages broadcast by aircraft, but also provide Traffic Information Service (TIS-B) and Flight Intelligence Service (FIS-B) to aircraft. Signal coverage of
base station is an important technical index of ADS-B system, which is closely related to flight safety. This paper proposes the simulation analysis of ADS-B base station signal coverage based on DEM, which can effectively improve base station signal coverage and provide basis for base station site selection.

2. Analysis on the influence of space propagation on ADS-B base station coverage
ADS-B operates at a frequency of 1090MHz, belonging to the UHF band. Due to its high frequency, the electromagnetic wave propagates along the ground and is rapidly attenuated due to the absorption of the earth. Electromagnetic wave has weak diffraction ability when encountering obstacles, and cannot reflect back to the ground when projected to the ionosphere of high altitude. Therefore, ADS-B signals can only be transmitted by two modes: line of sight propagation and tropospheric scattering propagation [3]. The scattered signal of tropospheric scattering propagation is weak and requires high scattering communication, such as the use of high-power transmitter, high-sensitivity receiver and antenna with strong directivity, etc. Therefore, line-of-sight propagation is the main mode of ADS-B signal propagation.

2.1. Theoretical calculation of apparent distance propagation
Line-of-sight propagation means that the base station antenna and the airborne antenna can see each other. Since the ground is approximately circular, when the position and height of ADS-B base station are determined, the maximum distance and line of sight that can be reached can be calculated, as shown in Figure 1.

Where, earth radius is \( R_0 \), base station height is \( h_2 \), flight altitude is \( h_1 \), and line of sight distance is \( d \).

\[
d = \sqrt{2R_0 \left( \sqrt{h_1} + \sqrt{h_2} \right)}
\]

In the case of atmospheric refraction \( R_e \) the radius of the earth is substituted by \( R_e = KR_0 \)

\[
K = \frac{1}{1 - \frac{R_0}{R}}
\]

Where: \( K \) is the equivalent earth radius factor, \( R_e \) is the ratio of the equivalent radius of the Earth to the actual radius of the Earth, \( R \) is the radius of the Earth, \( K \) is the radius of the actual ray bending radius, and the average value is around 4/3, and the atmospheric refractive index of time is
usually called the standard refraction. Engineering usually will $K=4/3$. Therefore, the modified realization propagation distance is:

$$d = \sqrt{2R_e (h_1 + h_2)}$$

(3)

The approximate line of sight is:

$$d (km) = 4.12 \left( \sqrt{h_1 (m)} + \sqrt{h_2 (m)} \right)$$

(4)

It can be seen that the line of sight depends on the altitude and flight altitude of the base station. Therefore, terrain and ground objects should be used to raise the antenna mast as much as possible in the actual layout of ADS-B base station.

2.2. Calculation of spatial propagation field strength

On the surface of the earth, the distance between the base station and the aircraft varies, and the field intensity varies. For the convenience of analysis, communication lines are divided into bright area, half shadow area and shadow area according to the distance, as shown in Figure 2 [4].

![Fig 2. communication line partitioning](image)

Assuming that the distance between the transmitting and receiving antennas is $r$ and the line of sight is $d$, then:

1. When $r < 0.7d$, the region is called the bright area, such as point B;
2. When $0.7d < r < (1.2-1.4) d$, the region is called the half shadow area, such as point C;
3. When $r > (1.2-1.4) d$, the region is called the shadow area, like point D.

In the use of line-of-sight propagation, the appropriate antenna height should be chosen so that the aircraft is in the bright area.

As the propagation distance of ADS-B communication system is far, the curvature of the earth must be considered in the calculation of the field intensity. When calculating the receiving field intensity of the antenna, it is necessary to modify the antenna, as shown in Figure 3.

![Fig 3. reflection of the sphere](image)

The equivalent altitude of flight altitude and base station antenna is:
Where, $R_0$ is the radius of the earth (6371km). Due to the diffusion effect of the sphere, the reflection coefficient of the radio waves on the sphere is smaller than that on the plane. Therefore, the diffusion factor is defined, whose value is less than 1:

$$R_d = \frac{1}{\sqrt{1 + \frac{2d/d_1}{KR_0(t_1 + t_2)h_1} \sqrt{1 + \frac{2d/d_2}{KR_0(t_1 + t_2)h_2}}}}$$  \hspace{1cm} (6)$$

By combining the geometric parameters and diffusion factors on the path, the resultant field strength in the bright region can be obtained:

$$E = \frac{173 \sqrt{\frac{PG}{R_0}}}{\sqrt{1 + \frac{R_d^2 - 2R_0 \cos(4\pi h'_1 / \lambda r)}}}$$  \hspace{1cm} (7)$$

Where, $P_t$ is the transmitting power in unit of kw, $G_t$ is the antenna gain in unit of km, $E$ is mV/m, $\lambda$ is the working wavelength in unit of m. Due to the diffusion of reflected waves, the reflected field at any point in space becomes weaker or stronger.

The field strength effective value of the direct-fire wave is:

The effective value of field strength of direct wave is:

$$E = \frac{173 \sqrt{P_t G_t}}{r}$$  \hspace{1cm} (8)$$

3. Visual range model based on DEM

The relief of terrain and the shelter of ground objects have a great influence on the coverage area. Therefore, the site selection of base station must consider the real terrain factors. The shielding Angle refers to the minimum Angle of the aircraft to be found at a certain azimuth, as shown in Figure 4. Among them, the aircraft corresponding to the shelter Angle may not be detected by the terrain shielding, and the shelter Angle is the reference shelter Angle of this azimuth. The other two aircraft have no ground objects shielding.

**Fig 4.** Terrain masking

The slope determination method is consistent with the characteristics of ADS-B system, and only the shielding angle in a specific direction needs to be calculated:
\[ \theta_i = \arctan \left[ \frac{h_i - h_s}{d_s} - \frac{d_s}{2R_s} \right] \]  

(9)

Where, \( h_i \) and \( d_s \) are respectively the altitude of a certain point on the surface and the oblique distance to the base station, \( h_s \) are the antenna height of the ground station, and \( R_s \) are equivalent earth radius (8496km). The maximum value of \( \{ \theta_i \} \) serves as the reference shielding Angle \( \theta_o \).

The factor of radio wave diffraction should be considered in practical application. Only by taking the elevation angle of the wave ray when the diffraction factor is equal to 1 as the revised shielding Angle can the influence of the obstacle on the wave ray shielding be reflected objectively. According to the law of radio wave diffraction, the revised value can be calculated by the following formula:

\[ \Delta \theta = 31.6 \sqrt{\frac{\lambda}{d_{\text{max}}}} \]  

(10)

Where, \( \lambda \) is the wavelength and \( d_{\text{max}} \) is the oblique distance.

By integrating (8) and (9), it can be calculated that the modified shelter angle of ADS-B for the specified directional terrain is:

\[ \theta_s = \theta_o + \Delta \theta \]  

(11)

Using the modified shielding Angle calculated by Formula (10), the cut-off distance of the line of sight in all directions is calculated as follows:

\[ R(\theta) = \sqrt{\left( R \tan \theta \right)^2 + 2R_s(h_i - h_s) - R_s \tan \theta_i} \]  

(12)

4. Radiation Performance of ADS-B Base Station Antenna

In China, ADS-B mainly applies the 1090 ES data link. Its communication mode is very similar to the secondary surveillance radar, and its signal propagation distance is directly related to the antenna parameters, as shown in Formula (13). Where, \( R \) is the signal propagation distance, \( \theta \) is the antenna elevation Angle, \( P_t \) represents the transmitting power of ADS-B antenna, \( P_r \) is the power of its receiving antenna, \( G_t(\theta) \) is the gain of the transmitting antenna in the direction of elevation Angle \( \theta \), \( G_r \) is the gain of the receiving antenna, and \( L_{\text{prop}} \) is the loss caused by the signal in the process of propagation [5].

\[ R(\theta) = \frac{\lambda}{4\pi} \sqrt{P_t G_t(\theta) G_r P_r^{-1} L_{\text{prop}}^{-1}} \]  

(13)

The antenna of the ground station is composed of a double cone linear array antenna. The ADS-B antenna is modeled and simulated. The parameters are as follows: number of formations: 16; Spacing: 10 mm; Cone Angle on the antenna: 45 degrees; Antenna lower cone Angle: 30 degrees; Cone length: 60 mm, as shown in Figure 5.
Without considering the atmospheric dissipation, the simulation results of antenna radiation distance in free space are shown in Figure 6 and Figure 7.

![Fig 6. Relation between elevation Angle and radiation distance](image)

It can be seen from the simulation figure that in an ideal space, the coverage distance varies with the different height and elevation Angle. In China, civil air routes mostly focus on the altitude level of about 10,000 meters. Therefore, we focus on the 0 to 15 kilometers in the ordinate of the figure above, whose corresponding propagation distance (oblique distance) is 350 to 400 kilometers. Taking into account energy dissipation and vertical distance (antenna performance constraints only), the signal coverage radius of a standard ADS-B ground station is approximately 360 km.

5. Experimental simulation
ADS-B base station is arranged in E97°30’25” and N37°30’28”, and the base station topography is shown in Figure 8.
Fig 8. Base station topography

It can be seen from Figure 8 that the base station is surrounded by mountains. Combined with DEM data, the shielding Angle around the base station is calculated, as shown in Figure 9.

Fig 9. Analysis of shelter Angle

According to formula (12), the shielding Angle in each range is calculated. The cut-off distance of the shielding Angle in the interval First, in the range of [0, 30°], [330°, 360°], the shielding Angle reaches $d_1 = 50$ km at about 5°. Second, when the occlusion Angle in the [60°, 240°] interval exceeds 10°, the severe occlusion cut-off distance is only $d_1 = 25$ km; Third, in the range of [240°, 300°], the shelter Angle is less than 1° and the cut-off distance reaches $d_1 = 338$ km. It can be seen that the blocking of ground objects has a great influence on the visual cutoff distance.

The working frequency is 1090 Mhz and the wavelength is 0.2752m. The height of the base station is 20m and the flight height is 7500m. Both the base station and the airborne antenna are omnidirectional antennas with vertical polarization. The transmitting power of the base station is 10W and the gain is 10dB. In the engineering calculation, the antenna feeder loss, nodal loss, atmospheric attenuation and lens loss are 6dB. The minimum radio signal field intensity of the base station in the effective coverage range is 85 mV/m [6, 7].

Referring to formula (4), the maximum distance of line-of-sight propagation is:

$$d_z = 4.12(\sqrt{20} + \sqrt{7500}) = 375 \text{km}$$

Referring to formula (12), the maximum coverage distance of communication is:

$$d_1 = \frac{173\sqrt{P_G}}{E_{\text{min}}} \approx 407 \text{km}$$
According to formula (13), the antenna free radiation distance is $d_4 = 360 \text{km}$.

By comparing the above four distance in $360^\circ$, the minimum value $R = \min \{d_1, d_2, d_3, d_4\}$ can be taken to calculate the final coverage effect of the height layer of 7500m as shown in Figure 10. Where, $90^\circ$ is due north, the longest distance reaches 337km, and the cut off distance is only 25km due to the influence of terrain.

![Figure 10. Final overrides](image)

Based on the above analysis, the base station can only effectively monitor the aircraft at the position of $[240^\circ, 300^\circ]$. Other positions are covered by the terrain, which limits their coverage and affects the continuity and reliability of monitoring in the actual layout station. Considering the complicated terrain, inconvenient maintenance and data transmission, this location is not suitable for base station.

6. Conclusions
This paper analyzes the signal coverage analysis method of ADS-B base station based on DEM. The theory of space propagation is analyzed and the apparent distance and communication distance are calculated. Based on DEM terrain, the distribution of shadow Angle is simulated and the line-of-sight cutoff distance is calculated. ADS-B antenna is simulated and the free space radiation distance is calculated. Therefore, ADS-B base station coverage is calculated based on the above analysis. The experiment shows that the method fits the reality and can guide the base station effectively.

References
[1] Puricer P, Kovar P. Estimation of parameters for ground ADS-B radio channel model [C]. International conference radioelektronika, 2015: 199-202.
[2] WANG Ershen CONG Xiaolin XU Song PANG Tao QU Pingping ZHAO Weiping XIANG Song. Implementation of a BDS Portable Terminal Based on ADS-B Message. Telecommunication Engineering [J]. 2020,060(002):229-233.
[3] Caobo Liu Wen-ping Shen Xiao-yun. Modeling and Simulation of Aviation Wireless Channel [J]. Electronics Optics & Control, 2015,000(005):93-96.
[4] Song Wei Lou Liang. Influence Analysis of Sea Surface Multipath Effect on Radar Detection Capability. Computer Measurement & Control [J].2018 ,026(006): 110-112,125.
[5] Cao B,Liu W P,Li C S,Liu K. Application of AGA in Optimal Embattling of ADS-B [J]. Electronics Optics & Control, 2015,022(006):81-85,102.
[6] Liu W P,Cao B,Liu Z G,Tang Z H. Simulation Analysis to Influence of Irregular Topography on ADS-B Ground Station Signal Coverage[J]. Electronics Optics & Control, 2016,023(006):84-89.
[7] Shen X Y, Cao B,Zhang S Y,Jiao W D. Open Area ADS-B Ground Station Signal Coverage Simulation Analysis [J]. Computer Simulation, 2015, 032(003):94-99.